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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
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"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 book presents a new model that explicitly accounts for the interactions between the economy and the biosphere; that accounts for capital that has accumulated in the economy; and the

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

[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).

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 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

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

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

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

> 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] 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

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

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 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

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[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]

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 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)

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[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.

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).

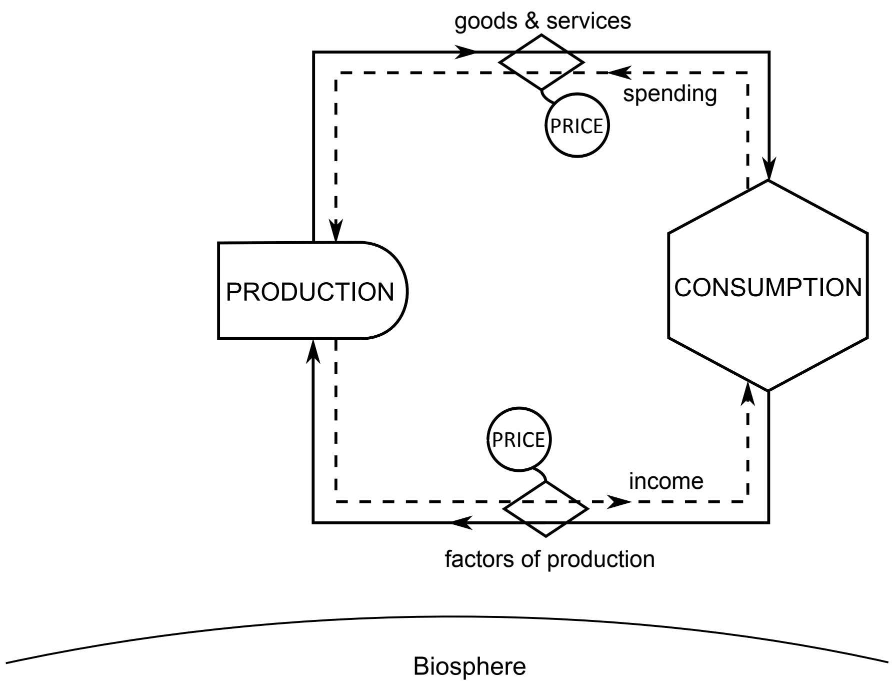

Fig. 1.1 In the traditional model, the economy is represented as a circular flow of goods and services between two sectors. The producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers.

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

[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]

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, 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]

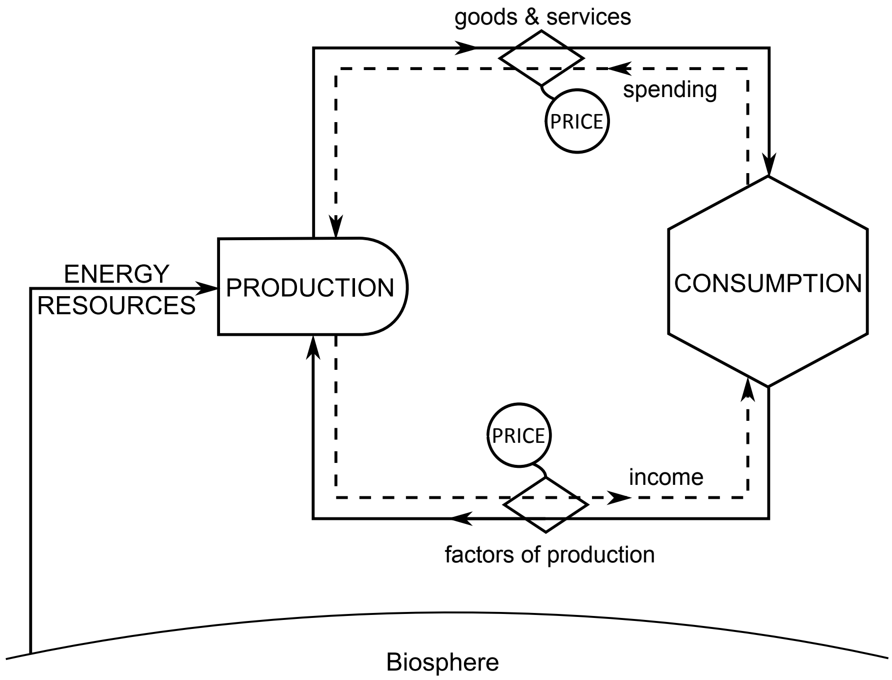

Fig. 1.2 The machine model of the economy includes flows of energy into the economy from the biosphere. This may be considered a perpetual motion machine of the second kind.

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

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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.

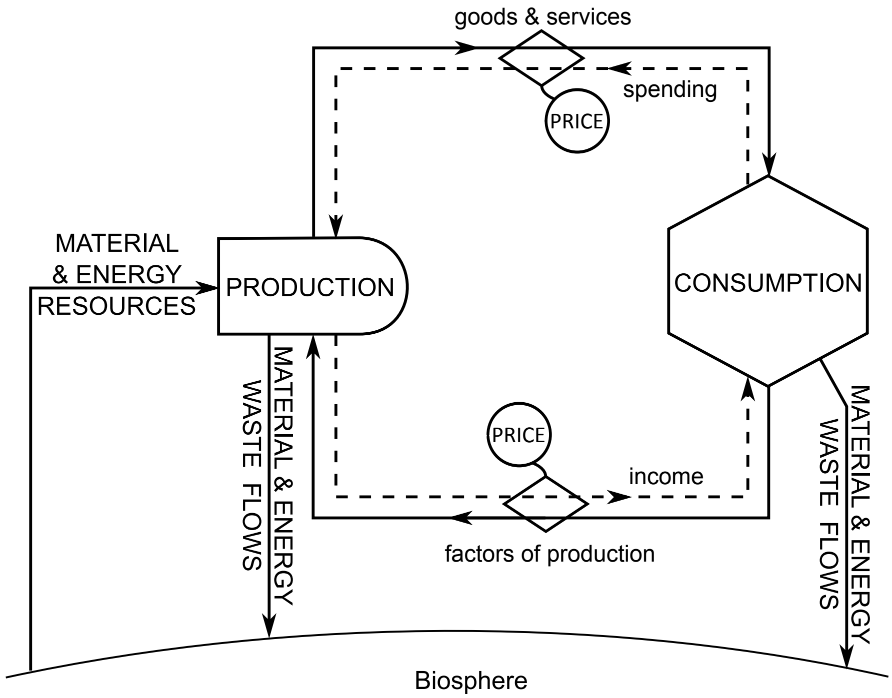

Fig. 1.3 The metabolism model provides a comprehensive view of the economy, fully consistent with the laws of thermodynamics, including degraded resources (waste) expelled to the environment as a necessary consequence of economic activity.

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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Part I
Material and Energy Flows

Chapter 2
Material flows

Well, I have my rights, sir, and I'm telling you I intend to go on doing just what I do! And, for your information, you Lorax, I'm figgering on biggering and BIGGERING and BIGGERING and BIGGERING. . . [1]

—The Once-ler

In Chapter 1, we put forward the idea that the economy is society's metabolism. This chapter explores this idea further by observing the interchange of materials *within* an economy, as well as exchanges of materials between an economy and surrounding environment—the biosphere.

There are many easily observable instances of material accumulations within an economy. A typical office contains a computer screen, coffee cup and myriad other items. Beyond the window, there is a street and building opposite.

There are also innumerable material flows caused by an economy that most of us do not observe. The extraction of raw materials generates additional overburden—earth that must be extracted and processed and ultimately discarded without ever entering the economy proper. Other flows occur around us unseen. The cars outside in the street suck in nitrogen and oxygen (without which the engine would not work) and emit water, carbon dioxide, and other, more harmful, wastes.

Even services that we consider "non-material" require at least some material infrastructure. The hairdresser requires scissors (and to a greater or lesser extent some hair) with which to work. Even the internet, often lauded as the exemplar of dematerialization of the economic process, requires a whole host of infrastructure including uninterrupted electricity, data servers, telephone networks, and a computer by which to access it.

It almost goes without saying that all materials within the economy (the *econosphere* [2]) started their "lives" within the biosphere, be they food, water or paper, petroleum or rock. In fact, the economy is in a continual state of material exchange with the surrounding environment; raw materials are pulled in wastes are emitted. It is this exchange that intimately couples the two spheres, intertwining their mutual fate.

As discussed in the Preface, researchers are beginning to quantify these material exchanges. Further work, such as that by the United Nations Environment Programme (UNEP) International Resource Panel (IRP), is attempting to measure the total stock of materials within society.[3] Over the past two centuries, human demand for materials has increased at a phenomenal pace. This demand has driven ever increasing extraction of raw materials from the biosphere. Production of all materials increased from around 12 Gt (10^9 t) to around 35 Gt in the period 1945-1980 and up to 68 Gt by the year 2009.[4] That is, the flow of materials into the economy from the biosphere has grown over five-fold since the end of the Second World War and has doubled in the last thirty years. But what has driven this incredible growth?

An obvious answer to this question is population. The global population has increased by a factor of nearly three during the post-war period.[5] More people obviously leads to greater demand. Living standards have also increased, leading to still greater demands for material possessions. The UNEP-IRP report, *Metal Stocks in Society* estimates that if the global in-use per capita stock of metals were to increase to the level of industrialized nations, the total stock might be 3-9 times the present level.[3]

**** MCD - try to reduce treadmill logic to fewer bullet points **** **** MCD - done this. Becky, does the footnote look better now? ****

A less obvious answer comes from social science. In 1980, Schnaiberg [6] introduced the concept of the "treadmill of production" to describe the systemic process of ever-increasing capital investment (and thus demand for materials) inherent in capitalist society.[1] The treadmill leads to "higher and higher levels of demand for natural resources for a given level of social welfare".[7, p.297] The treadmill of production is evident today, driving up demand for many commodities. From an economic stand-point we may view the treadmill as the strive for productivity in factors of production. In the substitution of capital for labor, total factor productivity is increased. The substitution increases the requirement for natural resources (particularly energy to drive the capital equipment), but these are assumed to be "free" within economic models, hence do not count towards productivity; the substitution gets a free productivity boost from nature.

But what about the downstream effects of this increased materials extraction? Obviously all of that "stuff" has to go somewhere. As our economies pull in more materials from the biosphere, so too do they expel more wastes, leading to an increase in total throughput of materials. As we pointed out at the start of this chapter, not all materials flow straight through the economy. They accumulative as objects: buildings, cars, and even people.

When accumulation is not accounted for, the assumption is that all flows in and out balance instantaneously. Imagine a bath tub where the water flowing in through the tap is exactly balanced by the water flowing out the plughole. The state of the system (the amount of water within the bath) is fixed—therefore we say the system is in steady-state. Or, imagine a growing baby. The inputs of food and other materials,

[1] The logic of the treadmill is:
1. capital (production equipment) is accumulating in Western economies, to replace production labor with technologies to increase profits;
2. these technologies require far more materials and/or energy to replace previous, labor-intensive processes;
3. moreover, unlike the prior use of labor, the new technologies represent forms of sunk capital;
4. because worker inputs can more readily be cut back (as opposed to fixed costs of machine operations for sunk capital) labor is further reduced to sustain production at higher levels;
5. yet more capital is added to replace further reduced levels of labor. [7, p.296]

though small compared to an adult, exceed the output of excreta (gas, solid, and liquid). While this may be hard for new parents to believe (how can there be possibly be more going in than is coming out!), it is simply this imbalance that induces the growth of the baby. Materials accumulate within the baby's body. Obviously, this imbalance (and the subsequent growth induced) slows as the child grows up to adulthood. Nevertheless, adults still maintain the ability to accumulate materials. We can gain (or lose) weight; a fact to which any yo-yo dieter will readily attest.

Both population and capital equipment are stocks; accumulations that have built up over time. We contend that stocks are the drivers of demand, of flows of materials. People demand food, clothing, shelter, all of the basic necessities of life, as well as all of the trappings of modern life; buildings, vehicles, and computers. The delivery of all of these material wants requires capital equipment; more stocks which also have needs. They require flows of materials and energy to build, operate and maintain them. This is why we assert that, in order to properly understand the economic structure and the real drivers of change, we must understand the accumulation of materials within our economies.

In the rest of this chapter, we will define a mathematical accounting framework to track the flow and accumulation of materials within an economy, building from a one-sector economy up to examples of both two- and three-sector economies. We will finally apply this framework to the illustrative example of the US automobile industry that runs through the whole book. First, we outline the basic methodology.

2.1 Methodology

This book is about tracking (accounting) flows through the economy with a focus on counting materials, energy, and value. That an entire academic discipline and industry are focused on counting money ("accounting") is evidence of its importance in today's economies. That energy is required to do *anything* is evidence of its importance in the economic activity of our daily lives. And, we believe that the interplay between money and energy has shaped the past and will continue to influence the future. In this section, we define rigorous "counting" methods that will be applied to materials, energy and money throughout this book.

2.1.1 Accounting in everyday life

We all count material (and non-material) stocks and flows every day, be it the people in a room, the gasoline we consume on our way to work, or the money in our bank account. Rigorous counting at the scale of whole economies requires precise definition of *what* we will be counting, as well as both *when* and *where* we will be doing the counting. Engineers often call the spatial definition a "control volume." Another way to think of creating a control volume is drawing a boundary. What gets counted is what passes through the boundary. For example, we may wish to count (or "make an accounting of") the stock of apples in our home over the course of a week. We draw a spatial boundary (control volume) around our house and a temporal boundary "around" the week. We count the apples that enter and leave our home, any apples that are eaten (consumed), and, if we own an apple tree (lucky us!), apples that are grown (produced) during a week. A rigorous apple accounting equation, in units of apples, is:

$$\Delta\text{apples} = \text{apples in} - \text{apples out} + \text{apples grown} - \text{apples eaten}. \tag{2.1}$$

More generally, we may say:

$$\text{accumulation} = \text{transfers in} - \text{transfers out} + \text{production} - \text{consumption}. \tag{2.2}$$

Notice that, when discussing apples we use the specific terms "grown" and "eaten," instead of the more general terms "produced" and "consumed." Later, in Chapter 5, when discussing economic value, we will use the terms "generated" or "added" and "destroyed." For our purposes, these terms all have equivalent meanings and we use them interchangeably.

After accounting for the stock of apples in a week, we can reframe the question to ask, "at what rate does the stock of apples change $\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)$?" That is, we can examine the rate of change of the apple stock per unit of time relative to the flow of apples ($\dot{a}$), in which case our accounting equation becomes:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \dot{a}_{in} - \dot{a}_{out} + \dot{a}_{grown} - \dot{a}_{eaten} \tag{2.3}$$

where the dot above the variable ($\dot{a}$) indicates a flow rate per unit time [apples/time] and the time derivative $\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)$ is the rate of change of the stock of apples per time unit, or more simply, the accumulation rate.

Instead of focusing on apples as our unit of accounting, we could track the mass flow (in units of mass per unit time, for instance [kg/sec]) of the main chemical elements within the apples. From this perspective, although an *apple* may be consumed, the *elements* of which the apple is composed—hydrogen, oxygen (coupled together as water to form the overwhelming majority of the mass), and carbon (which, bonded with hydrogen as carbohydrates make up most of the remaining mass)—are *not* consumed. They flow through the consumption process unaffected. The chemical elements will instead be either stored within our body, leave the house as waste (in the apple core), remain in the house (stored within the apple seed that rolled under the sofa) or, eventually, leave via the air (as carbon dioxide and water vapor) or otherwise (as excreta) after they have been metabolized.

If, instead of a home, we drew a spatial control volume around a sector of an economy, similar accounting methods can be applied. In fact, throughout this book, we will illustrate theoretical concepts with a running example of a control volume (boundary) around the US auto industry. If we account for steel (in units of kg) in the auto industry, we might write an equation like this:

$$\Delta\text{steel} = \text{steel in} - \text{steel out} \tag{2.4}$$

Note that the production and consumption terms are zero since steel is not created or destroyed within the automobile sector. Tracking the rate flows of steel, $\dot{s}$ (in kg/s), we would write the following equation:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = \dot{s}_{in} - \dot{s}_{out} \tag{2.5}$$

Again, the last two terms (representing steel production and consumption) are not present. This is in direct contrast with apple accounting outlined in Equation 2.3. Despite the fact that steel is neither produced nor consumed within the *automobile sector*, there *are* sectors of the economy that *do* produce steel, by mixing molten iron with varying amounts of carbon. The flow of steel through an economy illustrates that although economic products (steel) may be produced or destroyed, the mass flows of *elemental materials* (iron and other chemical elements) is unaffected even as the structure changes form (e.g. from iron to steel) through the many economic processes.[2] In fact, we may go further. Every act of economic production has an associated act of consumption or destruction. Indeed, within the car industry, inputs of steel, glass, plastic, rubber, etc. are *consumed* in the very process of producing cars, such that *cars* are (literally) *created* within the automobile industry. You can't make an omelet without breaking a few eggs; you can't make a car without consuming a few sheets of steel. An accounting equation for cars within the economy must include terms for production and destruction[3] of cars. Again, focusing on mass flows of the chemical elements avoids this necessity, because mass is *conserved* in physical processes. Any mass entering a control volume (transfer in) must go somewhere, whether it stays within the volume (accumulation) or is transferred out. Conservation of mass is expressed in equations such as the ones above for apples in a home and steel in the auto industry.

Another important conservation principle is the conservation of energy. Similar to the principle of the conservation of mass, the First Law of Thermodynamics says that *energy can neither be created nor destroyed*. In the discussion that follows (Chapters 3 and 4 in particular), we will make great use of the First Law. If I eat an apple, it is no longer an apple, but the materials (i.e. chemical elements) and energy contained within the apple can still be traced via their elemental mass and energy, even if they change form (apples into compost or chemical potential energy into thermal energy). Thus, the apple accounting equation (Equation 2.3) can include

[2] For the sake of absolute rigor, we must point out that, in actuality, iron *is* created within the core of silicon-burning stars. Mass and energy may also be converted in such processes, such that only mass-energy is conserved. However, for the purposes of terrestrial processes, the total mass (in kg) of iron (Fe) is constant. There are, additionally, some economic processes, within nuclear reactors, that change the atomic structure of elements and thus violate the accounting law presented here. Because the mass flows involved with these nuclear plants is negligible compared with total materials flows, we shall assume that the mass of elements are conserved for this book.

[3] In economic terms, destruction of physical goods is often called "depreciation." We shall explore the importance of and distinctions between physical depreciation and economic depreciation in Chapters 4–7.

terms accounting for the production and consumption of apples. However, mass and energy accounting equations *never* include terms for the production or destruction of mass or energy. Rather, any addition of material or energy *into* the economy or discharge of waste material or energy *from* the economy occurs as an interaction between the economy and the biosphere. This chapter, as well as Chapters 3 and 4, cover mass and energy accounting for economies. Accounting for economic value, in contrast, *requires* terms for both the creation and destruction of economic value, as discussed in Chapter 5.

2.1.2 Product, resource, short-lived, and capital flows

When applying accounting equations to economic sectors, we distinguish among four types of materials flowing into or out of a production sector: products (P), resources (R), short-lived goods (S), and capital goods (K), as shown in Figure 2.1.

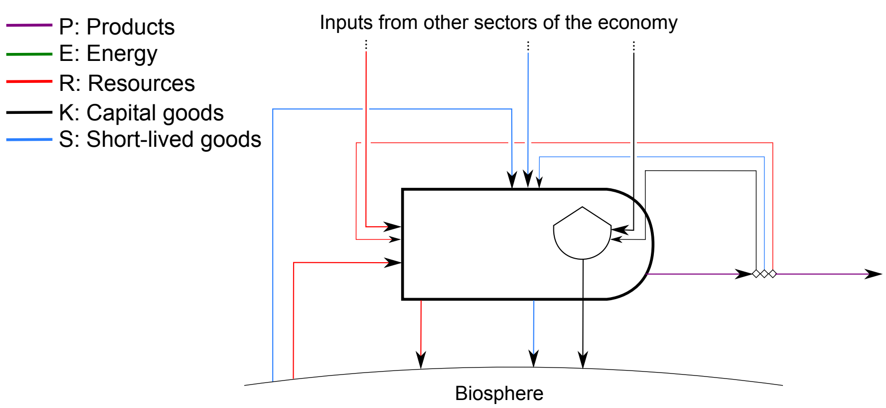

Fig. 2.1 Material flows into and out of a single sector of the economy. Resource flows ($\dot{R}$) enter the sector from the left and are embodied in products ($\dot{P}$) which leave from the right. Some waste resources are leave the sector at the bottom and are returned to the biosphere. Short-lived material flows ($\dot{S}$) enter the sector from above and leave from below to return to the biosphere. Only capital stock ($\dot{K}$) may accumulate within the sector, depicted by the storage tank. These also enter the sector from above. Depreciated capital leaves the sector from below and is returned to the biosphere.

Resource materials ($\dot{R}$) enter the sector from the left. They comprise those materials that are destined to be *embodied* in the goods produced by the sector ($\dot{P}$), which leave from the right, except for some proportion that is wasted. All wastes depart from the bottom of the sector and are returned to the biosphere. For example, sheet metal, rubber, and glass (as well as many other materials) enter the automobile sector as resources and end up as material parts of the cars that are produced. Some fraction of these resources ($\dot{R}$) may not make it into the final product, such as trimming scrap from metal parts stamping, and may be either recycled internally, or wasted to the biosphere. In this material accounting framework, resource materials are not accumulated within a sector.

Short-lived goods ($\dot{S}$) include those materials that are necessary for the production processes of a sector, but are neither accumulated within the sector, nor destined to be materially part of the product of the sector. They enter the sector from above and leave the sector from below to return to the biosphere. Examples of these short-lived flows include energy resources, such as the electricity needed to run automobile factories and process water used by the sector. Resources and short-lived materials make up Georgescu-Roegen's "flow" elements[4] [8] or Daly's "material causes." [9]

Many of the material flows into the sector, such as production equipment, are necessary for the continued operation of a sector but are not counted as short-lived goods, because the operation of the sector is dependent upon the accumulation of these materials within the sector. Such flows are counted as capital goods (K). Capital flows ($\dot{K}$) also enter from above, but are stored within the sector (represented by a storage tank) and are returned to the biosphere as physical capital depreciation. Examples of these capital flows would be the factory and office buildings or manufacturing equipment within the automobile industry. We assume (for simplicity) that there is no re-use of capital stock by other sectors of an economy, e.g. resale of vehicles or other equipment after depreciation, or recycling of material from capital stock into other goods, e.g. scrap metal. The issue of recycling is discussed in greater detail in Section 7.4.

All products ($\dot{P}$) leave to the right of the sector. A fraction of the $\dot{P}$ flow may be returned to the sector as self-consumption, accounted either as resources destined to be embodied in the product ($\dot{R}$), as short-lived materials ($\dot{S}$), or as capital goods ($\dot{K}$). The remainder flows to other sectors within the economy or to Final Consumption (1). In this material accounting framework, energy may be accounted as either an $\dot{R}$ flow or an $\dot{S}$ flow. An example of energy as an $\dot{R}$ flow is crude oil to be converted into gasoline within a refinery: the resource inflow (crude oil) is *literally* embodied within the out-flowing product (gasoline). An example of energy as an $\dot{S}$ flow is electricity used by an automobile factory: the resource inflow (electrons) is not embodied *literally* in the out-flowing product (automobiles). Similarly, the coal or natural gas flowing into a power plant is accounted as an $\dot{S}$ flow, because the incoming chemical elements (carbon and hydrogen) *do not* depart the plant as the product. (The product of a power plant is electrons that "travel" through electricity transmission lines.) We also set up another material flow, that of *wastes* ($\dot{W}$) which include both resource and short-lived goods flowing to the biosphere from sector j, such that:

$$\dot{W}_{j0} = \dot{R}_{j0} + \dot{S}_{j0} \tag{2.6}$$

This waste flow will be useful later in Section 4.4. We now track these material flows through some model economies.

[4] In fact, Georgescu-Roegen does not make a distinction between resource flows (that are *physically embodied* in the product) and other flows necessary to support production of the product.

2.2 Example A: single-sector economy

Our first example looks at the case where all processes within the economy occur within one sector—Society (1)—which exchanges materials with the Biosphere (0) as depicted in Figure 2.2.

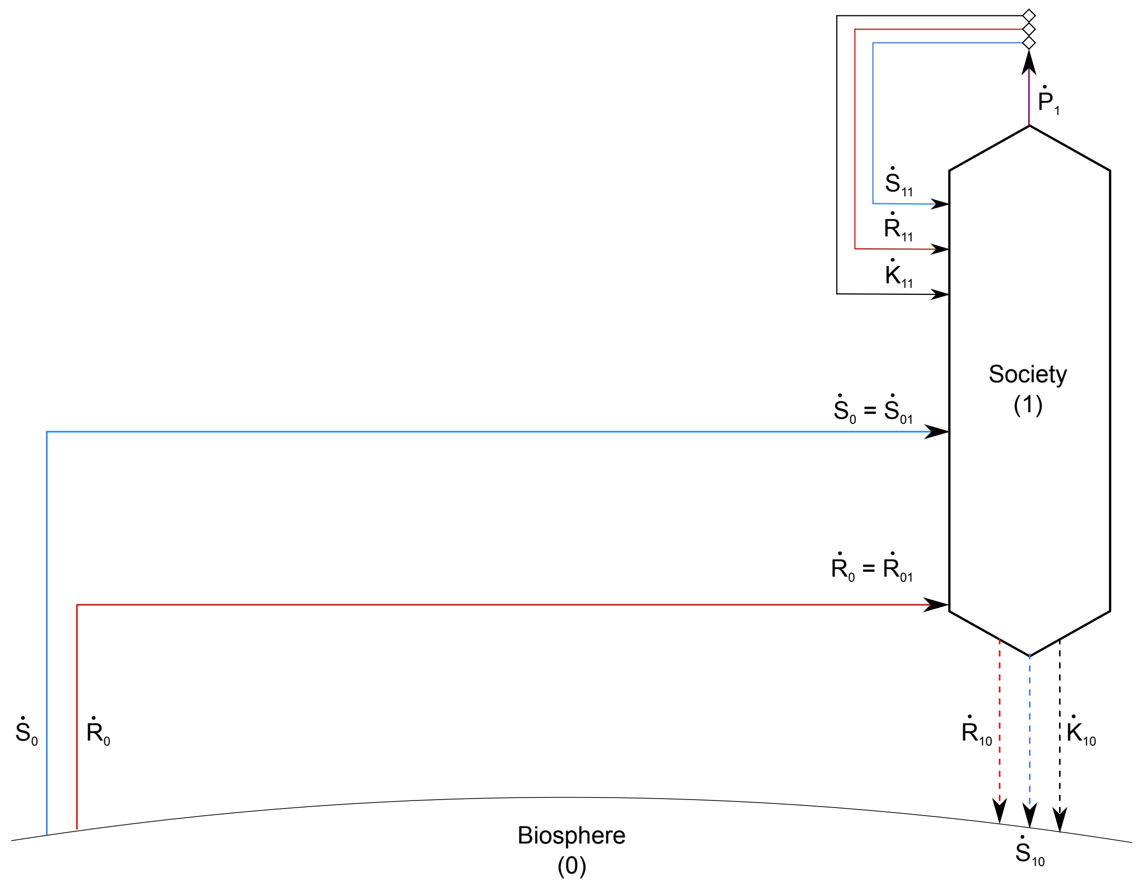

Fig. 2.2 Flows of materials for a one-sector economy. Resources ($\dot{R}_{01}$) and short-lived materials ($\dot{S}_{01}$) flow into the Society (1) from the Biosphere (0). Waste resources ($\dot{R}_{10}$) short-lived materials/goods ($\dot{S}_{10}$) and capital goods ($\dot{K}_{10}$) are returned to the biosphere.

Resources, or perhaps more accurately raw materials ($\dot{R}_{01}$), such as crude oil or iron ore, and short-lived materials ($\dot{S}_{01}$), such as oxygen or water that flow *through* economic processes but are not literally *embodied* within the output, flow into Society (1) from the Biosphere (0).[5] These materials are processed within the economy into products ($\dot{P}_1$) consisting of resource goods ($\dot{R}_{11}$), short-lived goods ($\dot{S}_{11}$), and capital goods ($\dot{K}_{11}$) which are able to be accumulated at some rate $\frac{\mathrm{d}K_1}{\mathrm{d}t}$ within the stock of materials within society.[6] Waste resources ($\dot{R}_{10}$) and used short-lived materials/goods ($\dot{S}_{10}$) are returned to the biosphere without accumulating in Society (1). Capital goods are returned to the biosphere when they are physically depreciated ($\dot{K}_{10}$).

Drawing control volumes around both the Biosphere (0) and Society (1) in Figure 2.2, we can construct material accounting equations, such that:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} + \frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{S}_{10} + \dot{K}_{10} - \dot{R}_0 - \dot{S}_0 \tag{2.7}$$

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} + \frac{\mathrm{d}S_1}{\mathrm{d}t} + \frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} + \dot{S}_{01} + \dot{R}_{11} + \dot{S}_{11} + \dot{K}_{11} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}. \tag{2.8}$$

Because mass is conserved, we find that:

$$\dot{R}_0 = \dot{R}_{01}, \tag{2.9}$$

$$\dot{S}_0 = \dot{S}_{01}, \tag{2.10}$$

$$\dot{P}_1 = \dot{R}_{11} + \dot{S}_{11} + \dot{K}_{11}, \tag{2.11}$$

Clearly, $\dot{R}_{01} \neq \dot{R}_{10}$ because some resources are converted into short-lived goods ($\dot{S}_{11}$) or man-made capital ($\dot{K}_{11}$) and are only returned to the biosphere as either $\dot{S}_{10}$ or $\dot{K}_{10}$, respectively. Hence, we may say that:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \dot{R}_{10} - \dot{R}_{01} \neq 0. \tag{2.12}$$

Similarly, we know that $\dot{S}_{01} \neq \dot{S}_{10}$.[7]

In this framework, neither resources (R) nor short-lived goods (S) accumulate within economic sectors, so we may state:

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[5] Double subscripts on quantities (e.g., $\dot{R}_{ij}$) indicate a flow from sector i to sector j. The first index always indicates the sector *from* which a quantity flows, and the second index indicates the sector *to* which a quantity flows. Single subscripts on quantities such as K can mean one of two things: $\dot{K}_j$ (with a dot to indicate a flow) refers to the outflow of capital from sector j, whereas K_j (without the dot) denotes the capital stock of sector j.

[6] See Section 8.7 for more discussion on the inclusion of human beings as societal capital stock.

[7] While this inequality may be true in theory, it may be that in practice, the large amount of material, e.g. water or oxygen, that passes straight through the economy “unaffected,” i.e. without being embodied in products, is very large compared to the additional flow of short-lived goods produced within the economy, i.e. $\dot{S}_{11} << \dot{S}_{01}$.

$$\frac{dR_1}{dt} = 0, \tag{2.13}$$

$$\frac{dS_1}{dt} = 0. \tag{2.14}$$

Because the only "capital" that accumulates in the biosphere is that which is a waste flow (capital depreciation) from the economy, (worn-out machines in the scrap yard), we may say that:

$$\frac{dK_0}{dt} = \dot{K}_{10} \tag{2.15}$$

Looking deeper at flows of resources and short-lived goods, we can make some further observations. Imagine following a kilogram of coal on its journey through the economy. It is pulled out of the earth as part of flow $\dot{R}_{01}$. It enters the economy and while most is transformed into useful products (part of $\dot{P}_1$) some (hopefully small) fraction is wasted ($\dot{R}_{10}$). Some of the coal is destined for electricity generation and so re-enters the economy as part of flow $\dot{S}_{11}$, because the coal is *not physically embodied* in the electricity and leaves the economy (in the form of carbon dioxide and ash) as part of flow $\dot{S}_{10}$. Some of the coal is destined for metallurgical processes (such as the production of steel) and so re-enters the economy within flow $\dot{R}_{11}$, because the carbon in the coal ends up *physically embodied* within the steel in flow $\dot{P}_1$. Again, some of the coal is wasted (maybe within slag), leaving the economy as flow $\dot{R}_{10}$. The steel may re-enter the economy as part of the resource flow $\dot{R}_{11}$ and be manufactured into steel products (maybe a car) to leave as part of flow $\dot{P}_1$ (again some being discharged within $\dot{R}_{10}$). At this point the carbon (within the steel, within the car) re-enters the economy as part of flow $\dot{K}_{11}$ and is accumulated within stock K_1. Here it sits until such time as it is depreciated, to leave the economy bound up in flow $\dot{K}_{10}$. In summary, we may say that short-lived materials flow "straight through" the economy and end up in the biosphere. Resources are destined to end up either physically embodied within products or waste "resources." They cycle through the economy, entering and re-entering, until they are turned either into short-lived goods, whereupon they flow "straight through" into the biosphere, or they are turned into capital good and accumulate.

As such, we may state that:

$$\frac{dR_1}{dt} = \dot{R}_{01} + \dot{R}_{11} - \dot{P}_1 - \dot{R}_{10} = 0, \tag{2.16}$$

$$\frac{dS_1}{dt} = \dot{S}_{01} + \dot{S}_{11} - \dot{S}_{10} = 0, \tag{2.17}$$

We may rearrange these equations in terms of the important variable as:

$$\dot{P}_1 = \dot{R}_{01} + \dot{R}_{11} - \dot{R}_{10}, \tag{2.18}$$

and

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{01}. \tag{2.19}$$

Substituting Equations 2.9, 2.10 and 2.15 into Equation 2.7 we obtain:

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} = \dot{R}_{10} + \dot{S}_{10} - \dot{R}_{01} - \dot{S}_{01}. \tag{2.20}$$

Equation 2.20 states that the rate of "accumulation" (or more accurately depletion) of natural capital (R_0 and S_0) is dependent on the rates at which society extracts these materials from the biosphere ($\dot{R}_{01}$ and $\dot{S}_{01}$) and the rates of disposal of waste materials back to the biosphere ($\dot{R}_{10}$ and $\dot{S}_{10}$). Notice however, that although Equation 2.20 is true for total mass of materials, it does not account for the *quality* of these materials. Society relies heavily on extracted resources from naturally occurring accumulations that are far from equilibrium with their surroundings, e.g. fossil fuel reservoirs or seams of high-grade ore. As these high quality material reserves are depleted and society must turn to lower grade reserves, more material must be processed (requiring the deployment of more productive capital) in order to maintain the same level of production.[8][10]

It is likely that the quality of flow $\dot{R}_{01}$ is higher than flow $\dot{R}_{10}$ (e.g. overburden from mining operations). If this were not the case, $\dot{R}_{10}$ could be easily substituted into the production process (i.e. recycled) thus offsetting the need for primary resource extraction. The issue of recycling is discussed in more detail in Section 7.4. The issue of material (and energy) quality is discussed in more detail in Section 8.4.

Substituting Equation 2.17 into Equation 2.8, we obtain:

$$\frac{dK_1}{dt} = \dot{R}_{01} + \dot{R}_{11} + \dot{K}_{11} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10}. \tag{2.21}$$

Since we have two different formulations for $\dot{P}_1$, represented by Equations 2.11 and 2.18, we may substitute either into Equation 2.21. Substituting Equation 2.18 into Equation 2.21, we obtain:

$$\frac{dK_1}{dt} = \dot{K}_{11} - \dot{K}_{10}, \tag{2.22}$$

which tells us that accumulation of capital in society (K_1) is dependent only on inflows of capital into society ($\dot{K}_{11}$) and depreciation of capital to the biosphere ($\dot{K}_{10}$).

Substituting instead Equation 2.11 into Equation 2.21, we obtain:

[8] This theme will be revisited in later sections, in relation to both energy (direct energy in Chapter 3 and embodied energy in Chapter 4) and value (Chapter 5).

$$\frac{dK_1}{dt} = \dot{R}_{01} - \dot{R}_{10} - \dot{S}_{11} - \dot{K}_{10}. \tag{2.23}$$

The last depreciation term ($\dot{K}_{10}$) may be rewritten as the total stock of man-made capital (K_1) multiplied by some depreciation rate (γ_{K_1}),[9] where γ_{K_j} is defined as:

$$\gamma_{K_j} \equiv \frac{\dot{B}_{j0}}{B_j}, \tag{2.24}$$

i.e. the depreciation *per unit* of capital stock,[10] such that Equation 2.23 may be rewritten:

$$\frac{dK_1}{dt} = \dot{R}_{01} - \dot{R}_{10} - \dot{S}_{11} - \gamma_{K_1} K_1. \tag{2.25}$$

We may rearrange Equation 2.25 as:

$$\dot{R}_{01} - \dot{R}_{10} = \frac{dK_1}{dt} + \dot{S}_{11} + \gamma_{K_1} K_1. \tag{2.26}$$

Noticing that the left-hand side of Equation 2.26 is the negation of the right-hand side of Equation 2.12, we may rewrite Equation 2.26 in terms of the accumulation (or more accurately, depletion) of natural resources:

$$-\frac{dR_0}{dt} = \frac{dK_1}{dt} + \dot{S}_{11} + \gamma_{K_1} K_1. \tag{2.27}$$

Equation 2.27 tells us that depletion of natural resources $\left(-\frac{dR_0}{dt}\right)$ is used within society to:

- build up societal capital stock $\left(\frac{dK_1}{dt}\right)$,
- provide short-lived goods and energy to run society ($\dot{S}_{11}$), and
- overcome depreciation ($\gamma_{K_1} K_1$).

In other words, the economy is completely dependent on stocks of natural resources within the biosphere for all of these activities. We now turn to a slightly more disaggregated model of the economy.

