Lecture Notes in Energy 26

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Beyond GDP

National Accounting in the Age of Resource Depletion

Springer

Lecture Notes in Energy

Volume 26

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ISSN 2195-1284 ISSN 2195-1292 (electronic)
Lecture Notes in Energy
ISBN 978-3-319-12819-1 ISBN 978-3-319-12820-7 (eBook)
DOI 10.1007/978-3-319-12820-7

Library of Congress Control Number: 2015931624

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

“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.

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, pp. 259–261]

—John Godfrey Saxe

In 1992, the Union of Concerned Scientists published the *World Scientists' Warning to Humanity*,[1] an appeal for humanity to "bring environmentally damaging activities under control to restore and protect the integrity of the earth's systems we depend on" [2]. The *Warning* stated that "[h]uman beings and the natural world are on a collision course," warned of "[h]eedless exploitation" of natural resources, and explained that "[d]estructive pressure" on water, soil, and atmosphere "put at serious risk the future that we wish for human society. . . ." More than two decades later, 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 [3].

In contrast, the vast majority of economists and policy makers predict that the 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

[1] The *World Scientists' Warning to Humanity* was signed by some 1700 of the world's leading scientists, including the majority of Nobel laureates in the sciences.

the poorest nations are "accelerating markedly" [4]. They expect GDP per capita and living standards to grow continuously into the foreseeable future, even under the most pessimistic assumptions [4, p. 170]. The Organisation for Economic Co-operation and Development (OECD), for example, forecasts an average global GDP growth rate of approximately 2 % per year for the next several decades [5, 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 declining quality of life. Economists observe the stock of manufactured capital growing, and growing increasingly efficient, and foresee continued improvement in the quality of life.

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 availablility of natural capital, but ignore the multiplying power of manufactured capital. Conversely, economists place their faith in the ability of manufactured capital to continually increase production rates, but ignore constraints of natural capital.

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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Acknowledgments

We extend our thanks and appreciation to. . .

- Frederick Soddy, Lesley White, Eugene Ayres, Charles Scarlott, Nicholas Georgescu-Roegen, Herman Daly, and Kenneth Boulding for being so far ahead of the curve,
- Fred Cottrell, Peter Chapman, Gerald Leach, Malcolm Slesser, John Peet, Cutler Cleveland, Robert Costanza, and Charles Hall for showing the way on energy-economy interactions,
- Clark W. Bullard III, Robert Herendeen, and Stephen Casler for leading the way with energy input–output analysis,
- David Wasshausen, Erich Strassner, and Dennis Fixler at the US Bureau of Economic Analysis for clear explanations and wise guidance in using the industry and national accounts,
- Kurt Schaefer (Calvin College) for insightful comments on the discussion of theories of value,
- Charlie Barnhart, Adam Brandt, Carey King, David Murphy, Sally Benson, Pat Bodger, Nate Hagens, Hannes Kunz, Rembrandt Koppelaar, John Peet and Susan Krumdieck for many, many enlightening and engaging conversations and insightful comments on all matters energy related,
- John Wertz (Calvin College) for insightful comments on the metabolism metaphor, and
- Janet Weathers and Maria Steblay for important editorial comments on early drafts of the manuscript.

Without the support and encouragement of our spouses (Tracy Kuperus, Patricia Carbajales-Dale, and Lawrence Haney) and families, none of this would have been possible. We are eternally grateful!

Matthew Kuperus Heun
Michael Carbajales-Dale
Becky Roselius Haney

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

One of the first calls for integrated and comprehensive reporting of environmental-economic data, including natural and manufactured capital, came from the Brundtland Commission (1983–1987), which 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 highlighted the need 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, Chap. 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 edition [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 accounts 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 (NAS), 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 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]. Five years later, 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 expressly 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 believe that the benefits of accounting for the environment by including both natural and manufactured capital will be worth the political efforts needed to resume the practice. After reading this book, we hope you will agree.

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Roman

a	stock of apples [-]
a	input output ratio, mixed units
a_0	LINEX fitting parameter [-]
$\dot{a}$	apple flow rate [apples/s]
A	technology augmentation factor [-]
$\mathbf{A}$	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]
$\boldsymbol{B}_{\dot{W}}$	column vector of waste flows [MJ/year]
c_t	LINEX fitting parameter [-]
e	indexed energy [-]
E	direct energy [MJ]
E_s	elasticity of substitution [-]
E_s	elasticity of supply [-]
$\dot{E}$	direct energy flow rate [MJ/year]
$\mathbf{E}_0$	column vector of direct energy inputs from the biosphere [MJ/year]
$EROI$	Energy return on (energy) invested [-]
f_E	energy cost share [-]
k	indexed capital stock [-]
K	mass of capital goods [kg]
$\dot{K}$	capital goods mass flow rate [kg/year]
l	indexed labor [-]
m	mass [kg]
n	number of sectors in the economy
p	a system property
P	ecosystem photosynthetic energy production rate [J/year]
P	price [$]
P	mass of products [kg]

$\dot{P}$ product mass flow rate [kg]
Q quantity of production or demand [various]
q_0 proportionality constant [W/kg$^{3/4}$]
$\dot{Q}$ energy consumption rate in Kleiber's Law [W]
$\dot{Q}$ 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 [\$/year]
$\mathbf{X}_t$ transaction matrix [\$/year]
$\hat{\boldsymbol{X}}$ diagonal matrix of sector outputs in mixed units [\$/year or MJ/year]
y indexed economic output [-]

Greek

α ratio of inflowing capital stock rate to capital stock [1/year]
α output elasticity of capital [-]
$\hat{\boldsymbol{\alpha}}$ diagonal matrix of ratios of incoming flows of energy embodied in capital to total energy embodied in capital stock [1/year]
β output elasticity of labor [-]
δ_{ij} Kronecker delta
ε energy intensity [MJ/\$]
$\boldsymbol{\varepsilon}$ column vector of sector energy intensities [MJ/\$]
$\eta_{\dot{R}}$ resource effciency [kg/kg]
γ output elasticity of energy [-]
γ depreciation rate [1/year]
$\hat{\boldsymbol{\gamma}}$ diagonal matrix of depreciation rates [1/year]
ρ_k ratio of indexed capital to the average of indexed labor and energy [-]
ρ_l ratio of indexed labor to indexed energy [-]
$\rho_{\dot{S}}$ 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)

a	pertaining to making available to society
B	pertaining to embodied energy
c	pertaining to consumption
$dest$	destruction
gen	generation
i	energy type
i	economic sector index
in	inflow
j	economic sector index
k	economic sector index
K	pertaining to capital stock
out	outflow
soc	society
t	transaction
$waste$	pertaining to waste

Chapter 1
Introduction: The End of an Era

> *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

The world is entering in a new economic era. There is widespread agreement that economic growth in mature economies is unlikely reach the rates seen in the twentieth century ever again. Indeed, over the last 50 years, Fig. 1.1 shows that the economic growth rate for the Organisation for Economic Co-operation and Development (OECD) member states has fallen precipitously. The long-term forecast from the OECD is that mature economies will grow only 1.5–2.0 % annually over the next 50 years. Similarly, the US Congressional Budget Office forecasts an average growth rate of 2.2 % for the US economy from 2018 to 2024 [2, 3].

The stagnation of economic growth for mature economies (as measured by annual percentage change in gross domestic product (GDP) per capita) is even more striking when compared to the explosive growth of emerging economies. Figure 1.1 shows economic growth rates for China and India since 1965. The trendline of the OECD is clearly downward, while the trendline of Chinese and Indian growth is clearly upward. Indeed, the OECD itself says that the "combined GDP of China and India was 33 % of the OECD in 2010 (on a PPP basis), but is expected to rise to 73 % by 2060" [2, p. 214]. Slowing OECD growth illustrates that mature economies are hitting a wall.

Is stalled economic growth a problem? Most analysts believe it is. History suggests that GDP growth raises living standards and human well-being, as measured by various indices. Julian Simon's volume, *The State of Humanity*, catalogues the great improvements in life span, housing, environment, food quality and availability, water cleanliness, etc. that have coincided with economic growth over the last three centuries [5].

Thus, stalled economic growth can be expected to be accompanied by slowing or reversing of the upward trend in quality of living. The economic establishment's

M. K. Heun et al., *Beyond GDP,* Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_1

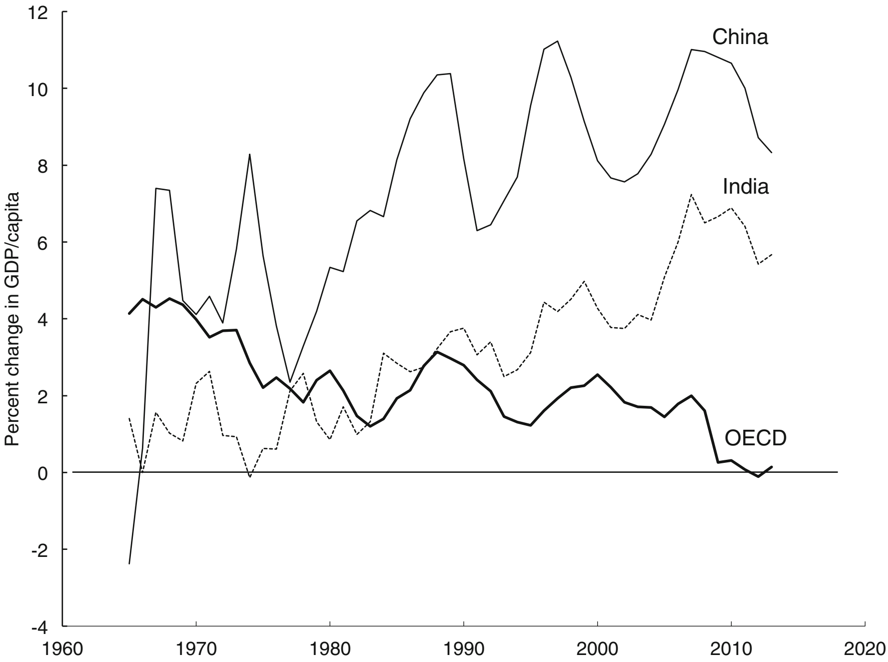

Fig. 1.1 Five-year trailing averages of economic growth, 1965–2013 [4]

prescription to avoid backsliding of quality of life and human well-being is continued economic growth by (nearly) any means necessary. And, at the moment, continued economic growth appears to be the only politically viable policy instrument.

What do economists believe is causing the slowdown of economic growth in mature economies?

Mainstream economic theory considers economic growth to be driven by four factors: (1) increasing labor utilization as a result of increasing the number of workers or worker hours, (2) increasing human capital through improved education levels, skill levels, or health, (3) increasing capital/labor ratio because of expanded capital investments, and (4) increasing worker productivity due to technological innovation. In recent years, OECD economies have deteriorated on all four factors. Economist Tyler Cowen argues that large productivity gains through innovation have permanently plateaued leading to a "great stagnation" in economic growth [6]. The Cato Institute's economic growth specialist, Brink Lindsey, suggests that growth has permanently stalled, because *all four* of the primary drivers of economic growth have plateaued; hours worked, worker skill level, and the amount of capital invested per worker have reached a low, slow, steady state and are unlikely to improve [7].

The Cowen and Lindsey analyses represent mainstream explanations for the growth slowdown, and they are based squarely on the assumption that technology augments capital and labor, the inputs to economic growth.[1] If economic slowdown is caused by anything besides technology, capital, or labor, mainstream economic analysis cannot provide any assistance in either diagnosing the problem or prescribing a cure.

We believe that the mainstream approach is too narrow and that there may be other factors that cause economic slowdown. In particular, we contend that binding constraints on economic growth may arise from at least two sources: material inputs from the biosphere and the energy to run the "economic engine."

Our approach may be outside the economic mainstream, but we are not alone. There are several interdisciplinary fields (industrial ecology, ecological economics, biophysical economics, and materials flow analysis) where the relationship between the economy and the biosphere is a natural feature of the intellectual landscape, and assessment of patterns of economic growth and economic downturns includes consideration of biophysical limits. This emerging paradigm is taking shape with the leadership of theorists such as Robert Ayres [8], Kenneth Boulding [9], Roger Boyd [10], Robert Costanza [11], Herman Daly [12], Blair Fix [13], Charles Hall [14], Steven Kopits [15], Marina Fischer-Kowalski [16], and others. Throughout this book, we will refer to this alternative approach as a "biophysical" approach to the economy.

Those who adopt the biophysical approach to economics have consistently raised the concern that material and energy constraints could lead to the end of the era wherein economic growth could be achieved simply by increasing consumption. And the explanatory power of the biophysical paradigm is becoming increasingly difficult to ignore. With startling prescience, Robert Ayers predicted in 1996 that this era would end in a great recession within 20 years:

> It is difficult to say when, or how, the current economic growth "system" will collapse; it has proved more resilient than many would have predicted. But, unless job-creating growth can be sharply accelerated the choice facing governments is stark: either there will be very sharp and painful cuts in entitlements and social welfare or there will be a financial crisis, probably sudden (like the onset of the Great Depression) and probably within twenty years. The traditional Keynesian job creation mechanisms are ineffective or inapplicable, while trade liberalization and "globalization" are making the unemployment problem worse, not better. Western democracies are, like the passengers on the Titanic, heading "full steam ahead" into extremely dangerous waters. Icy reality lies dead ahead, already dimly visible through the fog. Collision is inevitable, unless we change course sharply. [17]

---

[1] The mainstream model for economic growth is encapsulated in the Cobb–Douglas production function, which takes the mathematical form

$$y = Ak^{\alpha}l^{1-\alpha},$$

where y is the economic output, A is the technological progress, k is the capital stock, l is the labor, α is the factor share of capital, and $1 - \alpha$ is the factor share for labor.

1.1 (Mis)measuring the Wealth of Nations

An ironic consequence of economists taking biophysical reality seriously is a return to the roots of classical economic theory. At some point between Adam Smith and the present day, economic attention veered away from the nature and causes of the *wealth* of nations toward stimulating and counting the *income* of nations. Today's mainstream quantification of economic health, GDP, measures only income, a *flow* of money (currency) in units of, say, \$/year. Many now raise the concern that the economic mainstream's focus solely on GDP mismeasures economic health and reveals little about a nation's *wealth*. The missing piece in mainstream economic theory is a biosphysical understanding of the role of a nation's *capital*.

A nation's wealth consists of physical *stock*, including both manufactured and natural capital. The word "capital" can be used in many ways, usually referring to assets of one form or another: financial capital, natural capital, human capital, social capital, physical capital, and manufactured capital, to name a few. In this book, we use the term "manufactured capital" or simply "capital" to indicate things such as machines, buildings, roads, vehicles, and computers, all physical items used in and necessary for the production process. Manufactured capital is not normally used up during production of goods and rendering of services, although it depreciates over time. As manufactured capital depreciates, future income is put at risk. We use the term "natural capital" to include oil, coal, and natural gas deposits. But, clean air and water, soils, forests, and natural areas[2] are counted as natural capital too. Natural capital depletes when consumed (e.g., fossil fuels) or degrades when soils are mistreated, clean air, and water are polluted, or wetlands are contaminated. In a manner similar to manufactured capital, as natural capital dwindles, the future capacity for income generation dwindles.

Both manufactured and natural capital (as well as human, social, and financial capital) provide the services an economy uses to produce income. To provide a constant or increasing standard of living into the future, each generation must forego some consumption to invest in maintenance, repair, and replacement of its capital for the future. From Robinson Crusoe to the US, every economy must answer this question: How much of our income should be consumed today and how much should be saved for tomorrow?

Now, let us turn back to GDP as a quantification of economic health. GDP is an estimate of the *income* of an economy. Because firms gain income from the consumption of natural and manufactured capital, estimates of GDP include these transactions. Thus, depletion of natural capital and consumption of manufactured capital (both stocks) are counted as "income" (a flow) in national accounts, and both are "good" for the economy. The focus on GDP as the indicator of economic health creates a perverse incentive to consume the very stocks upon which economic health

---

[2] Natural areas provide ecosystem services such as water purification, carbon sequestration, and erosion control.

depends. There is no incentive to manage a nation's stock of natural capital for the future because depletion of natural capital increases GDP today.

There are many examples of the perverse accounting that arises from the use of GDP to (mis)measure economic health. When Lake Erie turned toxic for several days in 2014 due to algae blooms caused by agricultural runoff, GDP grew by the spending on bottled water and goods and services to repair the damage. Clearcutting of forests improves GDP in the short run but eliminates opportunities for recreation-related income in the future. Sickness adds the cost of health care to GDP.

Using GDP as the measure of economic health mismeasures economic health, because it blurs the distinction between stocks and flows and masks the fundamental tradeoff between today and tomorrow. Economic expansion (as measured by GDP) beyond the rate at which stocks can be replenished deprives the economy of the wealth it needs to generate future income! And, continued economic expansion (in GDP terms) is likely to cause the economy to reach biophysical limits in terms of both the stock of nonrenewable resources supplied by the biosphere and the capacity of the biosphere to assimilate all of society's pollution and physical waste.

Thus, both stocks and flows of both natural and manufactured capital are important, and both should be accounted and reported in addition to GDP in national accounts. National accounts gather, evaluate, and disseminate data on economic activity at the national level. The UN's international standards for national accounting, aptly named the System of National Accounts (SNA), recommend accounting for natural capital that is both owned (by firms or the government) and used in production. However, not all countries base their national accounts on the SNA (the US, China, and France, e.g., do not), and not all natural capital is "owned." Clean air and water are not accounted in the SNA, for example. The US ignores natural capital outright.

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) [18, p. 415]. This predilection results in national accounting, particularly in the US, that collects and analyzes a trove of data to produce a robust *income statement* of financial flows within the economy (GDP); yet it mostly ignores the data needed to produce a similarly rigorous *balance sheet* of assets (stocks) that measure the value of a nation's wealth, including manufactured and natural capital. It counts all forms of productive capital (natural, human, and manufactured). By focusing nearly exclusively on income, today's national accounting is blind to an important aspect of the modern world: 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.

1.2 Nations at Risk

The risk to a nation's living standards from ignoring the effect of economic activity on the nation's balance sheet is borne out in the UN's *Inclusive Wealth Report 2012* [19]. This report sums together all forms of productive capital (natural, human, and manufactured) as a measure of wealth for each nation. This biophysical and social approach to economic measurement reveals that several nations' wealth is currently declining even as their GDP grows. For the years 1990–2008, Saudi Arabia, Russia, Venezuela, South Africa, and Nigeria had declining wealth coincident with income growth, thereby diminishing the productive capacity of future generations in order to support consumption by the current generation. Saudi Arabia's GDP per capita grew at 0.4 % per year, while its wealth declined at a rate of 1.1 % per year, and Nigeria's GDP per capita grew at 2.5 % per year, while its wealth declined at a rate of 1.8 % per year. According to the *Inclusive Wealth Report*, 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 wealth grew at only 0.7 % per year [19, p. 44].

Because society (mis)measures economic health by focusing nearly completely on GDP, countries adopt policies that encourage consumption. Such policies lead to high flow-to-stock ratios, and economies with these policies are more likely to deplete natural resources faster due to unsustainable natural resource extraction rates. The end result is that we can consume manufactured and natural capital (our wealth) in the hopes of increasing today's income. As Robert Ayres foresaw, this is not a sustainable approach.

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 (both natural and manufactured) and the state of that capital. Many important questions, such as "How might an economy be affected as an increasing share of production is directed toward replacing degraded ecosystem services," and others enumerated in the next chapter (in Sect. 2.3) are unanswerable without both.

But, how could we do better? How could we structure a biophysical approach to national accounting? We must first understand the biosphysical economy. We must go *beyond GDP*!

1.3 Understanding the Biophysical Economy

As mentioned above, very little of the discourse about mature economy slowdown in mainstream economic circles involves biophysical factors.[3] Mainstream economics

[3] In this context, we are using the term "biophysical factors" to indicate any factor related to the extraction, transport, processing, manipulation, and disposal of the physical (as opposed to financial) manifestation of any material or energy resource in the economy.

considers biophysical factors to be *exogenous* to the economy.[4]

Arguably, the most important (but certainly not the only) biophysical factor vis-à-vis the economy is energy. If we are to understand how exogenous factors can cause economic slowdown and, conversely, drive economic growth, we would do well to understand how energy operates in the economy. Thus, we first discuss the correlation between energy consumption and economic activity (Sect. 1.3.1). Then, we show how economic demands for energy and materials are related to important stocks of raw materials and energy resources in the biosphere (Sect. 1.3.2) and the stocks of manufactured capital in the economy (Sect. 1.3.3).

1.3.1 Coupling Between Energy and the Economy

All manufactured goods are made and services provided from raw materials that have been manipulated, processed, transported, or otherwise transformed using energy. Indeed, energy consumption and economy activity are highly correlated, as Cleveland et al. [11] showed in a 1984 cover story for *Science* (see Fig. 1.2).

Because of the high correlation between energy consumption and economic activity, it stands to reason that energy shortage relative to demand will hinder economic activity. Of course, there are degrees of shortage. In extreme cases, and in the absence of price controls, goods become hard to find and prices spike as observed in the US during 1970s oil crisis. (See Fig. 1.3).

In mild cases, shortage of any good relative to demand leads to rising prices, even when goods remain available. For example, Fig. 1.4 shows oil prices (line) and worldwide oil production (vertical bars) before, during, and after the Great Recession. Demand for oil increased steadily in the early 2000s due to worldwide economic growth, and production mostly kept pace through early 2005. However, demand continued to increase while production flatlined from early 2005 through late 2007, leading to a steep price increase. From late 2007 through the end of 2008, the small amount of remaining reserve oil production capacity was brought online, but it was too little, too late. Prices spiked above $130/barrel in mid-2007. The Great Recession reduced demand slightly (by about 2 Mb/day) and the price collapsed to about $40/barrel. Thereafter, demand and price rose to their previous levels as the world pulled out of the Great Recession. In the years since 2008, oil production has risen slightly past the previous record highs as additional production capacity has come online.

[4] Of course, mainstream economics discusses *prices* of raw materials, goods, and services. And, to the extent that biophysical factors affect prices, it could be said that mainstream economic discussions involve biophysical factors. However, biophysical factors are rarely acknowledged as causal for establishing the prices of goods and services and the raw materials of which they are comprised.

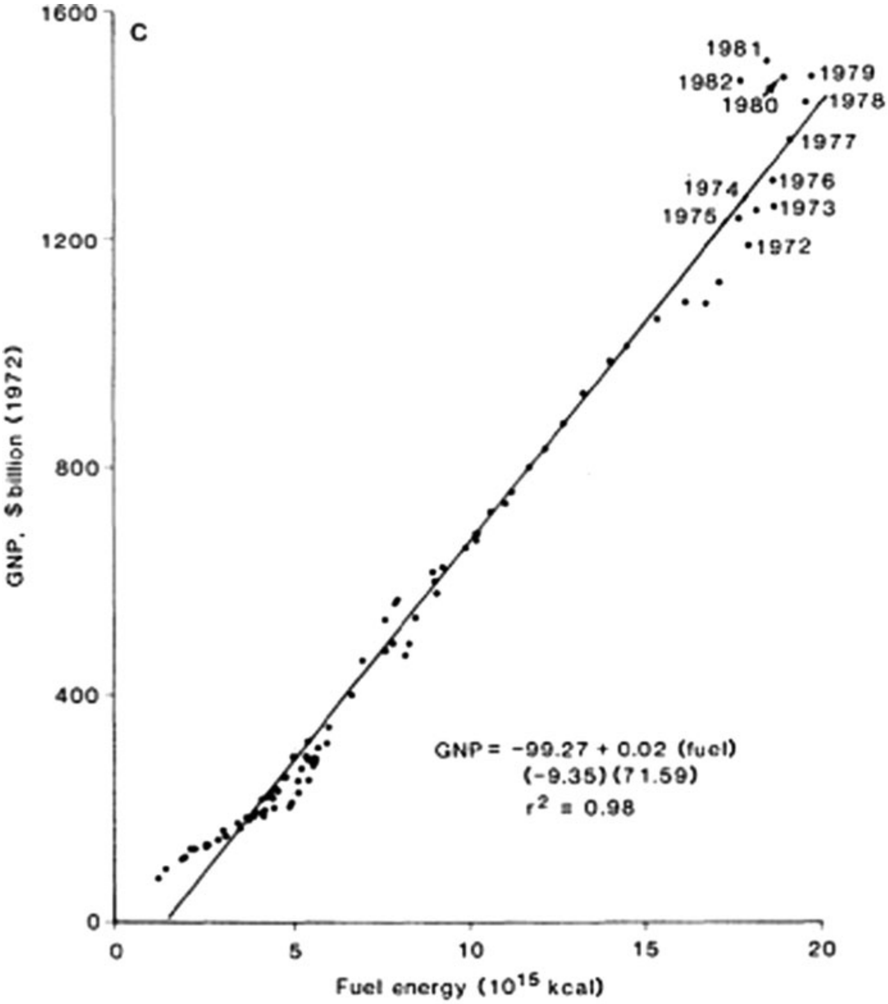

Fig. 1.2 Correlation between energy consumption and economic activity in the US from 1890 to 1982. From Cleveland et al. [11]. Reprinted with permission from AAAS

In both cases (1970s and 2000s), significant slowing of economic activity (recessions) followed the oil shortages and prices spikes. These were not isolated cases. Hamilton noted that 10 of the 11 US postwar recessions involved the same pattern [21, p. 45]. It is clear that there is a correlation between energy consumption and economic activity.

But, what are the dynamics that cause economic slowdowns to follow energy price spikes? When prices rise faster than the cost of production, the profit motive should, according to economic theory, induce new firms to enter the market and established firms to increase production. However, the timing of supply and demand

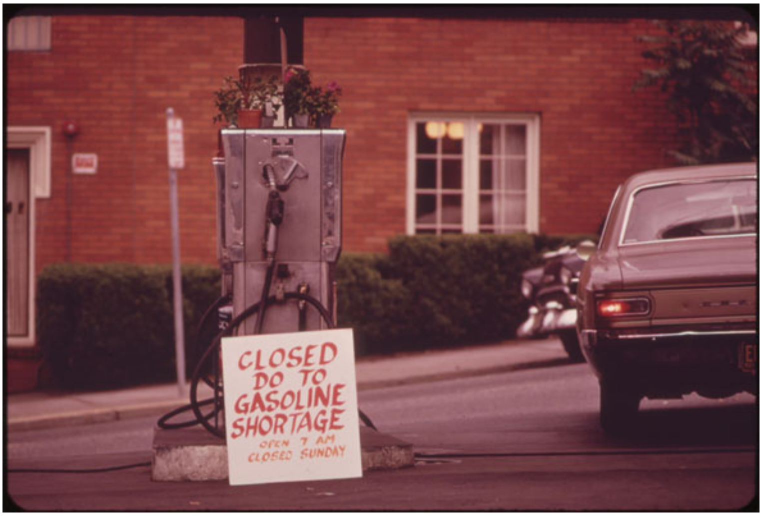

Fig. 1.3 Gasoline shortages in 1973. [20]

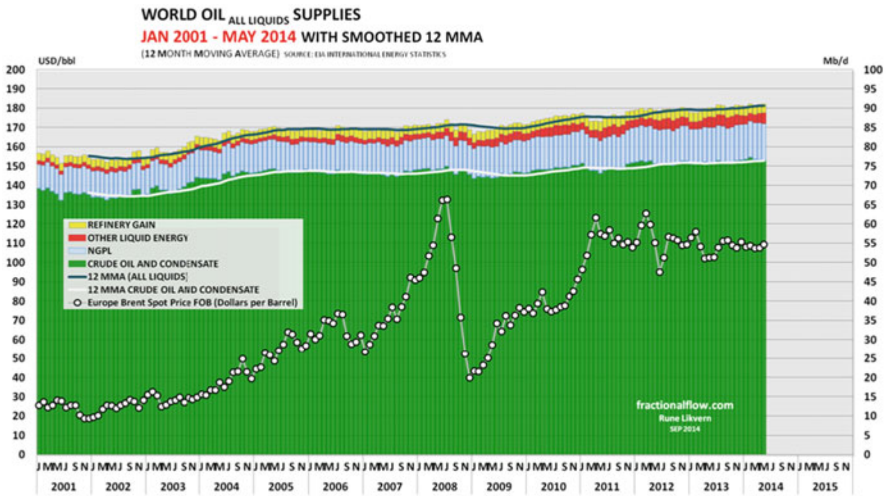

Fig. 1.4 Oil prices (*left* axis, data .2points) and production (*right* axis, vertical bars). © *2014 Rune Likvern, http://www.fractionalflow.com. Used by permission*

events is crucial. If firms cannot or do not increase production to meet demand, prices will remain elevated. Even without increased production, falling demand will bring prices back to earth.

In terms of energy, and oil in particular, the *rate* at which production can be increased is of the utmost importance, and there are physical and technological limits. Consider this series of thought experiments: we know that increasing the worldwide oil production rate by, say, 20 % involves finding additional oil deposits, drilling additional wells, installing new pumps, and expanding transport and delivery infrastructure worldwide. In 1960, would it have been possible to achieve such an increase over a span of 5 years? Yes. In fact, the worldwide oil production rate increased at a faster rate during the 1960s. There was enough oil in the ground, and the economy could absorb the demand for additional steel, vehicles, energy, etc., required to emplace the required infrastructure. The impact on the financial system was minimal, because the cost of materials, equipment, labor, and energy was spread out over a long-enough timeframe (in this thought experiment, 5 years). But, in 1960 could the oil production rate have been increased by 20 % in 3 months? No. There was enough oil in the ground, but it would have been practically impossible to manufacture, transport, and put into service all the necessary capital in such a short time. Biophysical constraints limit the rate at which oil production can be increased. What about 2 years? Probably not. It might have been physically possible, but the financial cost would have been too much to bear over such a short timeframe, and the profit motive would evaporate.