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[9] γ_{K_1} has units of inverse time, e.g. 1/year, and is inversely proportional to the average lifetime of man-made capital.

[10] This depreciation term will be discussed in more depth in Sections 4.2.3 and 7.2.2.2.

2.3 Example B: two-sector economy

In our second example B, we split society into two sectors: Production (2) and Final Consumption (1), as depicted in Figure 2.3. Production (2) makes all of the goods and services that are delivered to Final Consumption (1), as well as all of the intermediate goods that are not "consumed" by Final Consumption, but stay within Production, such as manufacturing equipment.

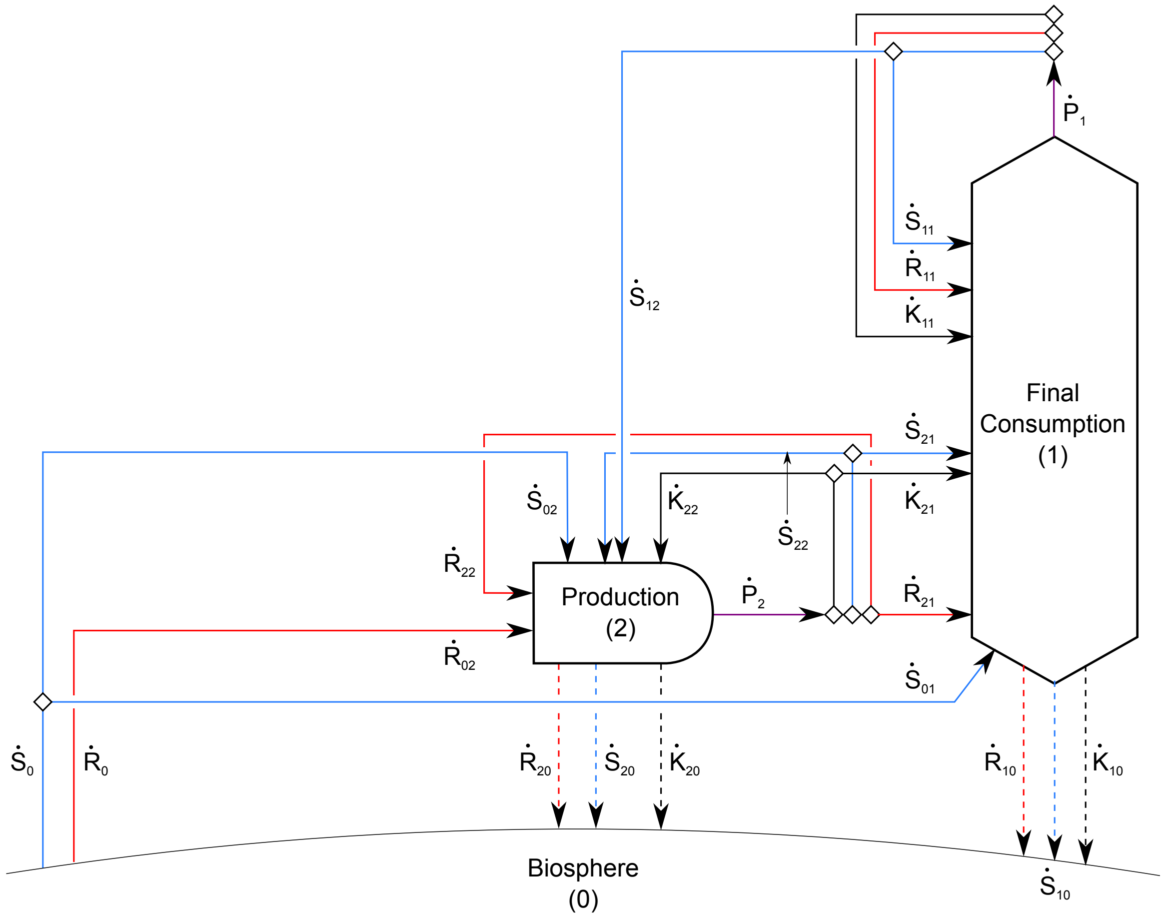

Fig. 2.3 Flows of materials for a two-sector economy.

As can be seen in Figure 2.3, Production (2) resembles very closely the basic unit shown in Figure 2.1. Resource flows from the biosphere ($\dot{R}_{02}$) and those produced by Sector (2) itself ($\dot{R}_{22}$) are *transformed* into product flow ($\dot{P}_2$). Flows of short-lived goods ($\dot{S}$) and capital ($\dot{K}$) are required to support this transformative process. Much of the product flow from ($\dot{P}_2$) enters Final Consumption (1) as resource flows ($\dot{R}_{21}$), short-lived goods ($\dot{S}_{21}$) and capital goods ($\dot{K}_{21}$) flows.

One point worth noting is that our flow of "capital goods" into Final Consumption ($\dot{K}_{21}$) includes consumer durables and housing in addition to typical items such as bridges and other public infrastructure. We chose this approach because some goods (refrigerators, televisions, apartment blocks) may accumulate within Sector (1) and would be represented within flow $\dot{K}_{21}$, whereas other short-lived goods (newspapers, plastic packaging, electricity) do not accumulate within Sector 1 and are represented by flow $\dot{S}_{21}$.

There is also a product outflow from Final Consumption ($\dot{P}_1$), some of which is returned to Final Consumption (1) as resources ($\dot{R}_{11}$), short-lived goods ($\dot{S}_{11}$) and capital goods ($\dot{K}_{11}$) flows.[11] There is no resource ($\dot{R}_{12}$) nor capital good ($\dot{K}_{12}$) flow from Final Consumption (1) to Production (2). This is because the "product" of Final Consumption (1) is labor services and because Final Consumption (1) consumes, rather than produces, final goods. No resource materials flow from Final Consumption (1) to be *physically embodied* within the product output ($\dot{P}_2$), therefore $\dot{R}_{12} = 0$. Additionally, no capital *goods* flow from Final Consumption (1) to accumulate within the production sector, therefore $\dot{K}_{12} = 0$. The flow of short-lived goods ($\dot{S}_{12}$) from Final Consumption (1) to Production (2) represents labor, specifically the material flow associated with labor's energy which is used within the production sector.[12]

Resource flow $\dot{R}_{21}$ into Final Consumption represents the material flow that will be *physically embodied* within the "product" of Final Consumption (1)—human labor—which is food produced by the agriculture industry

As in Example A, we set control volumes around the biosphere and our two economic sectors, such that the material accounting equations become:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} + \frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} + \dot{S}_{10} + \dot{S}_{20} + \dot{K}_{10} + \dot{K}_{20} - \dot{R}_0 - \dot{S}_0 \tag{2.28}$$

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} + \frac{\mathrm{d}S_1}{\mathrm{d}t} + \frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{11} + \dot{R}_{21} + \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} + \dot{K}_{11} + \dot{K}_{21} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}, \tag{2.29}$$

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} + \frac{\mathrm{d}S_2}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{R}_{22} + \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} + \dot{K}_{22} - \dot{P}_2 - \dot{R}_{20} - \dot{S}_{20} - \dot{K}_{20}, \tag{2.30}$$

[11] In actuality, both $\dot{R}_{11}$ and $\dot{S}_{11}$ are zero, as will be discussed shortly.

[12] We assume that flow ($\dot{S}_{12}$) is the adenosine triphosphate (ATP), used as an energy carrier within the cells of organisms, which is consumed during activity (labor)

Because no resources flow directly to Final Consumption (1) from the Biosphere (0),[13] we may say:

$$\dot{R}_0 = \dot{R}_{02}. \tag{2.31}$$

In contrast, short-lived materials *do* flow directly to Final Consumption (1) from the Biosphere (0), for example the flow of photons in Sunlight or oxygen into car engines and lungs. We can redefine flow $\dot{S}_0$:

$$\dot{S}_0 = \dot{S}_{01} + \dot{S}_{02}. \tag{2.32}$$

As in Example A, we may easily define the balance of resources ($\dot{R}$), short-lived materials ($\dot{S}$) and capital ($\dot{K}$) within the biosphere:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} - \dot{R}_{02}, \tag{2.33}$$

$$\frac{\mathrm{d}S_0}{\mathrm{d}t} = \dot{S}_{10} + \dot{S}_{20} - \dot{S}_{01} - \dot{S}_{02}, \tag{2.34}$$

$$\frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{K}_{10} + \dot{K}_{20}. \tag{2.35}$$

Because we are assuming that only man-made capital (and not human beings themselves) are accounted within the physical stock of Final Consumption[14] (K_1) and that the "product" of Final Consumption (1) is labor (a short-lived material flow, $\dot{S}$), then we may also state that

$$\dot{R}_{11} = 0, \tag{2.36}$$

since labor is not a resource flow—it is not *physically embodied* within products produced within the production sector—and additionally that,

$$\dot{K}_{11} = 0, \tag{2.37}$$

because all capital goods are produced within the Production sector (2).

From conservation of mass, we can also define product flows $\dot{P}_1$ and $\dot{P}_2$ as:.

$$\dot{P}_1 = \dot{S}_{11} + \dot{S}_{12}, \tag{2.38}$$

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[13] A counter-example to this assumption is the production of food outside of the agricultural industry, i.e. by households, which may be large in agrarian economies.

[14] If we were assuming that the human population was accounted within $\dot{K}_1$, then the "product" of Final Consumption (1) would be human beings (and the labor they provide), resource flow $\dot{R}_{11}$ would be material resources provided to human reproduction and "capital goods" flow $\dot{K}_{11}$ would be material added to the human population stock. Again, this issue is discussed in greater detail in Section 8.7.

and

$$\dot{P}_2 = \dot{R}_{21} + \dot{R}_{22} + \dot{S}_{21} + \dot{S}_{22} + \dot{K}_{21} + \dot{K}_{22} \tag{2.39}$$

Again, remembering that resources (R) and short-lived goods (S) do not accumulate within any sectors of the economy:

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} = 0, \tag{2.40}$$

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} = 0, \tag{2.41}$$

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = 0, \tag{2.42}$$

and

$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = 0. \tag{2.43}$$

As in Example A, we may also define the resource-product and short-lived goods flows balances separately for each of the sectors of the economy:

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} = \dot{R}_{21} - \dot{P}_1 - \dot{R}_{10} = 0, \tag{2.44}$$

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} - \dot{S}_{10} = 0, \tag{2.45}$$

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{R}_{22} - \dot{P}_2 - \dot{R}_{20} = 0, \tag{2.46}$$

and

$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} - \dot{S}_{20} = 0. \tag{2.47}$$

We may rearrange these equations in terms of the important variables to obtain:

$$\dot{P}_1 = \dot{R}_{21} - \dot{R}_{10} \tag{2.48}$$

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{21}, \tag{2.49}$$

$$\dot{P}_2 = \dot{R}_{02} + \dot{R}_{22} - \dot{R}_{20}, \tag{2.50}$$

and

$$\dot{S}_{22} = \dot{S}_{20} - \dot{S}_{02} - \dot{S}_{12}. \tag{2.51}$$

Substituting Equations 2.31-2.35 into Equation 2.28, gives,

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} + \dot{S}_{10} + \dot{S}_{20} - \dot{R}_{02} - \dot{S}_{01} - \dot{S}_{02}. \tag{2.52}$$

Substituting Equations 2.40, 2.45 and 2.47 into Equations 2.29 and 2.30, respectively, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{21} + \dot{K}_{21} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10} \tag{2.53}$$

and

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{R}_{22} + \dot{K}_{22} - \dot{P}_2 - \dot{R}_{20} - \dot{K}_{20}, \tag{2.54}$$

As in Example A, we again have two definitions for $\dot{P}_1$ (Equations 2.38 and 2.48) and $\dot{P}_2$ (Equations 2.39 and 2.50) which may be substituted into Equations 2.53 and 2.54, respectively. Let us start by substituting Equations 2.48 and 2.50, in which case we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{K}_{21} - \dot{K}_{10}, \tag{2.55}$$

and

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{K}_{22} - \dot{K}_{20}, \tag{2.56}$$

Equations 2.55 and 2.56 tell us that accumulation of man-made capital (K) in each sector (j) is dependent only on inflows of capital goods into that sector ($\dot{K}_{2j}$) and depreciation of capital to the biosphere from that sector ($\dot{K}_{j0}$).

Now, substituting Equations 2.38 and 2.39, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{21} + \dot{K}_{21} - \dot{S}_{11} - \dot{S}_{12} - \dot{R}_{10} - \dot{K}_{10}, \tag{2.57}$$

and

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} - \dot{R}_{21} - \dot{S}_{21} - \dot{S}_{22} - \dot{K}_{21} - \dot{R}_{20} - \dot{K}_{20}, \tag{2.58}$$

to which we may make the substitution of the depreciation term (as in Example A) and rearrange to obtain:

$$-\dot{R}_{10} = \frac{\mathrm{d}K_1}{\mathrm{d}t} - \dot{R}_{21} - \dot{K}_{21} + \dot{S}_{11} + \dot{S}_{12} + \gamma_{K_1} K_1, \tag{2.59}$$

and

$$\dot{R}_{02} - \dot{R}_{20} = \frac{\mathrm{d}K_2}{\mathrm{d}t} + \left(\dot{R}_{21} + \dot{S}_{21} + \dot{K}_{21}\right) + \dot{S}_{22} + \gamma_{K_2} K_2. \tag{2.60}$$

Equation 2.60 tells us that the resources extracted and used by the production sector ($\dot{R}_{02} - \dot{R}_{20}$) are for the purposes of:

- building up capital stock in the production sector $\left(\frac{\mathrm{d}K_2}{\mathrm{d}t}\right)$,
- providing goods for Final Consumption $\left(\dot{R}_{21} + \dot{S}_{21} + \dot{K}_{21}\right)$,
- providing short-lived goods to support the production sector ($\dot{S}_{22}$), and
- overcoming depreciation of production capital stock ($\gamma_{K_2} K_2$).

Adding Equations 2.59 and 2.60 together, we obtain:

$$\begin{aligned}
-\frac{\mathrm{d}R_0}{\mathrm{d}t} &= \dot{R}_{02} - \dot{R}_{10} - \dot{R}_{20} \\
&= \frac{\mathrm{d}K_1}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} + \dot{S}_{11} + \dot{S}_{12} + \dot{S}_{21} + \dot{S}_{22} + \gamma_{K_1} K_1 + \gamma_{K_2} K_2.
\end{aligned} \tag{2.61}$$

which tells us that the depletion of natural resources $\left(\frac{\mathrm{d}R_0}{\mathrm{d}t}\right)$ is used within the whole economy to:

- build up capital stock $\left(\frac{\mathrm{d}K_1}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t}\right)$,
- produce short-lived goods ($\dot{S}_{11} + \dot{S}_{12} + \dot{S}_{21} + \dot{S}_{22}$), and
- overcome depreciation $\left(\gamma_{K_1} K_1 + \gamma_{K_2} K_2\right)$.

We now turn to a three-sector model of the economy in order to generalize these results.

2.4 Example C: three-sector economy

In Example C, we differentiate between two production sectors, sector (2) produces energy and sector (3) produces other goods and services, as depicted in Figure 2.4.

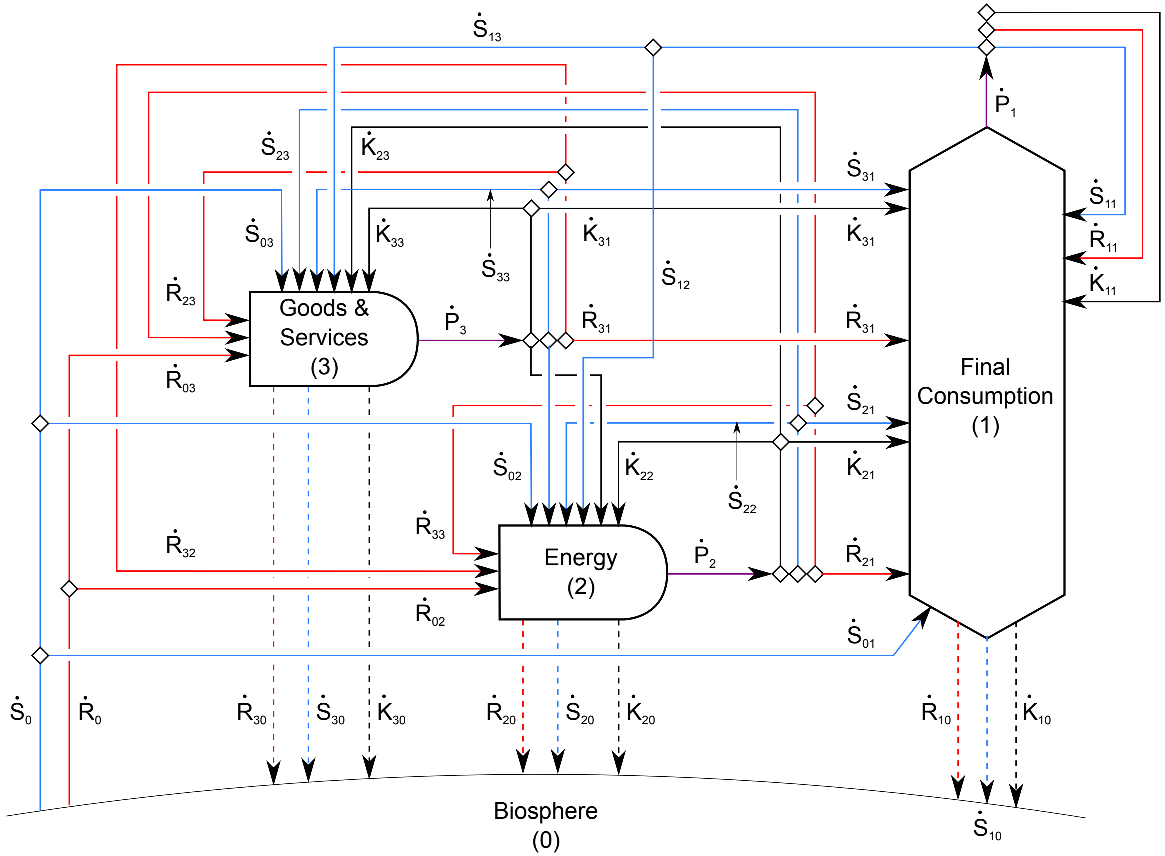

Fig. 2.4 Flows of materials for a three-sector economy.

In this example, we will take a slightly different approach than in the previous two examples. Instead of discerning whether or not certain flows exist (asking for example, "is there a flow of resources ($\dot{R}_{21}$) from Energy (2) to Final Consumption (1)?"), we shall account for all flows, *even if* those flows are zero. In this way, we may build up a completely general framework for material accounting within an economy of any size.

Accounting for the material flows into and out of the Biosphere (0) gives the following equation:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} + \frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} + \dot{R}_{30} + \dot{S}_{10} + \dot{S}_{20} + \dot{S}_{30} + \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30} - \dot{R}_0 - \dot{S}_0, \tag{2.62}$$

which may be rewritten as:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} + \frac{\mathrm{d}K_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{R}_{i0} + \sum_{i=1}^{3} \dot{S}_{i0} + \sum_{i=1}^{3} \dot{K}_{i0} - \dot{R}_0 - \dot{S}_0, \tag{2.63}$$

where the sum represents flows into the biosphere from each of the other i sectors. Similarly, flows for the other sectors may be written:

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} + \frac{\mathrm{d}S_1}{\mathrm{d}t} + \frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} + \dot{S}_{01} + \sum_{i=1}^{3} \dot{R}_{i1} + \sum_{i=1}^{3} \dot{S}_{i1} + \sum_{i=1}^{3} \dot{K}_{i1} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}, \tag{2.64}$$

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} + \frac{\mathrm{d}S_2}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{S}_{02} + \sum_{i=1}^{3} \dot{R}_{i2} + \sum_{i=1}^{3} \dot{S}_{i2} + \sum_{i=1}^{3} \dot{K}_{i2} - \dot{P}_2 - \dot{R}_{20} - \dot{S}_{20} - \dot{K}_{20}, \tag{2.65}$$

and

$$\frac{\mathrm{d}R_3}{\mathrm{d}t} + \frac{\mathrm{d}S_3}{\mathrm{d}t} + \frac{\mathrm{d}K_3}{\mathrm{d}t} = \dot{R}_{03} + \dot{S}_{03} + \sum_{i=1}^{3} \dot{R}_{i3} + \sum_{i=1}^{3} \dot{S}_{i3} + \sum_{i=1}^{3} \dot{K}_{i3} - \dot{P}_3 - \dot{R}_{30} - \dot{S}_{30} - \dot{K}_{30}. \tag{2.66}$$

As in previous examples, we may define the balance of resources ($\dot{R}$), short-lived materials ($\dot{S}$) and capital ($\dot{K}$) within the biosphere as:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} + \dot{R}_{30} - \dot{R}_{01} - \dot{R}_{02} - \dot{R}_{03}, \tag{2.67}$$

$$\frac{\mathrm{d}S_0}{\mathrm{d}t} = \dot{S}_{10} + \dot{S}_{20} + \dot{S}_{30} - \dot{S}_{01} - \dot{S}_{02} - \dot{S}_{03}, \tag{2.68}$$

and

$$\frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30}. \tag{2.69}$$

which may be rewritten:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{R}_{i0} - \sum_{j=1}^{3} \dot{R}_{0j}, \tag{2.70}$$

$$\frac{\mathrm{d}S_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{S}_{i0} - \sum_{j=1}^{3} \dot{S}_{0j}, \tag{2.71}$$

and

$$\frac{\mathrm{d}K_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{K}_{i0}. \tag{2.72}$$

Applying conservation of mass allows us to define the product flows ($\dot{P}$) as:

$$\dot{P}_1 = \sum_{j=1}^{3} \dot{R}_{1j} + \sum_{j=1}^{3} \dot{S}_{1j} + \sum_{j=1}^{3} \dot{K}_{1j}, \tag{2.73}$$

$$\dot{P}_2 = \sum_{j=1}^{3} \dot{R}_{2j} + \sum_{j=1}^{3} \dot{S}_{2j} + \sum_{j=1}^{3} \dot{K}_{2j}, \tag{2.74}$$

$$\dot{P}_3 = \sum_{j=1}^{3} \dot{R}_{3j} + \sum_{j=1}^{3} \dot{S}_{3j} + \sum_{j=1}^{3} \dot{K}_{3j} \tag{2.75}$$

As in Example B, Final Consumption (1) provides only labor (represented by $\dot{S}$ flows) to the other sectors of the economy. The Energy sector (2) provides energy products ($\dot{S}_{2j}$) to the other sectors of the economy. It may also provide resources to itself ($\dot{R}_{22}$) and to the Goods and Services sector (3), as in the case of metallurgical coke or natural gas for fertilizer. The energy sector does not produce capital goods, hence, for $j \in [1,3] : \dot{K}_{2j} = 0$. The Goods and Services sector (3) does not provide resources for the Energy sector (2),[15] hence $\dot{R}_{32} = 0$.

Because we do not allow accumulation of either resources (R) or short-lived capital goods (S) in economic sectors, then we may say:

$$\frac{dR_j}{dt} = 0, \qquad j \in [1,3], \tag{2.76}$$
$$\frac{dS_j}{dt} = 0, \qquad j \in [1,3]. \tag{2.77}$$

As before, we may also define the resource-product and short-lived goods flows balances separately for each of the sectors of the economy:[16]

$$\frac{dR_1}{dt} = \dot{R}_{01} + \dot{R}_{11} + \dot{R}_{21} + \dot{R}_{31} - \dot{P}_1 - \dot{R}_{10} = 0, \tag{2.78}$$
$$\frac{dS_1}{dt} = \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} + \dot{S}_{31} - \dot{S}_{10} = 0, \tag{2.79}$$
$$\frac{dR_2}{dt} = \dot{R}_{02} + \dot{R}_{12} + \dot{R}_{22} + \dot{R}_{32} - \dot{P}_2 - \dot{R}_{20} = 0, \tag{2.80}$$
$$\frac{dS_2}{dt} = \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} + \dot{S}_{32} - \dot{S}_{20} = 0, \tag{2.81}$$
$$\frac{dR_3}{dt} = \dot{R}_{03} + \dot{R}_{13} + \dot{R}_{23} + \dot{R}_{33} - \dot{P}_3 - \dot{R}_{30} = 0, \tag{2.82}$$
$$\frac{dS_3}{dt} = \dot{S}_{03} + \dot{S}_{13} + \dot{S}_{23} + \dot{S}_{33} - \dot{S}_{30} = 0, \tag{2.83}$$

and then rearrange the equations in terms of the important variable:

$$\dot{P}_1 = \dot{R}_{01} + \dot{R}_{11} + \dot{R}_{21} + \dot{R}_{31} - \dot{R}_{10} \tag{2.84}$$
$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{01} - \dot{S}_{21} - \dot{S}_{31}, \tag{2.85}$$
$$\dot{P}_2 = \dot{R}_{02} + \dot{R}_{12} + \dot{R}_{22} + \dot{R}_{32} - \dot{R}_{20}, \tag{2.86}$$
$$\dot{S}_{22} = \dot{S}_{20} - \dot{S}_{02} - \dot{S}_{12} - \dot{S}_{32}, \tag{2.87}$$
$$\dot{P}_3 = \dot{R}_{03} + \dot{R}_{13} + \dot{R}_{23} + \dot{R}_{33} - \dot{R}_{30}, \tag{2.88}$$
$$\dot{S}_{33} = \dot{S}_{20} - \dot{S}_{03} - \dot{S}_{13} - \dot{S}_{23}. \tag{2.89}$$

We now make use of Equations 2.76, 2.79, 2.81 and 2.83, in simplifying Equations 2.64 - 2.66, to obtain:

[15] There may be some exceptions to this, as in the case of energy from industrial waste streams.

[16] It is worth remembering here that $\dot{R}_{01} = \dot{R}_{21} = 0$, because Final Consumption (1) takes resources (in the form of food) from Goods and Services (3) only and that $R_{32} = 0$ because the Goods and Services sector (3) does not provide resources to the Energy sector (2).

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} + \sum_{i=1}^{3}\dot{R}_{i1} + \sum_{i=1}^{3}\dot{K}_{i1} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10}, \tag{2.90}$$

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \sum_{i=1}^{3}\dot{R}_{i2} + \sum_{i=1}^{3}\dot{K}_{i2} - \dot{P}_2 - \dot{R}_{20} - \dot{K}_{20}, \tag{2.91}$$

and

$$\frac{\mathrm{d}K_3}{\mathrm{d}t} = \dot{R}_{03} + \sum_{i=1}^{3}\dot{R}_{i3} + \sum_{i=1}^{3}\dot{K}_{i3} - \dot{P}_3 - \dot{R}_{30} - \dot{K}_{30}. \tag{2.92}$$

As in previous examples, we have two different formulations for the $\dot{P}$ terms. Substituting, first, Equations 2.84, 2.86 and 2.88, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \sum_{i=1}^{3}\dot{K}_{i1} - \dot{K}_{10}, \tag{2.93}$$

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \sum_{i=1}^{3}\dot{K}_{i2} - \dot{K}_{20}, \tag{2.94}$$

and

$$\frac{\mathrm{d}K_3}{\mathrm{d}t} = \sum_{i=1}^{3}\dot{K}_{i3} - \dot{K}_{30}, \tag{2.95}$$

which we may rewrite as the more general result:

$$\frac{\mathrm{d}K_j}{\mathrm{d}t} = \sum_{i}\dot{K}_{ij} - \dot{K}_{j0}. \tag{2.96}$$

Equation 2.96 states that for any economic sector, j, the accumulation of man-made capital stock (K_j) is dependent only on inflows of capital stock from other economic sectors ($\dot{K}_{ij}$) and depreciation of capital stock back to the biosphere from sector j, ($\dot{K}_{j0}$).

Instead, substituting the alternative formulation for $\dot{P}$ from Equations 2.73 - 2.75 into Equations 2.90 - 2.92, respectively, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} + \sum_{i=1}^{3}\dot{R}_{i1} + \sum_{i=1}^{3}\dot{K}_{i1} - \sum_{j=1}^{3}\dot{R}_{1j} - \sum_{j=1}^{3}\dot{S}_{1j} - \sum_{j=1}^{3}\dot{K}_{1j} - \dot{R}_{10} - \dot{K}_{10}, \quad (2.97)$$

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \sum_{i=1}^{3}\dot{R}_{i2} + \sum_{i=1}^{3}\dot{K}_{i2} - \sum_{j=1}^{3}\dot{R}_{2j} - \sum_{j=1}^{3}\dot{S}_{2j} - \sum_{j=1}^{3}\dot{K}_{2j} - \dot{R}_{20} - \dot{K}_{20}, \quad (2.98)$$

and

$$\frac{\mathrm{d}K_3}{\mathrm{d}t} = \dot{R}_{03} + \sum_{i=1}^{3}\dot{R}_{i3} + \sum_{i=1}^{3}\dot{K}_{i3} - \sum_{j=1}^{3}\dot{R}_{3j} - \sum_{j=1}^{3}\dot{S}_{3j} - \sum_{j=1}^{3}\dot{K}_{3j} - \dot{R}_{30} - \dot{K}_{30}. \quad (2.99)$$

As before, we can rearrange these equations to obtain:

$$\dot{R}_{01} - \dot{R}_{10} = \frac{\mathrm{d}K_1}{\mathrm{d}t} - \sum_{i=1}^{3}\dot{R}_{i1} - \sum_{i=1}^{3}\dot{K}_{i1} + \sum_{j=1}^{3}\dot{R}_{1j} + \sum_{j=1}^{3}\dot{S}_{1j} + \sum_{j=1}^{3}\dot{K}_{1j} + \dot{K}_{10}, \quad (2.100)$$

$$\dot{R}_{02} - \dot{R}_{20} = \frac{\mathrm{d}K_2}{\mathrm{d}t} - \sum_{i=1}^{3}\dot{R}_{i2} - \sum_{i=1}^{3}\dot{K}_{i2} + \sum_{j=1}^{3}\dot{R}_{2j} + \sum_{j=1}^{3}\dot{S}_{2j} + \sum_{j=1}^{3}\dot{K}_{2j} + \dot{K}_{20}, \quad (2.101)$$

and

$$\dot{R}_{03} - \dot{R}_{30} = \frac{\mathrm{d}K_3}{\mathrm{d}t} - \sum_{i=1}^{3}\dot{R}_{i3} - \sum_{i=1}^{3}\dot{K}_{i3} + \sum_{j=1}^{3}\dot{R}_{3j} + \sum_{j=1}^{3}\dot{S}_{3j} + \sum_{j=1}^{3}\dot{K}_{3j} + \dot{K}_{30}. \quad (2.102)$$

Summing Equations 2.100 - 2.102, we obtain:

$$\begin{aligned} -\frac{\mathrm{d}R_0}{\mathrm{d}t} &= \sum_{j=1}^{3}\dot{R}_{0j} - \sum_{i=1}^{3}\dot{R}_{i0} \\ &= \frac{\mathrm{d}K_1}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} + \frac{\mathrm{d}K_3}{\mathrm{d}t} - \sum_{j=1}^{3}\sum_{i=1}^{3}\dot{R}_{ij} - \sum_{j=1}^{3}\sum_{i=1}^{3}\dot{K}_{ij} + \sum_{j=1}^{3}\sum_{i=1}^{3}\dot{R}_{ij} \\ &\quad + \sum_{j=1}^{3}\sum_{i=1}^{3}\dot{S}_{ij} + \sum_{j=1}^{3}\sum_{i=1}^{3}\dot{K}_{ij} + \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30}, \end{aligned} \quad (2.103)$$

which, after substituting for the depreciation term ($\dot{K}_{i0}$), can be simplified to:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{j=1}^{3} \frac{\mathrm{d}K_j}{\mathrm{d}t} + \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{S}_{ij} + \sum_{j=1}^{3} \gamma_{K_j} K_j \tag{2.104}$$

or, more generally:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{j} \frac{\mathrm{d}K_j}{\mathrm{d}t} + \sum_{i,j} \dot{S}_{ij} + \sum_{j} \gamma_{K_j} K_j. \tag{2.105}$$

Similarly to what we saw in Examples A and B, Equation 2.105 tells us that depletion of natural resources in the biosphere $\left(-\frac{\mathrm{d}R_0}{\mathrm{d}t}\right)$ by the economy is used for the purposes of:

- increasing man-made capital stocks within the economy $\left(\frac{\mathrm{d}K_j}{\mathrm{d}t}\right)$,
- providing short-lived goods exchanged within the economy ($\dot{S}_{ij}$), and
- overcoming depreciation of man-made capital stocks ($\sum_j \gamma_{K_j} K_j$).

This implications of this will be discussed in greater detail in Section 7.5 concerning sustainable scale of the economy and the concept of a steady-state economy.

The exchange of resources ($\dot{R}$) and short-lived goods ($\dot{S}$) among each of the four "sectors" (the biosphere and the three economic sectors) may be thought of as four matrices (as depicted in Figure 2.5 for $\dot{S}$ flows): one 3×3 matrix of flows entirely within the economy, a 3×1 row vector of flows from the biosphere into the economy (extraction), a 1×3 column vector of flows from the economy into the biosphere (waste), and a 1×1 matrix of flows solely within the biosphere (environment), that do not enter the economy.

We now see how the formulation derived here may be applied to the real-world case of the US auto industry.

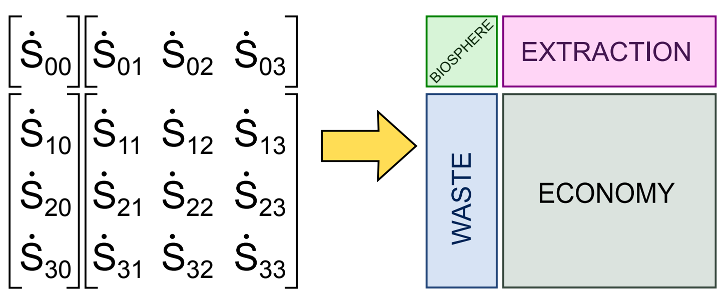

Fig. 2.5 The matrix of biosphere-economy flows.

2.5 Materials in the US auto industry

Throughout the book, we shall be applying the methodology that has been outlined through Examples A-C to the real-world case of the US auto industry. 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 [11–17] and Input-Output [18–20] 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.).

In Figure 2.6 we see the flows of resources, short-lived, and capital materials into the auto industry. Because the industry does not extract resources directly from the biosphere, the rate of flow of resources ($\dot{R}_{0j}$) from the biosphere to the auto industry has a zero value. Each of the other flows represented in the diagram is, in actuality, a vector of hundreds (or even thousands!) of elemental material flows, each of which must be accounted (and balanced) separately.

There are a number of key material inputs into the production of automobiles, directly as resources ($\dot{R}$) as well as short-lived materials ($\dot{S}$) and capital goods ($\dot{K}$) outlined in Table 2.1. Data on the actual flow rates at the industry level is very hard to obtain.[17] In Europe, economy-wide material flow accounts (EW-MFA) have been produced by measurement of the physical flows of materials into and out of economies of each of the member states.[21] Work is ongoing to characterize the inter-sectoral flows of these materials [22] which can be analyzed by converting financial data (which is available, as discussed in Section 5.5) into physical flow data via knowledge of the entry points of materials into the economy, i.e. via the extraction industries.

A number of studies have looked at the material and energy flows associated with specific or representative vehicle manufacturing *processes*, rather than industry-level activity.[14, 19, 23, 15, 20, 24, 16, 17] The US automobile industry is composed of many such manufacturing processes. According to the International Organization of Motor Vehicle Manufacturers (OICA), 2.7 million cars were produced in 2010[18] in the US.[25] In theory, a representation of the industry-level flows could be "built up" by assuming that the results from these process-based analysis methods represent average processes within the whole industry and scaling the material flows accordingly, with appropriately wide uncertainty bounds.

---

[17] The issue of lack of physical flow data is discussed in Section 8.1.

[18] In 2006, prior to the Great Recession, the automobile industry purchased 40 trillion kJ (4.0×10^{13} kJ) of total energy and produced 4.4 million cars.

Table 2.1 List of material input and output flows for the US auto industry (IOC:3361MV) as resources ($\dot{R}$), short-lived materials ($\dot{S}$), and capital goods ($\dot{K}$) using data from [14, 19, 23, 15, 20, 24, 16, 17]. This list is illustrative and by no means exhaustive.