This thought experiment shows that time constraints, layered upon physical and technological constraints, are the ties that bind the financial to the biophysical. Put another way, time constraints are the point at which the economy becomes coupled to the biosphere.

In economic terms, biophysical constraints reduce the price elasticity of supply: the percent change in supply for a 1 % change in price during a given period of time.[5] Figure 1.4 shows that a *very large* percentage change in the price of oil was required to increase production by only a *very small* percentage in the 2005–2008 timeframe. World oil production rose from 78 million barrels per day to 86 million barrels per day, an increase of only 10 % [22]. However, the inflation-adjusted price of oil increased 260 %, from around \$35 to a peak of \$126 per barrel (in constant 2010 USD). Thus, the supply of oil is nearly perfectly price inelastic; its short-run (2005–2008) price elasticity of supply is only 0.04.[6] Since 2010, the price of oil has remained over \$80 per barrel, suggesting that production cannot increase quickly enough relative to demand to bring prices back down to historical levels. Persistently high prices for such an important commodity suggest very real limits to production; supply is constrained relative to demand.

---

5 The mathematical definition of elasticity of supply (E_s) is

$$E_s \equiv \frac{\frac{1}{Q}\frac{\partial Q}{\partial t}}{\frac{1}{P}\frac{\partial P}{\partial t}} ,$$

where Q is quantity of production, P is price, and t is time.

6 That is, a 1 % change in the oil price will generate only a 0.04 % increase in oil supply. A price elasticity of 0.04 is extremely low (inelastic). For comparison, agricultural output is also considered fairly price inelastic in the short-run, but Pandey, et al. estimate the short-run (2-year) price elasticity of supply of Australian agricultural output to be around 0.30 [23, p. 215].

In these circumstances, oil supply is said to be very *inelastic* (unresponsive) to price. The observed price inelasticity is caused by the biophysical limits to oil production discussed above. Nothing, not even historically high prices, can induce producers to increase the rate of supply in the short term (say, a 5-year time span), because it is physically impossible to do so. In 2008, the world was running at full oil production capacity, but economies demanded more! Because it was physically impossible to meet that demand, prices spiked.

But, what caused the recession that followed? Recently, a few authors have found that *energy cost share*, the fraction of GDP spent on energy, is an explanatory variable for these dynamics.[7] To our knowledge, Bashmakov was the first to identify a long-term sustainable range for energy cost share in mature economies [24]. He also showed that developed economies can sustain high total energy cost share for a short period of time (possibly 2–3 years) before recessionary pressures destroy energy demand,[8] stimulate energy efficiency,[9] reduce energy prices, and return total energy cost share to its long-term sustainable range. On the other hand, reduction of total energy cost share below a lower bound provides economic stimulus, increases energy demand, provides upward pressure on energy prices, and returns energy cost share to its long-term sustainable range. Bashmakov speculates that "energy affordability thresholds and behavioral constants" are responsible for the stable range of energy cost share over many decades [24, p. 3585]. The long-term stable range for economy-wide energy cost share (which includes all forms of energy, including oil, natural gas, and electricity) is 9–11 % for the OECD. For oil only, Murphy and Hall found that the oil cost share threshold that correlates with the US recessions is about 5.5 % [25].

The picture emerging from this research shows that the cost share of energy in the economy (and, perhaps more narrowly, oil cost share in the economy) is an important factor in stimulating or restraining economic growth, despite its small numerical value (typically, less than 10 %).[10] It appears that the economy-biosphere system has a built-in feedback mechanism that enforces alignment between biophysical limits and the economy.

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[7] Mathematically, energy cost share (f_E) is defined as

$$f_E \equiv \frac{1}{GDP} \sum_i P_i Q_i \ ,$$

where the subscript i indicates types of energy (electricity, gasoline, natural gas, etc.), P indicates the price of energy, Q indicates the quantity of energy purchased within the economy, and GDP is gross domestic product.

[8] Note that "destruction of energy demand" is accomplished through recession in the short run.

[9] Like increasing oil production, increasing energy efficiency also has physical and technological limits. Improving energy efficiency is a medium- to long-term process.

[10] Embarking on an economic growth path appears to reduce the energy cost share in an economy from very high values (indicating that nearly all economic activity is focused on procuring energy) to small values that remain within a stable range. For example, Sweden's energy cost share has stabilized at 12 % since 1970, although it was nearly 100 % in 1800 [26].

This result may be somewhat surprising in light of mainstream economic theory, which ascribes economic importance based on financial cost share, not biophysical factors. Indeed, the cost share of energy in mature economies is low, and viewing energy as relatively unimportant is justified if one's view of "importance" is limited to financial information only. But, many have noted that the physical importance of energy to the economy far exceeds its cost share [27]. And, as discussed above, because the economy is coupled to the biophysical world through time constraints (as manifest by the low price elasticity of energy supply), the physical importance of energy far exceeds its financial importance. Ironically, low energy cost share is precisely the condition that has allowed economies to be incredibly productive over the last century.

The connection between energy and the economy may be difficult to see, but, eventually, it becomes impossible to ignore.

1.3.2 Stalled Growth Is Related to Nonrenewable Stocks

Given the tight coupling between the biosphyical world and the economy, especially regarding energy, discussed in Sect. 1.3.1 above, it is prudent to consider the important economic role of material and energy stocks in the biosphere.

The best-first principle [28] indicates that the economy will extract the easiest-to-obtain stocks of mineral and energy resources first. "Best" and "easiest" can be assessed in several ways, but physical factors that make a resource "best" or "easiest to extract" eventually manifest as lower cost. For example, inexpensive-to-obtain West Texas crude oil was extracted before expensive-to-obtain offshore oil. Surface deposits of gold and diamonds are exhausted before subsurface veins and kimberlite pipes are exploited. High-purity mineral deposits are exploited before low-purity deposits. As a result, it becomes more "difficult" to continually increase extraction rates as time proceeds. To continue with our energy example, historical oil production trends reflect these realities. Through time, the annual rate of increase of worldwide oil production has declined from 7.2 %/year to 1.7 %/year (see Fig. 1.5).

It is important to realize that it takes energy to make energy available to society. Oil production requires energy for the ongoing operation of pumps, transportation of crude to the refinery, refinement of crude to useable petroleum products, and transportation of refined products to consumers and firms. In addition, it takes energy to manufacture the wells, pumps, tankers, pipelines, and refineries used in oil production and distribution. Furthermore, it takes energy to use energy. The economy uses energy to manufacture the machines (vehicles, mostly) that consume refined oil products.

Application of the best-first principle to the energy production process indicates that it will take more energy to make the same rate of energy available to society as nonrenewable energy resources in the biosphere are depleted. The metric that measures the energy impacts of the best-first principle is energy return on investment ($EROI_{soc}$), the ratio of energy provided to society by the energy consumed in

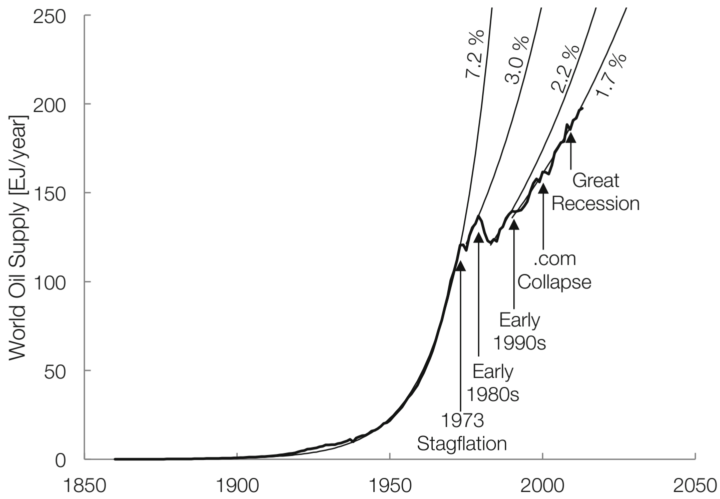

Fig. 1.5 Slowing growth in world oil supply. Data from [29, Fig. A.2, p. 274]. © *Gail Tverberg, http://www.ourfiniteworld.com*. Used by permission

making it available.[11] As energy resources in the biosphere are depleted, the best-first principle entails that $EROI_{soc}$ will decline. Indeed it has.

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 50 years [30, 31, 32]. Turning again to our oil example, $EROI_{soc}$ for production of US oil has declined from a value of 23 in the 1950s to 10 in 2007 [33, Fig. 2]. $EROI_{soc}$ for production of oil worldwide has declined from a value of 35 in 1999 to 18 in 2006 [34, Fig. 1]. In other words, it takes about twice as much energy today than in years past to make a barrel of oil available to society.

Decreasing $EROI_{soc}$ means that less *net energy* is available for downstream uses, given the same gross energy production. If the downward tendency of net energy availability outpaces technological advances in energy efficiency, there may be negative effects on economic output. The need to increase productive capacity

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[11] Energy return on investment ($EROI_{soc}$) at the societal level is defined as

$$EROI_{soc} \equiv \frac{\dot{E}_a}{\dot{E}_c} \, ,$$

where $\dot{E}_a$ is the rate of energy made available to society in MJ/year and $\dot{E}_c$ is the rate of energy consumed in the energy production process in MJ/year. Note that this definition of $EROI_{soc}$ is flow based. Other definitions of *EROI* are accounted over the full lifetime of a project, e.g., comparing the lifetime electricity generation of a wind turbine to the energy required in its manufacture (including extraction of raw materials), installation, operation, and decommission.

merely to maintain the current level of production has been termed the "Red Queen syndrome;"[12] we must run faster and faster just to stay in place [35].

Economic impacts of declining $EROI_{soc}$ are observable over the past few decades. Both Heun and de Wit [36] and King and Hall [37] show that declining $EROI_{soc}$ correlates with higher prices for oil, because declining $EROI_{soc}$ provides upward pressure on production costs, and therefore, prices as time proceeds.

Given constant "effort" for resource extraction, the best-first principle can also indicate that the additional physical effort required to extract increasingly marginal resources will lead to decreased extraction rates. The early nineteenth century economist David Ricardo applied this principle to the theory of land rents. As population increases, the demand for food will increase. Because arable land is not reproducible, less-productive land will be utilized for crops. These factors lead to increasing profits accruing to owners of the best land.

In the energy markets, recent increases in unconventional oil production (from tar sands and shale) have been made possible by new extraction and refining technologies. But most unconventional oil production is accompanied by the same or lower $EROI_{soc}$ compared to conventional crude oil production.

Furthermore, similar to farming marginal land, today's unconventional oil comes from "marginal" locations and is more expensive to produce than the crude of yesteryear. Consequently, oil prices must remain high for unconventional production to remain financially feasible into the foreseeable future. Unfortunately, Sect. 1.3.1 showed that high energy prices can lead to high energy cost share in the economy and recessionary pressure.

The fact that shortages of crude oil provide incentives for technological advancements that bring unconventional production online appears, at first glace, to be a good thing. However, energy substitutions are beneficial to society in the long run only when the $EROI_{soc}$ of the substitute is equal to or higher than the original. Thus, the benefits of unconventional oils are modest, at best, when the high financial and energy costs of production are considered.

That said, transitions to new sources of energy will be a feature of the economy in the age of resource depletion. But, there is evidence of limits to energy substitution at the macroeconomic level. Pelli, in a study of 21 countries found that clean[13] and dirty[14] inputs to electricity production are complementary (as opposed to substitutable) [38]. 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,

[12] Of course, in any deck of cards there are two Red Queens. In Sect. 8.2.2, we discuss the need to increasingly divert production to maintain levels of capital stock.

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

[14] Coal, petroleum, natural gas, and other gasses.

> 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. [38, p. 25]

In a meta-analysis of 15 papers that studied the economic evidence for macrosubstitutability among factors of production (materials, capital, labor, and energy), de Wit et al. [39] found that the elasticity of substitution was below unity for all combinations of factors of production. Furthermore, they argue that

> [because all of the] results show elasticity of substitution below unity, none of the factor inputs are perfectly substitutable, and all tend toward complementarity in varying degrees. Such results suggest that transitions from one production or consumption structure to another can be disruptive and that the transitions need to be modeled dynamically to the extent possible. [39, p. 8]

The challenges of energy substitutions are highlighted when examining the financial situation of oil producers. The EIA indicated in July 2014 that the free cash flow[15] of oil producers was negative, despite the increase in oil production rate and (at the time) continued high prices [40]. In the second half of 2014 oil prices fell, and several articles confirmed the earlier EIA report of financial difficulty for oil producers and their financiers [41–43]. This situation implies that capital investments are unproductive to date at current oil prices. It remains to be seen how oil producers can continue advancing the oil production rate (which implies capital investment) while their free cash flow is negative. One possible cure for negative free cash flow is higher oil prices. But higher oil prices will lead to increasing energy cost share, and we saw in Sect. 1.3.1 that high energy cost share provides recessionary pressure.

All of this comes about simply because it is more physically "difficult," and, as a consequence, more financially expensive to extract oil today than it was just a few decades ago. It is more difficult to obtain oil today because we have depleted the stocks of easy-to-obtain crude oil from the biosphere. And, the remaining stocks are either lower quality (e.g., shale) or further away (e.g., deeper offshore).

We contend that similar dynamics will apply to any nonrenewable material (e.g., copper, soil and timber) or energy stock (natural gas and hydro dam sites) in the biosphere for which substitution is difficult. Using oil as our example, we observe that stocks of natural capital, especially energy resources, have significant economic implications. Both the declining *quantity* and the diminishing *quality* of remaining nonrenewable biosphere stocks are contributing to the slowdown of growth in mature economies discussed at the outset of this chapter.

Stocks of another sort also play a role in the slowdown of growth experienced by mature economies, because they are important drivers of material and energy consumption. In the next section, we turn our attention away from the biosphere toward the economy and its stock of capital.

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[15] Free cash flow is defined as the cash produced by a firm's operations less the cost of expanding its asset base. Free cash flow is different from profit, and is thought to be a more-reliable indicator of the ability of a firm to produce profit.

1.3.3 Stalled Growth Is Related to Capital Stock

Capital is extremely valuable and, in most cases, essential to production processes: machines reduce per-unit costs of production; buildings provide space to work and protection for capital; roads provide networks for vehicular transport of raw materials, finished goods, and capital itself; and computers enhance the efficiency of workers and enable technological breakthroughs. There are several types of capital flows to and from its stock in the economy. We use the term "emplacement" to denote a flow of capital into the economy, for example, when a new machine is put into service, when a new building is constructed, or when a new road is opened. "Depreciation" is normal wear-and-tear experienced by capital, a type of outflow of capital from the economy. Financial depreciation involves the write-off of a percentage of the value of capital each year. Physical depreciation involves wear and tear of parts within or sections of the capital. Financial depreciation usually occurs faster than physical depreciation. "Maintenance" is servicing of capital to overcome the effects of physical depreciation. "Disposal" is the physical outflow of capital from the economy to the biosphere upon removal from service. Capital "formation" is the rate of net addition to capital stock in the economy, the difference between inflows and outflows during a time interval. Traditionally, stocks and flows of capital are measured in currency units, $ and $/year, respectively. However, we argue later (Sect. 8.2) that a physical basis for capital accounting is also warranted.

It is important to note that it takes materials and energy to manufacture and emplace capital at its point of use. Furthermore, once emplaced, capital consumes energy to process raw materials into intermediate and finished products and for its own maintenance. The energy required to manufacture and emplace capital (including all upstream processes) is called *embodied* energy. In addition to capital, energy is embodied in all manufactured materials and products.[16] The ratio of energy embodied in products to their price is the energy *intensity* of output (ε, in units of J/$).[17] Both embodied energy and energy intensity are key metrics for understanding the economy. To first approximation, energy embodied in capital provides an estimate of the energy needed for replacement. The distribution of energy intensity across products and sectors provides a picture of energy demands caused by consumption.

Most capital (especially machines) is considerably more expensive than the individual products it makes. So, it takes significant financial resources (relative to sales) to purchase and emplace capital. Capital is so beneficial (i.e., productive in the economic sense), that firms pursue and obtain debt financing to cover large capital expenses. In the case of public goods like roads, bridges, and utilities, governments pursue debt financing via municipal bonds. The long-term financial obligations associated with capital financing mean that the capital is expected to be in service for at least the repayment period of the debt, usually much longer.

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[16] See Chap. 5 for more details on embodied energy.

[17] See Chap. 7 for more details on energy intensity.

The long-term commitment to capital and production means that emplacement of capital is itself a bond, a claim on future raw material and energy *consumption*. And, it is an assurance of raw material and energy *extraction* from the biosphere for many years to come. Furthermore, extant productive capital stock cannot be fed just any material or energy; capital is designed to work with only certain types of materials and energy. An auto body panel stamping machine is designed to form steel, perhaps even a specific grade or alloy of steel; feeding plastic will not do. The machine likely runs on electricity; feeding gasoline will not do.

Thus, the stock of capital in the economy is an important driver of not only the rate but also the type of material and energy flows from the biosphere. The emplacement of productive capital "locks in" demand for specific types of materials and energy for a long time to come. As such, long-term commitments associated with emplaced capital provide limits to the rate at which society can effect transitions to different raw materials and energy sources. Again, we observe tight coupling between the economy and the biosphere!

Given the discussion in Sect. 1.3.2 regarding the economic dynamics of biophysical limits to raw material and energy extraction, we see that expansion of an economy's capital stock may increase GDP in the short run, but it also "locks in" future material and energy demands from the biosphere. These "locked in" demands bring the economy closer to the biophysical extraction limits that will eventually lead to economic slowdown.

> Paradoxically, and contrasting with mainstream policy prescriptions, expansion of the stock of capital in the economy can contribute to the ultimate slowdown of economic growth.

1.4 Consumption-Driven Solutions Are Unsustainable

In Sect. 1.3.3 above, we noted that today's consumption-enhancing policies have the side-effect of increasing many material and energy flow rates into the economy. Thus, today's policies also hasten the day when we reach binding biophysical constraints due to resource depletion. Unfortunately, biophysical limits are not included in the mainstream economic thinking and modeling that informs today's policy decisions.[18] Three factors, in combination, are vitally important but nearly always ignored: (1) the economy is tightly coupled to the biosphere, (2) there are physical and technological limits to the rate at which materials and energy can be extracted from the biosphere, and (3) today's emplacement of manufactured capital locks in tomorrow's material and energy demands for both operation and maintenance of that capital. Set against

[18] More on the problematic nature of this oversight can be found in Chap. 2.

the backdrop of Sect. 1.3, we see that consumption-enhancing policies are ineffective because of the biophysical limits that ultimately constrain the scale of the economy.

In short, the economic analyses that support consumption-driven policies are incomplete, and consumption-driven economic growth is ultimately unsustainable.

Adoption of consumption-enhancing policies when society is already encountering resource depletion constraints will result in see-saw economic performance. In fact, we may have already entered a regime of boom–bust economic dynamics, because of a binding constraint for oil extraction rate as discussed in Sect. 1.3. In the face of see-saw dynamics, it is difficult to make wise and insightful long-term investment or policy decisions, because you are perpetually recovering from the most-recent bust.

In the age of resource depletion, we need to move beyond GDP. These dynamics should cause us to measure and report the material and energy demands that products and capital stock make upon the biosphere. We should know these factors in *physical* as well as financial terms, for the constraints of the physical world lead to problems in the economy. These data should be available routinely from a centralized location.

This is the end of an era. In mature economies, consumption–enhancing economic policies can no longer guarantee growth of living standards and well-being. But, the mainstream is blind to what should be done instead.

1.5 Change Is Needed!

The fact that we (as a society) do not include exogenous, biophysical factors in economic decision making indicates that we do not fully understand how the real economy operates. Society is ignorant of the role that natural and manufactured[19] capital together play in both sustaining today's economy and constraining future economic prospects and choices. At present, markets are virtually the only tool at our disposal to help us understand the characteristics of the real economy. What benefits do markets provide? Markets are, at least in economic theory, extremely efficient allocators of resources, provided that all relevant information is available to market participants. Mainstream economic theory holds that prices are the mechanism by which signals of value are communicated to sellers and buyers: sellers receive information about how goods are valued by consumers, and buyers receive information about the costs of input materials accrued by producers.

In the age of resource depletion, are price signals sufficient to indicate shortages, especially of important and difficult-to-substitute resources? It appears that some signals are getting through. Heun and de Wit [36] showed that scarcity (as indicated by low $EROI_{soc}$) correlates with higher oil prices. And, higher prices spur energy efficiency improvements [44].

However, the market's price mechanism may not be enough. We showed in Sect. 1.3.1 that the physical importance of scarce and difficult-to-substitute

[19] Manufactured capital presupposes the existence of sufficient levels of human and social capital.

resources (e.g., oil) far exceeds cost share in the economy, suggesting that prices alone cannot provide comprehensive signals of importance to producers and consumers. Consequently, producers and consumers participate in the market with incomplete information. This is a serious problem, because the allocative efficiency of markets is predicated upon correct and complete information being available to all market participants.

Furthermore, a good must be owned before it can be sold. Thus, prices cannot be set and market value cannot be determined for goods that are not considered "property," such as clean water, clean air, and other "ecosystem services." In addition, today's markets are simply incapable of deciding important issues such as the optimal scale (size) of the economy relative to the biosphere (see Sect. 2.2.4.).

In the age of resource depletion, the allocative efficiency of markets is attractive. Indeed, life would be better if the markets could simply and automatically shift supply and demand away from binding biophysical constraints when they are encountered. But, lack of information in today's markets leads us to argue that they are not up to the task. Today's markets are a poor choice for allocative decisions about scarce and difficult-to-substitute resources (such as oil) or nonproperty goods (such as clean air, clean water, and other ecosystem services).

What additional information would be helpful? We contend that detailed information about energy, embodied energy, and energy intensity would be a good place to start. We, as a society, routinely account and publish data on energy flow rates only.[20] We do not, however, routinely update energy *intensity* estimates (ε) and, therefore, we have little idea of where energy is embodied in our capital stock and in the products we consume. Furthermore, when energy intensity (ε) of products is estimated, it does not account for the energy embodied in our stock of capital and is therefore in error.[21]

We suggest that all of this information (economic, material, and energy indicators) should be collated by a single agency and reported from a single location. Doing so will provide convenience and consistency and indicate the interconnectness of the economy and the biosphere to both policymakers and researchers.

We understand that these suggested changes will be both revolutionary in scope and challenging to implement politically. Therefore, we would do well to be sure of our direction. We would do well to put ourselves on rigorous and firm theoretical ground *before* proceeding toward implementation. The role of this book is to provide just that: a rigorous theoretical framework for a better system of national accounts, one that goes beyond GDP and one that is relevant to the age of resource depletion.

Until these crucial pieces of information are routinely available in a centralized location within a rigorous theoretical framework, society will be unable to properly frame and conceptualize the "problem" of "stalling" growth. Until this information is available to markets, investment, consumption, and policy decisions cannot lead to socially optimal outcomes.

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[20] Energy consumption rates are routinely published by the US Energy Information Agency (EIA) and the International Energy Agency (IEA).

[21] See Sect. 8.2 for our suggested remedy.

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Chapter 2
Accounting for the Wealth of Nations

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

—George E. P. Box

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

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

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

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

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

M. K. Heun et al., *Beyond GDP*, Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_2

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

2.1 Three Eras

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

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

2.1.1 Era of Abundance

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

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

[3] Approximately, 1973–2003.

[4] From 2003 to the present.

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

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

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

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

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

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

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

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

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

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

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

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

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

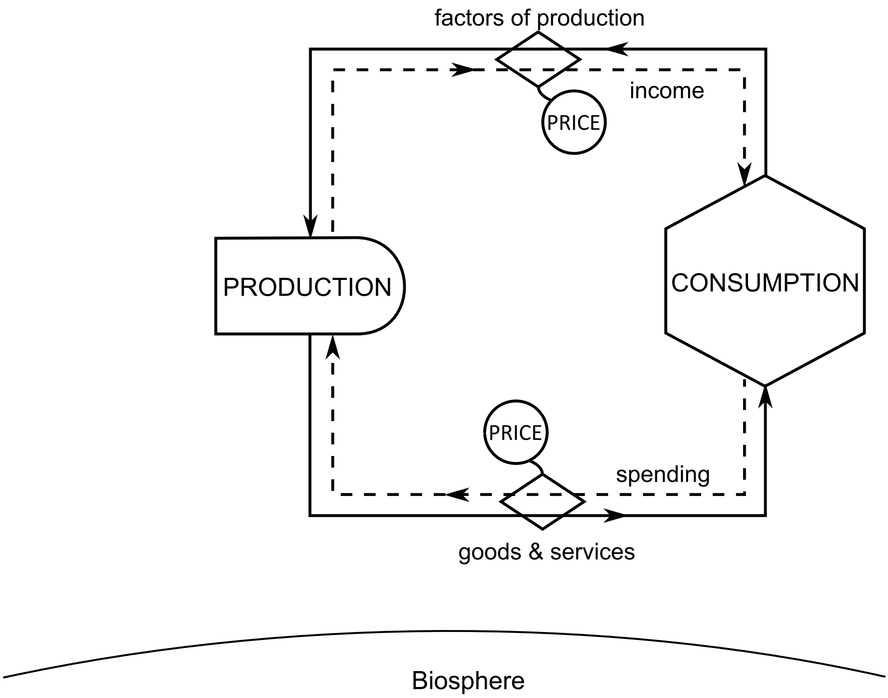

Fig. 2.1 In the traditional economic model, the economy is represented as a circular flow of goods and services between two sectors. Producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers.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

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

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

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

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

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

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

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

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

2.1.2 Era of Energy Constraints

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

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

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

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

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

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

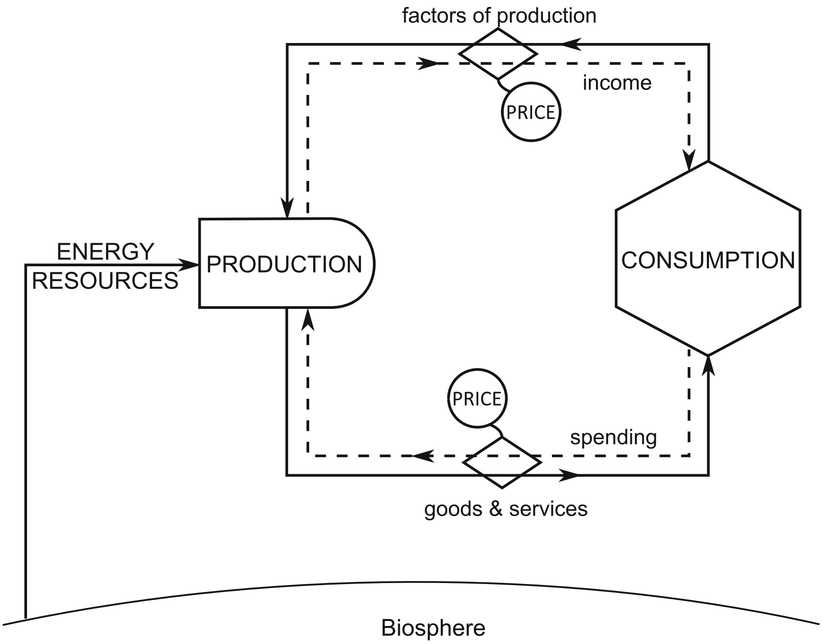

Fig. 2.2 The machine model of the economy includes flows of energy into the economy from the biosphere. This may be considered a perpetual motion machine of the second kind

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The answer arrived with the age of resource depletion.

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

2.1.3 Age of Resource Depletion

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

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

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

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

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

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

2.2 The Economy is Society's Metabolism

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

1. Intake material and energy from the biosphere;
2. Exchange materials, energy, and information internally;
3. Discharge material and energy wastes to the biosphere;
4. Are affected by energetic costs;
5. Are affected nonlinearly by scarcity in the face of low substitutability;
6. Can change nonlinearly or in discrete steps with the potential for structural transformation;
7. Accumulate embodied energy in material stocks; and
8. Maintain organizational structure despite changes in their environment.[24]

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

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

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

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

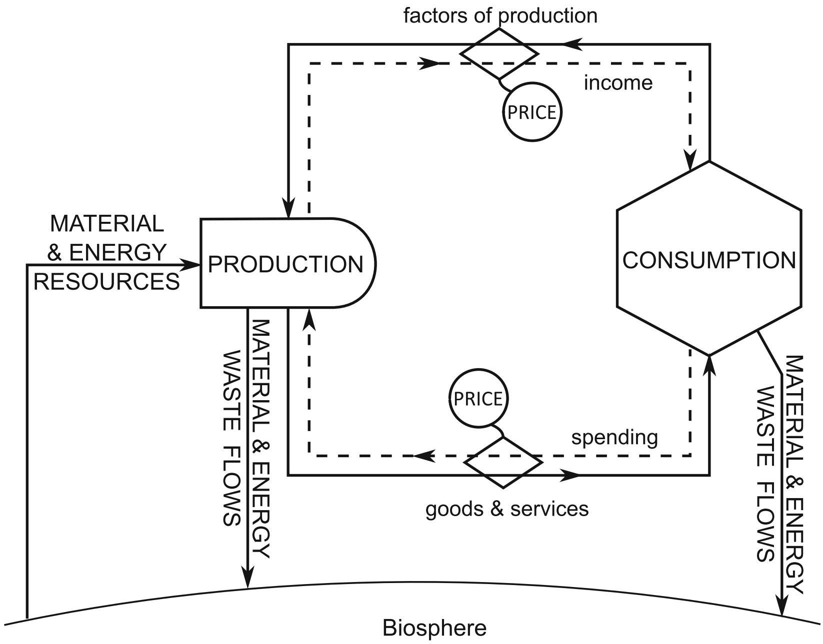

Fig. 2.3 The metabolism model provides a comprehensive view of the economy, fully consistent with the laws of thermodynamics, including degraded resources (waste) expelled to the environment as a necessary consequence of economic activity

Although we are not the first to suggest the metabolism metaphor for the economy, we believe that the metabolism metaphor is underutilized on both practical and theoretical levels. On the practical level, the metabolism metaphor is underutilized because SNAs, to date, are built upon the clockwork metaphor and traditional model for the economy (Sect. 2.1.2). This book attempts to correct that oversight by using the metabolism metaphor to develop a rigorous theoretical framework for comprehensive national accounting (see Chaps. 3–7). On a theoretical level, the metabolism metaphor is underutilized, because, many researchers (with the exception of the authors listed in Footnote 23) use the metabolism metaphor merely as framing device for analyses of raw material flows into the economy for the purpose of understanding stocks of raw materials in the biosphere.[26] Some who employ the metabolism

[26] The field most closely associated with the metabolism metaphor is materials flow analysis (MFA). To be fair, materials flow analysts clearly acknowledge that materials flow into the economy (minerals and ores, especially), in part, for the purpose of building up stocks of technical infrastructure (buildings), livestock, and people [38, p. 116]. However, there is little emphasis on quantifying *levels* of material stock in Materials *Flow* Analysis, as its name implies. In fact, the equations in MFA [38, Eq. 1] are almost always written as

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

metaphor tend to focus little attention on capital stock within the economy itself. In effect, this is the same oversight as national accounting: under-appreciation of the important role of capital in determining material and energy demand for its emplacement, use, maintenance, and replacement.