Material Flow		**Materials**
Resources from biosphere	$\dot{R}_{0j}$	none
Short-lived from biosphere	$\dot{S}_{0j}$	oxygen, nitrogen, water
Resources from other sectors	$\dot{R}_{ij}$	cast iron (engine block); steel (chassis, panels); aluminum (body parts); copper (wiring); zinc, chromium, carbon (alloying); lead, nickel (battery cells); glass (windows, wind shield); rubber (tires); plastic (bodywork, interiors, seals) petroleum (paints, lubricants)
Short-lived from other sectors	$\dot{S}_{ij}$	energy (oil, natural gas, electricity) water (process) petroleum (solvents) plastic (packaging) paper (towels, packaging)
Capital from other sectors	$\dot{K}_{ij}$	steel (buildings, equipment) concrete (buildings) glass (windows, screens) plastic (fixtures, fittings, equipment) petroleum (paints, lubricants)
Product output	$\dot{P}_j$	auto parts and motor vehicles
Resource self-consumption	$\dot{R}_{jj}$	auto parts
Short-lived self-consumption	$\dot{S}_{jj}$	none
Capital self-consumption	$\dot{K}_{jj}$	motor vehicles
Resources to biosphere	$\dot{R}_{j0}$	trimmings and dust (metal, plastic, rubber)
Short-lived to biosphere	$\dot{S}_{j0}$	air emissions (GHG, NO_x, SO_x) emissions to water
Capital to biosphere	$\dot{K}_{j0}$	depreciated equipment depreciated buildings

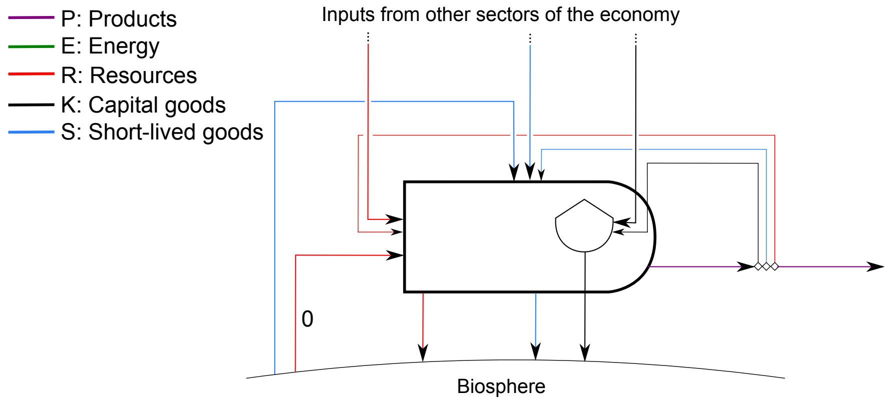

Fig. 2.6 Material flows for the US automobile industry using data from [14, 19, 23, 15, 20, 24, 16, 17].

2.6 Summary

In this chapter we saw how we all use accounting in our everyday lives to count not just physical things (people, apples) but also non-physical things (money). We developed a rigorous procedure for accounting by defining the *what*, *when*, and *where*: what are we counting, when we begin and end counting, and where is our system boundary (control volume) located. We saw that some things (e.g., apples) can be created and destroyed, but other things (mass, energy) are neither created nor destroyed.

We then applied this accounting procedure to materials flowing through an economy. We defined four different types of materials: *resources*, *short-lived goods*, and *capital* which are used to make *products* and specified that only capital may accumulate within economic sectors. We used these definitions in three examples, building from a one-sector model of the economy to a general framework for flows (and accumulation) of materials. Finally, we applied the accounting framework to the real-world example of the US auto industry. We categorized the types of materials used to produce automobiles, but found that industry-level data are difficult to obtain.

In the following two chapters of Part I, we will apply our accounting framework to direct energy (Chapter 3) and embodied energy (Chapter 4).

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Chapter 3
Direct energy flows

> *Living organisms need to be open to a constant flow of resources (energy and matter) to stay alive;*
> *human organizations need to be open to a flow of mental resources (information and ideas), as well as to the flows of energy and materials that are part of the production of goods or services.* [1, p.117]
>
> —Fritjof Capra

In Chapter 1, we formulated a model of economies consisting of producers and consumers who exchange goods and services and factors of production while extracting resources and disposing of wastes. In Chapter 2, we established the material basis of economies: economies are analogous to organisms with metabolisms that processes raw resources for the benefit of producers and consumers while generating unavoidable wastes. In this chapter, we describe and analyze the direct energy that is associated with material flows through an economy.

All forms of energy provide the potential to do mechanical work.[1] Energy (as mechanical work) is an essential aspect of the metabolic economy; with it, materials are refined, shaped, and assembled into useful intermediate and final products; food is made available to people in society; jobs are made easier for workers; human ingenuity is multiplied; and complex systems and civilizations are possible. In the absence of high rates of energy availablity at low cost, life becomes much more difficult, even impossible, for many people.

The analogy for this chapter is this: energy is to thermodynamics as money is to financial accounting. Or, energy is the *currency of thermodynamics*. Just as an accountant understands a firm by watching how and where currency flows through it, so we can understand an economy by watching how and where energy flows through it. Accounting for energy flows through an economy is essential for developing a dynamic picture of its metabolism.

The purpose of this chapter is to develop a framework for accounting energy flows within economies. With an energy framework in hand, we will be positioned to assess the rate at which consumed direct energy becomes embodied within the products and services that an economy provides (Chapter 4).

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[1] The quantification of the mechanical work potential of energy is *exergy*. When energy is “consumed” by an economy, exergy (work potential) is destroyed. These topics are discussed in greater detail in Section 8.4.2.

3.1 Methodology

We begin by noting that direct energy travels with material through an economy. "Direct" energy refers to forms of energy accounted by the First Law of Thermodynamics, including chemical potential energy, nuclear potential energy, gravitational potential energy, thermal energy, and kinetic energy. We use the term "direct" energy distinct from "embodied" energy, which will be discussed in Chapter 4. Examples of direct energy flows include the chemical potential energy of coal inflows to an energy sector, the thermal energy of process steam into a textile plant, and the thermal energy of CO_2 automobile exhaust. Each of these example flows is an example of a "transfer in" or a "transfer out," in the language of Section 2.1.1. In each case, the material (coal, steam, and CO_2) carries direct energy with it. Figure 3.1 shows a corresponding direct energy flow for each material flow of Figure 2.1.

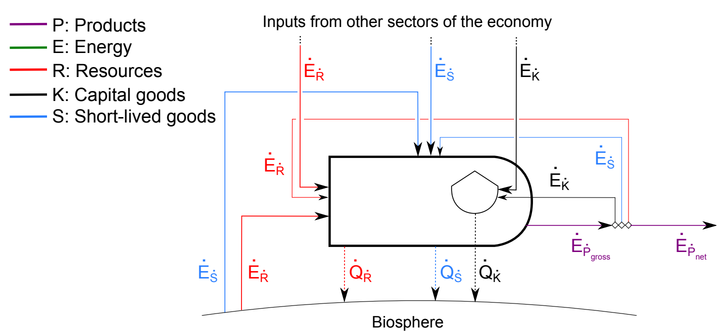

Fig. 3.1 Energy content ($\dot{E}$) of material flows ($\dot{R}$, $\dot{S}$, and $\dot{K}$) from Figure 2.1.

For any boundary (around, say, a machine, a plant, a sector of the economy, or the entire economy itself), the First Law of Thermodynamics says that the accumulation rate of direct energy within the boundary $\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)$ is equal to the sum of the incoming and outgoing direct energy transfer rates ($\dot{E}$) less outflowing energy carried by wastes ($\dot{Q}_{out}$). Energy is conserved: it be neither created nor destroyed.

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \sum \dot{E} - \sum \dot{Q}_{out} \tag{3.1}$$

When there is no accumulation of direct energy within the boundary $\left(\frac{\mathrm{d}E}{\mathrm{d}t} = 0\right)$, the sum of all signed direct energy flow rates ($\dot{E}$) and waste heats ($\dot{Q}_{out}$) will be zero.

$$0 = \sum \dot{E} - \sum \dot{Q}_{out} \tag{3.2}$$

It is important to note that the direct energy associated with some material flows can be so small as to be negligible compared to other direct energy flows in the economy. For example, there is a small amount of chemical energy in steel that could be released upon combustion. However, the direct energy associated flows of steel within the economy is almost negligible. (The *embodied* energy of the steel is most certainly *not* negligible, as will be discussed in Chapter 4.) On the other hand, the direct energy flow rates for fossil fuels (coal, oil, and natural gas) are typically orders of magnitude larger than any other material flows due to large chemical potential energy content.

To simplify the direct energy analysis, we can aggregate the direct energy flows of Figure 3.1 into single arrows when appropriate. For example, the direct energy inputs from other sectors of the economy (labeled as $\dot{E}_{\dot{R}}$, $\dot{E}_{\dot{S}}$, and $\dot{E}_{\dot{K}}$ at the top of Figure 3.1) can be summed to $\dot{E}$ (in Figure 3.2) such that

$$\dot{E} = \dot{E}_{\dot{R}} + \dot{E}_{\dot{S}} + \dot{E}_{\dot{K}}. \tag{3.3}$$

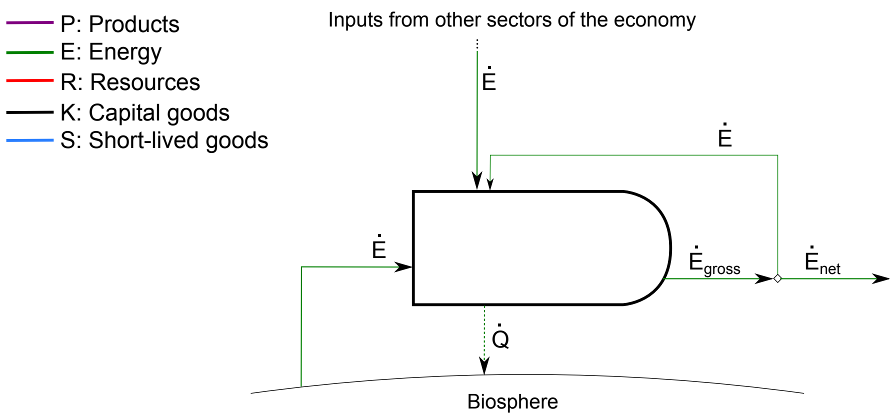

Fig. 3.2 Aggregated direct energy flows ($\dot{E}$) around the producer of Figure 3.1.

3.2 Example A: single-sector economy

Aggregated direct energy flows are now applied to Example A, the single-sector economy shown in Figure 2.2. By summing the direct energy flows associated with each material flow of Figure 2.2, we obtain a simplified picture of direct energy flows in the economy, as shown in Figure 3.3.

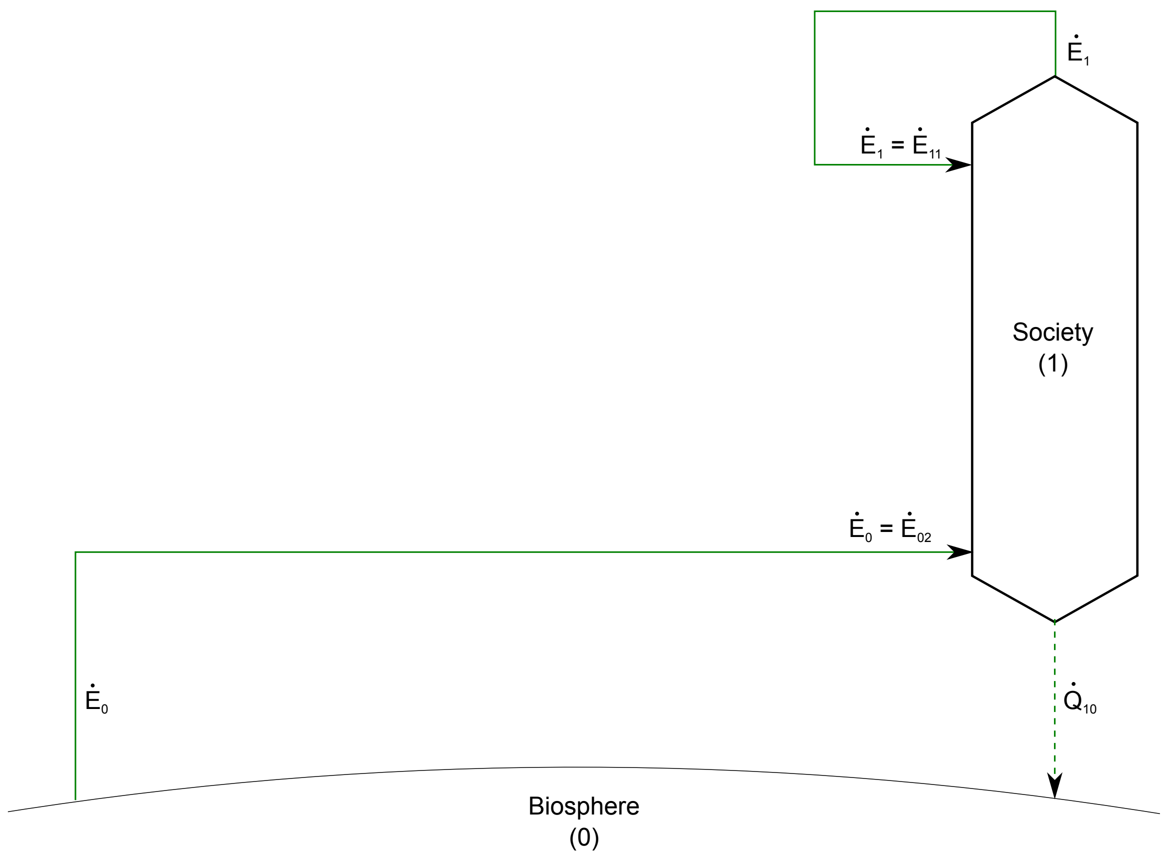

Fig. 3.3 Direct energy flows ($\dot{E}$) a one-sector economy.

We distinguish useful direct energy inputs to a sector of the economy ($\dot{E}_{01}$ in Figure 3.3) from wasteful direct energy flows ($\dot{Q}_{10}$ in Figure 3.3), because $\dot{Q}$ typically denotes thermal energy, and most waste energy is in the form of thermal energy, i.e., waste heat. In Figure 3.3, direct energy input to the economy ($\dot{E}_{01}$) is shown as being extracted from the biosphere, because the vast majority of direct energy today is derived from fossil fuels. Waste heat from the economy ($\dot{Q}_{10}$) is shown as returning to the biosphere.

As discussed in Section 3.1, both direct energy ($\dot{E}$), and waste heat ($\dot{Q}$) are accounted by the First Law of Thermodynamics. Accounting for possible accumulation of direct energy, the First Law of Thermodynamics for Example A indicates that

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \dot{Q}_{10} - \dot{E}_{01} \tag{3.4}$$

and

$$\frac{\mathrm{d}E_1}{\mathrm{d}t} = \dot{E}_{01} + \dot{E}_{11} - \dot{E}_1 - \dot{Q}_{10}. \tag{3.5}$$

Note that $\dot{E}_1$ is the gross direct energy production rate of society. For example, firms extract crude oil (a component of $\dot{E}_{01}$) and refine it into petroleum products (a component of $\dot{E}_1$) that are consumed by society. The direct energy consumption of extraction and refining firms is a component of $\dot{E}_{11}$.

Aside from, for example, the US Strategic Petroleum Reserve, we are not stockpiling oil and coal at any meaningful rate, i.e. we consume fossil fuels at a rate equal to their extraction rate. Thus, the world is not accumulating direct energy in the economy.[2] (The world *is*, however, accumulating *embodied* energy in the economy as we shall see in Chapter 4.) Thus, the accumulation rates for direct energy $\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)$ in the above equations could be set to zero as follows:

$$0 = \dot{Q}_{10} - \dot{E}_{01} \tag{3.6}$$

and

$$0 = \dot{E}_{01} + \dot{E}_{11} - \dot{E}_1 - \dot{Q}_{10}. \tag{3.7}$$

However, we shall see later (in Chapter 3) that keeping direct energy accumulation terms $\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)$ provides an advantage when deriving embodied energy accounting equations.

[2] A counter-example could be made for nuclear fuels where “spent” fuel represents a large exergetic stockpile. However, this reserve is not (presently) economically useful.

3.3 Example B: two-sector economy

For Example B, we split Production (2) from Society (1). Figure 3.4 shows aggregated direct energy flows associated with the material flows of Figure 2.3.

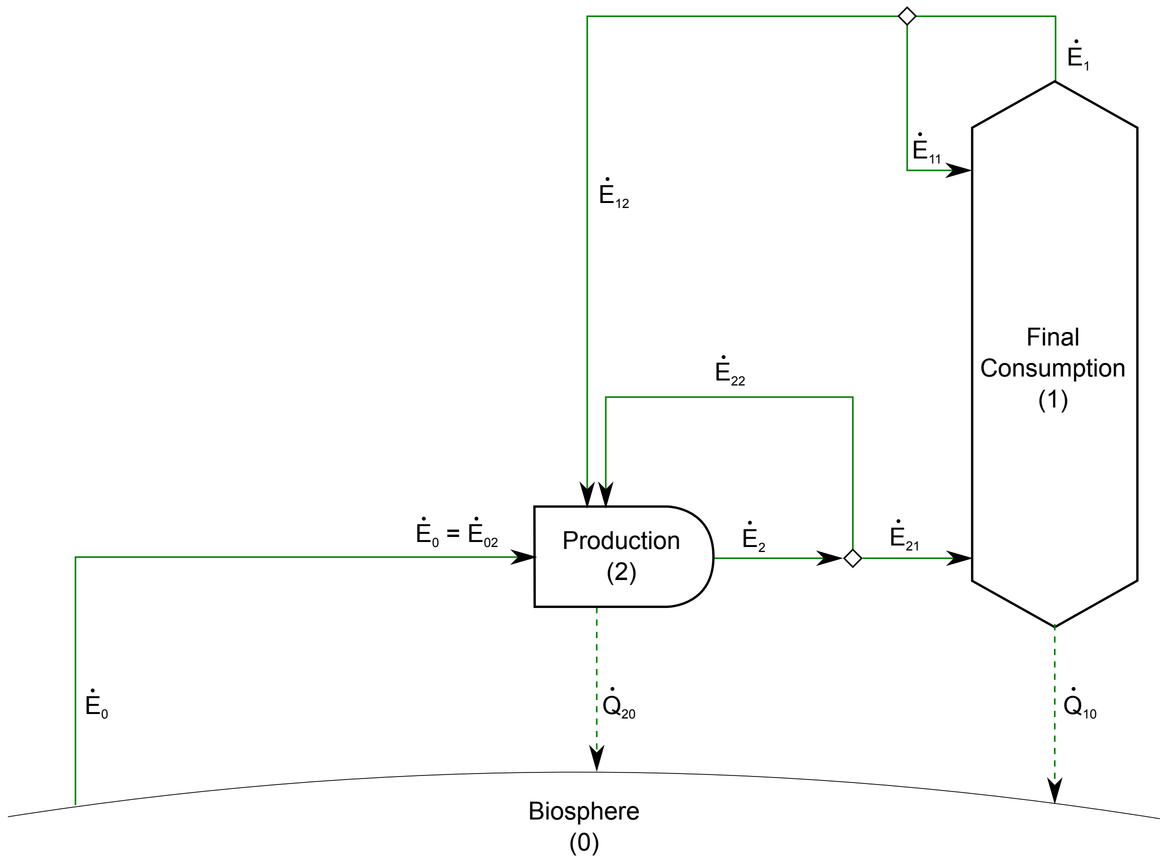

Fig. 3.4 Direct energy flows ($\dot{E}$) for a two-sector economy.

The First Law of Thermodynamics requires that both direct energy and waste heat be conserved around each entity (1 and 2) as well as around the Biosphere (0). First Law energy accounting around the Biosphere (0) and Society (1) gives

$$\frac{dE_0}{dt} = \dot{Q}_{10} + \dot{Q}_{20} - \dot{E}_{02}, \tag{3.8}$$

and

$$\frac{dE_1}{dt} = \dot{E}_{11} + \dot{E}_{21} - \dot{E}_1 - \dot{Q}_{10}. \tag{3.9}$$

Note that $\dot{E}_{12}$ represents useful work that people and draught animals contribute to Production (2). Ayres and Warr [2, 3] call this "muscle work." $\dot{E}_{11}$ represents the muscle work required for consumption. Direct energy (electricity, oil, natural gas, etc.) required for consumption by final demand is included in $\dot{E}_{21}$.

The First Law around Production (2), including the accumulation rate of direct energy in the sector $\left(\frac{dE_2}{dt}\right)$, yields

$$\frac{dE_2}{dt} = \dot{E}_{02} + \dot{E}_{12} + \dot{E}_{22} - \dot{E}_2 - \dot{Q}_{20}. \tag{3.10}$$

It is notable that Production (2) consumes ($\dot{E}_{22}$) a portion of its gross energy output ($\dot{E}_2$): *it takes energy to make energy*. The gross direct energy production of the Energy sector (2) is $\dot{E}_2$, and the direct energy consumption of the Energy sector (2) is $\dot{E}_{12} + \dot{E}_{22}$. The net direct energy production Energy (2) is given by $\dot{E}_2 - (\dot{E}_{12} + \dot{E}_{22})$. The *energy return on investment* (*EROI*) of the Energy sector (2) is given by

$$EROI_2 = \frac{\dot{E}_2}{\dot{E}_{12} + \dot{E}_{22}}. \tag{3.11}$$

EROI represents the energy production *per unit* of energy invested by society in the production process and may be considered a measure of the ease of obtaining energy resources from the biosphere. Although the definition of EROI, as outlined here, is easy to articulate $\left(\text{essentially, } \frac{\text{energy out}}{\text{energy in}}\right)$, the EROI calculation involves a multitude of system boundary considerations. These issues are well covered by both Murphy, et al. [4] and Brandt, et al. [5, 6] who outline varying EROI ratios according to what factors are included in the calculation. Because we are dealing only with direct energy in this chapter (and not upstream energy embodied in materials), the EROI defined here is $\text{EROI}_{2,d}$ [4, Table 1] or GER_γ [7, Table 1], where GER stands for *gross energy ratio* an equivalent metric to EROI.

**** MCD discussion of resource quality ****

As discussed in Chapter 2, society relies heavily on concentrations of high quality material resources. As we mine lower quality material resources we require larger inputs of energy both directly, to process greater volumes of material, but also indirectly to build the extra capital equipment necessary to do the processing. The same is also true of energy resources within the environment. Fossil fuels represent stocks of solar energy accumulated (in the form of biomass) over many millions of years. These resources are extremely far from equilibrium with the environment. EROI can be considered an indicator of energy resource quality. As EROI (and thus energy quality) declines, more energy is needed to extract and deliver energy from the environment, both directly, for example the energy to pump oil from deeper underground, and indirectly, in order to build the extra oil rigs necessary to maintain production levels.[3]

****

Equation 3.8 can be generalized with a sum as

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \sum_{i=1}^{n} \left(\dot{Q}_{i0} - \dot{E}_{0i}\right), \tag{3.12}$$

where n is the number of economic sectors in the accounting framework (in this example, $n = 2$). Similarly, Equations 3.9 and 3.10 can generalized with a sum as

$$\frac{\mathrm{d}E_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{E}_{ij} - \dot{E}_j - \dot{Q}_{j0}, \tag{3.13}$$

where $j \in [1, n]$.

3.4 Example C: three-sector economy

We can extend Example B, to include an Energy sector (2) and a Goods and Services sector (3), thereby obtaining a fuller picture of direct energy flows among sectors (Figure 3.5).

[3] This issue of resource quality will be re-visited in Chapters 4 and 5 and discussed in more detail in Section 8.4.

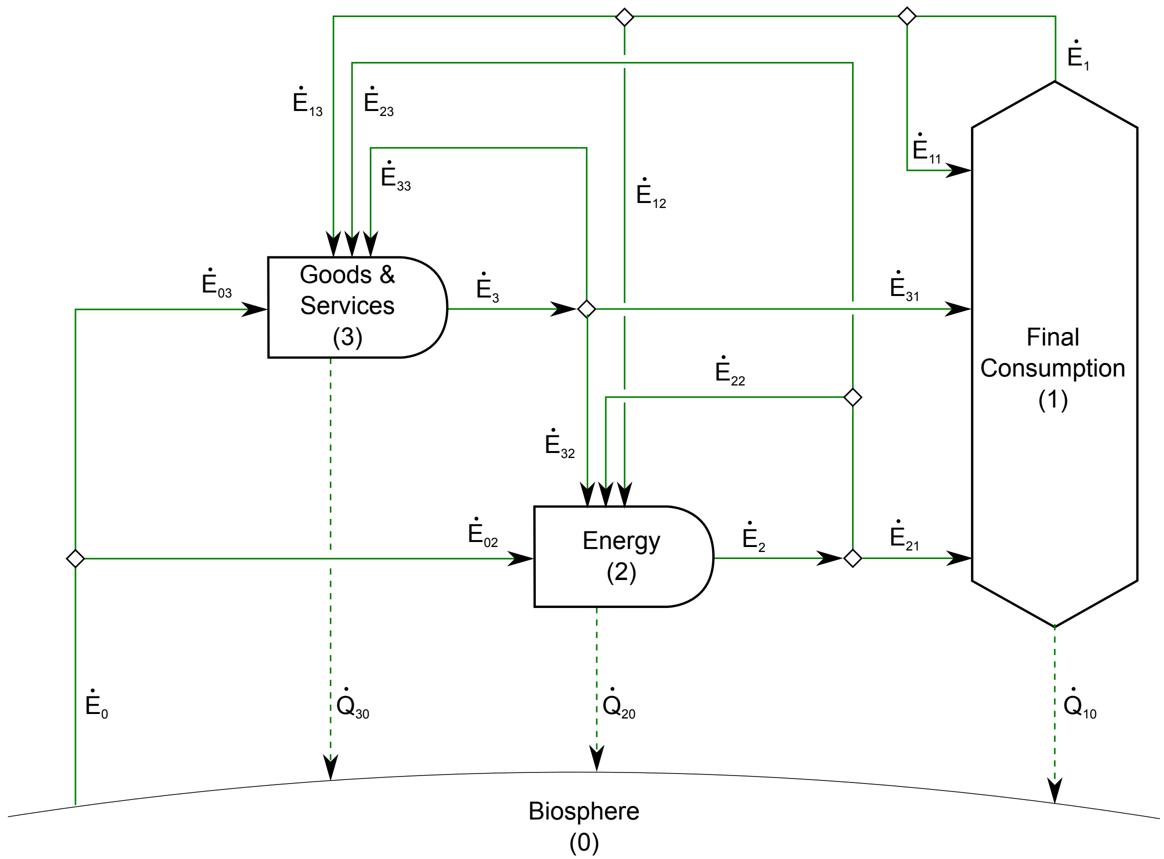

Fig. 3.5 Direct energy flows ($\dot{E}$) for a three-sector economy.

The First Law of Thermodynamics around the Biosphere (0), Society (1), and the Energy (2) gives

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \dot{Q}_{10} + \dot{Q}_{20} + \dot{Q}_{30} - \dot{E}_{02} - \dot{E}_{03}, \tag{3.14}$$

$$\frac{\mathrm{d}E_1}{\mathrm{d}t} = \dot{E}_{11} + \dot{E}_{21} + \dot{E}_{31} - \dot{E}_1 - \dot{Q}_{10}, \tag{3.15}$$

and

$$\frac{\mathrm{d}E_2}{\mathrm{d}t} = \dot{E}_{02} + \dot{E}_{12} + \dot{E}_{22} + \dot{E}_{32} - \dot{E}_2 - \dot{Q}_{20}. \tag{3.16}$$

The First Law around the Goods and Services sector (3) including, for now, the accumulation rate of direct energy in the sector $\left(\frac{\mathrm{d}E_3}{\mathrm{d}t}\right)$ yields

$$\frac{\mathrm{d}E_3}{\mathrm{d}t} = \dot{E}_{03} + \dot{E}_{13} + \dot{E}_{23} + \dot{E}_{33} - \dot{E}_3 - \dot{Q}_{30}. \tag{3.17}$$

Similar to Example B, we can generalize Equations 3.14–3.17 with sums to obtain

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{Q}_{i0} - \sum_{i=1}^{n} \dot{E}_{0i} \tag{3.18}$$

and

$$\frac{\mathrm{d}E_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{E}_{ij} - \dot{E}_j - \dot{Q}_{j0}, \tag{3.19}$$

where $j \in [1, n]$. Equations 3.18 and 3.19 are identical to Equations 3.12 and 3.13, indicating that we have successfully generalized the framework to any number of sectors.

In this economy, the purpose of Goods and Services (3) is to produce goods and provide services, it provides no direct energy to society. The purpose of Energy (2) is to make direct energy ($\dot{E}$) available to the economy and society in a useful form. We may simplify the above equations by realizing that (a) $\dot{E}_3 = \dot{E}_{3i} = 0$, because Goods and Services (3) is assumed to produce no direct energy, and (b) $\dot{E}_{03} = 0$, because Goods and Services (3) receives no direct energy from the Biosphere (0), except via the Energy sector (2). Thus, several terms in the sums of Equation 3.19 will be zero.

3.5 Direct energy in the auto industry

In this section we discuss inflow of direct energy into the automobile industry as shown in Figure 3.6. In 2010, the automobile industry purchased 28 trillion kJ of total energy from all sources. Table 3.1 shows the breakdown of energy by source.

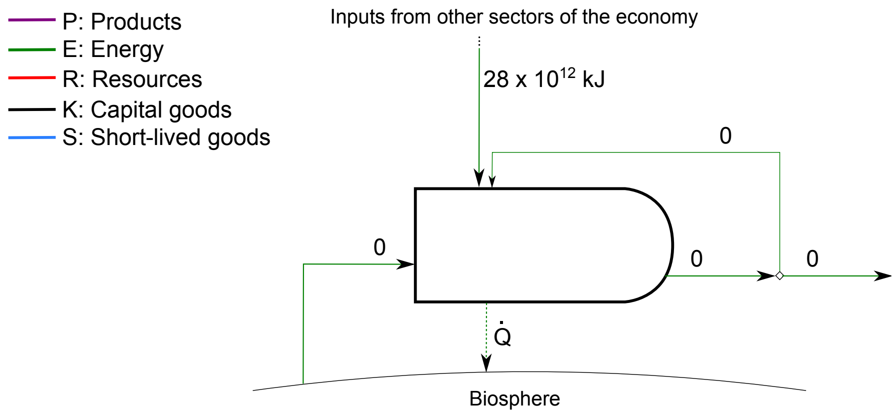

Fig. 3.6 Direct energy flows for the US automobile industry.[8, Table 7.6]

Table 3.1 Energy inputs to US auto industry (NAICS Code 336111) in 2010.[8, Table 7.6]

Source	Quantity
Electricity	3.0×10^{9} kW-hr
Natural gas	1.5×10^{10} ft^{3}
Other	1.0×10^{12} BTU
Total	2.8×10^{13} kJ (thermal equivalent)

Total energy use can also be estimated by summing the energy use of the underlying detailed processes in manufacturing automobiles. Sullivan et al. arrive at an estimate of the “gate-to-gate” energy used in the process of creating one automobile (the direct energy used within the automobile manufacturing process only).[9] This estimate can be mulitplied by the number of vehicles manufactured in a given year to obtain total energy use by the automobile industry. Sullivan estimated a total direct energy use of 34,000 MJ for a generic 1,532 kg vehicle.

3.6 Summary

In this chapter, we have developed equations, assisted by the First Law of Thermodynamics, that describe the flow of direct energy ($\dot{E}$) through economies (Section 3.1). Examples A–C afforded the opportunity to apply the equations to analyze economies with increasing levels of disaggregation (Sections 3.2–3.4). Finally, the energy flows for our running example, the US auto industry, were discussed in Section 3.5.

In the next chapter, the direct energy equations developed above will be used to develop *embodied* energy accounting equations for Examples A–C.

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Chapter 4
Embodied energy flows

One of the main sinks of energy in the "developed" world is the creation of stuff. In its natural life cycle, stuff passes through three stages. First, a new-born stuff is displayed in shiny packaging on a shelf in a shop. At this stage, stuff is called "goods." As soon as the stuff is taken home and sheds its packaging, it undergoes a transformation from "good" to its second form, "clutter." The clutter lives with its owner for a period of months or years. During this period, the clutter is largely ignored by its owner, who is off at the shops buying more goods. Eventually, by a miracle of modern alchemy, the clutter is transformed into its final form, rubbish. To the untrained eye, it can be difficult to distinguish this "rubbish" from the highly desirable "good" that it used to be. Nonetheless, at this stage the discerning owner pays the dustman to transport the stuff away. [1, p.88]

—David MacKay

**** Revisit issue of needing more capital equipment to process more material. This will embody more energy in the infrastructure of the economy. ****

**** MCD - introduce idea of resource quality to be revisited in value chapter ****

Need more energy to process more material. Ref Materials chapter.

Need more energy to make more capital equipment to process more material.

**** MCD From materials chapter:

Society relies heavily on extracted resources from naturally occurring accumulations that are far from equilibrium with their surroundings, e.g. fossil fuel reservoirs or seams of high-grade ore. As these high quality material reserves are depleted and society must turn to lower grade reserves, more material must be processed (requiring the deployment of more productive capital) in order to maintain the same level of production.[**?**]

****

In Chapter 3, the First Law of Thermodynamics accounted direct energy ($\dot{E}$) flowing among sectors of an economy. In this chapter, we will adapt the First Law to account *embodied* energy in the material flows of an economy.[1]

Energy can become "embodied" in the output of an economic sector and within the material in the sector itself. The energy embodied in the output of an economic sector (e.g., energy embodied in the automobiles produced by the automotive sector) is related to the sum of all direct energy consumed in the manufacture of its products, including all upstream processing stages. Embodied energy gives an indication of the energy demand created by consumption of goods and services within an economy.

[1] To the authors' knowledge, this is the first appearance in the literature of a systematic, detailed, and mathematically-rigorous derivation of embodied energy accounting equations based upon the laws of thermodynamics.

Energy that becomes embodied in the materials of an economic sector (such as the machines, factories, and dealerships within the automotive sector itself) is essential for the efficient operation of the sector. The amount of energy embodied in the sector is an indicator of the complexity of the sector.[2]

The purpose of this chapter is to develop a framework for accounting embodied energy flows within economies. With an embodied energy accounting framework in hand, we will be positioned to develop a method for analyzing the energy intensity of goods and services within an economy (Chapter 6).

4.1 Methodology

We begin the derivation of embodied energy accounting equations by defining the concept of *total* energy.

4.1.1 Total energy accounting

Total energy (T) is defined as the sum of direct energy (E, see Chapter 3) and embodied energy (B).

$$T \equiv E + B \tag{4.1}$$

The flow rate of total energy ($\dot{T}$) among sectors in the economy, the biosphere, and society is the sum of direct energy ($\dot{E}$) and embodied energy ($\dot{B}$).

$$\dot{T} = \dot{E} + \dot{B} \tag{4.2}$$

Figure 4.1 illustrates that total energy flows are comprised of direct energy ($\dot{E}$) and embodied energy ($\dot{B}$).

In some cases, a material flow may include either direct energy ($\dot{E}$) or embodied energy ($\dot{B}$), exclusively. For example, the flow of extracted crude oil from the earth consists of direct energy only ($\dot{B} = 0$ and $\dot{T} = \dot{E}$), because, in this framework, no embodied energy (B) is added to the crude oil until it reaches the downstream side of the oil rig. Conversely, the material produced by a non-energy sector of the economy consists of embodied energy only ($\dot{E} \approx 0$, and therefore $\dot{T} \approx \dot{B}$), because direct energy (E) produced by a non-energy sector is negligible in this framework.

In other cases, a material flow may include both a direct energy flow ($\dot{E}$) component *and* an embodied energy flow ($\dot{B}$) component. For example, the outgoing flow of refined petroleum from the energy sector has both a direct energy ($\dot{E}$, the energy content of the oil product, usually represented by chemical potential energy)

[2] The amount of energy embodied in an entire economy may be an indicator of its level of "development." See Section 7.3 for a discussion of several indicators of economic "development."

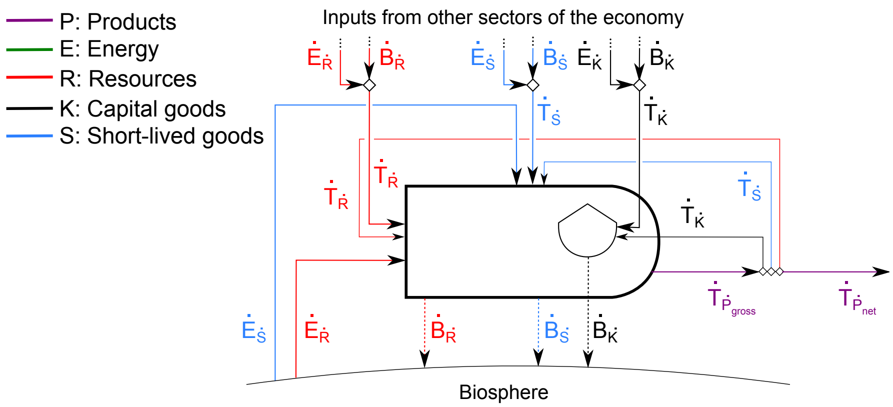

Fig. 4.1 Total energy flows ($\dot{T}$) for a single sector of an economy. For the sake of clarity, direct ($\dot{E}$) and embodied ($\dot{B}$) energy flows are shown separately for material inflows from other sectors only.

and embodied energy ($\dot{B}$, which accounts for the energy (a) consumed in upstream processes to extract and refine the crude oil and (b) consumed by the refinery itself).[3]

Most of the Energy Input-Output (EI-O) literature [2, 3] applies the following (and often unstated) assumptions:

- flows of total energy ($\dot{T}$) are conserved,[4]
- total energy does not accumulate in economic sectors,
- there is never a flow of embodied energy to the biosphere, and
- all total energy inflow to a sector is allocated to the products of that sector (i.e., there is no "waste" of total energy).

Like the EI-O literature, we assume that total energy (T) is conserved and never wasted.[5] However, we depart from the EI-O literature by explicitly accounting a stock for total energy accumulation in economic sectors.

Total energy (T) may accumulate within an economic sector as stocks of direct energy materials (piles of coal or tanks of oil)[6] but also as energy embodied in stocks of capital goods (e.g., machinery or buildings). The rate of accumulation of total energy in a sector of the economy, the biosphere, or society is given by the time derivative of total energy:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\mathrm{d}B}{\mathrm{d}t}. \tag{4.3}$$

[3] Outputs from agricultural sectors will be similar: both (a) the direct energy component (comprising chemical potential energy) and (b) the embodied energy component (representing upstream energy consumed in food production) will be non-zero.