It becomes a vicious cycle. By not accounting for capital stock on a physical basis in national accounting, society is unable to appreciate the important physical role that capital stock plays in the economy (Sect. 1.3.3). Because society under-appreciates the physical role of capital stock in the economy, there is little urgency to begin accounting for manufactured capital on a physical (rather than financial) basis.

We think that a deeper understanding of the metabolism metaphor can serve to both highlight the important physical roles of both resource extraction and manufactured capital stock and provide the basis for a rigorous theoretical framework for comprehensive national accounting. In the following sections, we deepen the metabolism metaphor by considering anabolism (capital formation), catabolism (energy production), autophagy (recycling), and issues of scale.[27] Thereafter, we summarize the benefits of the metabolism metaphor for national accounting.

2.2.1 Anabolism (Capital Formation)

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

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

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

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

thereby focusing on accumulation of stocks within the economy.

[27] For the purposes of this discussion, our focus is on metabolic processes as they occur in eukaryotic animal cells (cells with a nucleus containing genetic material), thereby avoiding complexities associated with organisms that also perform photosynthesis.

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

2.2.2 Catabolism (Energy Production)

Catabolic processes break down and destroy material stocks within an organism through an oxidation process. At the cellular level, catabolic oxidation releases chemical free energy, some of which synthesizes adenosine triphosphate (ATP), thereby providing fuel to cells. The remainder of the released energy is manifest as waste heat. One of the waste products of cellular catabolism is CO_2. Catabolic processes are part of a chain of material and energy transformations wherein stored chemical energy is converted to useful energy with waste heat and CO_2 as byproducts.

The analogy between catabolic processes and energy transformation processes within the economy is striking. Power plants (fired by coal, oil, natural gas, or refined liquid fuels) in either the energy sector or the final consumption sector break down fossil fuels in an oxidation process (combustion) to produce useful energy (typically, electricity or mechanical drive [23]), thereby providing energy to sectors of the economy. Both waste heat and CO_2 are byproducts of combustion, and O_2 is consumed in the process. Energy production in the economy is a chain of material and energy transformations wherein machines and engines convert stored chemical energy to useful energy with waste heat and CO_2 as byproducts.

We focus on energy flows among sectors of the economy in Chap. 4.

2.2.3 Autophagy (Recycling)

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

Again, the analogy between cellular metabolism and the economy is striking. Whereas cellular autophagy repurposes proteins and cell organelles for reuse by an organism, recycling repurposes degraded yet economically-valuable materials for reuse by the economy. Furthermore, recycling can also be an adaptive response to reduced material and energy inputs. One famous example can be found on the streets of Cuba. In the face of economic sanctions, government restrictions on vehicle purchases, and high import tariffs, automobile imports by Cuba are very low. As a result, Cuba hyper-recycles autos that were imported prior to sanctions and manufactures replacement parts locally. The average lifespan of automobiles has been extended

Fig. 2.4 Vintage autos ("yank tanks") in Cuba. ©2011 Larry Cowles, http://lcowlesphotography.wordpress.com. Used by permission.

such that an estimated 60,000, pre-1960 cars [41] (so-called "yank tanks") are in service on the island.[28] (See Fig. 2.4.)

Its not difficult to imagine that dynamics similar to Cuba's will emerge if the inflow rate of any important natural but recyclable resource is reduced to a trickle by the effects of depletion.[29]

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

We focus on recycling in Sect. 8.4.

2.2.4 Issues of Scale

The metabolism metaphor brings to light issues of scale (size) for economies and societies. First, scale is directly related to material flow rates. Larger organisms consume food at higher rates than smaller organisms, in part to obtain essential nutrients to replenish cellular structures. Similarly, economies with higher levels of emplaced capital require larger material flow rates to provide raw materials to machines and food to people. (See Sect. 1.3.3 for more on this topic.)

In Fig. 2.5, we see Max Kleiber's empirically-determined relationship between metabolic rate (heat production, in kcal/day) and animal mass (in kg) plotted on a

[28] Despite the recent change allowing new car purchases by individuals, astronomical import taxes mean that Cuban streets remain populated with vintage 1950s autos [42].

[29] See Sect. 1.3.2 for a discussion of depletion of a nonrecyclable natural resource, oil.

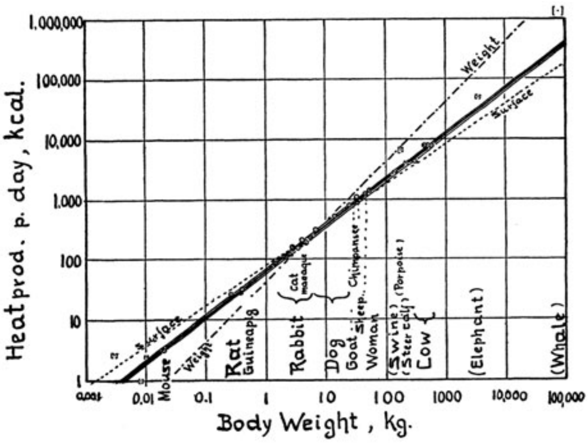

Fig. 2.5 Kleiber's law for metabolic rates (heat production) of different-sized animals [43, p. 530]. Larger animals, as determined by mass, have a higher metabolic rate, but the relationship between mass and metabolic rate is not linear

log-log scale for a variety of animals, from mice to whales. Dashed lines represent theoretical scaling due to either mass (weight) or surface area. The best fit to the data (thick line) passes between the weight and surface area lines.

Kleiber's law, which states this relationship mathematically, is defined as

$$\dot{Q} = q_0 m^{3/4} \tag{2.5}$$

where $\dot{Q}$ is metabolic rate (heat production), m is the mass of the animal, and q_0 is a mass-independent normalization constant. From Eq. 2.5, we see that doubling the mass increases the metabolic rate by $2^{3/4} = 1.68$ times. To compensate for higher rates of heat loss due to high surface area-to-volume ratio, small animals have higher metabolic rates and larger food requirements per unit mass.[30]

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

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[30] On a per-unit-mass basis, Kleiber's Law becomes

$$\frac{\dot{Q}}{m} = q_0 m^{-1/4} \,, \tag{2.6}$$

from which it can be seen that larger organisms (larger mass, m) consume less energy per unit mass ($\dot{Q}/m$), and smaller organisms consume more energy per unit mass.

2.2.5 *Benefits of the Metabolism Metaphor*

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

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

The metabolism metaphor teaches us that larger economies demand increasingly larger material and energy flow rates from the biosphere. We see that limits to economic growth are both possible and expected. From the metaphor we learn that economic "stall" is not pathological, but natural, especially in mature economies that have encountered some type of biophysical limit (see Sect. 1.3.2.). We might expect to encounter any number of limits: supply rates of materials from the biosphere, supply rates of energy from the biosphere, scale of the economy relative to the biosphere. In the metabolism metaphor, autophagy indicates that stocks of capital within society are reservoirs of material and (embodied) energy that can and should be broken down and reused or repurposed, rather than discarded, when out of service.

Through an understanding of the deep interconnectedness and complexity of organisms and species in the biosphere, we come to appreciate the interdependence among actors within and sectors of the economy. Furthermore, an appreciation of the complex nature of economies leads us to acknowledge the difficulty in discerning precisely which limit(s) is (are) encountered when growth stalls. In fact, there is no single explanation for the slowdown of growth in OECD economies discussed at the outset of Chap. 1. The best explanation to date involves many intertwining factors: slowing growth of energy input rate, decreasing energy return on investment in the liquid fuel sector, problems in the credit markets, and a natural tendency for growth to slow in economies just as growth slows in organisms as they approach adulthood.

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

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

2.3 New National Accounting

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

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

As discussed in the Prologue, the UN System of Environmental-Economic Accouting (SEEA) is a conceptual framework that was developed by a wide range of experts beginning in the early 1990s. This framework has just undergone a third, comprehensive revision using a global collaborative process. The SEEA are national accounts that capture data related to "interactions between the economy and the environment, and the stocks and changes in stocks of environmental assets" [44, p. 1]. These accounts measure physical as well as financial flows, and are designed to dovetail with the SNA. As such, the UN SEEA represents the state of the art, in terms of accounting material and energy resource flows through our economies. If implemented, the SEEA allows national governments to answer questions using national accounts that were previously unanswerable, such as, "At what rate do we use steel?" or "How much concrete is embodied within our economy?" Indeed, analyses similar to the one presented in Fig. 1.2 (GDP vs. as a function of fuel consumption) might be undertaken for any material (e.g., iron or water) tracked by the SEEA. Governments gain a great deal of understanding about the energetic and material requirements of the country through the use of SEEA.

However, because the SEEA framework is defined at the economy-wide (E-W) scale, there are many more important questions that still cannot be answered. One such question is, "What are the material and energetic requirements to scale-up the renewable energy industry?" This is a highly important question for future sustainable development, not just for nations, but for the globe as a whole. Furthermore, the accumulation of materials and embodied energy in the manufactured capital stock of a particular economic sector is impossible to estimate with economy-wide analyses.

Such an analysis would require measuring intersectoral (i.e., intra-economy) flows of materials and energy. In the age of resource depletion, we believe measuring intersectoral flows in both physical and financial units to be an essential aspect of extended national accounting.

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

The first question above ("What should we be counting and in what units?") is the topic for the remainder of this section, and the answer provides the structure for the heart of the book. The second question above ("How should the data be analyzed?") is the topic of Chaps. 7–9.

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

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

1. **How much energy was used in the manufacture and transport of two competing goods in the supermarket?** (Or, equivalently, how much energy is embodied in two competing goods in the supermarket?)
2. **What might be the optimal scale of an economy in terms of GDP and what are the impacts of an optimally-sized economy on natural capital?**
3. **How is dependence upon scarce fossil fuels embedded in the interwoven fabric of the economy?**
4. **How will economies that are dependent on coal, oil, and other forms of nonrenewable energy transition to renewable forms of energy?**
5. **How might an economy be affected as an increasing share of production is directed toward replacing degraded ecosystem services?** [45, p. 221]
6. **What are the material and energy requirements to scale-up the renewable energy industry?**

Our approach to developing a rigorous theoretical foundation for comprehensive national accounting is to develop a dynamic model by applying rigorous thermodynamics to materials and energy flows into, among, and out of economic sectors,

Table 2.1 Examples used throughout this book

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

informed by the metabolism metaphor, in a manner that is corresponds with existing (or expanded) national accounts.

2.4 Structure of the Book

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

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

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

Part III gives context to the framework developed in Parts I and II. Chapter 8 draws out some of the implications of our proposed framework. And, we end with a summary and a list of proposed next steps in Chap. 9.

Throughout the methodological chapters (3–7), our accounting framework is developed through a series of increasingly-disaggregated models of the economy (Table 2.1) using, as much as possible, the same structure for each. Doing so provides a detailed, step-by-step explanation of our proposed accounting framework. We use the US auto industry as a running example for application and discussion.

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Part I
Material and Energy

Chapter 3
Stocks and Flows of Materials

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 Chap. 2, we introduced the metaphor that the economy is society's metabolism, using energy and material resources extracted from the natural environment for the construction, maintenance, and growth of society. We also noted, in Sect. 2.3, that to utilize the metabolism metaphor, we must account for material and energy flows *and accumulations* not just at the economy-wide level, but also at the sectoral level. This chapter explores this idea further by observing the accumulation and interchange of materials *within* an economy, as well as exchanges of materials between an economy and its surrounding environment—the biosphere.

Just as a biological organism metabolizes food, water and air, so too an economy must take in raw materials from its environment. To a large extent, the major exchanges of materials between industrial economies and the natural environment mirror those of an animal. Large inputs of fresh water, hydrocarbons, and oxygen result in the emission of carbon dioxide and polluted water [2]. These materials inputs are used for a number of different purposes. In anabolic processes (see Sect. 2.2.1), materials extracted from the environment become the building blocks from which the physical structures within the economy—buildings, roads, even people—are composed. The extraction and processing of materials requires energy resources. In industrial economies, this is achieved primarily by combustion of fossil fuels, which requires the presence of oxygen in the atmosphere and results in the emission of carbon dioxide. Many processes also require flows of materials, especially fresh water, that are not directly embodied in the final product. As such, many material resources flow through the economy without accumulating within physical infrastructure.

There are, however, 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 the building opposite.

There are also innumerable material flows between the biosphere and the economy that most of us never 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 cannot be seen with the

M. K. Heun et al., *Beyond GDP*, Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_3

naked eye. The cars outside in the street suck in nitrogen and oxygen (without which the engine would not work) and emit water vapor, carbon dioxide, and other, more harmful, wastes.

Even services that we consider "nonmaterial" require at least some material infrastructure. The hairdresser requires scissors and hair (available to a greater or lesser extent!) 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 supply, 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* [3]) started their "lives" within the biosphere, be they food, water, paper, petroleum, or rock. In fact, the economy is in a continual state of material exchange with its surrounding environment; raw materials are pulled in and wastes are emitted. It is this exchange that intimately couples the two spheres, intertwining their mutual fate.

As discussed in the Preface and Chap. 2, 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 [4]. Over the past two centuries, human demand for materials has increased at a phenomenal pace. This demand has driven ever increasing extraction rates of raw materials from the biosphere. Production of all materials increased from around 12 Gt/yr (10^9 t/yr) to around 35 Gt/yr in the period 1945–1980 and up to 68 Gt/yr by the year 2009 [5]. 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 [6]. 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 [4].

A less obvious answer comes from social science. In 1980, Schnaiberg [7] 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

[1] The logic of the treadmill is:

a Capital (production equipment) is accumulating in Western economies as labor is replaced by technologies;

b These technologies require far more materials and/or energy than the previous, labor-intensive processes;

c Moreover, unlike labor, the new technologies represent forms of sunk capital;

natural resources for a given level of social welfare" [8, p. 297]. The treadmill of production is evident today, driving up demand for many commodities. From an economic perspective, we may view the treadmill as the striving for productivity from factors of production. In the substitution of capital for labor, total factor productivity (A in Eq. 2.1) 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 traditional economic growth models, hence do not count towards productivity; the substitution obtains 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. And, as we pointed out at the start of this chapter, not all materials flow straight through the economy. They accumulate as objects: buildings, cars, and even people.