[4] Total energy can be neither created nor destroyed.

[5] Of course, waste heat exists and is accounted by the First Law of Thermodynamics. However, waste heat is ignored when accounting for total energy.

[6] But little direct energy accumulation actually occurs. We use energy as fast as we make it available to society.

The following equation provides a total energy accounting for a sector of the economy, where the $\dot{T}$ terms are signed: positive for total energy input and negative for total energy output.

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \sum \dot{T} \tag{4.4}$$

By substituting Equations 4.2 and 4.3 into Equation 4.4, we obtain

$$\frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\mathrm{d}B}{\mathrm{d}t} = \sum \left(\dot{E} + \dot{B}\right). \tag{4.5}$$

4.1.2 Embodied energy accounting

We note that the definition of total energy (Equation 4.1) includes direct energy (E) and embodied energy (B) terms. On the other hand, the First Law of Thermodynamics (Equation 3.1) includes direct energy (E) and waste heat (Q) terms. The consequence of the foregoing difference is that an interesting relationship exists between embodied energy (B) and waste heat (Q), as we shall see below.

To derive an accounting equation for embodied energy, we substitute the First Law of Thermodynamics (Equation 3.1) into the total energy accounting equation (Equation 4.5).

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \sum \dot{B} + \sum \dot{Q}_{out} \tag{4.6}$$

The waste energy terms ($\dot{Q}_{out}$) in Equation 4.6 are *outflows* of energy from the sector. The embodied energy terms ($\dot{B}$) represent embodied energy of inflows and outflows of material. Splitting the $\dot{B}$ term into inflows and outflows gives

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \sum \dot{B}_{in} - \sum \dot{B}_{out} + \sum \dot{Q}_{out} \tag{4.7}$$

In words, the rate of accumulation of embodied energy in a sector of the economy $\left(\frac{\mathrm{d}B}{\mathrm{d}t}\right)$ is equal to the sum of the rates of inflow of embodied energy into the sector ($\dot{B}_{in}$) less the rate of output of embodied energy from the sector ($\dot{B}_{out}$) *plus* the rate of waste heat from the sector ($\dot{Q}_{out}$). The first two terms on the right side of Equation 4.7 are expected: accumulation is the difference between inflow and outflow rates. The final term ($\dot{Q}_{out}$) is a proxy for all direct energy ($\dot{E}$) consumed within the sector.

Rearranging Equation 4.7 yields another version of the embodied energy accounting equation: one that illuminates issues related to stages of growth for an economic sector.

$$\sum \dot{B}_{in} + \sum \dot{Q}_{out} = \frac{\mathrm{d}B}{\mathrm{d}t} + \sum \dot{B}_{out} \tag{4.8}$$

From Equation 4.8, we see that incoming embodied energy ($\dot{B}_{in}$) and waste heat[7] ($\dot{Q}_{out}$) can be used to increase either (a) the embodied energy within a sector of the economy $\left(\frac{\mathrm{d}B}{\mathrm{d}t}\right)$ or (b) the embodied energy output of a sector of the economy ($\dot{B}_{out}$), depending on decisions by actors (firms, households, or the government) within the sector. If the sector is "building up" production capacity, much of the incoming embodied energy ($\dot{B}_{in}$) and direct energy consumption (represented by $\dot{Q}_{out}$) will be used to increase infrastructure (and associated embodied energy, B) within the sector, and $\frac{\mathrm{d}B}{\mathrm{d}t}$ will be positive. If, on the other hand, the sector is not expanding, much of the incoming embodied energy ($\dot{B}_{in}$) and direct energy consumption (represented by $\dot{Q}_{out}$) will be used for production of goods ($\dot{B}_{out}$), and $\frac{\mathrm{d}B}{\mathrm{d}t}$ will be close to zero. Equation 4.7 shows that an economic sector in decline may experience an outflow of embodied energy (via products or depreciation) in excess of the sum of its embodied energy inflows ($\dot{B}_{in}$) and direct energy consumption (represented by $\dot{Q}_{out}$), and $\frac{\mathrm{d}B}{\mathrm{d}t}$ will be negative.

Equations 4.7 and 4.8 highlight a contrast between the present dynamic analysis and the EI-O literature. The traditional assumption of steady-state conditions in economic sectors is tantamount to assuming that $\frac{\mathrm{d}B}{\mathrm{d}t} = 0$ in Equations 4.7 and 4.8. That assumption precludes analysis of stages of growth and the embodied energy implications thereof.

Equations 4.7 and 4.8 are generalized embodied energy accounting equations that we will see again for Examples A–C in the sections that follow.

4.2 Example A: single-sector economy

Figure 4.2 shows the flows of total energy ($\dot{T}$) through the single-sector economy.

[7] Because we have substituted the First Law of Thermodynamics into the total energy accounting equation, $\dot{Q}_{out}$ is a proxy for direct energy consumption by the sector.

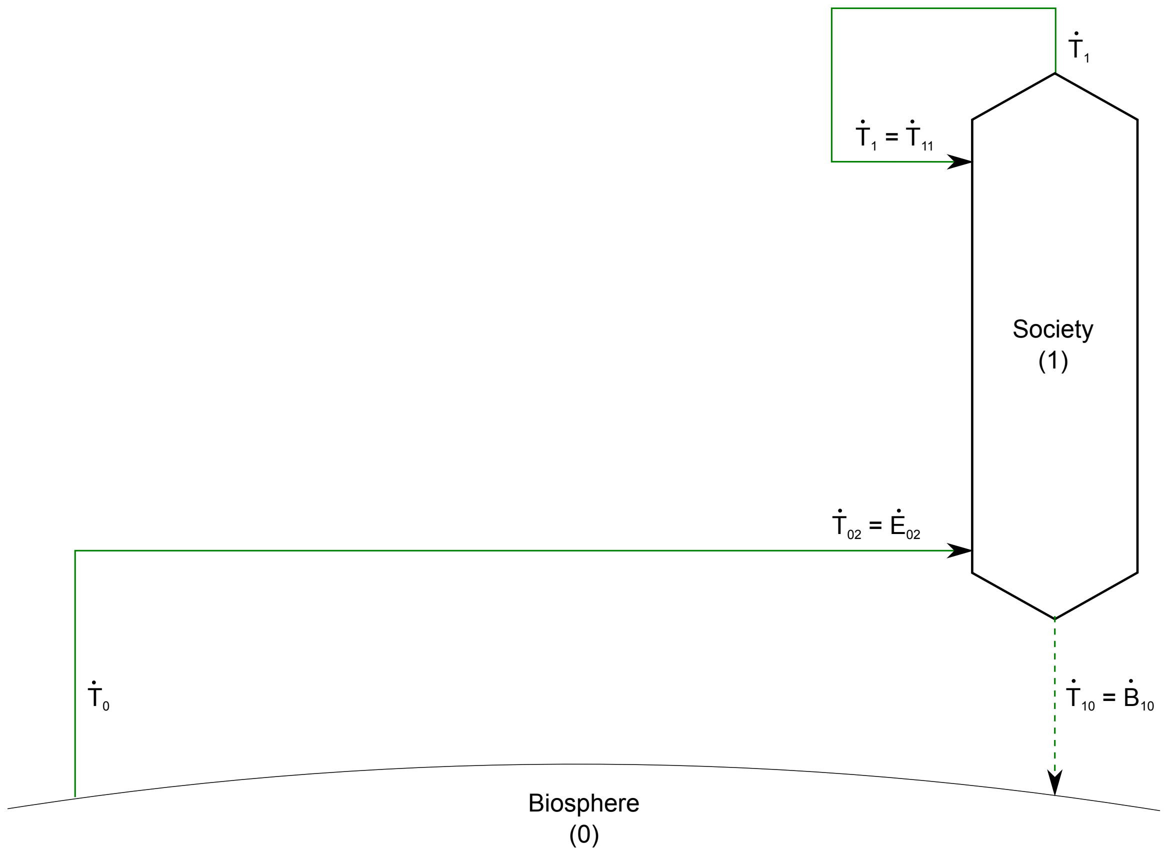

Fig. 4.2 Total energy flows ($\dot{T}$) in a one-sector economy.

As discussed above, we follow the EI-O literature in assuming that total energy (T) is conserved. A total energy accounting around the Biosphere (0) and Society (1) gives

$$\frac{\mathrm{d}T_0}{\mathrm{d}t} = \dot{T}_{10} - \dot{T}_{01}, \tag{4.9}$$

and

$$\frac{\mathrm{d}T_1}{\mathrm{d}t} = \dot{T}_{01} + \dot{T}_{11} - \dot{T}_1 - \dot{T}_{10}. \tag{4.10}$$

Substituting Equations 4.2 and 4.3 into Equations 4.9 and 4.10 yields

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} + \frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{E}_{10} + \dot{B}_{10} - \dot{E}_{01} - \dot{B}_{01} \tag{4.11}$$

and

$$\frac{\mathrm{d}E_1}{\mathrm{d}t} + \frac{\mathrm{d}B_1}{\mathrm{d}t} = \dot{E}_{01} + \dot{B}_{01} + \dot{E}_{11} + \dot{B}_{11} - \dot{E}_1 - \dot{B}_1 - \dot{E}_{10} - \dot{B}_{10}. \tag{4.12}$$

At this point, we can proceed in two directions. The first direction, simplifying Equations 4.11 and 4.12, provides an intuitive result. The second direction, substituting the First Law of Thermodynamics into Equations 4.11 and 4.12, provides the advantage of cancelling most of the direct energy terms. We begin with the first approach: simplification.

4.2.1 Simplification of the embodied energy accounting equation

To simplify Equations 4.11 and 4.12, we first realize that, by definition, no embodied energy flows from the earth with extracted material, so $\dot{B}_{01} = 0$ and $\dot{T}_0 = \dot{E}_{01}$ as shown in Figure 4.2. Second, we can assume that direct energy (E) does not accumulate in the economy such that $\frac{\mathrm{d}E_0}{\mathrm{d}t} = 0$ and $\frac{\mathrm{d}E_1}{\mathrm{d}t} = 0$. Finally, we note that $\dot{E}_{10} = 0$, because society does not supply direct energy to the biosphere. Thus, Equations 4.11 and 4.12 become

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{B}_{10} - \dot{E}_{01} \tag{4.13}$$

and

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \dot{E}_{01} + \dot{E}_{11} + \dot{B}_{11} - \dot{E}_1 - \dot{B}_1 - \dot{B}_{10}. \tag{4.14}$$

These equations show that direct energy consumed by a sector ($\dot{E}_{01}$) increases the energy embodied within the sector (B_1), whereas waste from the sector produces an embodied energy outflow ($\dot{B}_{10}$) that reduces the energy embodied within the sector.

4.2.2 Substitution of First Law into the embodied energy accounting equation

The second approach to the derivation of embodied energy accounting equations is to substitute the First Law (Equations 3.4 and 3.5) into the total energy accounting equations (Equations 4.11 and 4.12).

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{E}_{10} + \dot{B}_{10} - \dot{B}_{01} - \dot{Q}_{10} \tag{4.15}$$

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \dot{B}_{01} + \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} - \dot{E}_{10} + \dot{Q}_{10} \tag{4.16}$$

This substitution has the advantage of canceling most of the direct energy terms from the embodied energy accounting equations. And, it is no longer necessary to assume that the accumulation rate of direct energy $\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right)$ is zero, because the $\frac{\mathrm{d}E}{\mathrm{d}t}$ term is cancelled by the substitution.

We can simplify Equations 4.15 and 4.16 using the assumptions of Section 4.2.1 (namely, that $\dot{B}_{01} = 0$ and $\dot{E}_{10} = 0$) to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{B}_{10} - \dot{Q}_{10} \tag{4.17}$$

and

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} + \dot{Q}_{10}. \tag{4.18}$$

The material model of this framework (see Chapter 2) indicates that materials are comprised of resources (R), short-lived materials (S), and capital (K). Thus, we can write

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \frac{\mathrm{d}B_{R_1}}{\mathrm{d}t} + \frac{\mathrm{d}B_{S_1}}{\mathrm{d}t} + \frac{\mathrm{d}B_{K_1}}{\mathrm{d}t}, \tag{4.19}$$

but neither resources (R) nor short-lived materials (S) accumulate in economic sectors at a significant rate. Thus,

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \frac{\mathrm{d}B_{K_1}}{\mathrm{d}t}. \tag{4.20}$$

We can substitute Equation 4.20 into Equation 4.18 to obtain

$$\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} + \dot{Q}_{10}. \tag{4.21}$$

Equations 4.17 and 4.21 are the embodied energy accounting equations for Example A.

In Examples B and C following, we will choose the approach of this section, namely substitution of the First Law of Thermodynamics into the total energy accounting equation (instead of simplifying the total energy equation as discussed in Section 4.2.1), because of the benefit of canceling direct energy flow terms ($\dot{E}$).

4.2.3 *Physical depreciation*

The term $\dot{B}_{10}$ in Equation 4.21 represents the disposal rate of embodied energy from Society (1) to the Biosphere (0). Figure 2.2 shows that the outgoing material flow from Society (1) is comprised of resources ($\dot{R}_{10}$), short-lived materials ($\dot{S}_{10}$), and capital ($\dot{K}_{10}$). Each of these material flows will have associated embodied energy such that

$$\dot{B}_{10} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \dot{B}_{\dot{K}_{10}}. \tag{4.22}$$

The term $\dot{B}_{\dot{K}_{10}}$ represents the energy embodied in depreciated phyiscal assets. Physical depreciation is counted at the moment when material physically departs an economic sector and enters the biosphere, presumably a landfill, where the material in the wasted assets will decay. Financial depreciation is usually faster than physical depreciation according to rates set by accounting rules. The embodied energy associated with physical depreciation ($\dot{B}_{\dot{K}_{10}}$) can be represented by a depreciation term such as

$$\dot{B}_{\dot{K}_{10}} = \gamma_{B_1} B_{K_1}, \tag{4.23}$$

where γ_B represents the depreciation rate of embodied energy in units of inverse time (e.g., 1/year) with $\gamma_B > 0$.[8] The depreciation rate (γ_B) indicates that a fraction of the energy embodied in capital stock is disposed over a period of time (e.g., $\gamma_B = 0.05$/year). In the absence of other inputs or outputs, this depreciation function provides exponential decay of embodied energy (B) in an economic sector. γ_B is, in general, a function of time.

Equation 4.23 can be substituted into Equation 4.22 to obtain

$$\dot{B}_{10} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{B_1} B_{K_1}. \tag{4.24}$$

Equation 4.24 can be substituted into Equations 4.17 and 4.21 to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{B_1} B_{K_1} - \dot{Q}_{10} \tag{4.25}$$

and

$$\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{\dot{R}_{10}} - \dot{B}_{\dot{S}_{10}} - \gamma_{B_1} B_{K_1} + \dot{Q}_{10}. \tag{4.26}$$

[8] Note that γ_B will, in general, be different from γ_K defined in Section 2.2. γ_B will equal γ_K if and only if the depreciated capital has an embodied energy content that is identical to the average embodied energy content of the sector on a per-unit-mass basis.

Equation 4.26 indicates that the accumulation rate of embodied energy in an economic sector $\left(\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t}\right)$ is equal to the sum of the embodied energy input to the sector ($\dot{B}_{11}$) and waste heat from the economic sector ($\dot{Q}_{10}$), less embodied energy the leaves the sector in its products ($\dot{B}_1$), less the rate of disposal of embodied energy associated with scrap resources ($\dot{B}_{\dot{R}_{10}}$), short-lived material ($\dot{B}_{\dot{S}_{10}}$), and depreciated capital stock ($\gamma_{B_1} B_{K_1}$).

**** MCD discussion of resource quality ****

As discussed in previous Chapters, natural resource quality has a direct impact on both material and energy intensity of economic processes. As we extract lower quality resources we require larger inputs of materials and energy, to process greater volumes of material, and to build the extra capital equipment necessary to do the extra processing. An analogous impact is seen in the embodied energy. A greater amount of energy is embodied within the material and energy products of a sector and the extra capital equipment represents a greater amount of energy embodied within the production sector. Additionally, each unit of capital will have a greater amount of energy embodied within it due to increases in the material and energy intensity of upstream sectors.[9]

****

We turn now to Example B, a two-sector economy.

4.3 Example B: two-sector economy

For the two-sector economy of Figures 2.3 and 3.4, we again follow the EI-O literature by assuming that total energy (T) is conserved. Figure 4.3 shows total energy flows for the two-sector economy.

[9] This issue of resource quality will be re-visited in Chapter 5 and discussed in more detail in Section 8.4.

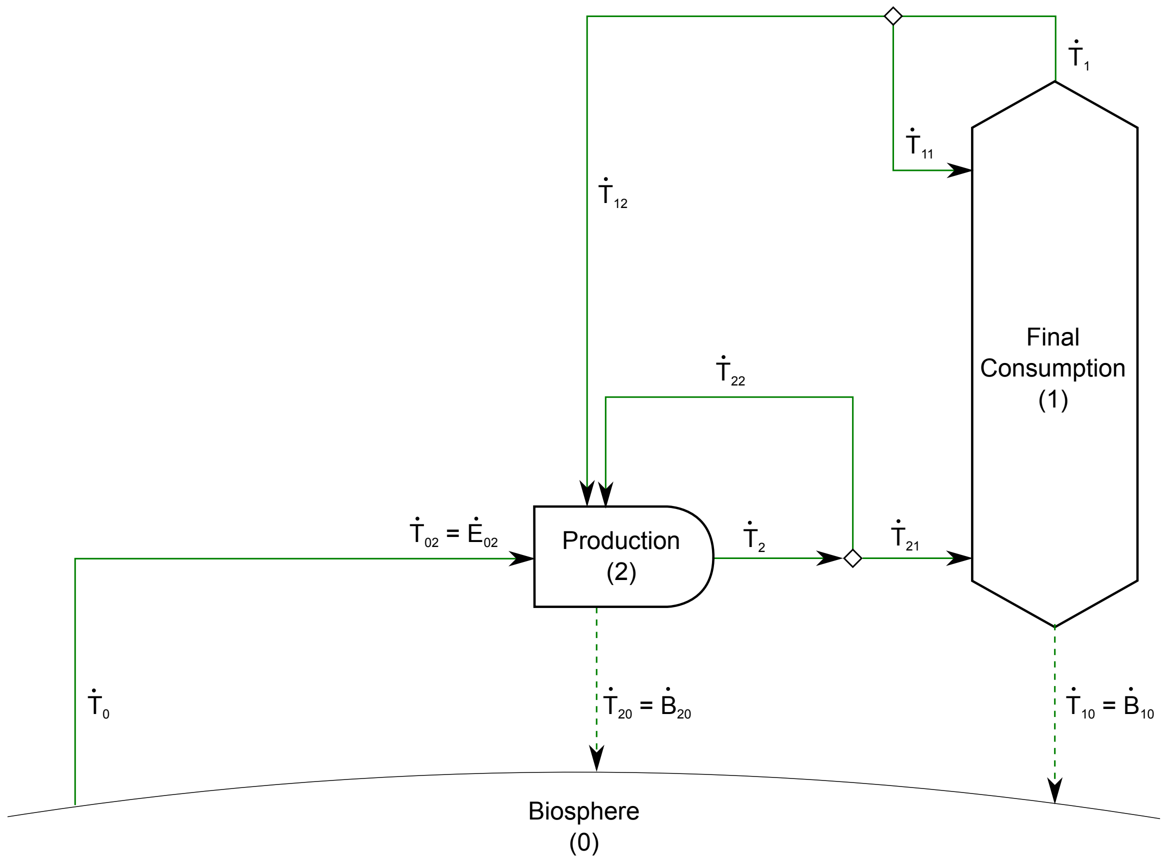

Fig. 4.3 Flows of total energy ($\dot{T}$) in a two-sector economy.

Accounting for accumulation of total energy and using the assumption that total energy is conserved, we can write the following equations.

$$\frac{dT_0}{dt} = \dot{T}_{10} + \dot{T}_{20} - \dot{T}_{02}, \tag{4.27}$$

$$\frac{dT_1}{dt} = \dot{T}_{11} + \dot{T}_{21} - \dot{T}_1 - \dot{T}_{10}, \tag{4.28}$$

and

$$\frac{dT_2}{dt} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} - \dot{T}_2 - \dot{T}_{20}. \tag{4.29}$$

Substituting Equations 4.2 and 4.3 into Equations 4.27 through 4.29 gives

$$\frac{dB_0}{dt} + \frac{dE_0}{dt} = \dot{E}_{10} + \dot{B}_{10} + \dot{E}_{20} + \dot{B}_{20} - \dot{E}_{02} - \dot{B}_{02}, \tag{4.30}$$

$$\frac{dB_1}{dt} + \frac{dE_1}{dt} = \dot{E}_{11} + \dot{B}_{11} + \dot{E}_{21} + \dot{B}_{21} - \dot{E}_1 - \dot{B}_1 - \dot{E}_{10} - \dot{B}_{10}, \tag{4.31}$$

and

$$\frac{dB_2}{dt} + \frac{dE_2}{dt} = \dot{E}_{02} + \dot{B}_{02} + \dot{E}_{12} + \dot{B}_{12} + \dot{E}_{22} + \dot{B}_{22} - \dot{E}_2 - \dot{B}_2 - \dot{E}_{20} - \dot{B}_{20}. \tag{4.32}$$

As in Example A, we can substitute the First Law of Thermodynamics (Equations 3.8–3.10) into the total energy accounting equations (Equations 4.30–4.32) and employ the assumptions that $\dot{E}_{i0} = 0$ and $\dot{B}_{0j} = 0$ to obtain

$$\frac{dB_0}{dt} = \dot{B}_{10} + \dot{B}_{20} - \dot{Q}_{10} - \dot{Q}_{20}, \tag{4.33}$$

$$\frac{dB_1}{dt} = \dot{B}_{11} + \dot{B}_{21} - \dot{B}_2 - \dot{B}_{10} + \dot{Q}_{10}, \tag{4.34}$$

and

$$\frac{dB_2}{dt} = \dot{B}_{12} + \dot{B}_{22} - \dot{B}_2 - \dot{B}_{20} + \dot{Q}_{20}. \tag{4.35}$$

Similar to Example A, we observe that the accumulation rate of embodied energy in the economic sectors (1 and 2) is the sum of the rates of waste heat flowing from the sector ($\dot{Q}_{20}$) and embodied energy into the sector ($\dot{B}_{12} + \dot{B}_{22}$) less the rate of embodied energy leaving the sector on its output streams ($\dot{B}_2 + \dot{B}_{20}$).

Equations 4.33–4.35 can be simplified using sums:

$$\frac{dB_0}{dt} = \sum_{i=1}^{n} \dot{B}_{i0} - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{4.36}$$

and

$$\frac{\mathrm{d}B_j}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{ij} - \dot{B}_j - \dot{B}_{j0} + \dot{Q}_{j0}, \tag{4.37}$$

where $j \in [1, n]$.

As in Example A, we can disaggregate the accumulation and waste embodied energy terms and express physical waste of capital stock as depreciation in Equations 4.36 and 4.37 to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \sum_{i=1}^{n} \left(\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K_i} \right) - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{4.38}$$

and

$$\frac{\mathrm{d}B_{K,j}}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{ij} - \dot{B}_j - \left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j} \right) + \dot{Q}_{j0}. \tag{4.39}$$

In the next section, we apply embodied energy accounting to Example C, a three-sector economy.

4.4 Example C: three-sector economy

Again, we begin with the diagram showing total energy ($\dot{T}$) flows among the economic sectors of Example C (Figure 4.4).

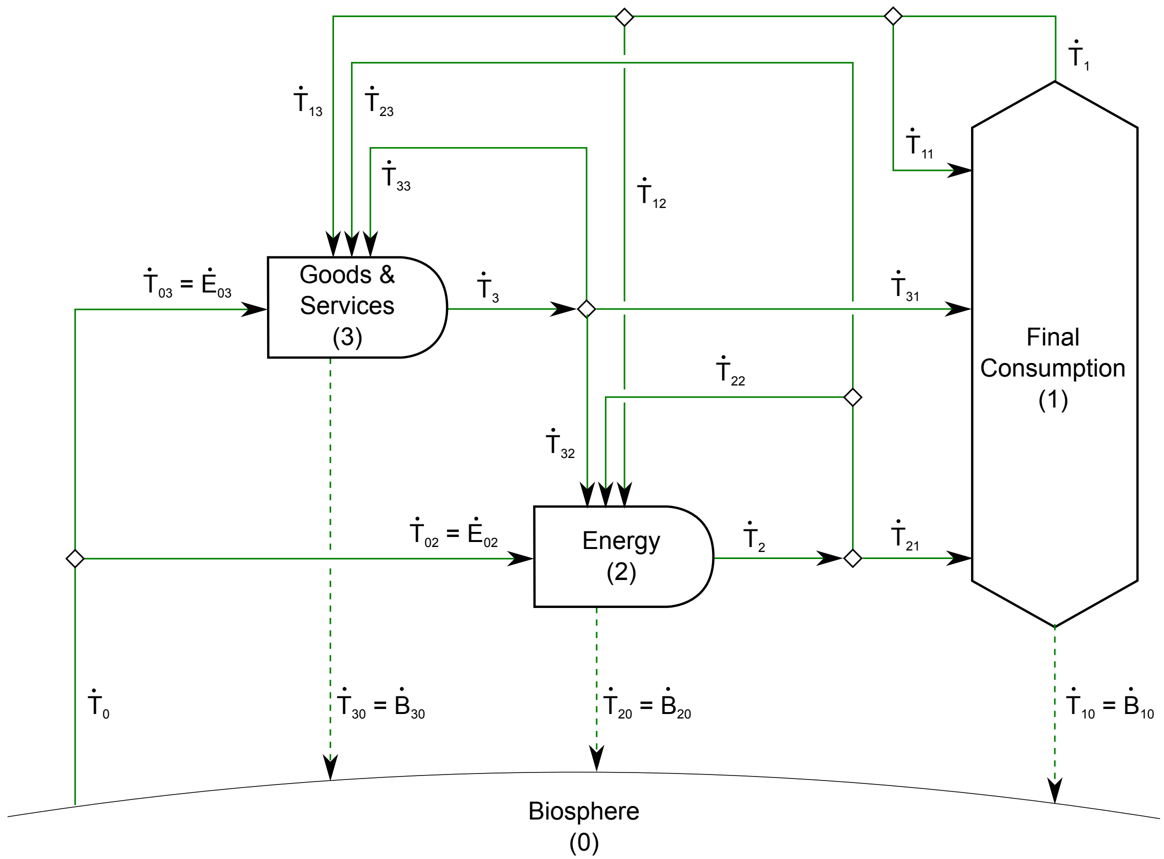

Fig. 4.4 Flows of total energy ($\dot{T}$) in a three-sector economy.

Accounting for accumulation of total energy and applying the assumption that total energy is conserved, we can write the following equations. We build from the derivation in Section 4.3 and utilize sums for each equation below.

$$\frac{dT_0}{dt} = \sum_{i=1}^{n} \dot{T}_{i0} - \sum_{j=1}^{n} \dot{T}_{0j} \tag{4.40}$$

and

$$\frac{dT_j}{dt} = \sum_{i=0}^{n} \dot{T}_{ij} - \dot{T}_j - \dot{T}_{j0}. \tag{4.41}$$

where $j \in [1, n]$.

Substituting Equations 4.2 and 4.3 into Equations 4.40 and 4.41 gives

$$\frac{dE_0}{dt} + \frac{dB_0}{dt} = \sum_{i=1}^{n} \dot{E}_{i0} + \sum_{i=1}^{n} \dot{B}_{i0} - \sum_{j=1}^{n} \dot{E}_{0j} - \sum_{j=1}^{n} \dot{B}_{0j} \tag{4.42}$$

and

$$\frac{dE_j}{dt} + \frac{dB_j}{dt} = \sum_{i=0}^{n} \dot{E}_{ij} + \sum_{i=0}^{n} \dot{B}_{ij} - \dot{E}_j - \dot{B}_j - \dot{E}_{j0} - \dot{B}_{j0}. \tag{4.43}$$

Substituting the First Law of Thermodynamics (Equations 3.18 and 3.19) into the total energy accounting equations (Equations 4.42 and 4.43) and recognizing that $\dot{B}_{0j} = 0$ for $j \in [1, n]$ and $\dot{E}_{i0} = 0$ for $i \in [1, n]$ gives embodied energy accounting equations for Example C:

$$\frac{dB_0}{dt} = \sum_{i=1}^{n} \dot{B}_{i0} - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{4.44}$$

$$\frac{dB_j}{dt} = \sum_{i=0}^{n} \dot{B}_{ij} - \dot{B}_j - \dot{B}_{j0} + \dot{Q}_{j0} \tag{4.45}$$

As in Example B, we can disaggregate the accumulation and waste embodied energy terms and express physical waste of capital stock as depreciation in Equations 4.44 and 4.45 to obtain

$$\frac{dB_0}{dt} = \sum_{i=1}^{n} \left(\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K_i} \right) - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{4.46}$$

and

$$\frac{dB_{K_j}}{dt} = \sum_{i=1}^{n} \dot{B}_{ij} - \dot{B}_j - \left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j} \right) + \dot{Q}_{j0}, \tag{4.47}$$

which are the same as Equations 4.38 and 4.39, indicating that we have successfully generalized the embodied energy equations to an arbitrarily-large economy.

To verify the above derivation, we sum Equations 4.46 and 4.47 for all sectors of the economy ($j \in [1, n]$) to obtain

$$\begin{aligned}\frac{\mathrm{d}B_0}{\mathrm{d}t} + \sum_{j=1}^{n} \frac{\mathrm{d}B_{K_j}}{\mathrm{d}t} = &\sum_{i=1}^{n}\left(\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K,i}\right) - \sum_{i=1}^{n} \dot{Q}_{i0} \\ &+ \sum_{j=1}^{n}\sum_{i=1}^{n} \dot{B}_{ij} - \sum_{j=1}^{n} \dot{B}_j \\ &- \sum_{j=1}^{n}\left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K,j}\right) + \sum_{j=1}^{n} \dot{Q}_{j0}.\end{aligned} \tag{4.48}$$

Using the identities

$$\dot{B}_j = \sum_{k=1}^{n} \dot{B}_{jk} \tag{4.49}$$

and

$$\sum_{j=1}^{n} \dot{B}_j = \sum_{j=1}^{n}\sum_{k=1}^{n} \dot{B}_{jk} = \sum_{i=1}^{n}\sum_{k=1}^{n} \dot{B}_{ik} = \sum_{i=1}^{n}\sum_{j=1}^{n} \dot{B}_{ij} = \sum_{j=1}^{n}\sum_{i=1}^{n} \dot{B}_{ij}, \tag{4.50}$$

Equation 4.48 becomes

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} + \sum_{j=1}^{n} \frac{\mathrm{d}B_j}{\mathrm{d}t} = 0, \tag{4.51}$$

as expected. The total embodied energy content of the system remains constant with respect to time in this framework.

We can further simplify the above equations by expressing the embodied energy of the inflowing capital ($\sum_{i=1}^{n} \dot{B}_{ij}$) as a fraction ($\alpha_{B,j}$) of the energy embodied in the capital stock (B_{K_j})

$$\alpha_{B,j} \equiv \frac{\sum_{i=1}^{n} \dot{B}_{ij}}{B_{K_j}} \tag{4.52}$$

and resource and short-lived material flows as waste

$$\dot{B}_{\dot{W}_j} \equiv \dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}}. \tag{4.53}$$

With the above definitions, Equation 4.47 can be expressed as

$$\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t} = (\alpha_{B_j} - \gamma_{B_j})B_{K_j} - \dot{B}_{\dot{W}_j} - \dot{B}_j + \dot{Q}_{j0}. \tag{4.54}$$

With Equation 4.54, we see that the rate of accumulation of embodied energy in the capital stock of an economic sector $\left(\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t}\right)$ is affected by the balance between the inflow (α_{B_j}) and depreciation (γ_{B_j}) rates, the rate of wasting embodied energy ($\dot{B}_{\dot{W}_j}$), the rate at which embodied energy leaves with the products of the sector ($\dot{B}_j$), and the waste heat that leaves the sector ($\dot{Q}_{j0}$).

4.5 Embodied energy in the US auto industry

In this section, we apply the framework developed above to flows of total energy in the US auto industry, as depicted in Figure 4.5. As in Section 2.5, we face difficulties due to lack of data. We know that some flows will have zero value, as shown in Figure 4.5. For instance, there is zero energy content (direct or embodied) associated with flows from the biosphere into the auto industry. Furthermore, we may assume that the resource flows ($\dot{R}$, red in Figure 4.5) and capital flows ($\dot{K}$, black in Figure 4.5) will have no direct energy ($\dot{E}$) associated with them.[10] Firstly, because energy products enter the industry as short-lived flows ($\dot{S}$, blue in Figure 4.5) and secondly, because energy products are not stored as capital within the sector. In fact, we can assume that all flows, other than inputs of short-lived goods ($\dot{S}$), will have no direct energy content ($\dot{E}$) associated with them.

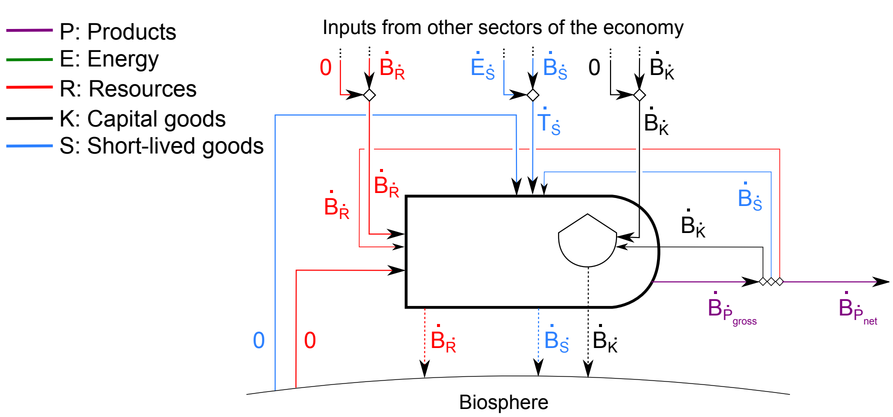

Fig. 4.5 Embodied energy flows ($\dot{B}$) for the US automobile industry.

Historically, very few estimates of embodied energy of automobiles have been made. In 1973, Berry and Fels, used a process-based analysis (rather than an input-

[10] Exceptions to this assumption may be the direct energy content of rubber, plastic and other petroleum products, e.g. motor oils which are used as resource inputs to the auto industry.

output analysis), to find that the energy cost of automobile manufacturing[11] in the US was 37,275 kW-hr (134 GJ or 134×10^9 J) per vehicle.[4, Table 2] Of this, 100 GJ was (upstream) energy embodied in the materials ($\dot{B}_{\dot{R}}$) and the remaining was (direct) energy used within the auto industry to manufacture, assemble, and transport the automobile.

Two decades later (1995), Stodolsky et al. estimated the energy consumed in materials and manufacturing automobiles to be 79 GJ per vehicle for a conventional automobile and 66 GJ per vehicle for an aluminum intensive vehicle, both under a maximum-recycling scenario.[5, p.11]. Three years later (1998), MacLean and Lave estimated the the embodied energy for an automobile to be 113.6 MBTU (120 GJ, of which 13 GJ were consumed upstream and 107 GJ were consumed direct in the auto sector) per vehicle [6, Figure 2], which they compare with contemporaneous estimates from Sullivan of 81 GJ per vehicle [7] and Volkswagen of 62 GJ per vehicle.[8]

Estimates of vehicle embodied energy are related to contemporary debates on whether Electric Vehicles (EVs) reduce CO_2 emissions relative to Internal Combustion Vehicles (ICVs), insofar as embodied energy includes upstream supply chain energy consumption, a major contributor to both EV and ICV lifecycle emissions. Although EVs have no direct emissions during operation, accounting for the upstream energy consumed in generating electricity, the manufacture of batteries, and the production of lightweight materials (employed to offset the weight of EV battery packs) leads to significantly increased lifecycle emissions. Many studies find that negligible or negative emissions savings are achieved by EVs compared to ICVs.[9–11]

4.6 Summary

This chapter relies upon the results from Chapter 3 to develop equations that describe the flow of *embodied* energy ($\dot{B}$) through economies (Section 4.1). We found that waste heat from a sector ($\dot{Q}$) is additive to the energy embodied within products of a sector, thereby providing the mechanism for accumulating embodied energy along the manufacturing supply chain. The embodied energy accounting equations were applied to example economies A–C in Sections 4.2–4.4. Finally, we discussed embodied energy in the context of our running example, the US auto industry (Section 4.5). We found that there are few historical estimates of energy embodied within automobiles, with a range of 62–134 GJ/vehicle.

In Chapter 5, we develop theory and equations to account for value flows though economies, leading (in Chapter 6) to techniques to estimate energy intensity of economic products.

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[11] The "energy cost" estimated by Berry and Fels is the energy embodied in a single automobile. The "energy cost" (in kW-hr/automobile) multiplied by the the production rate (in autmobiles/year) gives the rate of gross embodied energy outflow in the product stream of the auto sector ($\dot{B}_{\dot{P}_{gross}}$). A limitation of the process-based approach employed by Berry and Fels is trucation error for upstream energy demand. See Section 8.3 for details.