When accumulation is not accounted for, the hidden 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 unchanging—therefore we say the system is in steady-state. Or, imagine a growing baby. The inputs of food and other materials, 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 of people, machines, equipment, roads, and buildings that have built up over time. As discussed in Sect. 1.3.3, 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 the material to satisfy human wants requires capital equipment; more stocks which also have needs. They require flows of materials and energy to build, operate, and maintain them. Thus, 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.

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d Because the remaining labor inputs can more readily be cut back (as opposed to sunk capital, see Sect. 1.3.3) labor is further reduced to sustain production at higher levels;

e More capital is added to replace further reduced levels of labor [8, p. 296].

3.1 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 (this chapter), energy (Chap. 4), embodied energy (Chap. 5), and economic value (Chap. 6) throughout this book.

3.1.1 Accounting in Everyday Life

We all count material (and nonmaterial) 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 definition of a region in space over which accounting will be performed 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 ripen (are produced) during a week. A rigorous apple accounting equation, in units of apples, is:

$$\Delta\text{apples} = \text{apples in} - \text{apples out} + \text{apples grown} - \text{apples eaten}. \tag{3.1}$$

More generally, we may say:

$$\text{accumulation} = \text{transfers in} - \text{transfers out} + \text{production} - \text{consumption}. \tag{3.2}$$

Notice that, when discussing apples we use the specific terms "grown" and "eaten," instead of the more general terms "produced" and "consumed." Later, in Chap. 6, when discussing economic value, we will use the terms "generated" or "added" and "destroyed." For our purposes, these terms all have equivalent meanings, respectively, 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?" That is, we can examine the rate of change of the apple stock per unit of time$\left(\frac{\mathrm{d}a}{\mathrm{d}t}\right)$ relative to the flow of apples ($\dot{a}$), in which case our accounting equation becomes:

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \dot{a}_{in} - \dot{a}_{out} + \dot{a}_{grown} - \dot{a}_{eaten}, \tag{3.3}$$

where the dot above the variable ($\dot{a}$) indicates a flow rate per unit time [apples/time] and the time derivative $\left(\frac{da}{dt}\right)$ 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 (bonded with hydrogen in carbohydrates to 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:

$$\Delta \text{steel} = \text{steel in} - \text{steel out}. \tag{3.4}$$

Note that the production and consumption terms are zero because steel is neither created nor destroyed within the automobile sector. Tracking the rate flows of steel, $\dot{s}$ (in kg/s), we would write the following equation:

$$\frac{ds}{dt} = \dot{s}_{in} - \dot{s}_{out}. \tag{3.5}$$

Again, the terms representing steel production and consumption are not present. This is in direct contrast with apple accounting outlined in Eq. 3.3. 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

[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 atomic 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.

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 cannot 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. Similarly 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 (Chaps. 4 and 5 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 (Eq. 3.3) can include 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 mass 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 Chaps. 4 and 5, covers 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 Chap. 6.

3.1.2 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 Fig. 3.1.

Resource material flows ($\dot{R}$) 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

[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 Chaps. 5–8.

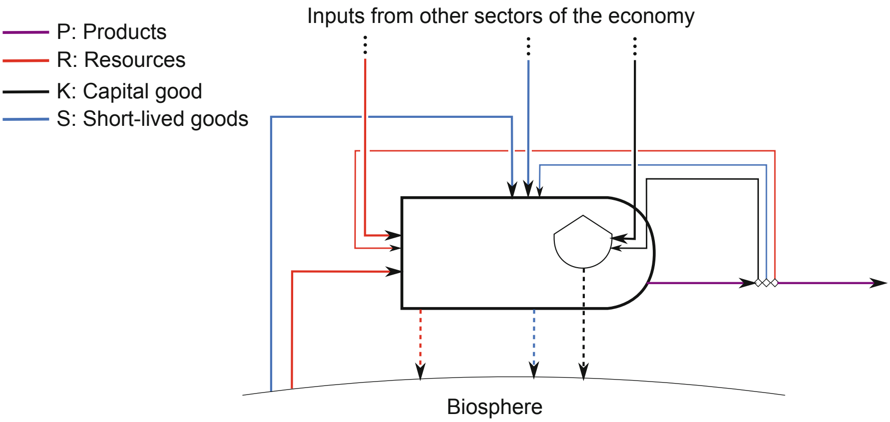

Fig. 3.1 Material flows into and out of a single sector of the economy. Resource flows ($\dot{R}$) enter the sector from the left and are embodied in products ($\dot{P}$) which leave from the right. Some waste resources are leave the sector at the bottom and are returned to the biosphere. Short-lived material flows ($\dot{S}$) enter the sector from above and leave from below to return to the biosphere. Only capital flows ($\dot{K}$) 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. Energy flows (green lines) are associated with all flows of materials, but are not drawn explicitly in this diagram. Flows of energy will be depicted in diagrams in later chapters

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 become 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 solvents used within automobile production and process water used by the sector. Resources and short-lived materials make up Georgescu-Roegen's "flow" elements[4] [9] or Daly's "material causes" [10].

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.

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[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.

We assume (for simplicity) that there is no reuse of capital stock by other sectors of an economy, e.g., resale of 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 Sects. 2.2.3 and 8.4.

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. 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* (i.e., atoms from the crude oil are physically contained) within the outflowing 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 outflowing 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 contained within the product, but leave the economy in the form of carbon dioxide. (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 (0) from sector j, such that:

$$\dot{W}_{j0} = \dot{R}_{j0} + \dot{S}_{j0}. \tag{3.6}$$

This waste flow will be useful later in Sect. 5.4. We now track these material flows through some example economies.

3.2 Example A: Single-Sector Economy

Our first example considers the case where all processes within the economy occur within one sector—Society (1)—which exchanges materials with the Biosphere (0) as depicted in Fig. 3.2.

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 $\frac{\mathrm{d}K_1}{\mathrm{d}t}$

[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 within the product outflow from sector j, whereas K_j (without the dot) denotes the capital stock of sector j.

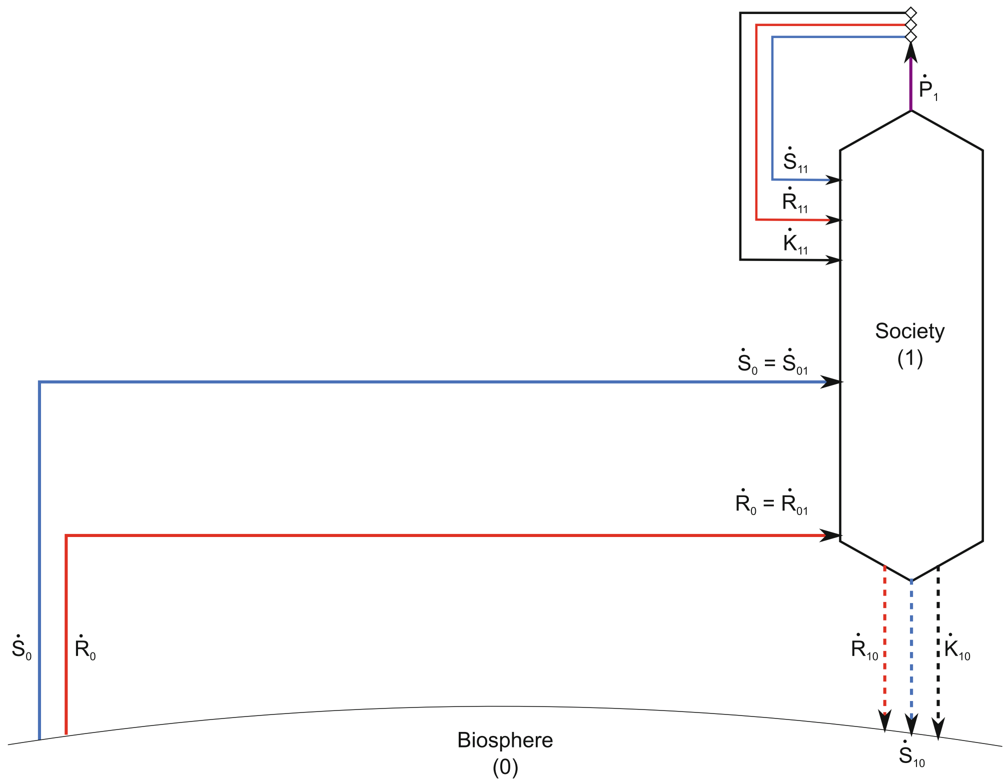

Fig. 3.2 Flows of materials for a one-sector economy. Resources ($\dot{R}_{01}$) and short-lived materials ($\dot{S}_{01}$) flow into Society (1) from the Biosphere (0). Waste resources ($\dot{R}_{10}$) short-lived materials/goods ($\dot{S}_{10}$) and capital goods ($\dot{K}_{10}$) are returned to the biosphere

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 Fig. 3.2, we can construct material accounting equations, such that:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} + \frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{S}_{10} + \dot{K}_{10} - \dot{R}_0 - \dot{S}_0. \tag{3.7}$$

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} + \frac{\mathrm{d}S_1}{\mathrm{d}t} + \frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} + \dot{S}_{01} + \dot{R}_{11} + \dot{S}_{11} + \dot{K}_{11} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}. \tag{3.8}$$

Because mass is conserved, we find that:

$$\dot{R}_0 = \dot{R}_{01}, \tag{3.9}$$

$$\dot{S}_0 = \dot{S}_{01}, \tag{3.10}$$

and

$$\dot{P}_1 = \dot{R}_{11} + \dot{S}_{11} + \dot{K}_{11}. \tag{3.11}$$

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

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \dot{R}_{10} - \dot{R}_{01} \neq 0. \tag{3.12}$$

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:

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} = 0. \tag{3.13}$$

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = 0. \tag{3.14}$$

[6] See Footnote 8 in this chapter 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. $\dot{S}_{11} << \dot{S}_{01}$. This is a matter for empirical investigation.

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:

$$\frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{K}_{10}. \tag{3.15}$$

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 reenters the economy as part of flow $\dot{S}_{11}$, because the coal is *not physically contained* 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 reenters the economy within flow $\dot{R}_{11}$, because the carbon in the coal ends up *physically contained* 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 reenter 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) reenters 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 $\dot{K}_{10}$.[8]

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

[8] 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 nonindustrial, agrarian societies, the proportion of total energy flow comprised by manual (or draft) 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. Agrarian societies are necessarily constrained by the fact that the energy content of the food delivered *must be* greater than the labor (and draft animal) energy required to produce it.

Another view is that societal capital (K_1) includes only human-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 [11]. However, the framework presented in this book is general enough to encompass either point of view.

economy, entering and reentering, until they are turned either into short-lived goods, whereupon they flow "straight through" into the biosphere, or they are turned into capital goods and accumulate.

As such, we may state that:

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} = \dot{R}_{01} + \dot{R}_{11} - \dot{P}_1 - \dot{R}_{10} = 0, \tag{3.16}$$

and

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = \dot{S}_{01} + \dot{S}_{11} - \dot{S}_{10} = 0. \tag{3.17}$$

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

$$\dot{P}_1 = \dot{R}_{01} + \dot{R}_{11} - \dot{R}_{10}, \tag{3.18}$$

and

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{01}. \tag{3.19}$$

Substituting Eqs. 3.9, 3.10 and 3.15 into Eq. 3.7 we obtain:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{S}_{10} - \dot{R}_{01} - \dot{S}_{01}. \tag{3.20}$$

Equation 3.20 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 Eq. 3.20 is true for the total mass of materials, it does not account for the *quality* of these materials. An intact brick is of higher material quality—and is of more use—than the brick dust that has been eroded by weather and scattered on the wind. Many material stocks or flows have been concentrated by natural biophysical processes. We do not mine desirable material from the average abundance of crustal materials. Instead, society relies heavily on extracting resources from naturally occurring , highly concentrated deposits of that are far from equilibrium with their surroundings, e.g., fossil fuel reservoirs or seams of high-grade ore. 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. 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.

As these high quality material reserves are depleted and society must turn to lower grade reserves (as predicted by the best-first principle), more total material must flow through the process (including overburden —what must be moved to access the resource—and tailings—the wasted portion that is extracted), more productive capital must be deployed, and the greater the wear and tear on equipment in order to maintain the same level of production [12, 13]. Additionally, it takes more energy to process less concentrated resources. This additional processing requirement entails that we will likely never mine average crustal abundance for needed materials, or mine gold or uranium 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 certainly impractical and may be impossible, even in theory.[9]

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.

We have here 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, processing 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 reuse 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 Fig. 3.3.[10] In this book we will continue with the assumption that there is only one product leaving a sector that stays within the economy, i.e. there is no recycling of products. The issue of recycling is discussed in more detail in Sect. 8.4.

Substituting Eq. 3.17 into Eq. 3.8, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} + \dot{R}_{11} + \dot{K}_{11} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10}. \tag{3.21}$$

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[9] 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 is discussed in reference to our framework in Sect. 8.4. 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. 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 ultralight, "hypercar" concept [14]. 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 occurred by exporting manufacturing to other countries [15]. The material footprint of OECD nations, when weighted by consumption, has increased significantly since 1990 [16].

[10] Note that such flows violate the "one sector-one product" assumption of the Leontief inversion method which we will use in Chap. 7. Other methods based on make-use tables, as developed by von Neumann [17] and Sraffa [18] are able to account for multiple products from each sector.

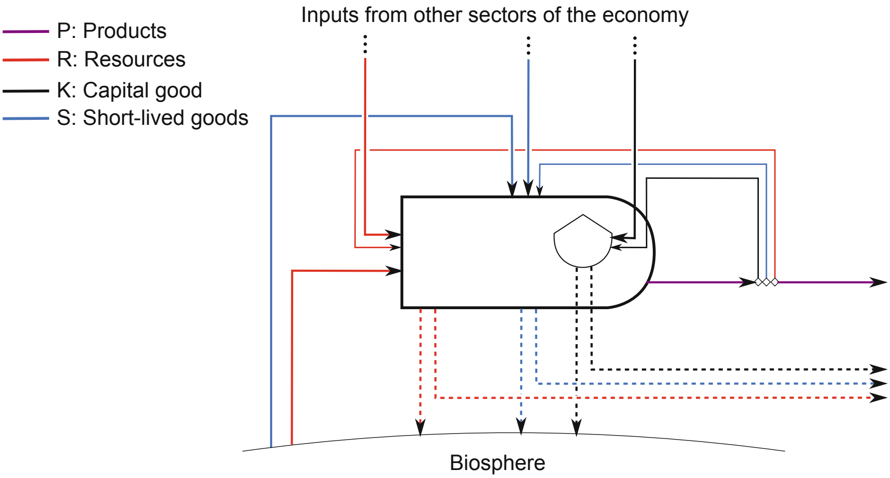

Fig. 3.3 Material flows through an economic sector with waste treatment flows to other economic sectors

Because we have two different formulations for $\dot{P}_1$, represented by Eqs. 3.11 and 3.18, we may substitute either into Eq. 3.21. Substituting Eq. 3.18 into Eq. 3.21, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{K}_{11} - \dot{K}_{10}, \tag{3.22}$$

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 Eq. 3.11 into Eq. 3.21, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} - \dot{R}_{10} - \dot{S}_{11} - \dot{K}_{10}. \tag{3.23}$$

The last depreciation term ($\dot{K}_{10}$) may be rewritten as the total stock of human-made capital (K_1) multiplied by some depreciation rate (γ_{K_1}),[11] where γ_{K_j} is defined as:

$$\gamma_{K_j} \equiv \frac{\dot{K}_{j0}}{K_j}, \tag{3.24}$$

i.e., The depreciation *per unit* of capital stock,[12] such that Eq. 3.23 may be rewritten:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{01} - \dot{R}_{10} - \dot{S}_{11} - \gamma_{K_1} K_1. \tag{3.25}$$

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

[12] This depreciation term will be discussed in more depth in Sects. 5.2.3 and 8.2.2.2.

We may rearrange Eq. 3.25 as:

$$\dot{R}_{01} - \dot{R}_{10} = \frac{\mathrm{d}K_1}{\mathrm{d}t} + \dot{S}_{11} + \gamma_{K_1} K_1. \tag{3.26}$$

Noticing that the left-hand side of Eq. 3.26 is the negation of the right-hand side of Eq. 3.12, we may rewrite Eq. 3.26 in terms of the accumulation (or more accurately, depletion) of natural resources:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \frac{\mathrm{d}K_1}{\mathrm{d}t} + \dot{S}_{11} + \gamma_{K_1} K_1. \tag{3.27}$$

Equation 3.27 tells us that depletion of natural resources $\left(-\frac{\mathrm{d}R_0}{\mathrm{d}t}\right)$ is used within society to:

- Build up societal capital stock $\left(\frac{\mathrm{d}K_1}{\mathrm{d}t}\right)$,
- 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.

3.3 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 Fig. 3.4. 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. As can be seen in Fig. 3.4, Production (2) resembles very closely to the basic unit shown in Fig. 3.1. 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

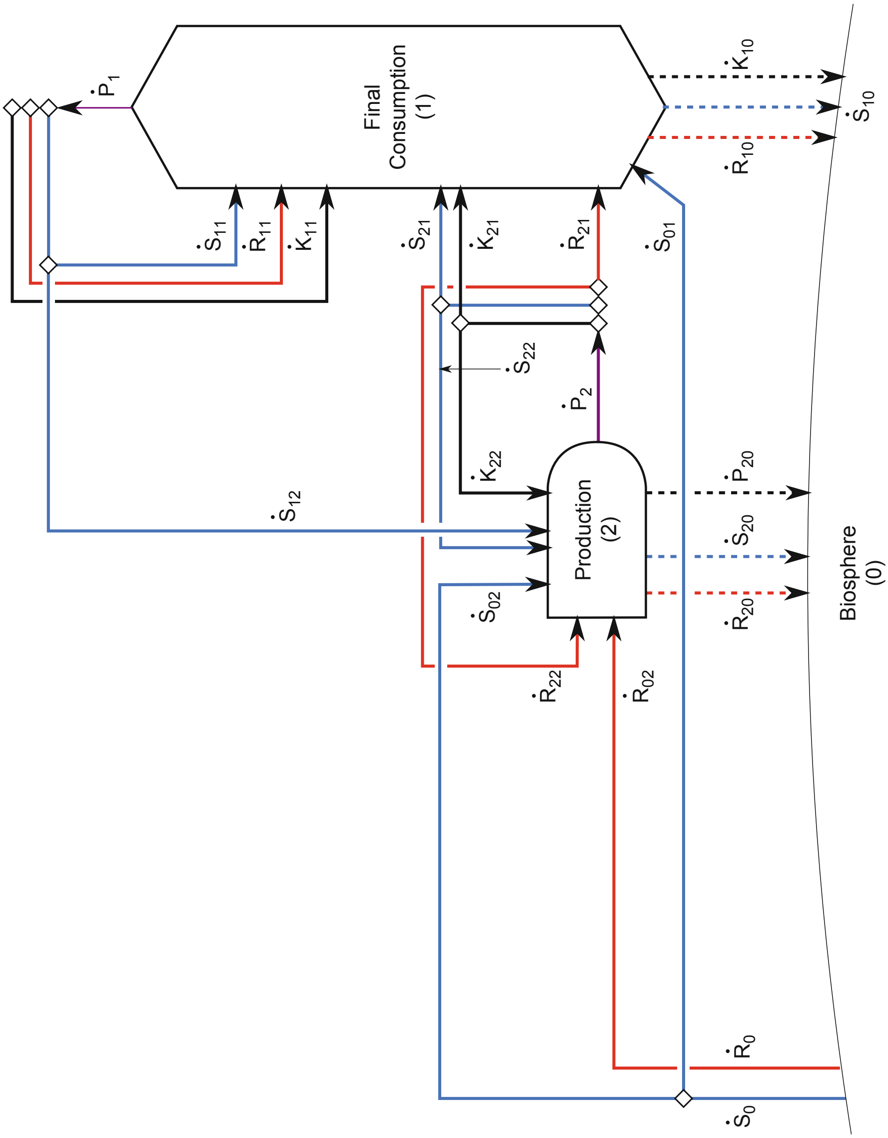

Fig. 3.4 Flows of materials for a two-sector economy

capital goods ($\dot{K}_{11}$) flows.[13] 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.[14]

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:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} + \frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} + \dot{S}_{10} + \dot{S}_{20} + \dot{K}_{10} + \dot{K}_{20} - \dot{R}_0 - \dot{S}_0, \tag{3.28}$$

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} + \frac{\mathrm{d}S_1}{\mathrm{d}t} + \frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{11} + \dot{R}_{21} + \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} + \dot{K}_{11} + \dot{K}_{21} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}, \tag{3.29}$$

and

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} + \frac{\mathrm{d}S_2}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{R}_{22} + \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} + \dot{K}_{22} - \dot{P}_2 - \dot{R}_{20} - \dot{S}_{20} - \dot{K}_{20}. \tag{3.30}$$

Because no resources flow directly to Final Consumption (1) from the Biosphere (0),[15] we may say:

$$\dot{R}_0 = \dot{R}_{02}. \tag{3.31}$$

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

$$\dot{S}_0 = \dot{S}_{01} + \dot{S}_{02}. \tag{3.32}$$

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:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} - \dot{R}_{02}, \tag{3.33}$$

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

[14] 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).

[15] 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.

$$\frac{\mathrm{d}S_0}{\mathrm{d}t} = \dot{S}_{10} + \dot{S}_{20} - \dot{S}_{01} - \dot{S}_{02}, \tag{3.34}$$

and

$$\frac{\mathrm{d}K_0}{\mathrm{d}t} = \dot{K}_{10} + \dot{K}_{20}. \tag{3.35}$$

Because we are assuming that only human-made capital (and not human beings themselves) are accounted within the physical stock of Final Consumption[16] (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:

$$\dot{R}_{11} = 0, \tag{3.36}$$

because labor is not a resource flow—it is not *physically embodied* within human labor, the product of Final Consumption (1)—and additionally that

$$\dot{K}_{11} = 0, \tag{3.37}$$

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:

$$\dot{P}_1 = \dot{S}_{11} + \dot{S}_{12}, \tag{3.38}$$

and

$$\dot{P}_2 = \dot{R}_{21} + \dot{R}_{22} + \dot{S}_{21} + \dot{S}_{22} + \dot{K}_{21} + \dot{K}_{22}. \tag{3.39}$$

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

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} = 0, \tag{3.40}$$

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} = 0, \tag{3.41}$$

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = 0, \tag{3.42}$$

and

$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = 0. \tag{3.43}$$

[16] 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 Footnote 8 of this chapter.

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:

$$\frac{\mathrm{d}R_1}{\mathrm{d}t} = \dot{R}_{21} - \dot{P}_1 - \dot{R}_{10} = 0, \tag{3.44}$$

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} - \dot{S}_{10} = 0, \tag{3.45}$$

$$\frac{\mathrm{d}R_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{R}_{22} - \dot{P}_2 - \dot{R}_{20} = 0, \tag{3.46}$$

and

$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} - \dot{S}_{20} = 0. \tag{3.47}$$

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

$$\dot{P}_1 = \dot{R}_{21} - \dot{R}_{10}, \tag{3.48}$$

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{21}, \tag{3.49}$$

$$\dot{P}_2 = \dot{R}_{02} + \dot{R}_{22} - \dot{R}_{20}, \tag{3.50}$$

and

$$\dot{S}_{22} = \dot{S}_{20} - \dot{S}_{02} - \dot{S}_{12}. \tag{3.51}$$

Substituting Eqs. 3.31–3.35 into Eq. 3.28, gives

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} + \frac{\mathrm{d}S_0}{\mathrm{d}t} = \dot{R}_{10} + \dot{R}_{20} + \dot{S}_{10} + \dot{S}_{20} - \dot{R}_{02} - \dot{S}_{01} - \dot{S}_{02}. \tag{3.52}$$

Substituting Eqs. 3.40, 3.45 and 3.47 into Eqs. 3.29 and 3.30, respectively, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{21} + \dot{K}_{21} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10}, \tag{3.53}$$

and

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} + \dot{R}_{22} + \dot{K}_{22} - \dot{P}_2 - \dot{R}_{20} - \dot{K}_{20}. \tag{3.54}$$

As in Example A, we again have two definitions for $\dot{P}_1$ (Eqs. 3.38 and 3.48) and $\dot{P}_2$ (Eqs. 3.39 and 3.50) which may be substituted into Eqs. 3.53 and 3.54, respectively. Let us start by substituting Eqs. 3.48 and 3.50, in which case we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{K}_{21} - \dot{K}_{10}, \tag{3.55}$$

and

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{K}_{22} - \dot{K}_{20}. \tag{3.56}$$

Equations 3.55 and 3.56 tell us that accumulation of human-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 Eqs. 3.38 and 3.39, we obtain:

$$\frac{\mathrm{d}K_1}{\mathrm{d}t} = \dot{R}_{21} + \dot{K}_{21} - \dot{S}_{11} - \dot{S}_{12} - \dot{R}_{10} - \dot{K}_{10}, \tag{3.57}$$

and

$$\frac{\mathrm{d}K_2}{\mathrm{d}t} = \dot{R}_{02} - \dot{R}_{21} - \dot{S}_{21} - \dot{S}_{22} - \dot{K}_{21} - \dot{R}_{20} - \dot{K}_{20}, \tag{3.58}$$

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

$$-\dot{R}_{10} = \frac{\mathrm{d}K_1}{\mathrm{d}t} - \dot{R}_{21} - \dot{K}_{21} + \dot{S}_{11} + \dot{S}_{12} + \gamma_{K_1} K_1, \tag{3.59}$$

and

$$\dot{R}_{02} - \dot{R}_{20} = \frac{\mathrm{d}K_2}{\mathrm{d}t} + \left(\dot{R}_{21} + \dot{S}_{21} + \dot{K}_{21}\right) + \dot{S}_{22} + \gamma_{K_2} K_2. \tag{3.60}$$

Equation 3.60 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 Eqs. 3.59 and 3.60 together, we obtain:

$$\begin{aligned} -\frac{\mathrm{d}R_0}{\mathrm{d}t} &= \dot{R}_{02} - \dot{R}_{10} - \dot{R}_{20} \\ &= \frac{\mathrm{d}K_1}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} + \dot{S}_{11} + \dot{S}_{12} + \dot{S}_{21} + \dot{S}_{22} + \gamma_{K_1} K_1 + \gamma_{K_2} K_2. \end{aligned} \tag{3.61}$$

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.

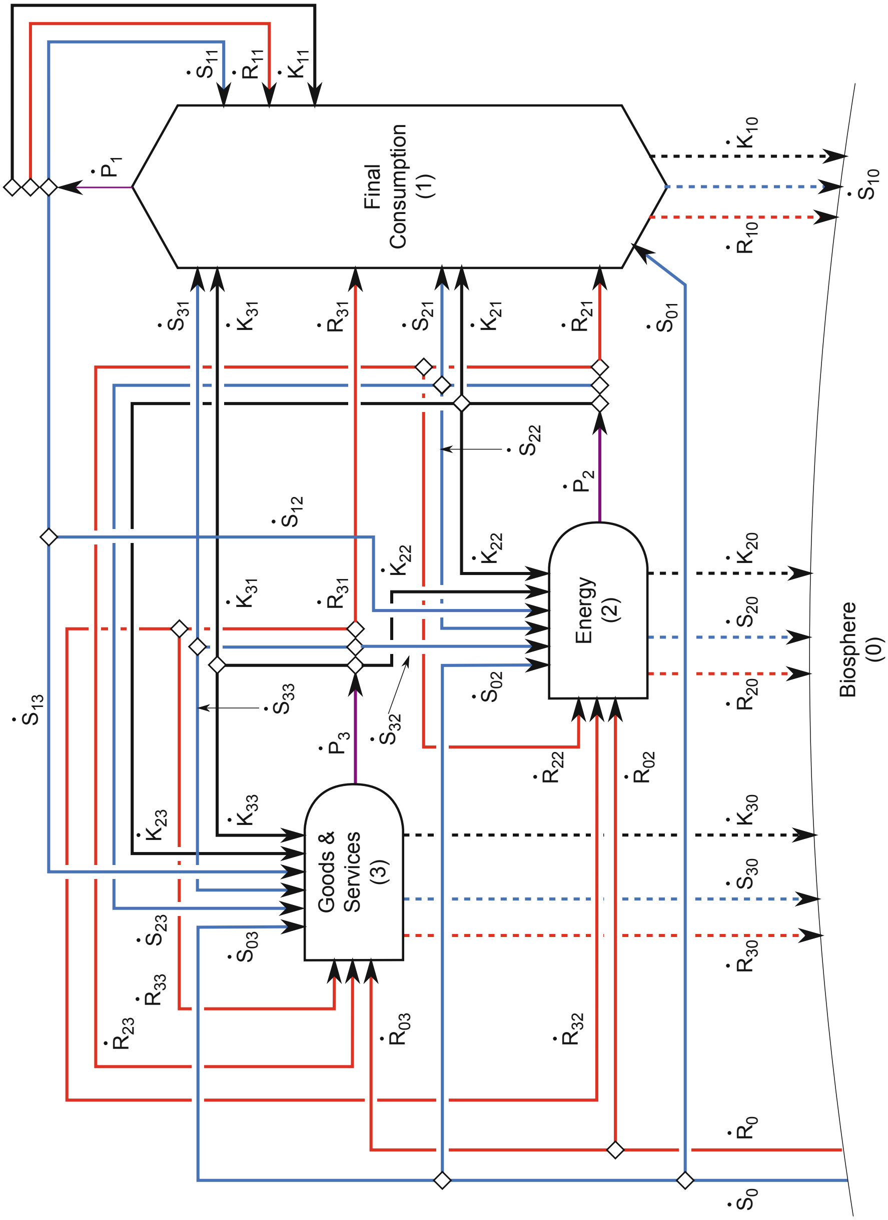

Fig. 3.5 Flows of materials for a three-sector economy

3.4 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 Fig. 3.5.