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Part II
Economic Value Flows and Energy Intensity

Chapter 5
Value flows

We try to measure what we value. We come to value what we measure. [1, p. 2]

—Donella Meadows

**** MCD - introduce idea of resource quality as discussed in materials and energy chapters ****

Many products will cost more, because of the additional capital equipment and energy needed to extract increasingly rare materials and process them within the economy.

All feeds toward Red Queen and Erlich and Simon wager. ****

In Chapters 3 and 4, we noted that energy is the currency of thermodynamics, and we developed accounting equations for flows of direct ($\dot{E}$) and embodied ($\dot{B}$) energy through an economy. In this chapter, we develop a framework for accounting value flows ($\dot{X}$) through economies. Accounting flows of value is a necessary step along the path to developing equations (in Chapter 6) that describe the energy intensity of intermediate and final products within an economy.

5.1 Methodology

We begin by explicitly stating what we mean by value. We follow the mainstream approach of using the market price at the time of an exchange to determine the value of the flows of products (goods, services and capital). As materials and energy flow in one direction between sectors, currency flows in the opposite direction. The monetary flow is an easy and logical proxy for the value of the material and energy flows. Market transactions are readily captured, and the data to estimate these flows is available in most countries.[2]

Although the market price is readily available and conveys important information (such as relative scarcity of the good and relative usefulness of the good to fulfill human wants), we note that market price is *subjective*. Value is based on the agreement of a mutally acceptable price by the human trading partners. The market price is not a measure of any *intrinsic* value of the goods (e.g., for bio-diversity or ecosystem services). Market prices ignore the costs and benefits that accrue to other parties (externalities), including the impact of trade on the quality of human relations, just distribution of resources, or sustainable scale of the economy.[3, p. 55] Section 8.2 contains further discussion of subjective and intrinsic theories of value.

Market prices also ignore any inherent value in the physical flows of materials and energy to and from the biosphere.[1] Although it would be nice to ascribe monetary value to material flows between the economy and the biosphere, it is very challenging to do so.[4, 5] However, an international experimental system for accounting environmental and economic flows is in place.[2][6] If and when the challenge of ascribing value to material resource, energy, and waste flows to and from the biosphere is addressed, our framework will be able to incorporate those values easily.

It is important to be clear that despite our focus on material and energy flows through an economy, our framework does not assume, nor does it lead to, an energy theory of value. And, our pragmatic use of the subjective theory of value does not indicate an endorsement. Rather, we accept the subjective theory of value despite several weaknesses. Our framework values goods and services at their market prices.

Because the basic unit of analysis in our framework is the economic sector, flows of value within the economy are based on the prices agreed upon in the transactions. The flows of value that accompany material and energy flows in and out of one sector in an economy are depicted in Figure 5.1.

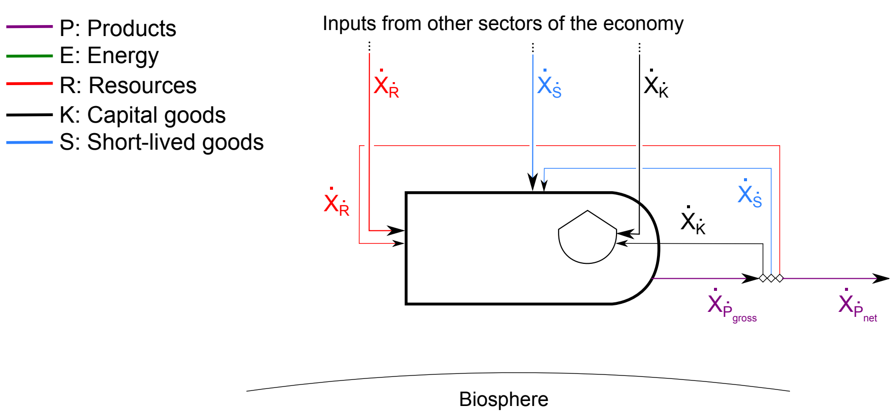

Fig. 5.1 Flows of value ($\dot{X}$) for a single sector. The value flows are associated with each of the different material and energy flows outlined in previous chapters.

We denote creation and destruction of value within a sector using the notion of "source" and "sink." In Figure 5.2, the open circle, "source," inside the economic sector represents the value-added, that is, the value that is created by the economic processes within that sector. The flows of value from a value-source are denoted $\dot{X}_{gen}$. Similarly, black circles represent the value "sinks" where value is destroyed

[1] Flows of value between the economy and the biosphere are conspicuously absent from the figures in this chapter. (See, for example, Figure 5.1.)

[2] As of this printing, the System of Environmental-Economic Accounting (SEEA) is in its third revision using a process of global consultation.

by economic processes or natural disasters. The flows of value into the value sinks are denoted $\dot{X}_{dest}$. Although we do not define the value creation and destruction processes any further (mathematically), we discuss what is meant by the underlying processes in more detail below.

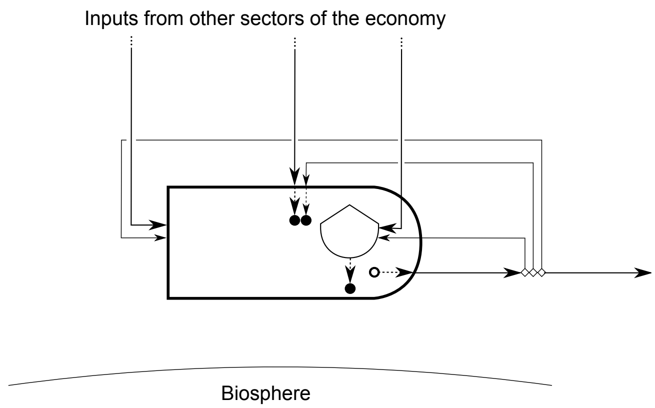

Fig. 5.2 Aggregated flows of value ($\dot{X}$) for a single sector. Distinction is made between value flows that enter the sector and are accumulated (i.e. capital goods) and value flows that are not accumulated. Within the sector there is destruction of value $\dot{X}_{dest}$, represented by the downward arrow flowing into the black sink and generation of value, represented by the arrow flowing out of a source.

5.2 Example A: single-sector economy

Figure 5.3 shows flows of value in the single-sector economy. Following typical assumptions in economic modeling, the economy is *completely isolated* from the biosphere in terms of both material inputs and wastes. In other words, the value flows of an economy are *independent from* material inputs and wastes. Value flows are independent from material inputs, because raw materials have no economic value until they have been removed from the biosphere by the extraction industry. Value flows are independent from wastes, because wastes, by definition, have no economic value upon leaving the economy.

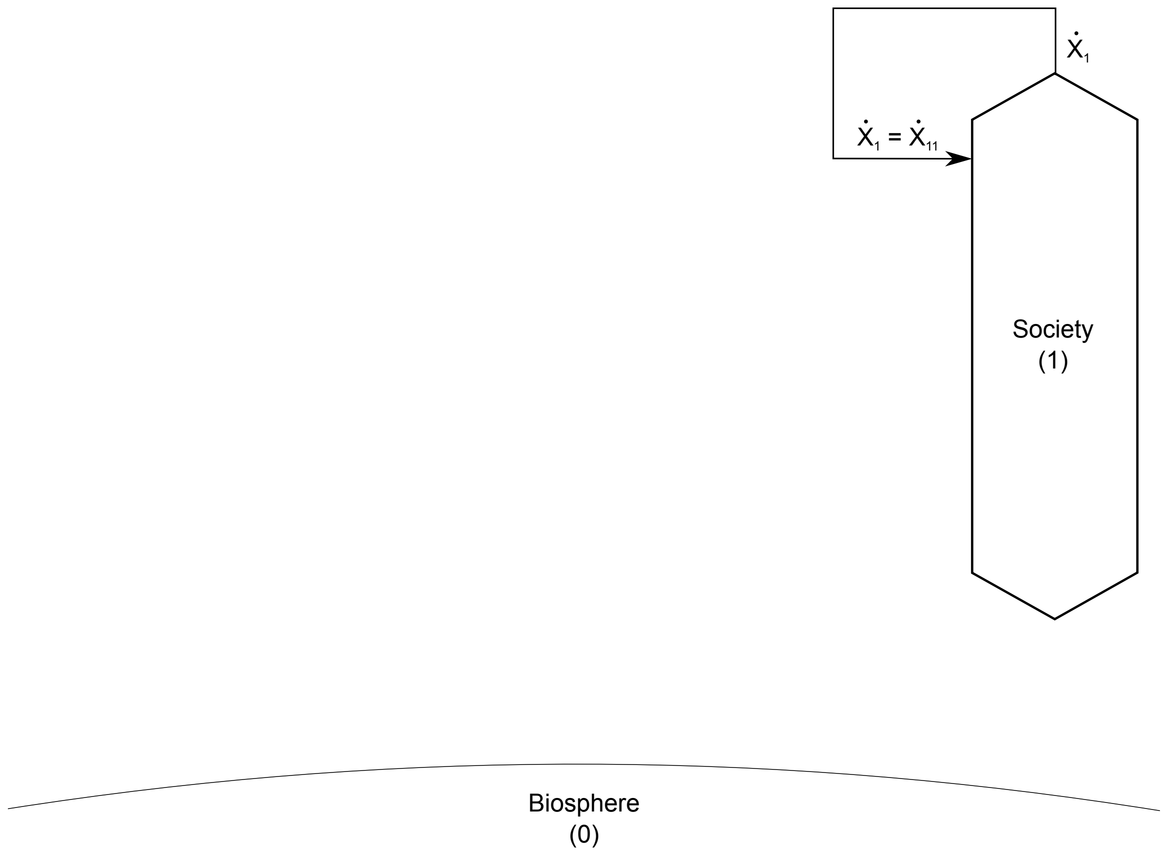

Fig. 5.3 Flows of value ($\dot{X}$) for a one-sector economy.

The contrast between Figures 2.2 and 3.3, on the one hand, and Figure 5.3, on the other, is striking. The picture of material and energy flows in Figures 2.2 and 3.3 indicates interaction with and dependence upon the biosphere that is not reflected in the value flows of Figure 5.3. The isloation of the value flows from the biosphere is a consequence of the subjective theory of value that underpins modern economics. The biosphere is akin to a third party with no voice in determining the value of a transaction: it is neither buyer nor seller.

Equation 5.1 describes the accumulation of value (X).

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = \dot{X}_{11} - \dot{X}_1 + \dot{X}_{gen,1} - \dot{X}_{dest,1}. \tag{5.1}$$

The following subsections discuss the terms in Equation 5.1.

5.2.1 Economic transactions ($\dot{X}_{11}$ and $\dot{X}_1$)

The returning arrow in Figure 5.3 represents transactions between

- buyers (who receive things of value, $\dot{X}_{11}$, in exchange for currency) and
- sellers (who give up things of value, $\dot{X}_1$, in exchange for currency).

It is interesting to note that when a good is sold for more than the producer paid for its inputs, the seller has created value and sold it into the economy. As a consequence, the seller's stock of currency grows, providing the seller with an increased level of claim on value in the economy.

The subjective theory of value (Section 5.1) posits that buyers and sellers agree on value at the time of the transaction. Thus, $\dot{X}_1 = \dot{X}_{11}$, and Equation 5.1 simplifies to

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = \dot{X}_{gen,1} - \dot{X}_{dest,1}, \tag{5.2}$$

indicating that value accumulates in the economy $\left(\frac{\mathrm{d}X_1}{\mathrm{d}t}\right)$ due to value generation ($\dot{X}_{gen,1}$) and destruction ($\dot{X}_{dest,1}$) processes only.

5.2.2 Value generation ($\dot{X}_{gen}$)

In Equation 5.1, the value generation term ($\dot{X}_{gen}$) is akin to growing apples in Section 2.1: value is generated, seemingly out of nothing. But, in fact, value is not created out of nothing. Rather, value is created from a variety of factors that have no apparent monetary cost to producers, including:

- flow of solar energy into the economy, as in the example of growing apples,
- extraction of resources (e.g., water, minerals, and fossil fuels) or any other unpriced goods from the biosphere, and

- exploitation of the unpriced waste assimilation capacity of the biosphere.

The subjective theory of value indicates that there is no economic value associated with these “transactions,” because no currency is exchanged.

The above factors indicate that the process of value generation has both direct and indirect impacts on the biosphere. The direct impacts are obvious: extraction of non-renewable resources from the biosphere, at rates greater than their natural accretion, represents unsustainable overuse of natural capital. The indirect impacts are less obvious: the value generated by these transactions can lead to increased wealth, leading to increased demand rates for goods and services, whose production requires ever-increasing rates of unsustainable natural resource extraction.

**** MCD discussion of resource quality. Becky, double-check. ****

As discussed in previous Chapters, natural resource quality has a direct impact on both material and energy intensity of economic processes. As we extract lower quality resources we require larger inputs of materials and energy, to process greater volumes of material, and to build the extra capital equipment necessary to do the extra processing. This requires the allocation of a greater amount of economic resources toward the primary production sectors. In order to make profit, these extra resources increase the value of the products from these sectors, to cover the added costs of production. These impacts ripple through the economy increasing the costs of production in all downstream sectors. **** DOES THIS INCREASE GDP, BAD NEWS IF IT DOES? **** [3]

****

$\dot{X}_{gen}$ is accounted as “value added” to an industry in national accounts. It is calculated as the difference between gross economic output of the industry and the cost of its intermediate inputs.[7] A simple way to think of value added is the increase in value of the raw materials from the work performed on them by workers and manufactured capital.

5.2.3 Value destruction ($\dot{X}_{dest}$)

In Equation 5.1, the value destruction term ($\dot{X}_{dest}$) is akin to consuming apples: value is destroyed by a process that consumes, or otherwise renders unusable, previously-valuable things in the economy (see Section 2.1). The factors that lead to value destruction ($\dot{X}_{dest}$) include:

- depreciation, usually associated with disposal of materials and equipment to the biosphere at end of life and
- natural disasters, such as hurricanes and typhoons, that destroy equipment and property.

[3] This issue of resource quality will be re-visited in Chapter 5 and discussed in more detail in Section 8.4.

$\dot{X}_{dest}$ is accounted as depreciation, or "consumpton of fixed capital," to an industry in the national accounts. It is a monetary estimate of the physical effects on assets from "wear and tear, obsolescence, accidental damage, and aging." [8]

5.2.4 GDP

If Society (1) in Figure 5.3 represents the economy of an entire country, $\dot{X}_1$ is its gross domestic product (GDP) in units of \$/year. GDP is a flow, not a stock. GDP is often considered a stock, but that is incorrect. X_1 is a stock, akin to monetary wealth. However, X_1 is a very narrow definition of wealth that neglects the value of natural resources, the value of social captial, and any other "wealth" that cannot be exchanged for money.

5.3 Example B: two-sector economy

Figure 5.4 shows flows of value ($\dot{X}$) within a two-sector economy. Again, we note the isloation of economic value from the biosphere.

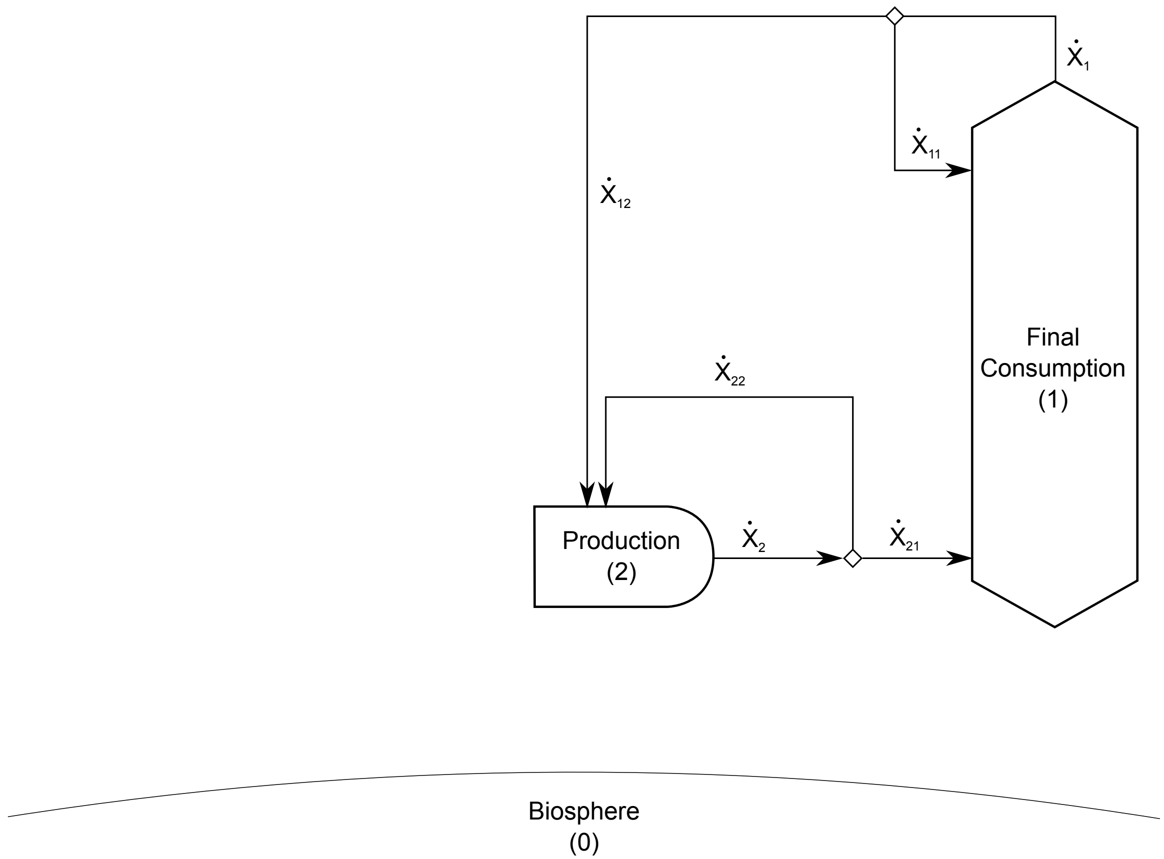

Fig. 5.4 Flows of value ($\dot{X}$) within a two-sector economy.

We can account for value flows by writing the following equations:

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = \dot{X}_{11} + \dot{X}_{21} - \dot{X}_1 + \dot{X}_{gen,1} - \dot{X}_{dest,1} \tag{5.3}$$

and

$$\frac{\mathrm{d}X_2}{\mathrm{d}t} = \dot{X}_{12} + \dot{X}_{22} - \dot{X}_2 + \dot{X}_{gen,2} - \dot{X}_{dest,2}. \tag{5.4}$$

Equations 5.3 and 5.4 can be generalized as

$$\frac{\mathrm{d}X_j}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{X}_{ij} - \dot{X}_j + \dot{X}_{gen,j} - \dot{X}_{dest,j}, \tag{5.5}$$

where n is the number of sectors in the economy, and $j \in [1, n]$.

5.4 Example C: three-sector economy

Figure 5.5 shows flows of value ($\dot{X}$) within a three-sector economy.

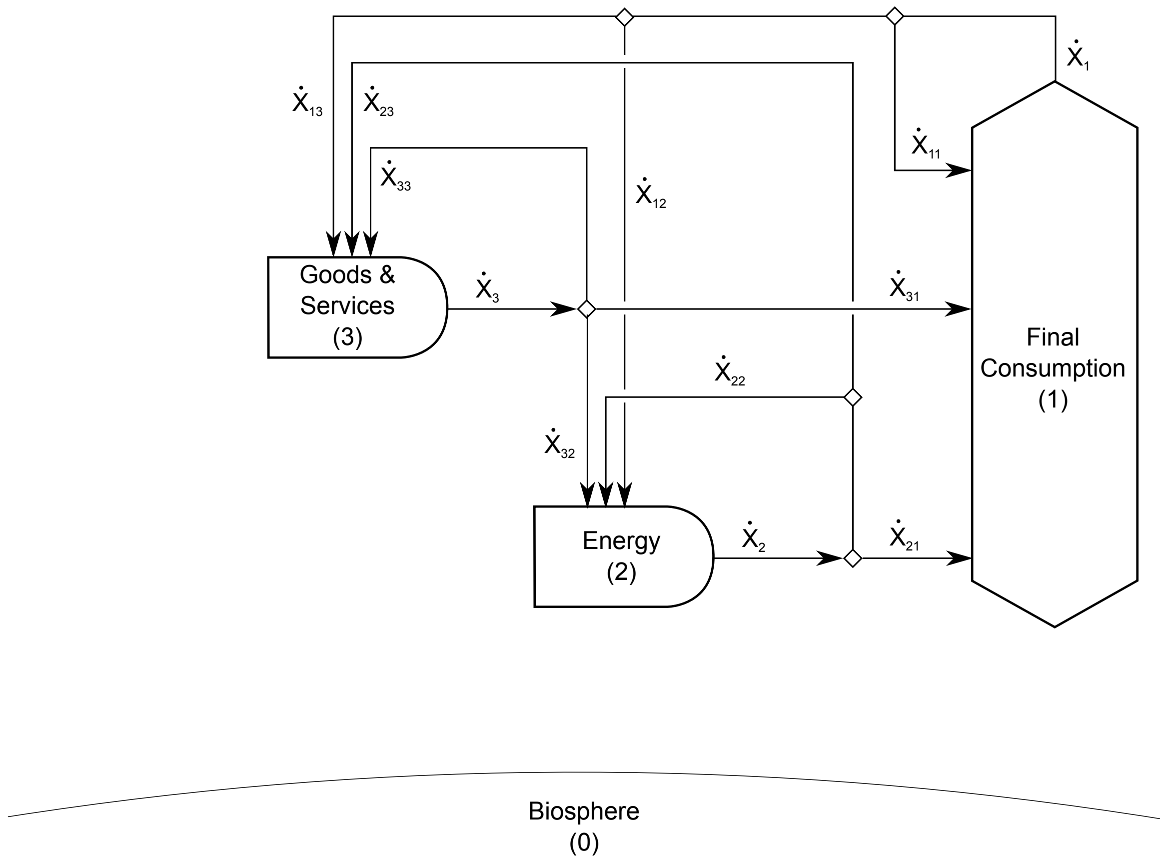

Fig. 5.5 Flows of value ($\dot{X}$) within a three-sector economy.

The equations representing flows of value in Example C are:

$$\frac{\mathrm{d}X_j}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{X}_{ij} - \dot{X}_j + \dot{X}_{gen,j} - \dot{X}_{dest,j}, \tag{5.6}$$

where n is the number of sectors in the economy, and $j \in [1,n]$. Equation 5.6 is identical to Equation 5.5. If we sum the value accounting equations for the entire economy, we obtain

$$\sum_{j=1}^{n} \frac{\mathrm{d}X_j}{\mathrm{d}t} = \sum_{j=1}^{n}\sum_{i=1}^{n} \dot{X}_{ij} - \sum_{j=1}^{n} \dot{X}_j + \sum_{j=1}^{n} \dot{X}_{gen,j} - \sum_{j=1}^{n} \dot{X}_{dest,j}. \tag{5.7}$$

With the identities

$$\dot{X}_j = \sum_{k=1}^{n} \dot{X}_{jk} \tag{5.8}$$

and

$$\sum_{j=1}^{n} \dot{X}_j = \sum_{j=1}^{n}\sum_{k=1}^{n} \dot{X}_{jk} = \sum_{i=1}^{n}\sum_{k=1}^{n} \dot{X}_{ik} = \sum_{i=1}^{n}\sum_{j=1}^{n} \dot{X}_{ij} = \sum_{j=1}^{n}\sum_{i=1}^{n} \dot{X}_{ij}, \tag{5.9}$$

Equation 5.7 becomes

$$\sum_{j=1}^{n} \frac{\mathrm{d}X_j}{\mathrm{d}t} = \sum_{j=1}^{n} \dot{X}_{gen,j} - \sum_{j=1}^{n} \dot{X}_{dest,j}, \tag{5.10}$$

for $j \in [1,n]$, indicating that value generation ($\dot{X}_{gen,j}$) and destruction ($\dot{X}_{dest,j}$) are the only mechanisms by which value is accumulated or lost $\left(\frac{\mathrm{d}X_j}{\mathrm{d}t}\right)$ within the economy. Equation 5.10 is a mathematical representation of the value-added approach to measuring GDP. The sum of the value-added across all industries is equivalent to the total value of final produced goods.[9, p. 196]

5.5 Value in the US auto industry

To estimate value flows through the automobile industry, we use publicly available data from the US BEA.[4] The tables needed to estimate dynamic value flows and capital accumulation within the economy are primarily the KLEMS[5] Intermediate Use tables and the fixed asset, non-residential detail table. The KLEMS data tables are based on the Input-Output (I-O) tables, but are at a lower level of aggregation and the inputs are categorized into three broad types: energy, materials, and services.

[4] A primer on using the US BEA industry data can be found on the BEA website.[10]

[5] KLEMS is an acronym for capital (K), labor (L), energy (E), materials (M), and services (S).

The KLEMS intermediate use data are categorized in the same way as the input flows on the PERKS diagram. The total material inputs into the auto industry (IOC 3361MV) represents the value of resource flows ($\dot{X}_{\dot{R}}$). Similarly, the total direct energy inputs into the auto industry represents the value of energy flows ($\dot{X}_{\dot{E}}$), and the total service inputs into the auto industry represents Short-lived goods ($\dot{X}_{\dot{S}}$). The fixed asset accounts are used to estimate capital value flows ($\dot{X}_{\dot{K}}$) as well as self-use of capital. The I-O tables are used to determine gross economic output of the auto industry ($\dot{X}_{\dot{P}_{Gross}}$). And subtracting self-use capital and resources from Gross Economic Output yields Net Economic Output ($\dot{X}_{\dot{P}_{net}}$).

Using these data, Figure 5.6 provides estimates of value flows for the US auto industry. Table 5.1 contains a brief summary of the data sources that were used to obtain the values in Figure 5.6. Appendix A contains detailed calculations and sources of data.

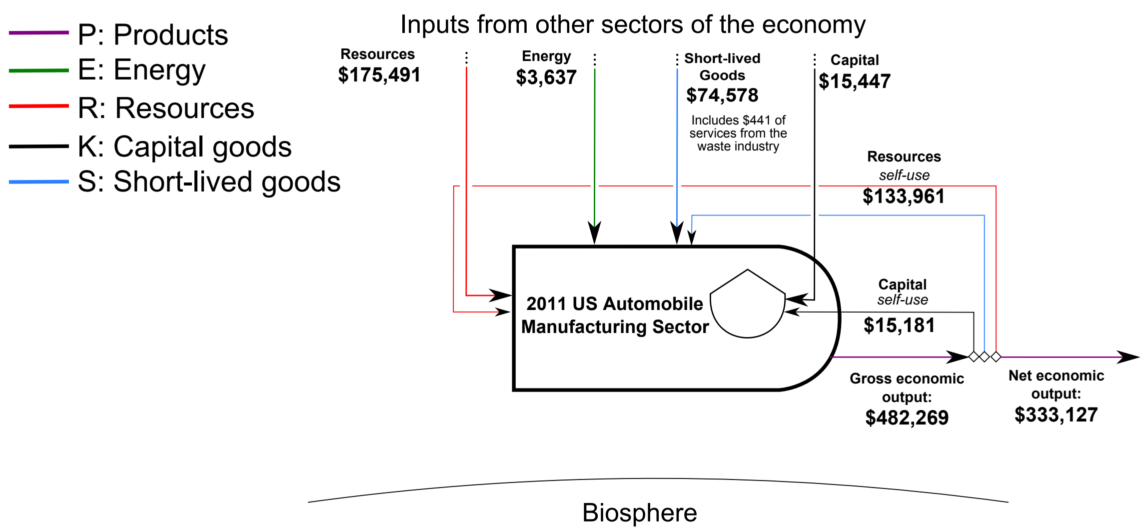

Fig. 5.6 Value of material and energy flows into and out of the US automobile industry (in millions of 2011USD).

Table 5.1 Data sources for auto industry (IOC 3361MV) example.

Value Flow	2011 USD (millions)	BEA Data Source
Resources	$175,491	2011 KLEMS Total Material Inputs
Energy	3,637	2011 KLEMS Total Energy Inputs
Short-lived Goods	74,578	2011 KLEMS Total Services Inputs
Capital	15,447	2011 Fixed Assets 2011 (non-residential detailed estimates)
Gross Economic Output	482,269	2011 Input-Output Use Tables
Resources (self-use)	133,961	2011 KLEMS Total Material Inputs
Capital (self-use)	15,181	2011 Fixed Assets (non-residential detailed estimates)
Net Economic Output	333,127	Author's calculations

5.6 Summary

In this chapter, we developed techniques to account for flows of economic value ($\dot{X}$) through economies (Section 5.1). We began with a discussion about theories of value and settled on the prevailing subjective theory of value for our framework. Thereafter, value accounting equations were developed and applied to example economies A–C in Sections 5.2–5.4. We noted the need for terms that describe creation and destruction of value ($\dot{X}_{gen}$ and $\dot{X}_{dest}$, respectively) within economic sectors. Finally, we explored value flows to and from the US auto economy (Section 5.5). In contrast to materials and energy, we found that there is no lack of data on value flows.

In Chapter 6, we combine results from Chapters 3, 4, and 5 to develop techniques the estimate the energy intensity of economic products.

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Chapter 6
Energy intensity

Accounting systems change behavior.
—unknown NASA JPL accountant

In Chapters 3, 4, and 5, we defined flows of direct energy, embodied energy, and value in an economy. In this chapter, we merge energy and value together to estimate the energy intensity (ε) of economic sectors, measured in joules per dollar.[1]

6.1 Background

Flesh out I-O History and background of I-O methods.

Explicitly say that were not planning to review long history of energy-economy modeling (Soddy, etc.).

Point to references on the topic: Leontief (I-O) Bullard and Herendeen (EI-O) Hendrickson and Lave (EIOLCA)

Refer to Giampietro for the dogfights.

6.2 Methodology

Energy intensity (ε) is the ratio of total energy ($\dot{T}$) and value ($\dot{X}$) outflow rates from an economic sector, such that for sector j,

$$\varepsilon_j \equiv \frac{\dot{T}_j}{\dot{X}_j}, \tag{6.1}$$

[1] The literature discusses the energy embodied in *products* for example, "The data and methodologies described in this report permit calculation of five types of energy 'embodied' in a particular goods [*sic*] or service." [1, p. 268] It can be meaningful to discuss the energy intensity of *processes*, too, and we switch between these two meanings of the word "embodied."

and ε is in units of J/\$.[2] Energy intensity (ε_j) represents the total energy demanded by sector j (both for sector j itself and the energy required to create the inputs to sector j) per dollar of output from sector j. Equation 6.1 includes the embodied energy of products in the numerator ($\dot{T}_j$) term. A narrower definition ef energy intensity would be $\varepsilon_j \equiv \frac{\dot{Q}_{j0}}{\dot{X}_j}$, which includes only energy consumed by sector j in the numerator and excludes the energy demanded upstream by the resource flows ($\dot{R}$) that comprise the product of the sector ($\dot{P}$). We choose the broader definition of Equation 6.1, because it accounts for upstream energy consumption, thereby providing an estimate of the true total energy cost of products.

For inter-sector flows, we have

$$\varepsilon_j = \frac{\dot{T}_{jk}}{\dot{X}_{jk}}. \tag{6.2}$$

for all k, because the energy intensity of output from sector j is independent of its destination (k). In other words, all goods produced by a sector are produced at the average energy intensity of that sector.[3]

We define the input-output ratio (a_{ij}) that represents the input of good i required to produce a unit of output from sector j.

$$a_{ij} \equiv \frac{\dot{X}_{ij}}{\dot{X}_j} \tag{6.3}$$

We note that the value ($\dot{X}$) of all material flows must be counted such that

$$a_{ij} = \frac{\dot{X}_{\dot{R}_{ij}} + \dot{X}_{\dot{S}_{ij}} + \dot{X}_{\dot{K}_{ij}}}{\dot{X}_{\dot{R}_j} + \dot{X}_{\dot{S}_j} + \dot{X}_{\dot{K}_j}}. \tag{6.4}$$

Input-output ratios (a_{ij}) are given in mixed units, depending on both the purpose of each sector of the economy and the type of input as shown in Figure 6.1.

Equations 6.2 and 6.3 can be combined to give

$$\dot{T}_{jk} = \varepsilon_j a_{jk} \dot{X}_k. \tag{6.5}$$

6.3 Example A: single-sector economy

With reference to Figures 3.3, 4.2, and 5.3, the energy intensity (ε_1) of a single-sector economy is calculated by

---

[2] It may be instructive to consider energy intensity as the quotient of embodied energy (in units of J/kg) and price (in \$/kg).

[3] If this approach is unsatisfactory, the sector may be divided into sub-sectors each with its own energy intensity.

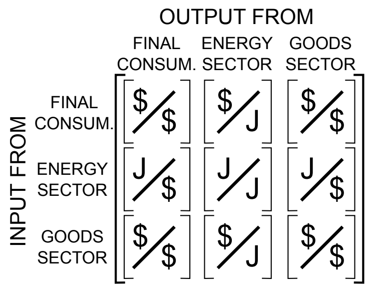

Fig. 6.1 Units for input-output ratios (a).

$$\varepsilon_1 = \frac{\dot{T}_1}{\dot{X}_1} = \frac{\dot{T}_{11}}{\dot{X}_{11}}. \tag{6.6}$$

Appendix B illustrates that the energy intensity of a single-sector economy (ε_1) is comprised of the sum of the infinite recursions of energy consumed during production of output ($\dot{X}_1$).

To estimate energy intensities when more than one economic sector is involved, we move to Examples B and C in the following sections.

6.4 Example B: two-sector economy

With reference to Figures 3.4, 4.3, and 5.4, the energy intensity (ε_2) of the production sector is given by

$$\varepsilon_2 = \frac{\dot{T}_2}{\dot{X}_2} = \frac{\dot{T}_{22}}{\dot{X}_{22}}. \tag{6.7}$$

Thus,

$$\dot{T}_2 = \varepsilon_2 \dot{X}_2, \tag{6.8}$$

The input-output ratio for the production sector's self-use of output (a_{22}) is

$$a_{22} = \frac{\dot{X}_{22}}{\dot{X}_2}, \tag{6.9}$$

thus

$$\dot{T}_{22} = \varepsilon_2 a_{22} \dot{X}_2. \tag{6.10}$$

We can rewrite the total energy accounting equation for Production (2)

$$\frac{\mathrm{d}T_2}{\mathrm{d}t} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} - \dot{T}_2 - \dot{T}_{20} \tag{4.29}$$

using energy intensity by realizing that:

- $\frac{\mathrm{d}E_2}{\mathrm{d}t} = 0$ meaning that $\frac{\mathrm{d}T_2}{\mathrm{d}t} = \frac{\mathrm{d}B_2}{\mathrm{d}t}$, because direct energy does not accumulate within economic sectors,
- $\frac{\mathrm{d}B_2}{\mathrm{d}t} = \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t}$, because resources ($R$) and short-lived materials (S) do not accumulate at appreciable rates in economic sectors,
- $\dot{B}_{02} = 0$ meaning that $\dot{T}_{02} = \dot{E}_{02}$, because flows from the biosphere have yet to have any energy from society embodied in them,
- $\dot{E}_{20} = 0$ meaning that $\dot{T}_{20} = \dot{B}_{20}$, because direct energy is not wasted to the biosphere at any significant rate,[4] and
- $\dot{B}_{20} = \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \dot{B}_{\dot{K}_{20}}\right) = \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}\right)$, as shown in Section 4.4.

If we substitute Equations 6.8 and 6.10 into Equation 4.29, we obtain

$$\frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} = \dot{E}_{02} + \dot{T}_{12} + \varepsilon_2 a_{22} \dot{X}_2 - \varepsilon_2 \dot{X}_2 - \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}\right). \tag{6.11}$$

Equation 6.11 can be solved for energy intensity (ε_2) to obtain

$$\varepsilon_2 = (1 - a_{22})^{-1} \dot{X}_2^{-1} \left[\dot{E}_{02} + \dot{T}_{12} - \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} - \dot{B}_{\dot{R}_{20}} - \dot{B}_{\dot{S}_{20}} - \gamma_{B_2} B_{B_2}\right] \tag{6.12}$$

To extend Equation 6.12 to a matrix formulation, we turn to Example C.

6.5 Example C: three-sector economy

The three-sector economy of Example C affords the opportunity to develop a matrix version of the total energy accounting equation (4.41) and to develop an equation that estimates the energy intensity of economic sectors. We begin by deriving a matrix version of the total energy accounting equation.

6.5.1 Total energy accounting equation

We apply Equation 4.41 to the three-sector economy shown in Figures 3.5, 4.4, and 5.5 to obtain the following total energy accounting equations for the Energy (2) and Goods and Services (3) sectors of Example C:

$$\frac{\mathrm{d}T_2}{\mathrm{d}t} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} + \dot{T}_{32} - \dot{T}_2 - \dot{T}_{20} \tag{6.13}$$

[4] Oil spills and gas leaks notwithstanding. Remember also that waste heat outflows ($\dot{Q}_{20}$) are allocated to the product.

and

$$\frac{\mathrm{d}T_3}{\mathrm{d}t} = \dot{T}_{03} + \dot{T}_{13} + \dot{T}_{23} + \dot{T}_{33} - \dot{T}_3 - \dot{T}_{30}. \tag{6.14}$$

Similar to Example B, we realize that:

- $\frac{\mathrm{d}E_i}{\mathrm{d}t} = 0$ meaning that $\frac{\mathrm{d}T_i}{\mathrm{d}t} = \frac{\mathrm{d}B_i}{\mathrm{d}t}$, because direct energy does not accumulate within economic sectors,
- $\frac{\mathrm{d}B_i}{\mathrm{d}t} = \frac{\mathrm{d}B_{K_i}}{\mathrm{d}t}$, because resources ($R$) and short-lived materials (S) do not accumulate at appreciable rates in economic sectors,
- $\dot{B}_{0j} = 0$ meaning that $\dot{T}_{0j} = \dot{E}_{0j}$, because flows from the biosphere have yet to have any energy from society embodied in them,
- $\dot{E}_{j0} = 0$ meaning that $\dot{T}_{j0} = \dot{B}_{j0}$, because direct energy is not wasted to the biosphere at any significant rate, and
- $\dot{B}_{j0} = \left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \dot{B}_{\dot{K}_{j0}}\right) = \left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j}\right)$, as shown in Section 4.4.

to obtain

$$\frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} = \dot{E}_{02} + \dot{T}_{12} + \varepsilon_2 \dot{X}_{22} + \varepsilon_3 \dot{X}_{32} - \varepsilon_2 \dot{X}_2 - \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}\right) \tag{6.15}$$

and

$$\frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} = \dot{E}_{03} + \dot{T}_{13} + \varepsilon_2 \dot{X}_{23} + \varepsilon_3 \dot{X}_{33} - \varepsilon_3 \dot{X}_3 - \left(\dot{B}_{\dot{R}_{30}} + \dot{B}_{\dot{S}_{30}} + \gamma_{B,3} B_{K_3}\right). \tag{6.16}$$

6.5.2 Matrix formulation

Equations 6.15 and 6.16 can be rewritten in vector notation as

$$\begin{aligned}\begin{Bmatrix} \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} \\ \frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} \end{Bmatrix} = \begin{Bmatrix} \dot{E}_{02} \\ \dot{E}_{03} \end{Bmatrix} + \begin{Bmatrix} \dot{T}_{12} \\ \dot{T}_{13} \end{Bmatrix} + \begin{bmatrix} \dot{X}_{22} & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} - \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} \\ - \begin{Bmatrix} \dot{B}_{\dot{R}_{20}} \\ \dot{B}_{\dot{R}_{30}} \end{Bmatrix} - \begin{Bmatrix} \dot{B}_{\dot{S}_{20}} \\ \dot{B}_{\dot{S}_{30}} \end{Bmatrix} - \begin{bmatrix} \gamma_{B_2} & 0 \\ 0 & \gamma_{B,3} \end{bmatrix} \begin{Bmatrix} B_{K_2} \\ B_{K_3} \end{Bmatrix}.\end{aligned} \tag{6.17}$$

If we define the following matrices and vectors:

$$\mathbf{B}_K \equiv \begin{Bmatrix} B_{K_2} \\ B_{K_3} \end{Bmatrix}, \tag{6.18}$$

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} \equiv \begin{Bmatrix} \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} \\ \frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} \end{Bmatrix}, \tag{6.19}$$

$$\mathbf{E}_0 \equiv \begin{Bmatrix} \dot{E}_{02} \\ \dot{E}_{03} \end{Bmatrix}, \tag{6.20}$$

$$\mathbf{T}_1 \equiv \begin{Bmatrix} \dot{T}_{12} \\ \dot{T}_{13} \end{Bmatrix}, \tag{6.21}$$

$$\mathbf{X}_t \equiv \begin{bmatrix} \dot{X}_{22} & \dot{X}_{23} \\ \dot{X}_{32} & \dot{X}_{33} \end{bmatrix}, \tag{6.22}$$

$$\boldsymbol{\varepsilon} \equiv \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}, \tag{6.23}$$

$$\mathbf{B}_{\dot{W}} = \begin{Bmatrix} \dot{B}_{\dot{W}_{20}} \\ \dot{B}_{\dot{W}_{30}} \end{Bmatrix} \equiv \begin{Bmatrix} \dot{B}_{\dot{R}_{20}} \\ \dot{B}_{\dot{R}_{30}} \end{Bmatrix} + \begin{Bmatrix} \dot{B}_{\dot{S}_{20}} \\ \dot{B}_{\dot{B}_{30}} \end{Bmatrix}, \tag{6.24}$$

$$\hat{\mathbf{X}} \equiv \delta_{ij}\dot{X}_j = \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix}, \tag{6.25}$$

and

$$\hat{\boldsymbol{\gamma}}_B \equiv \delta_{ij}\gamma_{B_j} = \begin{bmatrix} \gamma_{B_2} & 0 \\ 0 & \gamma_{B_3} \end{bmatrix}; \tag{6.26}$$

with the “Kronecker delta”

$$\delta_{ij} \equiv \begin{cases} 0 & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}; \tag{6.27}$$

we can rewrite Equation 6.17 compactly as

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + \mathbf{X}_t^{\mathrm{T}}\boldsymbol{\varepsilon} - \hat{\mathbf{X}}\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K. \tag{6.28}$$

Equation 6.28 can be simplified to

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + (\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}})\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K. \tag{6.29}$$

We can define the input-output matrix ($\mathbf{A}$) as

$$\mathbf{A} \equiv \begin{bmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{bmatrix}. \tag{6.30}$$

Appendix C shows that

$$\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I}), \tag{6.31}$$

which allows Equation 6.29 to be recast as

$$\frac{d\mathbf{B}_K}{dt} = \mathbf{E}_0 + \mathbf{T}_1 + \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K. \tag{6.32}$$

Equation 6.32 is the matrix version of the total energy accounting equation written in terms of embodied energy ($\mathbf{B}$), energy intensities ($\boldsymbol{\varepsilon}$), and input-output ratios ($\mathbf{A}$). Equation 6.17 applies for the three-sector economy of Example C, but the equivalent matrix formulation (Equation 6.32) can be extended to any desired level of economic and energy sector disaggregation by expanding the vectors and matrices in Equations 6.19–6.18 and 6.30 to include all sectors ($2 \ldots n$) of an n-sector economy.[1, 2]

Equation 6.32 provides a means to estimate the embodied energy accumulation rate in economic sectors $\left(\frac{d\mathbf{B}_K}{dt}\right)$ knowing only direct energy inputs to the economy from the biosphere ($\mathbf{E}_0$), total energy inputs from society to the economy ($\mathbf{T}_1$), sector outputs ($\hat{\mathbf{X}}$), sector input-output ratios ($\mathbf{A}$), sector energy intensities ($\boldsymbol{\varepsilon}$), energy embodied in wastes from the economy ($\mathbf{B}_{\dot{W}}$), and physical depreciation rates of capital stock ($\hat{\boldsymbol{\gamma}}_B\mathbf{B}_K$). In theory, the transaction matrix ($\mathbf{X}_t$) is not required if the input-ouput matrix ($\mathbf{A}$) is known, though in practice, knowledge of input-output matrix ($\mathbf{A}$) would be derived from the transaction matrix ($\mathbf{X}_t$), as shown in Appendix D.

Equation 6.32 can be rearranged to obtain

$$\hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\boldsymbol{\varepsilon} = \frac{d\mathbf{B}_K}{dt} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1 \tag{6.33}$$

and

$$\boldsymbol{\varepsilon} = \left[\hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\right]^{-1}\left[\frac{d\mathbf{B}_K}{dt} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1\right]. \tag{6.34}$$

We apply the matrix identity [3, Formula 6.2, p. 308]

$$(\mathbf{FGH})^{-1} = \mathbf{H}^{-1}\mathbf{G}^{-1}\mathbf{F}^{-1} \tag{6.35}$$

to the right side of Equation 6.34 to obtain

$$\boldsymbol{\varepsilon} = (\mathbf{A}^{\mathrm{T}} - \mathbf{I})^{-1}\hat{\mathbf{X}}^{-1}\left[\frac{d\mathbf{B}_K}{dt} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1\right]. \tag{6.36}$$

Finally, we can multiply both parenthetical terms[5] on the right side of Equation 6.36 by -1 to obtain

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1}\hat{\mathbf{X}}^{-1}\left[\mathbf{E}_0 + \mathbf{T}_1 - \frac{d\mathbf{B}_K}{dt} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K\right]. \tag{6.37}$$

Comparison of Equations 6.37 and 6.12 shows that the matrix form is an extension of the algebraic form of the energy intensity equation.

[5] The parenthetical terms on the right side of Equation 6.36 are $(\mathbf{A}^{\mathrm{T}} - \mathbf{I})$ and $\left[\frac{d\mathbf{B}_K}{dt} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1\right]$.

Equation 6.37 provides a means to estimate energy intensity (ε) of the sectors of the economy, under the assumption that Final Consumption (1) is exogenous to the economy (Sectors $2 \dots n$). We discuss Equation 6.37 further in Section 7.2. But first, the following section examines energy intensity in the context of our running example, the US auto industry.

6.6 Energy intensity in the US auto industry

Equation 6.37 shows that it is possible to estimate the energy intensity of products of economic sectors using the Input-Output (I-O) analysis method.[6] Several studies have used similar energy-based, input-output methods (EI-O) to estimate the energetic cost of goods and services produced by various economic sectors.[4–15] We review a few of these studies below.

Using national accounts data for 1967, Bullard and Herendeen calculated the total energy consumption rate ($\dot{T}$) of the US automobile industry as $13,240 \times 10^{15}$ J/year (13.24 EJ/year), which was around 20% of the nation's energy consumption in that year.[4] Around half of this energy was directly consumed within the auto industry itself ($\dot{Q}_{j0}$), meaning the rest was upstream consumption in material processing that entered the auto industry as embodied energy ($\sum_i \dot{B}_{ij}$). Given the number of autos produced per year, Bullard and Herendeen calculated that the embodied energy per vehicle was 148 GJ (10^9 J), 11% higher than the estimate obtained via process analysis in a study by Berry and Fels [16] two years earlier.[7]

In 1980, Costanza [5] estimated the energy intensity of all economic sectors of the US economy using the Input-Output method. Unfortunately, the energy intensity of the Motor Vehicles and Equipment sector (63) was not reported in [5]. Later, Costanza and Herendeen [6] re-estimated energy intensity and reported the energy intensity of outputs from all 87 BEA sectors. The energy intensity of the Motor Vehicles and Equipment sector (63) and selected other sectors are given in Tables 6.1 and 6.2.[8]

The Economic Input-Output Life Cycle Assessment (EIOLCA) online tool [7] is based on the framework outlined by Hendrickson and Lave [8] and allows computation of the energy flows through the economy based on US national accounts data from 1992, 1997 and 2002.[9] Using the tool with the 2002 producer price model, we find that \$1M of output from the automobile manufacturing industry (NAICS sector 336111) generates a total flow of 8.33 TJ (10^{12} J) of energy through the economy,

[6] For a discussion of differences between Equation 6.37 and similar equations in the literature, see Appendix E.

[7] See Section 4.5 for discussion of the Berry and Fels [16] paper.

[8] Values from Costanza and Herendeen's DIRECT method are provided here. See Section 7.6 for discussion of the differences between DIRECT and DEC methods and justification for reporting DIRECT method values only.

[9] The US national accounts data has not been updated since 2002. The issue of national accounts data is discussed in more detail in Section 8.1.

Table 6.1 Motor Vehicles and Equipment sector (63) energy intensity values.[6]

Year	Energy Intensity [kJ/$]
1963	1.16×10^5
1967	1.04×10^5
1972	0.95×10^5

Table 6.2 Selected US economic sector energy intensities, 1972.[6]

Sector	Energy Intensity [kJ/$]
Coal Mining (1)	3.23×10^6
Air Transport (73)	1.76×10^5
New Construction (14)	1.03×10^5
Motor Vehicles and Equipment (63)	9.50×10^4
Auto Repair (82)	8.35×10^4

2.19 TJ from the power generation and supply sector (221100) and 1.25 TJ from the iron and steel mills sector (331110).

Table 6.3 Automobile manufacturing sector (NAICS 33611x) energy intensity values.[7]

Year	Energy Intensity [kJ/$]
1992[a]	1.26×10^4
1997[b]	0.76×10^4
2002[c]	0.83×10^4

[a] Motor vehicles and Passenger Car Bodies (590301)

[b] Automobile and Light Truck Manufacturing (336110)

[c] Automobile Manufacturing (336111)

All of these estimates use product-focused accounting frameworks. In Section 7.2.1, we recommend a physical accounting framework. It would be interesting to know how the above energy intensity results vary (a) if a physical accounting framework is employed, (b) with time, and (c) across economies at different stages of industrialization. However, we know of no longitudinal estimates of the energy intensity of automobiles using the EI-O method. In fact, the current account records, upon which the estimates of energy intensity values above are based, are no longer maintained by the US government. So, we could not update the results presented in this section, even if we wanted to. Furthermore, few countries maintain and publish records with enough detail to perform these analyses. In Section 8.1, we discuss further the need for additional data.

Table 6.4 Selected US economic sector energy intensities, 1997.[7]

Sector	Energy Intensity [kJ/$]
Coal Mining (212100)	1.11×10^4
Air Transportation (481000)	2.62×10^4
Manufacturing and Industrial Buildings (230210)	0.76×10^4
Automobile and Light Truck Manufacturing (336110)	0.76×10^4
Automotive Repair and Maintenance, except car washes (8111A0)	0.52×10^4

6.7 Summary

In this chapter, we derived algebraic equations that describe the energy intensity (in units of J/$) of products of economic sectors. The algebraic equations were applied to Examples A–C to derive a matrix equation for a vector of energy intensities for the entire economy ($\boldsymbol{\varepsilon}$). We then reviewed several studies in the literature of energy intensity of the US auto industry and noted a wide range of results from one study to the next. The estimates of energy intensity also vary with time. The range of energy intensities for the auto sector is 0.83×10^4 kJ/$ to 11.6×10^4 kJ/$.

In the next chapter, we draw several implications from the material, energy, and value accounting framework presented in Chapters 2–6.

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Part III
Implications, Issues, and Summary

Chapter 7
Implications

Development without growth beyond the earth's carrying capacity is true progress. [1]

—Herman Daly

Several implications can be drawn from the detailed development of our framework for materials, energy, and value accounting (in Chapters 2–6). In the sections below, we discuss implications for the Energy Input-Output (EI-O) method itself, implications for economic "development," implications for recycling, reuse, and dematerialization, comparisons between our framework and the notion of a steady-state economy, and the choice of the energy input vector. We begin by examining the EI-O method through the lens of our framework.

7.1 Metrics

Our framework highlights the value that could be derived from continuous monitoring of several important metrics, including

* energy intensity of products of economic sectors (Ch 6)
* total accumulation of material (Ch 2) and embodied energy (Ch 4) in economic sectors
* the accumulation rate of material (Ch 2) and embodied energy (Ch 4) in economic sectors
* the flow rate of energy from the biosphere into economic sectors (Ch 3)
* the flow rate of materials from economic sectors to the biosphere (Ch 2)
* the flow rate of embodied energy from economic sectors to the biosphere (Ch 4)

It would be very helpful if these metrics were available for sectors and/or firms on a regular basis.

Both initial conditions and periodic reporting of important data are essential for the ongoing tracking of important economic indicators. Because initial conditions are not known and periodic reporting is not done, the dynamics of the accumulation of materials and embodied energy in economic sectors are not discernible at this time. For example, depreciation of some material from an economic sector will require replacement. The replacement material will have embodied energy. Production of the replacement places an energy drain on the economy. We have no way of quantifying that drain at the present time. If our model were implemented and periodic updates were available, society would understand better the costs (in terms of both dollars AND energy) of maintaining capital. And, society would understand how those maintenance flows constrain economic growth.

7.2 Implications for the I-O method

Extension of the Leontief Input-Output method for energy analysis has allowed energy analysts to estimate the energy intensity of economic products ($\boldsymbol{\varepsilon}$). As discussed in Section 5.1, we do not take the ability to estimate energy intensity as a license to declare an intrinsic "energy theory of value." Rather, we belive that energy intensity ($\boldsymbol{\varepsilon}$) is an important and useful metric that can assess the energy performance of economies, even within the prevailing subjective theory of value that underlies modern economics. It is important to consider the assumptions behind the literature's presentation of the EI-O method for estimating the energy intensity of economic output before drawing implications from our framework.

As we investigate, we will use the following coordinates of analysis: product-based vs. physical accounting frameworks, whether capital stock is included in the accounting framework, and whether energy input from society to the economy is included. (See Figure 7.1.) We will end with our suggestion for how best to estimate $\boldsymbol{\varepsilon}$ within a materials, energy, and value accounting framework.

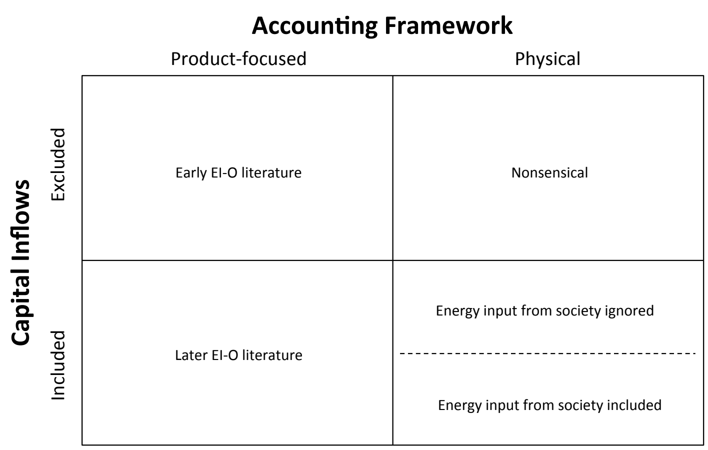

Fig. 7.1 Coordinates of analysis for implications for the EI-O method.

7.2.1 Product-based vs. physical approaches

The distinction between product-focused and physical accounting frameworks is located in the columns of Figure 7.1. A *physical accounting* framework strictly follows materials through the economy. Embodied energy is allocated to the material stock or material flow in which it resides—wherever it goes, so goes the embodied energy. When the material is scrapped, so is its embodied energy. For example, energy embodied within wastes ($\mathbf{B}_{\dot{W}}$) is not assigned to economic products. Rather, the energy embodied in wastes flows out of sectors into the biosphere *with the waste material*. In contrast, a *product-focused accounting* framework assigns energy embodied in wastes to the products of the sector. Both product-based and physical accounting frameworks assign direct energy ($\dot{E}$) consumed by each sector to the products of each sector.

Equation 7.1 below describes the outflow of embodied energy from sector j, for a physical accounting system that neglects both capital stock accumulation and capital inflow (upper-right quadrant of Figure 7.1).[1]

$$\dot{B}'_j = \sum_{i=1}^{n} \dot{B}'_{ij} - \dot{B}_{\dot{W}_j} + \dot{Q}_{j0} \tag{7.1}$$

Terms written with a "prime" (e.g. $\dot{B}'_j$) indicate definitions and terms that exclude input capital flows ($\dot{K}$) and capital stock (K). The term $\dot{B}_{\dot{W}_j}$ represents the energy embodied within wasted resource ($\dot{R}_{j0}$) and short-lived ($\dot{S}_{j0}$) material flows. The $\dot{B}_{\dot{W}_j}$ term is subtracted, because waste material flows *out of* the sector. In a physical accounting framework, the energy embodied in waste flows ($\dot{B}_{\dot{W}_j}$) is not assigned to the product ($\dot{B}'_j$).

In contrast, Equation 7.2 describes the outflow of embodied energy from sector j, exclusive of capital stock, for a product-focused accounting framework (upper left quadrant of Figure 7.1).

$$\dot{B}'_j = \sum_{i=1}^{n} \dot{B}'_{ij} + \dot{Q}_{j0} \tag{7.2}$$

Notice that Equation 7.2 does not subtract the energy embodied in waste resource and short-lived material flows ($\dot{B}_{\dot{W}_j}$) on the right side of the equation, because product-focused accounting systems assign energy embodied in wastes to products.

**** MCD - does this subsection flow from the IO method, or is it more general? I.e., should they be their own sections? ****

[1] Equation 7.1 is used for illustrative purposes only. A physical accounting framework would necessarily include both flows and stocks of capital. Thus, the upper-right quadrant of Figure 7.1 (physical accounting framework that neglects capital) is labeled as nonsensical.

7.2.2 *Capital flows and stock*

The rows of Figure 7.1 represent the role of capital flows and stock in an accounting framework. The BEA Industry Accounts include capital flows in the "make" tables for each industry [2, Table 1], but capital inflows are accounted separately from intermediate uses as "Private fixed investment" [2, Table 2]. During the earliest years of the EI-O method (prior to the mid-1970s) both capital inflows to economic sectors and stocks of capital were ignored. In essence, the state of the art was located in the upper-left quadrant of Figure 7.1. In time, Kirkpatrick [3], Bullard and Herendeen [4], and Casler [5] attempted to include inflows of capital in a product-focused accounting framework, thereby moving the state of the art to the lower-left quadrant of Figure 7.1.

We agree with this move, because of the many ways in which capital stock is important for economies. We can use the work of Eugene Odum [6] to explain the importance of capital stock within ecosystems, and we have Herman Daly to thank for making the connection between ecosystems and economies.[7]

In 1969, Odum outlined a number of defining characteristics of both *developmental* (growing) and *mature* (stable) ecosystems in terms of key properties of the system.[6] Ecosystems cannot grow indefinitely in their (photosynthetic) production rate (P) due to the necessity of increasing maintenance demands as the stock of biomass (B) increases. Eventually, all production is used in this manner and growth ceases $\left(\frac{\mathrm{d}}{\mathrm{d}t}(P) = 0\right)$.

In the early stages of ecosystem development, the energy production rate per unit of biomass stock $\left(\frac{P}{B}\right)$ is high. As the ecosystem approaches maturity, this ratio decreases. Put another way, the biomass stock (maintained) per unit of energy produced $\left(\text{the inverse ratio, } \frac{B}{P}\right)$ starts low and asymptotically increases to a maximum when growth (in both P and B) has ceased. The value of $\frac{B}{P}$ at the asymptote may be high or low[2] and may therefore be considered a measure of the "efficiency" to which the ecosystem applies energy production toward the goal of maintaining biomass stock.

Turning back to economies, Daly has, in our view, correctly applied this concept to societal patterns of economic consumption.[7] Our framework analogously suggests that as capital stock ($\mathbf{B}_K$) increases, an increasing flow of energy supply ($\mathbf{E}_0$) will be needed to maintain that stock.[3] Thus, it is important to account for capital stock in a material, energy, and value accounting framework.

To see the effect of the move from the upper-left to the lower-left quadrant of Figure 7.1, it is important to understand clearly both the assumptions and data that were used. Energy analysts in the mid-1970s were utilizing the BEA I-O tables,

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[2] The value of $\frac{B}{P}$ at maturity (and the time taken to reach it) "may vary not only with different climatic and physiographic situations but also with different ecosystem attributes in the same physical environment." [6, p.263]

[3] Today's economies (and economic models and economic assumptions) are still focused on the objective of growth. If energy supply rates ($\mathbf{E}_0$) are constrained, these dynamics provide a possible reason for the difficulty of maintaining high levels of economic growth in mature economies. Eventually, we must learn to maximize the $\frac{B}{P}$ ratios of our economies $\left(\frac{\mathbf{B}_K}{\mathbf{E}_0}\right)$.

which include capital flows on the output, but do not include capital flows on the input. Thus, this early literature implicitly assumes that

$$a'_{ij} \equiv \frac{\dot{X}_{\dot{R}_{ij}} + \dot{X}_{\dot{S}_{ij}}}{\dot{X}_{\dot{R}_j} + \dot{X}_{\dot{S}_j} + \dot{X}_{\dot{K}_j}} = \frac{\dot{X}'_{ij}}{\dot{X}_j}. \tag{7.3}$$

Comparison between Equations 6.4 and 7.3 highlights the fact that the early literature neglects flows of capital stock ($\dot{X}_{\dot{K}_{ij}}$) on the input. Thus, the Input-Output matrix in the early EI-O literature ($\mathbf{A}'$) is

$$\mathbf{A}' = \begin{bmatrix} a'_{22} & a'_{23} \\ a'_{32} & a'_{33} \end{bmatrix}. \tag{7.4}$$

The implicit assumptions of the early energy I-O literature are consistent with the upper-left quadrant of Figure 7.1, and the energy intensity equation found in most of the early literature is

$$\boldsymbol{\varepsilon}' = \left(\mathbf{I} - \mathbf{A}'^{\mathrm{T}}\right)^{-1} \left(\hat{\mathbf{X}}\right)^{-1} \mathbf{E}_0. \tag{7.5}$$

Bullard and Herendeen [4], following Kirkpatrick [3], added flows of capital as inputs to each sector [4, Figure 5], and, in so doing, changed Equation 7.5 to Equation 7.6:

$$\boldsymbol{\varepsilon} = \left[\mathbf{I} - \left(\mathbf{A}'^{\mathrm{T}} + \mathbf{A}_{\dot{K}}^{\mathrm{T}}\right)\right]^{-1} \left(\hat{\mathbf{X}}\right)^{-1} \mathbf{E}_0 \tag{7.6}$$

with

$$\mathbf{A}_{\dot{K}} \equiv \begin{bmatrix} a_{\dot{K}_{22}} & a_{\dot{K}_{23}} \\ a_{\dot{K}_{32}} & a_{\dot{K}_{33}} \end{bmatrix} \tag{7.7}$$

and

$$a_{\dot{K}_{ij}} \equiv \frac{\dot{X}_{\dot{K}_{ij}}}{\dot{X}_j}. \tag{7.8}$$

Bullard and Herendeen counted embodied energy from incoming capital stock in $\mathbf{A}_{\dot{K}}$ only if it was used for replacement.[4, p. 488] Consequently, they did not count incoming energy embodied in capital if the incoming capital was used to increase the stock of capital within a sector. In fact, Bullard and Herendeen's product-focused accounting framework did not include an embodied energy stock for economic sectors (**B**) at all. They assumed that half of the incoming capital went toward replacement. These early researchers moved from the upper-left quadrant to the lower-left quadrant of Figure 7.1. And, Equation 7.6 represents a partial step toward developing a method for estimating energy intensity ($\boldsymbol{\varepsilon}$) that fully accounts for capital stock.

As stated above, we agree with Kirkpatrick [3], Bullard and Herendeen [4], and Casler [5] that incoming capital is important and should be included in an accounting framework (i.e., we should be on the lower half of Figure 7.1). But, we recommend that inclusion of incoming capital should be done within a *physical* accounting framework, i.e. we should make a second move from the lower-left to the lower-right quadrant of Figure 7.1. Specifically, incoming capital should be included not only on incoming material streams but also as a stock that can accumulate within the economic sector itself.

Our recommendation is informed by the work of Odum [6] and Daly [7] and is based on the belief that accounting for stocks of capital is important for developing a coherent view of the structure of an economy. Stocks of capital are essential to the production process: without machines and factories, cars cannot be produced. And, in industrialized economies maintenance of captial stock becomes an important driver of demand and may also constrain available supply, as illustrated by this quote from Meadows,

> By year 50 the cost of maintaining the capital stock has overwhelmed the income from resource extraction, so profits are no longer sufficient to keep investment ahead of depreciation. The operation quickly shuts down, as the capital stock declines. The last and most expensive of the resource stays in the ground; it doesn't pay to get it out. [8, p. 62]

Thus, the buildup of capital stock (and associated embodied energy) within economic sectors is an essential aspect of industrialization. Carefully tracking (on a physical, as opposed to financial, basis) capital stock in each economic sector is essential for understanding the network effects of upstream energy demand as new industries and products arise (e.g., electric vehicles).

In a physical accounting system that includes capital stock (lower-right quadrant of Figure 7.1), energy embodied within accumulated capital stock is not assigned to products (**P**); rather, accumulated embodied energy is assigned to a stock of embodied energy for each sector ($\mathbf{B}_K$). And, the stock of embodied energy ($\mathbf{B}_K$) can depreciate.

A physical accounting framework that fully includes capital stock (lower-right quadrant of Figure 7.1) is described by Equation 7.9.

$$\boldsymbol{\varepsilon} = \left(\mathbf{I} - \mathbf{A}^{\mathrm{T}}\right)^{-1}\left(\hat{\mathbf{X}}\right)^{-1}\left[\mathbf{E}_0 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right]. \tag{7.9}$$

Differences between Equation 7.9 and Equation 7.6 include:

- Equation 7.9 includes **A** while Equation 7.6 splits **A** into $\mathbf{A}'$ and $\mathbf{A}_{\dot{K}}$ (a difference in appearance only),
- Equation 7.9 subtracts accumulation $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$ of energy embodied in capital stock, because energy embodied in the stock of capital for a sector (B_{K_j}) is assigned to products of the sector,
- Equation 7.9 subtracts waste ($\mathbf{B}_{\dot{W}}$), because energy embodied in waste products is not assigned to products of the sector, and
- Equation 7.9 subtracts depreciation ($\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K$) of energy embodied in capital stock, because energy embodied in depreciated capital ($\dot{B}_{\dot{K}_{j0}}$) is assigned to products of the sector.

There are two topics related to Equation 7.9 that are worthy of consideration: waste flows and an accounting equation for capital stock.

7.2.2.1 Waste flows

We are unaware of any estimates of the energy embodied in wasted material in an economy ($\mathbf{B}_{\dot{W}}$). But, it may be possible to develop a metric for the resource material efficiency of an economic sector ($\eta_{\dot{R}}$), i.e. the fraction of the material that actually makes it into the product, such that:

$$\eta_{\dot{R}_j} \equiv \frac{\dot{P}_j}{\sum\limits_{i=1}^{n} \dot{R}_{ij}}. \tag{7.10}$$

With the above definition, the scrap rate for resources could be expressed as $(1 - \eta_{\dot{R}}) \sum\limits_{i=1}^{n} \dot{R}_{ij}$. Allwood et. al. [9, p. 193] used a process-based approach to manufacturing efficiencies for metals used in manufacturing. The data are summarized in Table 7.1.

Table 7.1 Manufacturing efficiencies ($\eta_{\dot{R}}$, Equation 7.10) for selected manufactured goods.[9]

Product	$\eta_{\dot{R}}$ [%]
Steel I-beam	90
Car Door Panel	50
Aluminium Drink Can	50
Aircraft Wing Skin Panel	10

Furthermore, one could assume that the rate of short-lived materials ($\dot{S}$) used by a sector could be given as a fraction of the resource ($\dot{R}$) use rate such that:

$$\rho_{\dot{S}_j} \equiv \frac{\dot{S}_{j0}}{\sum\limits_{i=1}^{n} \dot{R}_{ij}} = \frac{\sum\limits_{i=1}^{n} \dot{S}_{ij}}{\sum\limits_{i=1}^{n} \dot{R}_{ij}}. \tag{7.11}$$

With the above definitions, the waste resource rate from an economic sector can be given as

$$\dot{R}_{j0} + \dot{S}_{j0} = (1 - \eta_{\dot{R}_j} + \rho_{\dot{S}_j}) \sum_{i=1}^{n} \dot{R}_{ij}. \tag{7.12}$$

The embodied energy in the waste materials would need to be estimated from the embodied energy of the incoming resource and short-lived material flows as

$$\dot{B}_{\dot{W}_j} = \dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}}. \tag{7.13}$$

7.2.2.2 Simplification via capital stock accounting equation

A possible simplification to Equation 7.9 can be obtained from a control volume around the stock of capital in sector j:

$$\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{\dot{K}_{ij}} - \gamma_{B_j} B_{K_j}. \tag{7.14}$$

We can express the incoming energy embodied in capital ($\sum_{i=1}^{n} \dot{B}_{\dot{K}_{ij}}$) as a fraction ($\alpha_{B_j}$) of the capital stock ($B_{K_j}$) as

$$\alpha_{B_j} \equiv \frac{\sum\limits_{i=1}^{n} \dot{B}_{\dot{K}_{ij}}}{B_{K_j}} \tag{7.15}$$

for $j \in [2,n]$.
Together with the Kronecker delta (δ_{ij}), we can write

$$\hat{\boldsymbol{\alpha}}_B \equiv \delta_{ij}\alpha_{B_j} = \begin{bmatrix} \alpha_{B_2} & 0 \\ 0 & \alpha_{B_3} \end{bmatrix}. \tag{7.16}$$

Thus, the embodied energy accounting equation around the stock of capital in the economy can be written in matrix form as

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \hat{\boldsymbol{\alpha}}_B \mathbf{B}_K - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K. \tag{7.17}$$

Rearranging slightly gives

$$\hat{\boldsymbol{\alpha}}_B \mathbf{B}_K = \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K, \tag{7.18}$$

which says that incoming capital ($\hat{\boldsymbol{\alpha}}_B \mathbf{B}_K$) can be used to either increase the stock of capital in the economy $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$ or overcome depreciation ($\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K$). Substituting Equation 7.18 into Equation 7.9 gives

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 - \hat{\boldsymbol{\alpha}}_B \mathbf{B}_K - \mathbf{B}_{\dot{W}}\right]. \tag{7.19}$$

7.2.3 Energy input from society

In Sections 7.2.1 and 7.2.2 above, we implicitly assumed that Society (1) (Final Consumption, in example economies A–C) contributes negligible energy to the economy. Thus, all vectors and matrices in Equation 7.9 involve Sectors 2–n, but not Sector 1.

Energy input from society to the economy ($\mathbf{T}_1$) is "muscle work" supplied by working humans and draft animals.[10–12] This muscle work term ($\mathbf{T}_1$) should include all upstream energy required to make the labor available.[4] Equation 6.37 adds the effect of energy input from society to the economy, effectively moving from the top half to the lower half of the lower-right quadrant in Figure 7.1.

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1}\hat{\mathbf{X}}^{-1}\left[\mathbf{E}_0 + \mathbf{T}_1 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right]. \tag{6.37}$$

For industrialized economies, the direct energy component ($\mathbf{E}_1$) of muscle work ($\mathbf{T}_1$) is likely to provide only a small fraction of the energy input from fossil fuels ($\mathbf{E}_0$). But, the embodied energy of the muscle work ($\mathbf{B}_1$) is likely to be large. For agrarian and developing economies, $\mathbf{T}_1$ and $\mathbf{E}_0$ could be on the same order of magnitude. For both industrial and agrarian economies, neglecting $\mathbf{T}_1$ could cause errors in estimates of $\boldsymbol{\varepsilon}$. To the extent that $\mathbf{T}_1$ is significant relative to $\mathbf{E}_0$, neglecting $\mathbf{T}_1$ will underpredict the energy intensity of economic output. Energy input from society is discussed further in Section 8.9.

7.2.4 Recommendation

Sections 7.2.1–7.2.3 discussed three factors that affect the form of the energy intensity equation: product-focused vs. physical accounting frameworks, whether capital stock is included, and whether energy input from society is included. The three factors are summarized in Figure 7.1.

At this point, it is instructive to look back at the product-focused vs. physical discussion in Section 7.2.1. We understand the argument for including capital stock in a product-focused accounting framework (lower-left quadrant of Figure 7.1): capital stock and waste exist solely due to product demand, therefore energy embodied in capital and waste should be assigned to products. However, a product-focused framework that includes capital stock (lower-left quadrant of Figure 7.1) masks structural aspects of economies that we believe are essential to fully understanding how and why energy flows through economies, namely the accumulation of capital and associated energy embodied within sectors.

The metabolic metaphor provides guidance here. If we were to create a model of an organism that neglects tissues that accumulate embodied energy, the organism (in

[4] At this point in the development of our framework, we are assuming that Final Consumption (Sector 1) is exogenous to the economy (Sectors $2\ldots n$), and upstream energy consumption needs to be included manually. However, in Section 8.9, we show that Final Consumption can be endogenized. Once endogenized, the energy intensity of Final Consumption (ε_1) will automatically include the upstream energy required to make labor available. (See Appendix B.)

It is important to note, too, that labor can have very high energy intensity, because ε_1 includes the energy required to supply food for and transport to workers.

the model) has nothing with which to absorb, process, waste, or otherwise exchange material with the biosphere. The organism doesn't physically exist (in the model)! Neglecting to account for the stock of capital (and its embodied energy) is tantamount to assuming that economic production occurs out of nothing! Accounting for capital stock is essential.

For our framework, we chose a physical accounting approach (which puts us in the right column of Figure 7.1). We chose the physical approach primarily because of our belief that capital is an important aspect of economies, and the physical accounting framework properly includes a stock of capital for each sector of the economy. Product-based accounting frameworks mask crucial aspects of why and how energy flows through economies. We acknowledge that the choice of a physical accounting framework necessitates careful tracking of capital flows (and associated embodied energy) through the economy. For more on data needs, see Section 8.1.

Finally, we suggest that accounting for energy input from society to the economy is important, and we need to be in the lower half of the bottom-right quadrant of Figure 7.1. So, the state of the art has moved from the nascent energy I-O literature located in the upper-left quadrant of Figure 7.1 as represented by Equation 7.5 through the lower-left quadrant of Figure 7.1 as represented by Equation 7.6 to the lower half of the bottom-right quadrant of Figure 7.1 as represented by Equation 6.37.

The implication of the detailed development of our framework on the EI-O method is some suggested enhancements to the EI-O method, including

- conversion to a physical accounting framework such as the one we propose herein,
- physical (as opposed to financial) tracking of accumulated capital stock within economic sectors,
- redefinition of $\mathbf{A}$ and $\boldsymbol{\varepsilon}$ to include embodied energy on inflows of material, and
- use of Equation 6.37 instead of Equations 7.5 or 7.6 for estimating energy intensity ($\boldsymbol{\varepsilon}$) of economic sectors within an economy.

7.3 Implications for economic growth

Across the world, economic health and well-being is measured almost exclusively by Gross Domestic Product (GDP). If GDP grows, the economy is said to be growing.[5] Our framework affords the opportunity to assess economic growth in several dimen-

[5] GDP is not the only indicator of well-being available; there are several other measures in use. The Human Development Index (HDI) is a globally accepted measure that augments GDP with education and life expectancy.[13] In the US, the state of Maryland has been tracking well-being using the *Genuine Progress Indicator* (MDGPI), which combines measures of economic transactions with environmental and social costs.[14, 15] The MDGPI is closely related to Herman Daly's Index of Sustainable Economic Welfare (ISEW) which allows policy-makers to account for contributions of and impacts on the natural environment.[16, 17] Another example is the Nation of Bhutan's *Gross National Happiness* (GNH), a systematic, annual compliation of survey and other data related to nine factors: ecological diversity and resilience, psychological well-being, health, education, culture,

sions. Viewing these dimensions through the lens of our framework illustrates some important points about measures of economic growth and well-being.

With reference to Figure 5.5, GDP is calculated by

$$GDP = \sum_{j=2}^{n} \dot{X}_j \tag{7.20}$$

where n is the number of sectors in the economy. Equation 7.20 clearly shows that GDP is a *flow* of value in units of \$/year.

A second possible measure of economic well-being is a *stock*, wealth:

$$X_j(t) = X_j(0) + \int_{t=0}^{t=t} \frac{\mathrm{d}X_j}{\mathrm{d}t} \mathrm{d}t, \tag{7.21}$$

where $j = 1$ for societal wealth and $j \in [2, n]$ for corporate wealth, both measured in dollars.

As an economy grows, sectors within the economy accumulate capital stock (K, typically expressed in units of dollars) and associated embodied energy (B_K, expressed in units of joules). If we turn this around, accumulation of embodied energy in economic sectors and society could be considered a *proxy* for growth.[6] Equation 7.22 indicates how accumulated embodied energy in the capital stock of an economy ($\mathbf{B}_K$) could be calculated:

$$\mathbf{B}_K(t) = \mathbf{B}_K(0) + \int_{t=0}^{t=t} \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} \mathrm{d}t, \tag{7.22}$$

where $\mathbf{B}_K$ is given by Equation 6.18. Equation 7.22 clearly shows that energy embodied in capital ($\mathbf{B}_K$) is a *stock* (in units of joules), not a flow.

The behavior of $\mathbf{B}_K$ with respect to $\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}$ is vitally important. As an economy transitions from agrarian to industrialized, its capital stock (K) and associated embodied energy (B_K) grows ever larger. The outflow of depreciated capital stock and its associated embodied energy will occur at a faster rate, too. As increasingly large amounts of energy are embodied in the capital stock of an economy (B_K), Equation 6.32 shows that increasingly large energy extraction rates ($\mathbf{E}_0$) are required to maintain capital stock in the sectors of the economy to offset the effects of depreciation ($\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K$), assuming that $\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} \geq 0$ is desired.

During a period of rapid industrialization and infrastructure build-out, we expect both GDP and energy embodied in the economy ($\mathbf{B}_K$) to increase. But, there is no guarantee that GDP and $\mathbf{B}_K$ move in the same direction at all times. Industrialized economies may experience GDP growth while the stock of embodied energy in the economy ($\mathbf{B}_K$) remains nearly constant, because the economy is running circles to overcome the effects of depreciation.

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time use, good governance, community vitality, and living standards.[18, 19] These alternatives to GDP are slowly gaining acceptance, particularly as their valuation methods are strengthened.[20]

[6] Embodied energy as a proxy for economic growth may be overly focused on capital stock, therefore one-dimensional, and reductive, but GDP and other measures are open to similar criticism.

There can be a time lag between movements of GDP and $\mathbf{B}_K$, too. At the beginning of an economic downturn (defined as prolonged GDP reduction), capital stock and associated embodied energy ($\mathbf{B}_K$) will remain approximately constant: GDP moves but $\mathbf{B}_K$ doesn't. But as the GDP decline continues, maintenance flows for capital stock will be reduced. If depreciation overtakes maintenance, $\mathbf{B}_K$ will decline.

"Extract and export" economies may exhibit different dynamics. GDP growth occurs as resources are extracted and sold, but $\mathbf{B}_K$ remains flat if that income is not invested back into the economy as capital. An example of this occured with rubber exports from the Amazon. Per capita incomes increased by an order of magnitude from 1820 to 1900 during the rubber export boom. However, as Amazon rubber exports dropped in value due to stiff competition from Asian rubber production, per capita incomes dropped precipitously back to original levels. Throughout this period, the capital stock, and presumably the stock of embodied energy ($\mathbf{B}_K$), remained nearly constant.[21]

In fact, capital (represented by energy embodied in infrastructure, $\mathbf{B}_K$) and financial resources or wealth (represented by $X_{2...n}$) are complementary factors of production for economic processes. But, we can go further than linking physical capital with financial resources. If capital ($\mathbf{B}_K$) is to be useful, we need financial resources or currency ($\dot{X}$) to

- purchase direct energy ($\dot{E}$) to power the capital,
- purchase resources ($\dot{R}$) to feed the capital, and
- pay workers (represented by societal energy input to the economy, $\mathbf{T}_1$) to operate the capital.

Thus, economic growth could be considered a "fully coupled" problem: understanding it requires breadth of knowledge and appreciation for interactions among many important factors. Each factor discussed above ($\dot{X}$, X, $\mathbf{B}_K$, $\dot{E}$, $\dot{R}$, and $\mathbf{T}_1$) is necessary, but not sufficient, for economic growth.

Our framework serves to highlight several issues in economic growth. Should it be measured by a stock or a flow? Which measure is most appropriate? What roles do currency, capital stock, energy, resources, and labor play in economic processes? These are overlapping and complementary areas of inquiry, and we encourage further research in all of these areas.

7.4 Implications for recycling, reuse, and dematerialization

Mik asks "Do we want to discuss the Simon-Erlich wager here?" I feel like it is important to discuss that Simon won more by luch than judgement. See [**?**]. AND [**?**],

Dematerialization is the idea that economic activity can be unlinked from material or energy demands.[22] One method for dematerializing an economy is reuse and recycling of materials[7] from both short-lived goods ($\mathbf{B}_{\dot{W}}$) and depreciated capital stock ($\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K$) that would otherwise have been discarded to the biosphere.[8]

In Chapter 6, we defined the rate of accumulation of embodied energy within the economy $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$ by the following equation:

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + \hat{\mathbf{X}}(\mathbf{A}^\mathrm{T} - \mathbf{I})\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K \tag{6.32}$$

One effect of recycling is to reduce the magnitude of the waste ($\mathbf{B}_{\dot{W}}$) and depreciation ($\hat{\boldsymbol{\gamma}}_B$) terms. As can be seen in Equation 6.32, reducing both $\mathbf{B}_{\dot{W}}$ and $\hat{\boldsymbol{\gamma}}_B$, puts *upward* pressure on the accumulation of energy embodied in capital stock $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$, all other things being equal.

Recycling has a mixed effect on energy demand ($\mathbf{E}_0$). Because recycled materials can displace newly-produced material in the economy and society, recycling will tend to reduce energy demand ($\mathbf{E}_0$). However, recycling processes require energy to operate, thereby putting upward pressure on energy demand ($\mathbf{E}_0$). If the energetic cost of recycling is lower than the energetic cost of obtaining virgin materials, as is the case for many metals (e.g. aluminum [25]), the result is a net reduction of energy demand from the biosphere ($\mathbf{E}_0$). Berry and Fels found that recycling of the material in automobiles would result in energy reduction of 12,640 kW-hr per vehicle.[26, p. 15] Therefore recycling will put *downward* pressure on the growth of embodied energy in the economy $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$, via reduced $\mathbf{E}_0$, all other things being equal.

If recycling produces a net reduction in energy demand ($\mathbf{E}_0$), the upward pressure on growth $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$ from decrease in depreciation ($\hat{\boldsymbol{\gamma}}_B$) and waste ($\mathbf{B}_{\dot{W}}$) and the downward pressure on growth from net reduction in energy demand ($\mathbf{E}_0$) can offset each other. Under those conditions, the accumulation rate of energy embodied in capital stock $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$ will remain near zero and total embodied energy ($\mathbf{B}_K$) will remain constant. In that scenario, dematerialization can occur: reduced material and energy input ($\mathbf{E}_0$) can be accompanied by no change in the growth of the economy $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$. However, as will be discussed in Section 8.4.2, recycled materials can never entirely replace the need for virgin materials.

7.5 Comparison to a steady-state economy

> Growth means larger jaws and a bigger digestive tract for more rapidly converting more resources into more waste, in the service of unexamined and frequently destructive individual wants. Development means better digestion of a non-growing throughput, and more worthy and satisfying goals to which our life energies could be devoted.[1]

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[7] How our accounting framework may be extended to include recycling is discussed more in Section 8.6

[8] The other prevailing theory in the economics literature, that dematerialization will occur as the economy substitutes away from production of material goods toward information and services, has been strongly challenged by ecological economists.[23, 24]

As discussed in Chapter 1, the human economy is a subset of the biosphere, a finite, non-growing system. Thus, the human economy cannot physically grow indefinitely. The concept of a non-growing or "steady-state" economy has existed for centuries.

There are a number of different conditions that may characterize a system as steady-state. In thermodynamics, steady state is characterized by unchanging system properties (p), such that $\left(\frac{\mathrm{d}p}{\mathrm{d}t}\right) = 0$. In ecological economics, a steady-state economy has been defined as a constant rate of material throughput that maintains the stock of ecological capital and provides a qualitatively well-lived life for the population.[27, p. 32] This definition is consistent with zero rate of accumulation of stock. Ecological capital is not drawn down, nor is manufactured capital quantifiably increased. Increases in living standards result from economic "development," in which qualitative improvement in life occurs through increases in "efficiency, technology, and ethics." [27, p. 167]

Two other conditions that might define a steady-state economy are constant GDP or constant population. Our framework, can address the first three steady-state conditions (constant capital stock, constant throughput, and constant GDP). The fourth condition (constant population) could be accommodated with some adaptation of the framework. The issue of human population as part of society's capital stock is addressed in Section 8.7.

7.5.1 Constant level of capital stock

In Chapter 2, we introduced Equation 2.105:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_j \frac{\mathrm{d}K_j}{\mathrm{d}t} + \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j. \tag{2.105}$$

which indicates that natural resources in the biosphere $\left(-\frac{\mathrm{d}R_0}{\mathrm{d}t}\right)$ are depleted by the economy for the purposes of:

- increasing man-made capital stocks within the economy $\left(\frac{\mathrm{d}K_j}{\mathrm{d}t}\right)$,
- providing short-lived goods exchanged within the economy $\left(\dot{S}_{ij}\right)$, and
- overcoming depreciation of man-made capital stocks $\left(\gamma_{K_j} K_j\right)$.

Assuming, first, that a steady-state economy exists when the level of capital stock remains constant $\left(\sum_j \frac{\mathrm{d}K_j}{\mathrm{d}t} = 0\right)$,[9] we can see that Equation 2.105 reduces to:

[9] Note that the steady-state condition does not preclude expansion of some sectors of the economy, provided that there is equal contraction elsewhere.

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j. \tag{7.23}$$

A number of interesting concepts may be understood via Equation 7.23. Firstly, if our steady-state economy is to be supported sustainably, then withdrawal of natural resources from the biosphere $\left(\frac{\mathrm{d}R_0}{\mathrm{d}t}\right)$ had better be at some rate lower than the biosphere can replenish those stocks. In reality, $\frac{\mathrm{d}R_0}{\mathrm{d}t}$ is really the sum of many different resources (flora and fauna, water) each of which will have its own natural rate of regeneration. As such, the sustainability criterion is a vector of values, one for each natural resource, all of which must be met individually.

Secondly, the steady state condition $\left(\sum_j \frac{\mathrm{d}K_j}{\mathrm{d}t} = 0\right)$ says nothing about the transfer rates of short-lived goods within in the economy $\left(\sum_{i,j} \dot{S}_{ij}\right)$ or the depreciation of capital stock back to the biopshere $\left(\sum_j \gamma_{K_j} K_j\right)$. Equation 7.23 indicates that the higher the rates of these flows, the greater the rate of depletion of natural resources, and the more difficult it will be to meet the sustainability condition (that the withdrawal rate of natural resources from the biosphere is lower than the biosphere replenishment rate). Within industrial society, the flow of short-lived goods (packaging, paper products, disposable tableware, cutlery, and napkins) is large, and, presumably, attaining a sustainable steady-state economy will be difficult. This definition of steady state, constant capital stock $\left(\sum_j \frac{\mathrm{d}K_j}{\mathrm{d}t} = 0\right)$, does not necessarily coincide with sustainability.

As discussed in Chapter 2, the rate of depreciation (γ_K) is inversely proportional to the average lifetime of capital stock—as the average lifetime of capital stock decreases, the rate of depreciation of capital stock increases thereby increasing the draw on natural resources (by Equation 7.23). It is likely that the average lifetime of capital stock has decreased over the last century, due to a decrease in durability of capital stock (the average table built today is not as durable as the average table built in the early twentieth century) and also due to increasing proportions of consumer electronics with short lifetimes (cell phones, laptops, tablets).[10] Decreasing lifetime causes higher rates of flow for replacement materials. In the absence of extreme recycling of materials, these large replacement flows place large demands on natural resources.

Thirdly, the maintenance flows necessary to overcome depreciation $\left(\sum_j \gamma_{K_j} K_j\right)$ are proportional to the magnitude of the capital stock (K_j). As such, a larger stock of capital requires greater draw on natural resources and is thus harder to maintain within any sustainability constraint. These points emphasize that constant capital stock (or analogously constant population) is not a sufficient condition for environmental sustainability.

[10] In fact, cell phones are rarely included as capital goods by economists **** BECKY DOUBLE-CHECK ****

7.5.2 Constant material throughput

Herman Daly has placed great emphasis on a steady-state economy as having a constant rate of material throughput [28, 27] which, as discussed above, should be below biophysical limits if sustainability is to be achieved. This is often referred to as the “scale” issue—how large is the (currently growing) human economy in relation to the finite, non-growing biosphere of which it is a sub-system? Growth of the human economy must either displace other natural ecosystems (replacing old growth forest with cultivated crops) or deplete natural capital stocks, be they renewable (fisheries) or non-renewable (fossil fuels). As shown in Figure 2.4, material throughput is composed of two distinct processes: exchange of material *from* the biosphere *into* the economy (extraction) and exchange of material *from* the economy *into* biosphere (waste and depreciation). We may characterize constant material throughput as either constant rate of extraction, constant rate of waste disposal, or both. In the language of our framework, we could write:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{R}_0\right) = 0, \tag{7.24}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{S}_0\right) = 0, \tag{7.25}$$

and

$$\sum_i \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{R}_{i0}\right) + \frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{S}_{i0}\right) + \frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{K}_{i0}\right)\right] = 0. \tag{7.26}$$

The above equations say nothing about the level of man-made capital stock (K) or the flow rate of short-lived goods ($\dot{S}$). Thus, within the constant throughput constraint, increasingly effective use of materials could theoretically allow increasing accumulation of man-made capital (K) and increasing flow of short-lived goods ($\dot{S}_{ij}$) as society learns to use resources better. Eventually, physical limits would entail that capital stock could no longer be increased. Presumably, society would desire that the throughput of materials would be within levels that could be sustained by the biosphere, both at the input side—natural resources extracted at rates lower than natural regeneration rates—and at the output side—wastes emitted at rates below which the biosphere can assimilate. Otherwise, the condition of constant material throughput does not guarantee societal sustainability.

7.5.3 Constant GDP

Although one definition of a steady-state economy is based upon constant levels of *material* throughput, it is possible to examine the implications of constraining the *value* of GDP to be constant.[11] Within our framework, a condition of constant GDP would be characterized by the following equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}(GDP) = \sum_j \frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{X}_j\right) = 0. \tag{7.27}$$

Because, under the subjective theory of value, no value is attributed to the flow of materials to or from the biosphere, it is unclear what impact constant GDP would have on capital stock (K) or material throughput (both extraction and waste disposal). If we constrained $\dot{R}_0$ and $\dot{S}_0$, it is likely that economic growth would decrease or even become zero or negative $\left(\frac{\mathrm{d}}{\mathrm{d}t}(GDP) \leq 0\right)$. It is conceivable that constraining economic growth may act to constrain material throughput, though this is certainly not assured.

Although constraining GDP may not achieve the desired restraint on material throughput, increasing GDP may not produce a desired increase in material well-being, either. This is particularly true for countries that have already achieved high levels of wealth. Many authors argue that increasing GDP no longer guarantees increasing welfare [29–33] for two main reasons:

- firstly, that the costs of growth in GDP (e.g., externalities and defensive expenditures) outweigh any benefit that comes from increasing GDP; and
- secondly, that increased GDP increases relative income inequality, which decreases welfare for both rich and poor alike.[32]

Indeed, it may be the case that at the margin an increase in GDP produces more "illth" than "wealth," resulting in "uneconomic" growth.[32, p. 42] Uneconomic growth is much more likely to occur in a wealthy society than in a poor one, according to the law of diminishing returns.[12] Thus, a case could be made for constraining GDP growth in wealthy countries so that resources may be allocated to poorer countries where growth in GDP is still likely to be "economic." [32]

7.6 Choice of energy input vector

There is discussion in the literature about the $\mathbf{E}_0$ vector and how it should be applied to the economy. Costanza and Herendeen [34] counted fossil fuel input from the biosphere to the economy at both

1. the points where direct energy physically enters the economy from the biosphere, typically energy-producing sectors (called the DIRECT method), and

[11] This is a theoretical exercise, as Daly takes great pains to be clear that the steady-state economy is materially-based. "It is not to be thought of as 'zero growth in GNP'." [27, p. 32]

[12] Measuring whether or not growth is "economic" cannot be done with traditional measures, such as GDP, since there is no debit column in the ledger for GDP. However, alternative metrics, such as ISEW or GPI, can perform such a function.

2. the points of conversion to useful work, typically all energy *consuming* sectors (called the Direct Energy Conversion (DEC) method).

Costanza and Herendeen justified the Direct Energy Conversion (DEC) approach on both thermodynamic and economic grounds. The thermodynamic justification derived from the purpose of energy consumption in an economy, namely to produce useful work. If direct energy flows *through* a sector, it should not be counted *against* that sector: only energy that is converted to useful work *within* a sector should be counted against that sector. The economic justification derives from the typical treatment of transportation sectors of the economy. Costanza and Herendeen note:

> The primary energy sectors functions [*sic*] ~~are~~ like the transportation sectors, which alse [*sic*] require special treatment in I-O analysis based on the difference between the services they provide and their physical inputs and outputs. If a strictly physical interpretation were applied to the transportation sectors, they would receive almost all goods produced in the whole economy as inputs and redistribute them as output, masking information on transfers of goods between sectors. For this reason, the transportation sectors in I-O analysis are thought of as providing transportation services that are purchased by the producing sector, preserving the connection between the producing and consuming sector but adding a 'transportation margin.' For analogous reasons, the primary energy sectors should be thought of as providing a 'transportation service' in moving primary energy from nature to the consuming sectors. The DEC energy input vector incorporates this interpretation.[34, p. 151]

The derivation of the materials, energy, and value accounting framework presented herein counts energy flows from the biosphere to the economy at the point of physical inflow to the economy. That is, elements of the energy input vector ($\mathbf{E}_0$) are non-zero only for those sectors that receive energy directly from the biosphere. So, for example, in Figure 3.5 from Example C, $\dot{E}_{03} = 0$ and $\dot{E}_{02} \geq 0$. Our approach is equivalent to Costanza's DIRECT method. We believe that the DIRECT approach is correct and that the DEC method is unwarranted.

Justification for our position comes from the detailed derivation of the materials, energy, and value framework presented in Chapters 2–5.

1. Firstly, $\mathbf{E}_0$ was defined as a flow from the biosphere to economic sectors into which direct energy *physically* flows. It is inappropriate to route the energy elsewhere.
2. Secondly, Costanza and Herendeen's concern [34, pp. 130 & 138] about flow-through of direct energy is unfounded, because direct energy outflows from a sector are *never* counted against the sector with the DIRECT method. We see this fact in the following terms:

   a. $-\dot{E}_1$ in Equation 4.12,
   b. $-\dot{E}_j$ in Equation 4.43,
   c. $-\begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}$ in Equation 6.17, and
   d. $-\hat{\mathbf{X}}\boldsymbol{\varepsilon}$ in Equation 6.28.

3. Thirdly, further proof that the DEC approach is unwarranted comes from equations that show waste heat ($\dot{Q}_{j0}$) as counting toward the accumulation of embodied energy within an economic sector. Equation 4.16 of Section 4.2.2 is an

example. It is the waste heat ($\dot{Q}_{10}$), i.e. the energy *burned within* the sector, that counts against the sector.

The DIRECT approach *already always* provides the effect that Costanza and Herendeen [34] desired from the DEC approach. Because the DEC approach is unwarranted, we quoted DIRECT energy intensity values only when discussing energy intensities in Section 6.6.

7.7 Summary

In this chapter, we discussed several implications that arise from the detailed development of our dynamic framework for material, energy, and value accounting. The first implications are for the EI-O method itself. We recommend a physical accounting framework that fully accounts for capital stock and energy input from society (normally assumed to not provide direct energy to the economy). We then discussed implications for economic "growth," namely that economic growth could be considered a "fully coupled" problem: understanding it requires breadth of knowledge and appreciation for interactions among many important factors, including financial capital, physical capital and associated embodied energy, direct energy, resources, and societal inputs. Each, alone, is necessary, but not sufficient, for economic growth. We discussed implications for recycling and reuse of materials as well as the concept of dematerialziation. We viewed the concept of a steady-state economy through the lens of our framework. We found that there are many potential definitions of a steady-state economy, none of which are fully satisfying when compared against the ideal of sustainability. Finally, in Section 7.6, we discussed a technical issue regarding the choice of energy input vector ($\mathbf{E}_0$) and found that attempts in the literature to allocate energy at the point of use are unneeded.

In the next chapter, we point to some unfinished business.

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Chapter 8
Unfinished Business: Practical, Methodological, and Theoretical Issues

> *In a complex and wealthy country like the United States, providing information on the structure of the economy and the environment is an essential function of government. It deserves more support.* [1, p. 49]
>
> —William D. Nordhaus

With any endeavor of this magnitude, namely development and presentation of a comprehensive framework for economies of the world, unfinished business is inevitable. This chapter discusses several practical, methodological, and theoretical issues that should be addressed in the future. On a practical level, additional data are needed to fully utilize the framework developed herein. In terms of methodological issues, the issue of co-products needs to be addressed. Finally, several theoretical issues, including theories of value, material and energy quality, boundaries, and the Sun are addressed. We begin with the issue of data.

8.1 Data

In Chapter 1, we noted the importance of "counting" materials, energy, and value as each flows through economies. Unfortunately, unless data on these flows is collected and disseminated routinely, such counting is impossible. At several points in this manuscript, we have noted the very practical issue of the need for additional data, information, and analysis.

In Section 2.5, our attempt to account the physical flows of materials through the US auto industry was severely hampered by the lack of any data on material flows. Work to account such flows is starting to be addressed at the level of economies, particularly within Europe.[2] This work needs to continue, but sub-economy, inter-industry material accounts need to be developed, too. Chapter 6 noted the need to collect data on human and draught animal physical work input to sectors of economies, espeically for those economies where muscle work is on the same order of magnitude as fossil fuel energy input.

The need for rigorous and accurate data is all the more pressing in light of the need to track physical capital in sectors, as suggested in Chapter 6. If this accounting relies on process-type analysis, then there is a critical need for systematic collection and public dissemination of such data. Some of these data are available only in proprietary format; e.g., the latest version of the ecoinvent database (v3) contains detailed analysis of over 10,000 processes.[3] This is a fantastic effort, but more needs to be done to bring this crucial information into the public arena.

Environmental economic accounting in the US national accounts is currently non-existent. It was suspended by congress after the first tables were published and has been on hold for twenty years. The BEA developed the Integrated Environmental and Economic Satellite Accounts to complement the national accounts and track the "interactions of the economy and the environment." [4, p. 33] In 1994, the BEA published the first phase of tables, for subsoil resources, along with detailed economic accounting and environmental valuation methodology behind the new data.[4, 5] The first set of tables valued the stock of subsoil assets: oil, gas, coal, metals, and some major nonfuel minerals for the years 1947 to 1991. Each year of data included values for *Opening stock*, *Additons*, *Depletion*, *Revaluation adjustment*, and *Closing stock*. Several alternative valuation methods were used to provide a range of estimates.

Unfortunately, Congress ordered the BEA to suspend all work on environmental accounting, including development of additional accounts for renewable and environmental resources. Congress asked for an independent panel of scientists to review the BEA's methodology. In 1999, the review panel submitted its thorough evaluation as well as its strong recommendation that the BEA be funded to continue its work.[6] William Nordhaus, chair of the panel, summarized the panel's recommendations in the lead quote for this chapter, "In a complex and wealthy country like the United States, providing information on the structure of the economy and the environment is an essential function of government. It deserves more support." [1, p. 49] Fifteen years later, Congress has yet to act on this recommendation and lift the embargo on environmental accounting.

The business axiom "you can't control what you don't measure" seems appropriate here. As the world confronts significant challenges of material and energy supplies in the coming years, it will be impossible to make wise decisions about which materials to use, which energy sources to develop, and which products to incentivize.

The lede quote for Chapter 5 ("We try to measure what we value. We come to value what we measure." [7, p. 2]) points out that we are not presently valuing highly enough the important flows that describe our metabolic economies. We add our voices to those encouraging governments and institutions to collect high-quality data on material and energy flows.

8.2 Theories of value

As stated in Chapter 5, mainstream economics assumes a *subjective* theory of value, in which value is determined by the relative ability of products to satisfy the wants of buyers and sellers alike. However, a person's wants are malleable and are, in turn, formed within a "constellation of shared goals to which a society aspires." [8] Thoughout history, economists (particularly the classicals) and non-economists have searched for an invariant, objective, *intrinsic* determinant of value.[1] Adam Smith, Karl Marx, David Ricardo, and neo-Ricardian Piero Sraffa all proposed alternative determinants of value. Their proposed objective theories of value were based on identifying the primary input into production, such as *labor* (Marx) or *land* (Malthus), and using that input in the sense of a numeraire, a way to measure value across the entire spectrum of goods and services in commensurate units.

Costanza [8] makes the case for energy as the only truly primary input into production and thus an, or rather *the*, objective determinant of value. On a global scale, he notes, (solar) energy (including that which is stored in fossil fuels) is the only primary input into production: everything else is an intermediate input. Thus, free energy input to production (accounting for all upstream energy) could be the basis for an objective (intrinsic), energy theory of value.[2] However, mainstream economics has rejected an energy theory of value, in favor of the subjective theory of value discussed in Section 5.1. Because energy intensity ($\boldsymbol{\varepsilon}$) and the Energy Input-Output (EI-O) method were significant aspects of the proposal for an energy theory of value, many mainstream economists spurn analyses aimed at determining $\boldsymbol{\varepsilon}$.

In contrast, we observe that energy intensity does not necessarily lead to an energy theory of value and claim that energy intensity is inherently useful as a metric describing the energy pathways traveled by economic products. Energy intensity can provide important information for purchasing decisions in increasingly interconnected economies.

In the development of our framework, we used the subjective theory of value (i.e., value based on market prices at the time of transaction) for pragmatic, rather than philosophical, reasons. We believe that the information and signals provided by markets and prices are not sufficient to guide economies situated within a "full" earth. And, national economic accounting limits its focus to measuring value-added, but ignores that to which value is being added, thereby distorting economic value flows. As easily accessible forms of energy (e.g., oil extracted from the Texas panhandle) are used up and more difficult locations must be tapped (e.g., Alaskan north slope) the economy appears to grow. The "value-added" by human and manufactured capital increases, as humans must do more work to extract domestic energy sources. However, what is actually happening is that the stock of natural resource is diminishing, and the drawdown of natural capital is mis-measured by GDP as income.[9, pp. 66 and 75]

Therefore, as "that to which value is added" diminishes, economic growth begins to reach binding constraints. Identifying the optimal economic scale—rate of materials put through the economy—that is viable for the biosphere to handle becomes an optimization problem. However, this is an optimization problem that the market is unable to solve on its own.

Our framework provides a natural starting place for extending existing economic analysis methods to better guide economies situated within a "full" earth. Instead of

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[1] Following the ecological economics literature, we use the term intrinsic in the sense of "objective." Costanza [8] notes that a better term would be objective in order to avoid moral overtones associated with the term intrinsic.

[2] This line of inquiry has yielded some interesting analysis of the amount of solar energy required to run the economy. See Section 8.8 for further discussion of the concept of *emergy*.

turning to an energy theory of value, a system of envrionmental-economic accounting could be put in place to estimate the value of flows to and from the biosphere.[3] Such a system could be included in our framework to reconnect the economy to the biosphere, and flows that were conspicuously absent from Figure 5.1 will be included, as shown in Figure 8.1.

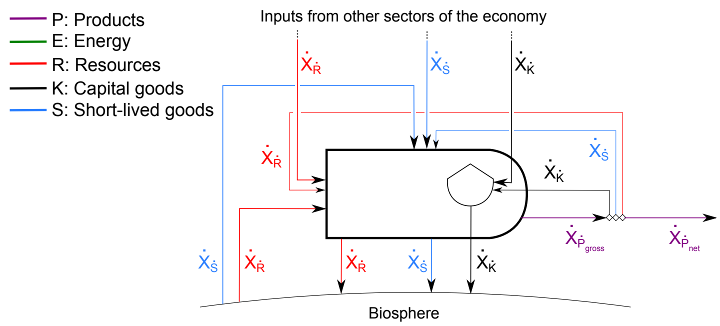

Fig. 8.1 Aggregated flows of value for a single sector including flows to and from the biosphere.

8.3 Hybrids of I-O and process-based methods

In early chapters, we made the distinction between process-based (often called “bottom-up”) and Input-Output (often called “top-down”) analyses. The advantages and disadvantages of each type of analysis are outlined in Figure 8.2.

Process analysis is based on detailed technological or engineering models of specific economic processes. Model specification and data collection is arduous, time-consuming, and costly. The aim of process analysis is to calculate the energetic and material flows associated with the process under study by disaggregating the process into several components or sub-processes. In reality, any economic process exists as part of a complex network of interacting processes that encompass the entire economy. Bullard et al. said “each step in a process analysis may be viewed as an expansion of the system boundary (around the item being analyzed) into the economic system.” [10, p. 281] Figure 8.3 shows that every process calls on every other process within the economy, even if only minutely and indirectly at many steps removed. Obviously, the time, effort, and cost involved with trying to model and measure all of the flows involved becomes daunting for even low numbers of interacting processes. The decision of where to draw the boundary of a process analysis is known in

[3] As of this printing, the System of Environmental-Economic Accounting (SEEA) [**?**] is in its third revision using a process of global consultation. This system contains internationally agreed-upon standards for quantifying value flows to and from the biosphere. SEEA is a system analogous to the System of National Accounts (SNA), a framework for measuring economic value creation consistently across nations.

the lifecycle assessment literature as the *truncation problem*.[11] One method to extend the comprehensiveness of process analyses is to use a hybrid method, utilizing data from an EI-O analysis to supplement the missing data from the truncation of the process analysis. The financial cost of goods and services identified by the process analysis are converted to energy (or material) flows via the EI-O method. The truncation error is replaced by a smaller aggregation error due to limitations of the EI-O method.[10] A variety of other hybrid methods exist which also aim to overcome the limitations of either process or I-O method individually.[10–14]

At several points in this book, we noted the need to track accumulation of embodied energy in sectors of the economy. It may be that process-based methods are best for doing so. However, we realize the limitations of process-based methods (time, cost, etc.). Perhaps hybrid methods can provide the necessary data without the high cost of a full process-based approach.

8.4 Resource quality and irreversibility

The quality of both materials and energy play a role in the efficiency with which economies convert material resources into products.

Raw material and energy resources must first be extracted from the natural environment before they are utilized in the economy to provide goods and service to society. Despite increasing levels of technological efficiency, for example in consumer goods such as refrigerators and cars, evidence shows that the energy intensity of primary resource extraction, i.e. the energy required to extract raw materials from the environment, has been steadily increasing over the last fifty years.[16–18] This increasing energy requirement for primary extraction means that less *net energy* is available for downstream uses. An important metric in this regard is *energy return on investment* (EROI), outlined in Section 3.3, which measures the energy production *per unit* of energy investment by society. As resource quality declines, more energy is needed to extract resources, EROI decreases, and there is less net energy available to society. If this decline in net energy availability outpaces technological advances in energy efficiency, there may be deleterious impacts on the economic output of the economy. This need to increase productive capacity merely to maintain the current level of production has been termed the "Red Queen syndrome";[4] we must run faster and faster just to stay in place.[19]

Within our framework, we do not account for either the material or energetic quality of resources that pass through the economy nor the irreversibility of economic processes. The following two subsections (8.4.1 and 8.4.2) briefly discuss energy and material quality. Thereafter, we raise the issue of thermodynamic irreversibility.

[4] Of course, in any deck of cards there are two Red Queens. The other was described in Section 7.2.2, regarding the increasing need to divert production to maintain capital stock.

	PROS	CONS
TOP-DOWN	* Comprehensiveness * Economy-wide analysis * System-level comparison * Publicly available data * Reproducible results * Assessment of future product development	* Aggregated data * Process analysis difficult * Reliance on financial data * Imports treated as domestic products * Lack of physical data * Data uncertainty
BOTTOM-UP	* Detail and specificity * Comparison of specific products or processes * Identifies process improvements * Assessment of future product development	* Subjective system boundary * Time intensive and costly * Difficult to apply to new product or process * Lack of data or reliance on proprietary data * Reproducibility of results * Data uncertainty

Fig. 8.2 Advantages (pros) and disadvantages (cons) of "top-down," I-O and "bottom-up," process-based analyses, adapted from [15].

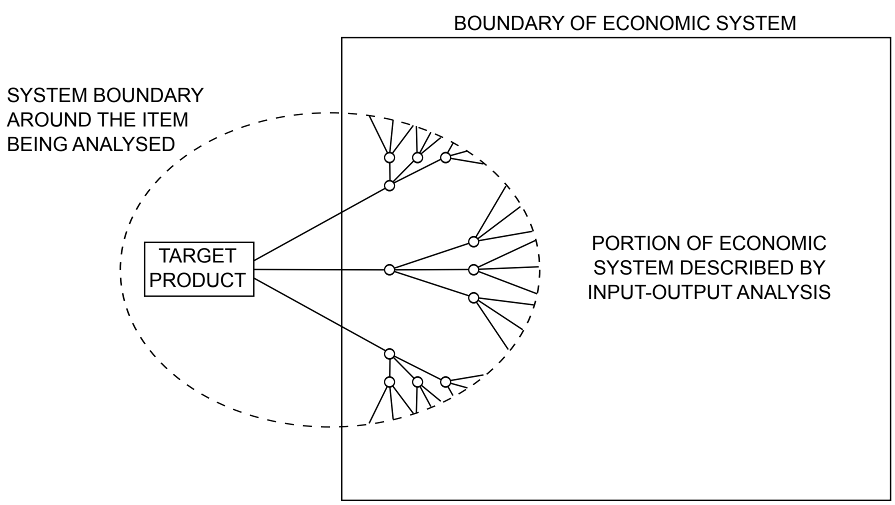

Fig. 8.3 System boundary for process and I-O analyses, adapted from [10].

8.4.1 Quality of energy

The First Law of Thermodynamics tells us that the quantity of energy is conserved in every process. The First Law does not speak about the quality of energy—not all forms of energy are equally *useful*. For instance, a bath-full of water has as much thermal energy as can be provided by a pint (half liter) of gasoline.[5] However, the gasoline is a much higher quality store of energy than the water. It is much more useful for performing tasks.

There are several ways to assess the quality of energy. The Second Law of Thermodynamics provides, among other things, a framework for discussing the *quality* of energy. Hammond and Winnett [20] reviewed the influence of thermodynamics on ecological economics and noted the importance of the concept of *exergy*, which combines the First and Second Laws of thermodynamics to describe the maximum physical work which can be performed by an energy resource in coming into equilibrium with its environment, stating that exergy:

> represents the thermodynamic 'quality' of an energy carrier, and that of the waste heat or energy lost in the reject stream. Electricity, for instance, may be regarded as an energy carrier having a high quality, or exergy, because it can undertake work. In contrast, low temperature hot water, although also an energy [re]source, can only be used for heating purposes. This distinction between energy (strictly enthalpy) and exergy is very important when considering a switch, for example, from traditional internal combustion engines to electric, hybrid, or fuel cell vehicles. Thus, ... it is important to employ exergy analysis alongside a traditional First Law energy analysis in order to illuminate these issues.

As such, exergy is a measure of how far a resource is from thermodynamic equilibrium with its environment. The further a resource is from equilibrium with the environment—the biosphere—the higher the exergy and the higher the quality of the resource.

The quality of energy can be assessed in terms of economic value, too. Some energy resources, such as liquid fuels, are more economically valuable than others, i.e. within society, there is a preference for these resources, such that, "accounting for energy quality reveals a relatively strong relationship between energy use and economic output." [21, p. 313] We see this preference played out on a daily basis when coal is converted to electricity at an average efficiency of around one third. Society is willing to pay a premium for electricity over coal due to its vastly superior usefulness for a multitude of tasks.

8.4.2 Quality of materials

Similar to energy resources, non-energy resources have a range of quality, despite being conserved in mass through every process. An intact brick is of higher material quality—is of more use—than after it has been ground to dust and scattered on

[5] This assumes a 230 liter bath at 40° C, i.e. 20° C above ambient.

the wind. Society relies on material stocks or flows that have been concentrated by natural biophysical processes, for example mineral seams or water courses. We do not mine desirable material from locations with the average abundance of crustal materials. As with energy, we may measure the material quality of a resource in reference to its environment, in this case, the average chemical composition of its environment. The more concentrated the resource, the further it is from chemical equilibrium with the environment and the higher the quality. Again, exergy is a measure of this kind of quality. The further a resource is from chemical equilibrium with its environment, the higher the exergetic content.

Additionally, it takes more energy to process less concentrated resources and more total material must flow through the process (including overburden—the wasted portion that is extracted) and the greater wear and tear on equipment. This additional processing requirement entails that we will likely never mine average crustal abundance for needed materials, or mine gold from seawater. Furthermore, it also entails that recycling—the act of turning low quality materials into high quality resources—requires energy and degrades equipment. The lower quality the waste, the more energy and degradation occurs such that one hundred percent recycling of materials is almost certainly practically (and possibly theoretically) impossible. As such, we can deduce that the economy *must always* be a subsidiary of the biosphere, *open* to flows of materials both from (resources) and to (wastes) the biosphere. This fact has direct implications for dematerialization of our economies, which was discussed in reference to our framework in Section 7.4. There are fundamental limits to the amount of material that must be directed to desired end services. For example, automobiles must have a minimum level of embodied materials.[6] Despite the drive to dematerialization and the apparent “unhooking” of the material and energy intensity of GDP, much of the dematerialization of “developed” nations has been by exporting manufacturing to other countries.[23] The material footprint of OECD nations, when weighted by consumption, has increased significantly since 1990.[24]

8.4.3 Process irreversibility

Our framework implicitly assumes, since we make no use of the Second Law, that all economic processes could be run in reverse; that products could be unmade into resources and that the energy and other short-lived material inputs would be spontaneously upgraded back into their original form. This of course is not true. Irreversibility is the concept that naturally-occurring processes are uni-directional in time. For example, bouncing a rubber ball heats it up; heating up a rubber ball does not cause it to spontaneously jump off the table.

Considering the production of electricity from coal, we note that two important processes within a power plant are *irreversible*:

[6] Note that this minimum is likely many times lower than the mass of current automobiles, which are driven largely by preference. The Rocky Mountain Institute has done some work on the ultra-light, “hypercar” concept.[22]

- the combustion process that converts coal to CO_2 and ash (with associated thermal energy release, $\dot{Q}$) and
- the heat transfer process wherein $\dot{Q}$ flows from high temperature to low temperature (with associated mechanical work production).[7]

Thermal energy does not spontaneously flow from low temperature to high temperature. Neither do ash and CO_2 spontaneously combine to form coal.

The concepts of resource quality and irreversibility are inextricably linked. One statement of the Second Law indicates that heat flow is irreversible: it flows only from hot to cold. Because lower-temperature heat is less useful, we say that the thermal energy has degraded when it has been used (comes into equilibrium with the environment). Again, exergy is a measure of irreversibility of processes. Exergy cannot be created, it can only be destroyed, hence a process is *irreversible* if exergy is destroyed during the process.[8]

Energy resources, such as coal, are useful since they are far from equilibrium with their environment, energy may be released into the environment by splitting the carbon-carbon bonds to form carbon-oxygen bonds with free oxygen within the atmosphere. The exergy content of the coal is destroyed during the equilibration process.[9]

Similarly, high grade mineral ores, such as bauxite, are useful since they are far from equilibrium with their environment—the average abundance of materials within the earth's crust. The chemical exergy of materials may be upgraded during processing—bauxite is refined into pure aluminum—but only at the expense of a greater amount of exergy destruction elsewhere—the coal burned to generate the electricity—i.e. the process is irreversible.

We recommend that future work be done to incorporate concepts of resource quality and irreversibility into our framework by accounting for flows and destruction of exergy within economic processes.

8.5 Co-products

Our materials, energy, and value accounting framework has been developed under the assumption that each economic sector makes a single product ($\dot{P}$). This assumption

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[7] Note that the process of generating electricity via mechanical work is (at least in theory) a *reversible* process. The generator could be run as a motor by electricity to produce mechanical work. In theory, electrical work and mechanical work are fully exchangeable; in reality, efficiency losses mean this is not quite the case.

[8] The concept of irreversibility is often discussed in terms of *entropy*, which can only be created and cannot be destroyed. A process that generates entropy is said to be irreversible and all real processes generate entropy.

[9] Strictly speaking, the exergy content of the coal is only fully destroyed when the CO_2 and ash have dispersed to their average concentration within the environment since, in theory, this diffusion (which happens spontaneously) could be used to perform work.

dates from the early days of the EI-O method.[25] In particular, the matrix mathematics of Chapter 6 relies heavily on this assumption. However, in later years, the EI-O method was extended in the literature to include co-products for each economic sector.[26, 27] To do so, both *make* and *use* data are employed.[10]

We decided to leverage the older, single-product formulation of the EI-O method for the purposes of simplicity. The materials, energy, and value accounting framework presented herein is more easily understood without the additional complexity of the make-use formulation of the EI-O method. However, work remains to adapt the framework developed herein to the make-use formulation of the EI-O method.

8.6 Extending the methodology to include recycling and waste treatment

In the accounting framework presented in Chapters 2-6, we assumed that all waste flows ($\dot{W}_{j0}$) and depreciated capital flows ($\dot{K}_{j0}$) from economic sector j flowed straight to the biosphere. In general, this is not the case within the economy. The Waste Management and Remediation Services sector (NAICS 562) has the responsibility, within the US economy, of collecting and disposing of wastes. Additionally, much material is recycled within the economy (rather than being disposed into the biosphere) and many capital goods are sold for re-use prior to recycling of materials, for example second-hand cars and office equipment.

We may represent these flows of resources ($\dot{R}_j$), short-lived goods ($\dot{S}_j$), and capital goods ($\dot{K}_j$) as flows other than the product flow ($\dot{P}_j$) leaving sector j as in Figure 8.4.

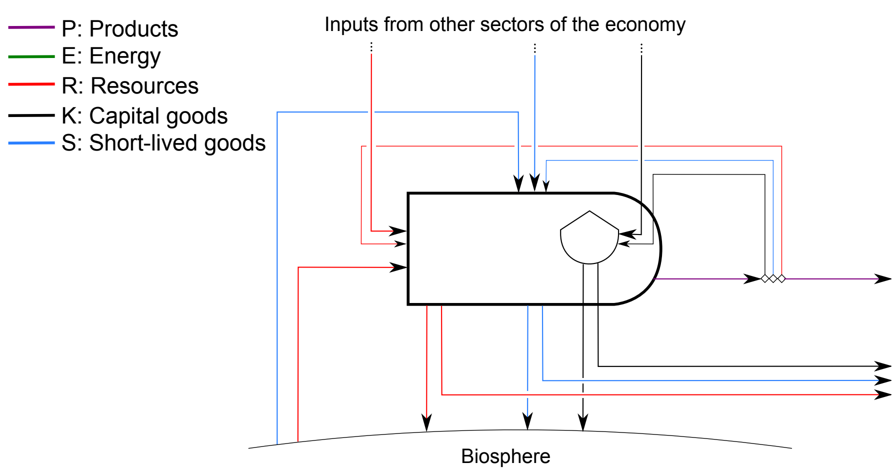

Fig. 8.4 Material flows through an economic sector with waste treatment flows to other economic sectors.

[10] The *make-use* method is sometimes also called the *supply-use* method.

Such flows violate the ‘one sector-one product’ assumption of the Leontief inversion method. Methods based on make-use tables, as developed by von Neumann [28] and Sraffa [29] are able to account for multiple products from each sector.

8.7 Are people capital stock?

There is an open question as to what sort of *stuff* should be included within the capital that accumulates in society. Should the material constituting literal *human capital*—human bodies—be included? If humans are to be included within K_1, some resource flow ($\dot{R}_{i1}$) must be converted into human capital flow ($\dot{K}_{11}$) which then adds to the stock of human capital (K_1) within society. This resource flow is food. Food itself represents a large “resource” flow and has a large associated energy content. Additionally, within industrial economies, a large amount of energy resources are channeled toward the production of food, meaning that the *embodied energy* of food may actually be several times larger than the direct energy content of the food itself.

Further questions arise. What is the “product” of society? A materialistic view might hold that the product of society is human bodies and the labor they can accomplish. If so, should the agriculture industry be accounted as part of the energy sector because its aim is to provide an energy service (labor)? For non-industrial, agrarian societies, the proportion of total energy flow comprised by manual (or draught) energy may be large. In industrialized societies, it may be negligible, however, the energy flows necessary to support agriculture may be many times larger than the food energy (and certainly many times larger than the labor energy) delivered, therefore entailing an EROI of less than unity. Agrarian societies are necessarily constrained by the fact that the energy content of the food delivered *must be* greater than the labor (and draft) energy required to produce it.

Another view is that societal capital (K_1) includes only man-made capital, i.e. items manufactured by humans, but not humans themselves. For the purposes of the framework outlined in this book, we favored the latter view. Other researchers favor the opposing view.[30] However, the framework presented in this book is general enough to encompass either point of view.

8.8 What about the Sun?

Costanza [31] included an option to consider solar energy as an input to the economy, thereby significantly increasing the energy intensity of agricultural sectors and other sectors that depend upon agricultural outputs. However later work by Costanza [26, 32] did not include solar input to the economy. Whether solar input to the economy should be considered in a materials, energy, and economic value accounting framework is probably dependent upon the objectives of the analysis.

The motivation for this particular book is primarily the effects of declining energy resource quality due to fossil fuel depletion on industrialized economies. As such, inclusion of solar flows is probably unnecessary. However, expanding the framework to include non-industrialized or agrarian societies may require accounting for solar energy flows.

There are a number of means by which solar flows can be accounted. Solar energy flows could be accounted as short-term flows ($\dot{S}$) for agricultural and forestry sectors, as well as solar thermal, solar photovoltaic, wind, ocean thermal, hydro, and biomass renewable energy production sectors. Doing so would not account for longer-term storage of solar energy used to form fossil fuels, but fossil fuels are already accounted by the energy input vector ($\mathbf{E}_0$) in the framework presented in this book.

A different approach that fully integrates solar into an energy framework is *emergy* accounting. The emergy method counts *all* material flows in terms of *em*bodied solar en*ergy*.[33, 34] The basic unit of measure is the *em*joule which is often given in terms of flows of solar energy embodied in the energy (or material)—the solar emjoule—per unit of resource, abbreviated to seJ/J for energy resources, or seJ/kg for materials. As such, even fossil fuels, e.g. coal, extracted from the earth have an embodied energy of around 67,000 seJ/J.[35]

8.9 What is endogenous?

There is debate in the literature about whether government and households (Final Consumption (1) in Figure 2.3) should be endogenous to economic models. This debate is a discussion about the appropriate analysis boundary. Costanza [32] was the first to endogenize government and households, because households provide services to the economy (labor) in exchange for wages and government provides services to the economy in exchange for taxes, both of which require energy. Costanza [32] also demonstrated that energy intensity results are a function of boundary (control volume) selection. By including government and households as sectors in the model, the variation of energy intensity is significantly reduced across all sectors of the economy.

The key energy intensity equation in this book (Equation 6.37) was derived under the assumption that Final Consumption (1) is exogenous to energy intensity calculation. However, Equation 6.37 could be re-derived to endogenize Final Consumption (1).

The total energy accounting equation for Final Consumption (1) in Figure 4.4 can be written analogously to Equations 6.15 and 6.16 as

$$\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t} = \dot{E}_{01} + \varepsilon_1 \dot{X}_{11} + \varepsilon_2 \dot{X}_{21} + \varepsilon_3 \dot{X}_{31} - \varepsilon_1 \dot{X}_1 - \left(\dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{K,1} B_{K_1} \right). \tag{8.1}$$

Furthermore, Equations 6.15 and 6.16 can be rewritten as

$$\frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} = \dot{E}_{02} + \varepsilon_1 \dot{X}_{12} + \varepsilon_2 \dot{X}_{22} + \varepsilon_3 \dot{X}_{32} - \varepsilon_2 \dot{X}_2 - \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{K,2} B_{K_2}\right) \tag{8.2}$$

and

$$\frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} = \dot{E}_{03} + \varepsilon_1 \dot{X}_{13} + \varepsilon_2 \dot{X}_{23} + \varepsilon_3 \dot{X}_{33} - \varepsilon_3 \dot{X}_3 - \left(\dot{B}_{\dot{R}_{30}} + \dot{B}_{\dot{S}_{30}} + \gamma_{K,3} B_{K_3}\right). \tag{8.3}$$

Following the derivation of Chapter 6, we can obtain an updated version of Equation 6.37:

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right], \tag{8.4}$$

wherein

- the vectors and matrices of Equations 6.18–6.26 and 6.30 have been extended to include Final Consumption (1) and
- Final Consumption (1) has been endogenized (the $\mathbf{T}_1$ term of Equation 6.37 has been subsumed into the $(\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1} \hat{\mathbf{X}}^{-1}$ term of Equation 8.4).

Future work could estimate energy intensity ($\boldsymbol{\varepsilon}$) using Equations 6.37 and 8.4 with updated economic data for a wider range of countries.[11] Doing so could provide further insight on Costanza's result [32] that endogenizing Final Consumption (1) reduces variation of energy intensity across all sectors of the economy ($\boldsymbol{\varepsilon}$).

8.10 Summary

Any project with scope as large as this will, out of necessity, leave several items undone. This chapter reviewed our list of unfinished business.

Section 8.2 called for new approaches to ascribe value to material flows between the economy and the biosphere. Thereafter, we reviewed our call for better data collection and reporting in Section 8.1.

The remainder of this chapter discussed several questions and methodological issues that arise from the framework developed in this book. Section 8.3 discussed opportunities to utilize hybrid EI-O and process methods to estimate embodied energy and energy intensity. Resource quality and co-products were discussed in Sections 8.4 and 8.5, respectively. An extension to our accounting framework necessary to account waste treatment and recycling was discussed in Section 8.6. Then, several questions were posed:

- are people capital stock?
- what about the Sun? and
- what is endogenous?

[11] Costanza's analysis [32] was conducted using US data for 1963, 1967, and 1972.

In all of the above areas, we called for additional inquiry and research into the questions raised by our framework.

The following chapter summarizes the book.

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Chapter 9
Summary

Only a crisis—actual or perceived—produces real change. When that crisis occurs, the actions that are taken depend on the ideas that are lying around. [1, p. ix]

—Milton Friedman

We said at the outset (Chapter 1) that this book would be about counting and change: counting materials, counting energy, and counting economic value, so that we can manage the upcoming energy transition. Our motivation for counting more carefully is mounting evidence that scarcity of materials, energy, and assimilation capacity within the biosphere are affecting the economies of our world, thereby affecting us all. We should know precisely *how* and *at what rate* we are using our material and energy resources today if we are to undertake the necessary transition to a more sustainable global economy.

We discussed the importance of metaphors and models: because they become a lens through which we perceive the world, we had better get them right. Historically, mainstream economists have used the *machine* metaphor to describe economies. In fact, much of mathematical economic modeling today relies upon mechanistic conceptual foundations whose roots are in Newtonian physics and The Enlightenment.[1] If your metaphor is a machine, it makes sense to analyze economies with equations that describe machines. In the mainstream, such equations are usually, but not exclusively or restrictively, developed assuming that the economic machine is an *isolated* system, with no material or energy flows between the biosphere and the economy.

In contrast, we take the strong position that economies are better-represented as open, organic organisms with active metabolisms. Economies, like organisms, exchange material, energy, and wastes with the biosphere. Because economies are, in this way, *coupled* to the biosphere, we must develop materials, energy, and value accounting frameworks *under the assumption of* and *including* vigorous and necessary interactions between the economy and the biosphere. Our use of the metabolic metaphor is anathema to many mainstream economists but embraced by many ecological economists.

To develop our accounting framework, we applied thermodynamic control volume accounting equations to economies that are *open* to their surroundings (Chapters 2–5).

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[1] The subfield of longwave economic growth modeling, as an example, uses mechanistic language to describe their equations. Jones refers to the ordinary differential equations that describe births, deaths, and the production of ideas as "laws of motion." [2, pp. 6 & 18]

Similar equations are often applied to thermodynamic machines: engines, refrigerators, heat pumps, and power plants. Our equations are unabashedly mechanistic, and, in this regard, we are similar to mainstream economics. Some ecological economists, who would otherwise be predisposed to view the economy as metabolic, would reject our use of mechanistic equations to describe the economy, in part because such equations often assume a machine that operates independently from the biosphere. Other ecological economists dismiss mainstream economics and its mechanistic equations out of hand.[2]

But, it doesn't have to be this way. We claim that it is not the mechanistic mathematical models and their equations that are the problem. Rather, it is the application of such equations to an assumed isolated system that is is worthy of criticism.

When accounting for material flows through economies (Chapter 2), we found that resources extracted from the biosphere are used for (a) build-up of capital stock within society and economic sectors, (b) production of short-term material flows among economic sectors, or (c) overcoming depreciation of capital. When accounting for both materials and energy (Chapter 3), we noted that the material and energy resources upon which economies depend are obtained from the biosphere and wastes and depreciated material return to the biosphere. In this sense, economies are "coupled" to the biosphere. When accounting for embodied energy (Chapter 4), we found that the waste heat from each sector is *additive to* the embodied energy of the products of the sector.

As we accounted for economic value (Chapter 5), we found it necessary to develop careful definitions. We pragmatically accepted the subjective theory of value espoused by mainstream economics, despite our misgivings about externalities, intergenerational equity, and mis-measurement of economic growth. Although we emphatically stop short of an "energy theory of value," we agree with many ecological economists who find it important to estimate and communicate the energy intensity of economic products (Chapter 6). With such information, consumers will be able to make better choices about the products and services they use.

In Chapter 7, we noted several implications that our framework brings to previous methods of analyzing the interactions among materials, energy, and the economy. In particular, we recommended that a physical accounting framework be adopted if we are to accurately determine both the accumulation rate of energy embodied in capital stock and the energy embodied in economic products.

Along the way, we noted several items of unfinished business that are collected in Chapter 8. Foremost is the paucity of data needed to account well for materials, energy, and economic value flows through our economies. For example, the US no longer maintains the current account data needed for the framework presented herein. And, few other countries have ever collected and disseminated required national accounts data on material flows that would allow estimation of the energy intensity of goods.

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[2] For example, Söllner pejoratively says "The prime example of physics envy and the desire to emulate the natural sciences is, of course, neoclassical economics which was explicitly and purposefully copied from classical mechanics." [3, p. 178]

So, in the end, this book is about *more than* counting and change. It is a call-to-arms of sorts for data gathering and analysis. If we are to successfully navigate the coming transitions to new materials and energy resources, we simply *must* understand how we are using materials and energy today. We cannot do so without an improved regime of data collection, dissemination, and analysis about the world's economic metabolism.

And, this book is also an attempt to reconcile mainstream and ecological economics. We hope that mainstream economists will see that it is both possible and essential to account for materials and energy flows between the economy and the biosphere. We believe there should be no reason to spurn metrics such as energy intensity that will become increasingly important into the future.

Finally, we hope ecological economists will see that application of mechanistic thermodynamic accounting equations and careful record-keeping can provide significant insights into the ways that economies interact with the biosphere, all the while living within the prevailing subjective theory of value. If we can find a little common ground, perhaps we can begin to collect the data and develop the analytical tools, metrics, and knowledge needed to make wise choices for the future.

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If we apply our minds directly and competently to the needs of the earth, then we will have begun to make fundamental and necessary changes in our minds. We will begin to understand and to mistrust and to change our wasteful economy, which markets not just the produce of the earth, but also the earth's ability to produce. We will see that beauty and utility are alike dependent upon the health of the world. But we will also see through the fads and the fashions of protest. We will see that war and oppression and pollution are not separate issues, but are aspects of the same issue. Amid the outcries for the liberation of this group or that, we will know that no person is free except in the freedom of other persons, and that man's only real freedom is to know and faithfully occupy his place—a much humbler place than we have been taught to think—in the order of creation.

—Wendell Berry. 2002. *The Art of the Commonplace: The Agrarian Essays.*
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Appendix A
Value flows for the US auto industry

This appendix describes the calculations used to estimate the value flows to and from the US Auto Industry in Chapter 5. The details of the calculations and assumptions made to calculate each of the value flows is described in Table A.1. The data sources are are described in Table A.2. These data are free and available for download from the BEA website. (See references in Table A.2.)

Table A.1 Data sources and calculations for auto industry (IOC 3361MV) example.

Value Flow	2011 USD (millions)	Data Calculations
Resources	$175,491	2011 KLEMS Total Material Intermediate Inputs into Auto Industry (IOC 3361MV). Total Material Inputs ($346,882), less self-use ($139,259) and inputs recategorized as services ($32,132).[1] Self-use Resources are defined as the two intermediate commodity inputs: Motor Vehicles, Bodies, Trailers & Parts (IOC 3361, $138,077), and Motor Vehicles (IOC 336A, $1,182).
Energy	3,637	2011 KLEMS Total Energy Intermediate Inputs into Auto Industry. The sum of the value of all "Energy" intermediate inputs.
Short-lived Goods	74,578	2011 KLEMS Total Service Intermediate Inputs into Auto Industry. Total Inputs from Service Sector ($42,446) plus Wholesale Trade and Truck Transportation from the KLEMS Material category.[1] The value of waste services that are part of this value flow is the sum of Water & Sewage (IOC 2213, $123) and Waste Management Services (IOC 5620, $381).
Capital	15,447	2011 Fixed Assets (non-residential detailed estimates). The total amount of Capital Investment by the Auto Industry ($61,260) less the purchase of capital made within the Auto Industry ($15,181, see calculation for Capital (self-use) below).
Gross Economic Output	482,269	2011 Input-Output accounts. The Use of Commodities by Industries before Redefinitions. (Producers' Prices). Total Industry Output for Industry 3361MV. Data downloaded from the Bea.gov website for the Automobile Industry (IOC 3361MV).
Resources (self-use)	133,961	2011 KLEMS Material Intermediate Inputs into Auto Industry (IOC 3361MV) that are goods produced by the Auto Industry. The sum of Motor Vehicles, Bodies, Trailers & Parts (IOC 336A, $138,077) and Motor Vehicles (3361, $1,182).
Capital (self-use)	15,181	2011 Fixed Assets (non-residential detailed estimates). Fixed Assets that appear to be capital made from within the Automobile Industry: Autos, Internal combustion engines, Light trucks (including utility vehicles), Other trucks, buses and truck trailers, Custom software, & Own account software.[2]
Net Economic Output	333,127	2011 Input-Output accounts. The Use of Commodities by Industries before Redefinitions. (Producers' Prices). Total Industry Output, less Self-Use of Capital ($15,181, calculated above) and less Self-Use of Resources (IOC 3361MV used by IOC 3361MV, $133,961).[3]

[1] Two commodities categorized in the KLEMS data as “Material” intermediate inputs are “Wholesale Trade” (IOC 4200, $26,580) and “Truck Transportation.” (IOC 4840, $5,552). For our calculations, these commodities were recategorized as “Services.” The value of the flows in the table reflects the fact that these dollar amounts were subtracted from this “Resource” flow and added to “Short-lived Goods.”

[2] To confirm that these fixed asset types (particularly “Custom Software” and “Own account software”) actually originated from the Auto Industry (that is, that they are truly self-made capital), the I-O “Make” table was consulted to ensure that these commodities were made by the Auto Industry.

[3] Note that this self-use of resources is slightly lower than the one used to calculate the total of self-use Resources ($139,259) that was subtracted from total Material inputs to arrive at a figure for Resources from all other sectors (above). This is because the KLEMS data, like the Fixed Asset data, are more detailed than the standard I-O accounts and may contain judgments and trend estimates. For example, in 2011, the KLEMS total intermediate inputs to the auto industry is higher than the amount from the Use table: $392,965 vs.$368,476.

Table A.2 BEA data sources.

Dataset	Details
Use Tables	Annual Input-Output accounts. These are the primary industry data collected by the BEA. The Use tables present what industries use what commodities as intermediate goods, and the value of the commodities that end up as final goods. The values are computed at Producers prices. That is, the value includes the sales price, plus sales and excise taxes, less any subsidies. This table provides a link from Industry data to National data. The sum of all final output is a measure of National GDP. An introduction to these data is available.[1] The tables can be found online.[2]
KLEMS	(K-capital, L-labor, E-energy, M-materials, and S-purchased services) refers to broad categories of intermediate inputs that are consumed by industries in their production of goods and services.[3] The detailed estimates of intermediate inputs of an industry are classified into one of three cost categories: energy (E), materials (M), and purchased services (S). The labor cost category (L) includes an industrys compensation to labor from value added, and the capital cost category (K) includes the industrys gross operating surplus plus taxes on production and imports less subsidies. The 1998–2011 KLEMS tables can be found online.[4]
Fixed Assets	Fixed Assets Table. Detailed Fixed Assets Table. Categorizes capital investment by industry into three categories: equipment, structure, and software. To obtain an estimate of self-use of capital, we went to the more detailed tables, which are less reliable than the standard tables. The BEA notes on the detailed tables indicates that "the more detailed estimates are more likely to be based on judgmental trends, on trends in the higher level aggregate, or on less reliable source data." [5, Table 2.5]

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Appendix B
Infinite series representation of energy intensity

In this appendix, we show that the EI-O method accounts for the infinite recursion of energy demands for production.

The single-sector economy of Figures 2.3, 3.4, 4.3, and 5.4 can be re-drawn as shown in Figure B.1.

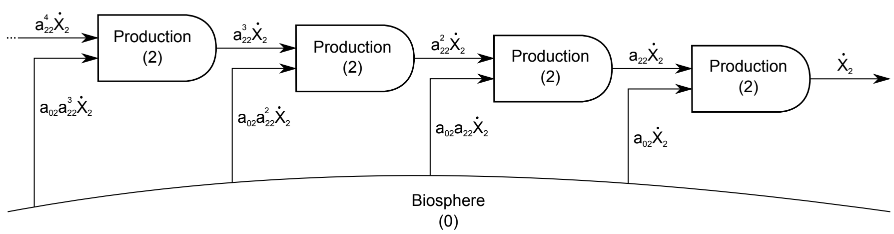

Fig. B.1 Process flows in a single-sector economy.

If we consider the Biosphere (0) to be producing a valuable product, namely energy, we can say

$$\dot{X}_{02} = \dot{E}_{02} \tag{B.1}$$

and

$$a_{02} \equiv \frac{\dot{E}_{02}}{\dot{X}_2}. \tag{B.2}$$

The economy produces output at a rate of $\dot{X}_2$, but it requires energy from the biosphere ($\dot{E}_{02} = a_{02}\dot{X}_2$) to do so. The economy also consumes a fraction of its own gross output ($\dot{X}_{22} = a_{22}\dot{X}_2$). To produce $a_{22}\dot{X}_2$, the economy requires an additional $a_{02}a_{22}\dot{X}_2$ of energy from the biosphere. The sum of all direct energy required for the economy to produce at a rate of $\dot{X}_2$ ($\dot{E}_{demand,tot}$) is an infinite sum.

$$\dot{E}_{demand,tot} = a_{02}\dot{X}_2 + a_{02}a_{22}\dot{X}_2 + a_{02}a_{22}^2\dot{X}_2 + \ldots \tag{B.3}$$

The energy intensity of the economy (ε_2) is

$$\varepsilon_2 = \frac{\dot{E}_{demand,tot}}{\dot{X}_2} = a_{02}(1 + a_{22} + a_{22}^2 + \ldots) = a_{02} \sum_{n=0}^{\infty} a_{22}^n. \tag{B.4}$$

Realizing that $\sum_{n=0}^{\infty} a_{22}^n = \frac{1}{1-a_{22}}$ and $a_{02} = \frac{\dot{E}_{02}}{\dot{X}_2}$ gives

$$\varepsilon_2 = (1 - a_{22})^{-1} \dot{X}^{-1} \dot{E}_{02}. \tag{B.5}$$

Accounting for the differences between scalar and matrix equations and neglecting energy flows from society to the economy ($\dot{T}_{12} = 0$), accumulation of embodied energy in the economy $\left(\frac{\mathrm{d}B_2}{\mathrm{d}t} = 0\right)$, and physical depreciation $\left(\gamma_{B_2} B_2 = 0\right)$, Equations 6.37 and B.5 are identical, indicating that the EI-O approach accounts for the infinite recursion of energy demand by the economy.

References

Appendix C
Proof of Equation 6.31

We begin with a restatement of Equation 6.31.

$$\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I}) \tag{6.31}$$

We expand the matrices to obtain

$$\begin{bmatrix} \dot{X}_{22} & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} \end{bmatrix} - \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} = \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \begin{bmatrix} a_{22}-1 & a_{32} \\ a_{23} & a_{33}-1 \end{bmatrix}. \tag{C.1}$$

Subtracting and multiplying matrices gives

$$\begin{bmatrix} \dot{X}_{22}-\dot{X}_2 & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33}-\dot{X}_3 \end{bmatrix} = \begin{bmatrix} \dot{X}_2 a_{22}-\dot{X}_2 & \dot{X}_2 a_{32} \\ \dot{X}_3 a_{23} & \dot{X}_3 a_{33}-\dot{X}_3 \end{bmatrix}. \tag{C.2}$$

Using $\dot{X}_j a_{ij} = \dot{X}_{ij}$ (see Equation 6.3) gives

$$\begin{bmatrix} \dot{X}_{22}-\dot{X}_2 & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33}-\dot{X}_3 \end{bmatrix} = \begin{bmatrix} \dot{X}_{22}-\dot{X}_2 & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33}-\dot{X}_3 \end{bmatrix} \tag{C.3}$$

to complete the proof.

Appendix D
Estimating the Input-Output matrix (A)

Using Equation 6.31, which is proved in Appendix C

$$\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I}); \tag{6.31}$$

we can derive an expression for estimating the Input-Output matrix ($\mathbf{A}$) given sector outputs ($\hat{\mathbf{X}}$) and the transaction matrix ($\mathbf{X}_t$). Premultiplying both sides of Equation 6.31 by $\hat{\mathbf{X}}^{-1}$ gives

$$\hat{\mathbf{X}}^{-1}\left(\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}}\right) = \mathbf{A}^{\mathrm{T}} - \mathbf{I} \tag{D.1}$$

Further rearranging gives

$$\mathbf{A}^{\mathrm{T}} = \hat{\mathbf{X}}^{-1}\left(\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}}\right) + \mathbf{I}, \tag{D.2}$$

$$\mathbf{A}^{\mathrm{T}} = \hat{\mathbf{X}}^{-1}\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}}^{-1}\hat{\mathbf{X}} + \mathbf{I}, \tag{D.3}$$

$$\mathbf{A}^{\mathrm{T}} = \hat{\mathbf{X}}^{-1}\mathbf{X}_t^{\mathrm{T}} - \mathbf{I} + \mathbf{I}, \tag{D.4}$$

$$\mathbf{A}^{\mathrm{T}} = \hat{\mathbf{X}}^{-1}\mathbf{X}_t^{\mathrm{T}}, \tag{D.5}$$

and

$$\mathbf{A} = \mathbf{X}_t\left(\hat{\mathbf{X}}^{-1}\right)^{\mathrm{T}}. \tag{D.6}$$

Both $\hat{\mathbf{X}}$ and $\hat{\mathbf{X}}^{-1}$ are diagonal matrices. Therefore, $\left(\hat{\mathbf{X}}^{-1}\right)^{\mathrm{T}} = \hat{\mathbf{X}}^{-1}$, and Equation D.6 becomes

$$\mathbf{A} = \mathbf{X}_t\hat{\mathbf{X}}^{-1}. \tag{D.7}$$

Expanding the matrices of Equation D.7 gives

$$\mathbf{A} = \begin{bmatrix} \dot{X}_{11} & \dot{X}_{12} & \cdots \\ \dot{X}_{21} & \dot{X}_{22} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \frac{1}{\dot{X}_1} & 0 & \cdots \\ 0 & \frac{1}{\dot{X}_2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix} = \begin{bmatrix} \frac{\dot{X}_{11}}{\dot{X}_1} & \frac{\dot{X}_{12}}{\dot{X}_2} & \cdots \\ \frac{\dot{X}_{21}}{\dot{X}_1} & \frac{\dot{X}_{22}}{\dot{X}_2} & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}, \tag{D.8}$$

as expected given the definition of the Input-Output ratio (a) in Equation 6.3:

$$a_{ij} \equiv \frac{\dot{X}_{ij}}{\dot{X}_j}. \tag{6.3}$$

Thus, Equation D.7 provides a method of estimating the Input-Output matrix ($\mathbf{A}$) using the transaction matrix ($\mathbf{X}_t$) and sector outputs ($\hat{\mathbf{X}}$).

Appendix E
Column vs. row vectors in energy intensity equations

In this manuscript, we choose to define energy intensity ($\boldsymbol{\varepsilon}$) and energy input ($\mathbf{E}_0$ and $\mathbf{T}_1$) as a column vectors (see Equations 6.23, 6.20, and 6.21, respectively), because it natural to solve a system of equations for a column vector rather than a row vector. And, Equation 6.17 could not be written as neatly if $\boldsymbol{\varepsilon}$ and $\mathbf{E}_0$ were row vectors.

In contrast, the EI-O literature (see, e.g., [1] and [2]) defines energy intensity and energy input as row vectors. The row vs. column difference is manifest in the appearance of the energy intensity matrix equation.

To demonstrate that our column vector formulation is equivalent to the literature's row vector formulation, this appendix derives a column vector version of the energy intensity equation that is often found in the literature. The point of comparison is Casler.[1] Casler's energy intensity (Equation 6) was derived from row vectors as[1]

$$\boldsymbol{\varepsilon} = \mathbf{E}\hat{\mathbf{X}}^{-1}(\mathbf{I} - \mathbf{A})^{-1}. \tag{E.1}$$

We begin with Equations 3 and 4 from Casler [1], converted to overdot notation for rates.

$$\varepsilon_1 \dot{X}_{11} + \varepsilon_2 \dot{X}_{21} = \varepsilon_1 \dot{X}_1 \tag{E.2}$$

$$\varepsilon_1 \dot{X}_{12} + \varepsilon_2 \dot{X}_{22} + \dot{E}_{02} = \varepsilon_2 \dot{X}_2 \tag{E.3}$$

Adding an $\dot{E}_{01}$ term[2] and utilizing matrix notation with column vectors (instead of row vectors) gives

$$\begin{bmatrix} \dot{X}_{11} & \dot{X}_{21} \\ \dot{X}_{12} & \dot{X}_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \tag{E.4}$$

Substituting $\dot{X}_{ij} = a_{ij}\dot{X}_j$ (from Equation 6.3) gives

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[1] Equation E.1 is written according to the variable conventions in this manuscript. The literal Equation 6 in Casler [1] is $\varepsilon = E\hat{X}^{-1}(I - A)^{-1}$.

[2] Note that $\dot{E}_{01} = 0$ for Casler [1], so $\dot{E}_{01}$ can be included without changing Equation E.2.

$$\begin{bmatrix} a_{11}\dot{X}_1 & a_{21}\dot{X}_1 \\ a_{12}\dot{X}_2 & a_{22}\dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \tag{E.5}$$

Expanding Equation E.5 gives

$$\begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \tag{E.6}$$

With the definitions of $\hat{\mathbf{X}}$, $\mathbf{A}$, $\boldsymbol{\varepsilon}$, and $\mathbf{E}_0$ from Equations 6.25, 6.30, 6.20, and 6.23, respectively, we can rewrite Equation E.6 as

$$\hat{\mathbf{X}}\mathbf{A}^{\mathrm{T}}\boldsymbol{\varepsilon} + \mathbf{E}_0 = \hat{\mathbf{X}}\boldsymbol{\varepsilon}. \tag{E.7}$$

Solving for $\boldsymbol{\varepsilon}$ gives

$$\boldsymbol{\varepsilon} = \left(\mathbf{I} - \mathbf{A}^{\mathrm{T}}\right)^{-1}\hat{\mathbf{X}}^{-1}\mathbf{E}_0. \tag{E.8}$$

The differences between Equations E.1 and E.8 are due to the choice of row vectors (for Equation E.1) or column vectors (for Equation E.8) only. Note that Equation E.8 is similar to Equation 6.37. A detailed discussion of the differences between Equations E.8 and 6.37 can be found in Section 7.2.

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Glossary

ATP	Adenosine Triphosphate
BEA	Bureau of Economic Analysis, US Department of Commerce (http://www.bea.gov)
DEC	Direct Energy Conversion
EIA	Energy Information Administration
EI-O	Energy Input-Output
EIOLCA	Economic Input-Output Life Cycle Assessment (http://www.eiolca.net)
EW-MFA	Economy-Wide Materials Flow Accounts
GDP	Gross Domestic Product
GER	Gross Energy Ratio
GHG	Greenhouse Gas
IE	Industrial Ecology
I-O	Input-Output
KLEMS	Capital (K), Labor (L), Energy (E), Materials (M), and Services (S)
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
NAICS	North American Industry Classification System
NEA	Net Energy Analysis

OICA	International Organization of Motor Vehicle Manufacturers
PERKS	Product, Energy, Resource, Capital (K), and Short-lived material diagram
UN	United Nations
US	United States

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