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:

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} + \frac{dK_0}{dt} = \dot{R}_{10} + \dot{R}_{20} + \dot{R}_{30} + \dot{S}_{10} + \dot{S}_{20} + \dot{S}_{30} + \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30} - \dot{R}_0 - \dot{S}_0, \tag{3.62}$$

which may be rewritten as:

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} + \frac{dK_0}{dt} = \sum_{i=1}^{3} \dot{R}_{i0} + \sum_{i=1}^{3} \dot{S}_{i0} + \sum_{i=1}^{3} \dot{K}_{i0} - \dot{R}_0 - \dot{S}_0, \tag{3.63}$$

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

$$\frac{dR_1}{dt} + \frac{dS_1}{dt} + \frac{dK_1}{dt} = \dot{R}_{01} + \dot{S}_{01} + \sum_{i=1}^{3} \dot{R}_{i1} + \sum_{i=1}^{3} \dot{S}_{i1} + \sum_{i=1}^{3} \dot{K}_{i1} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}, \tag{3.64}$$

$$\frac{dR_2}{dt} + \frac{dS_2}{dt} + \frac{dK_2}{dt} = \dot{R}_{02} + \dot{S}_{02} + \sum_{i=1}^{3} \dot{R}_{i2} + \sum_{i=1}^{3} \dot{S}_{i2} + \sum_{i=1}^{3} \dot{K}_{i2} - \dot{P}_2 - \dot{R}_{20} - \dot{S}_{20} - \dot{K}_{20}, \tag{3.65}$$

and

$$\frac{dR_3}{dt} + \frac{dS_3}{dt} + \frac{dK_3}{dt} = \dot{R}_{03} + \dot{S}_{03} + \sum_{i=1}^{3} \dot{R}_{i3} + \sum_{i=1}^{3} \dot{S}_{i3} + \sum_{i=1}^{3} \dot{K}_{i3} - \dot{P}_3 - \dot{R}_{30} - \dot{S}_{30} - \dot{K}_{30}. \tag{3.66}$$

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:

$$\frac{dR_0}{dt} = \dot{R}_{10} + \dot{R}_{20} + \dot{R}_{30} - \dot{R}_{01} - \dot{R}_{02} - \dot{R}_{03}, \tag{3.67}$$

$$\frac{dS_0}{dt} = \dot{S}_{10} + \dot{S}_{20} + \dot{S}_{30} - \dot{S}_{01} - \dot{S}_{02} - \dot{S}_{03}, \tag{3.68}$$

and

$$\frac{dK_0}{dt} = \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30}, \tag{3.69}$$

which may be rewritten as:

$$\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{R}_{i0} - \sum_{j=1}^{3} \dot{R}_{0j}, \tag{3.70}$$

$$\frac{\mathrm{d}S_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{S}_{i0} - \sum_{j=1}^{3} \dot{S}_{0j}, \tag{3.71}$$

and

$$\frac{\mathrm{d}K_0}{\mathrm{d}t} = \sum_{i=1}^{3} \dot{K}_{i0}. \tag{3.72}$$

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

$$\dot{P}_1 = \sum_{j=1}^{3} \dot{R}_{1j} + \sum_{j=1}^{3} \dot{S}_{1j} + \sum_{j=1}^{3} \dot{K}_{1j}, \tag{3.73}$$

$$\dot{P}_2 = \sum_{j=1}^{3} \dot{R}_{2j} + \sum_{j=1}^{3} \dot{S}_{2j} + \sum_{j=1}^{3} \dot{K}_{2j}, \tag{3.74}$$

and

$$\dot{P}_3 = \sum_{j=1}^{3} \dot{R}_{3j} + \sum_{j=1}^{3} \dot{S}_{3j} + \sum_{j=1}^{3} \dot{K}_{3j}. \tag{3.75}$$

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),[17] hence $\dot{R}_{32} = 0$.

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

$$\frac{\mathrm{d}R_j}{\mathrm{d}t} = 0, \qquad j \in [1,3], \tag{3.76}$$

$$\frac{\mathrm{d}S_j}{\mathrm{d}t} = 0, \qquad j \in [1,3]. \tag{3.77}$$

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

As before, we may also define the resource-product and short-lived goods flows balances separately for each of the sectors of the economy:[18]

$$\frac{dR_1}{dt} = \dot{R}_{01} + \dot{R}_{11} + \dot{R}_{21} + \dot{R}_{31} - \dot{P}_1 - \dot{R}_{10} = 0, \tag{3.78}$$

$$\frac{dS_1}{dt} = \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} + \dot{S}_{31} - \dot{S}_{10} = 0, \tag{3.79}$$

$$\frac{dR_2}{dt} = \dot{R}_{02} + \dot{R}_{12} + \dot{R}_{22} + \dot{R}_{32} - \dot{P}_2 - \dot{R}_{20} = 0, \tag{3.80}$$

$$\frac{dS_2}{dt} = \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} + \dot{S}_{32} - \dot{S}_{20} = 0, \tag{3.81}$$

$$\frac{dR_3}{dt} = \dot{R}_{03} + \dot{R}_{13} + \dot{R}_{23} + \dot{R}_{33} - \dot{P}_3 - \dot{R}_{30} = 0, \tag{3.82}$$

and

$$\frac{dS_3}{dt} = \dot{S}_{03} + \dot{S}_{13} + \dot{S}_{23} + \dot{S}_{33} - \dot{S}_{30} = 0, \tag{3.83}$$

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

$$\dot{P}_1 = \dot{R}_{01} + \dot{R}_{11} + \dot{R}_{21} + \dot{R}_{31} - \dot{R}_{10}, \tag{3.84}$$

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{01} - \dot{S}_{21} - \dot{S}_{31}, \tag{3.85}$$

$$\dot{P}_2 = \dot{R}_{02} + \dot{R}_{12} + \dot{R}_{22} + \dot{R}_{32} - \dot{R}_{20}, \tag{3.86}$$

$$\dot{S}_{22} = \dot{S}_{20} - \dot{S}_{02} - \dot{S}_{12} - \dot{S}_{32}, \tag{3.87}$$

$$\dot{P}_3 = \dot{R}_{03} + \dot{R}_{13} + \dot{R}_{23} + \dot{R}_{33} - \dot{R}_{30}, \tag{3.88}$$

and

$$\dot{S}_{33} = \dot{S}_{20} - \dot{S}_{03} - \dot{S}_{13} - \dot{S}_{23}. \tag{3.89}$$

We now make use of Eqs. 3.76, 3.79, 3.81 and 3.83 in simplifying Eqs. 3.64–3.66, to obtain:

$$\frac{dK_1}{dt} = \dot{R}_{01} + \sum_{i=1}^{3} \dot{R}_{i1} + \sum_{i=1}^{3} \dot{K}_{i1} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10}, \tag{3.90}$$

$$\frac{dK_2}{dt} = \dot{R}_{02} + \sum_{i=1}^{3} \dot{R}_{i2} + \sum_{i=1}^{3} \dot{K}_{i2} - \dot{P}_2 - \dot{R}_{20} - \dot{K}_{20}, \tag{3.91}$$

[18] It is worth remembering here that $\dot{R}_{01} = 0$ and $\dot{R}_{21} = 0$, 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).

and

$$\frac{dK_3}{dt} = \dot{R}_{03} + \sum_{i=1}^{3} \dot{R}_{i3} + \sum_{i=1}^{3} \dot{K}_{i3} - \dot{P}_3 - \dot{R}_{30} - \dot{K}_{30}. \tag{3.92}$$

As in previous examples, we have two different formulations for the $\dot{P}$ terms. Substituting, first, Eqs. 3.84, 3.86, and 3.88, we obtain:

$$\frac{dK_1}{dt} = \sum_{i=1}^{3} \dot{K}_{i1} - \dot{K}_{10}, \tag{3.93}$$

$$\frac{dK_2}{dt} = \sum_{i=1}^{3} \dot{K}_{i2} - \dot{K}_{20}, \tag{3.94}$$

and

$$\frac{dK_3}{dt} = \sum_{i=1}^{3} \dot{K}_{i3} - \dot{K}_{30}, \tag{3.95}$$

which we may rewrite as the more general result:

$$\frac{dK_j}{dt} = \sum_{i} \dot{K}_{ij} - \dot{K}_{j0}. \tag{3.96}$$

Equation 3.96 states that for any economic sector, j, the accumulation of human-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 Eqs. 3.73–3.75 into Eqs. 3.90–3.92, respectively, we obtain:

$$\frac{dK_1}{dt} = \dot{R}_{01} + \sum_{i=1}^{3} \dot{R}_{i1} + \sum_{i=1}^{3} \dot{K}_{i1} - \sum_{j=1}^{3} \dot{R}_{1j} - \sum_{j=1}^{3} \dot{S}_{1j} - \sum_{j=1}^{3} \dot{K}_{1j} - \dot{R}_{10} - \dot{K}_{10}, \tag{3.97}$$

$$\frac{dK_2}{dt} = \dot{R}_{02} + \sum_{i=1}^{3} \dot{R}_{i2} + \sum_{i=1}^{3} \dot{K}_{i2} - \sum_{j=1}^{3} \dot{R}_{2j} - \sum_{j=1}^{3} \dot{S}_{2j} - \sum_{j=1}^{3} \dot{K}_{2j} - \dot{R}_{20} - \dot{K}_{20}, \tag{3.98}$$

and

$$\frac{dK_3}{dt} = \dot{R}_{03} + \sum_{i=1}^{3} \dot{R}_{i3} + \sum_{i=1}^{3} \dot{K}_{i3} - \sum_{j=1}^{3} \dot{R}_{3j} - \sum_{j=1}^{3} \dot{S}_{3j} - \sum_{j=1}^{3} \dot{K}_{3j} - \dot{R}_{30} - \dot{K}_{30}. \tag{3.99}$$

As before, we can rearrange these equations to obtain:

$$\dot{R}_{01} - \dot{R}_{10} = \frac{\mathrm{d}K_1}{\mathrm{d}t} - \sum_{i=1}^{3} \dot{R}_{i1} - \sum_{i=1}^{3} \dot{K}_{i1} + \sum_{j=1}^{3} \dot{R}_{1j} + \sum_{j=1}^{3} \dot{S}_{1j} + \sum_{j=1}^{3} \dot{K}_{1j} + \dot{K}_{10}, \tag{3.100}$$

$$\dot{R}_{02} - \dot{R}_{20} = \frac{\mathrm{d}K_2}{\mathrm{d}t} - \sum_{i=1}^{3} \dot{R}_{i2} - \sum_{i=1}^{3} \dot{K}_{i2} + \sum_{j=1}^{3} \dot{R}_{2j} + \sum_{j=1}^{3} \dot{S}_{2j} + \sum_{j=1}^{3} \dot{K}_{2j} + \dot{K}_{20}, \tag{3.101}$$

and

$$\dot{R}_{03} - \dot{R}_{30} = \frac{\mathrm{d}K_3}{\mathrm{d}t} - \sum_{i=1}^{3} \dot{R}_{i3} - \sum_{i=1}^{3} \dot{K}_{i3} + \sum_{j=1}^{3} \dot{R}_{3j} + \sum_{j=1}^{3} \dot{S}_{3j} + \sum_{j=1}^{3} \dot{K}_{3j} + \dot{K}_{30}. \tag{3.102}$$

Summing Eqs. 3.100–3.102, we obtain:

$$\begin{aligned} -\frac{\mathrm{d}R_0}{\mathrm{d}t} &= \sum_{j=1}^{3} \dot{R}_{0j} - \sum_{i=1}^{3} \dot{R}_{i0} \\ &= \frac{\mathrm{d}K_1}{\mathrm{d}t} + \frac{\mathrm{d}K_2}{\mathrm{d}t} + \frac{\mathrm{d}K_3}{\mathrm{d}t} - \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{R}_{ij} - \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{K}_{ij} + \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{R}_{ij} \\ &\quad + \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{S}_{ij} + \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{K}_{ij} + \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30}, \end{aligned} \tag{3.103}$$

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

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{j=1}^{3} \frac{\mathrm{d}K_j}{\mathrm{d}t} + \sum_{j=1}^{3}\sum_{i=1}^{3} \dot{S}_{ij} + \sum_{j=1}^{3} \gamma_{K_j} K_j, \tag{3.104}$$

or, more generally:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{j} \frac{\mathrm{d}K_j}{\mathrm{d}t} + \sum_{i,j} \dot{S}_{ij} + \sum_{j} \gamma_{K_j} K_j, \tag{3.105}$$

Similarly to what we saw in Examples A and B, Eq. 3.105 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 human-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

$$\left[\dot{S}_{00}\right]\left[\dot{S}_{01}\ \dot{S}_{02}\ \dot{S}_{03}\right]$$
$$\begin{bmatrix}\dot{S}_{10}\\ \dot{S}_{20}\\ \dot{S}_{30}\end{bmatrix}\begin{bmatrix}\dot{S}_{11} & \dot{S}_{12} & \dot{S}_{13}\\ \dot{S}_{21} & \dot{S}_{22} & \dot{S}_{23}\\ \dot{S}_{31} & \dot{S}_{32} & \dot{S}_{33}\end{bmatrix}$$

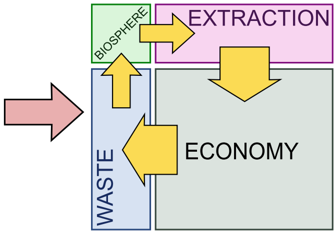

Fig. 3.6 The matrix of biosphere-economy flows. Note that flow $\dot{S}_{00}$ is not included within our framework

- Overcoming depreciation of human-made capital stocks ($\sum_j \gamma_{K_j} K_j$).

This implications of this result will be discussed in greater detail in Sect. 8.5 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 Fig. 3.6 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.

3.5 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:

- Currently available (e.g., economic value, Chap. 6 and direct energy, Chap. 4),
- Where it is old (e.g., energy intensity, Chap. 7), and
- Where it has never been available (e.g., materials, current chapter, and accumulated embodied energy, Chap. 5).

The US auto industry is, therefore, illustrative of the challenges inherent in obtaining data that would feed our framework.

Although our choice for using the auto industry is somewhat arbitrary, there are a number of compelling reasons for its selection. Automobile manufacturing has been used previously in the literature in both process-based [19–25] and Input-Output [26–28] analysis studies. The automobile boom was clearly central to the development of most Western countries during the Twentieth Century. Furthermore, the industry still remains a large portion of many industrialized economies. The automobile industry is a large consumer of material resources, some of which are listed below in Table 3.1.

Table 3.1 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 [22–25, 27, 28, 31, 32]. 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);
		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

The automobile has obvious links with the energy industry, both in the direct demand for energy used in automobile manufacture, and also indirectly for the refined oil products needed to operate vehicles. This dependence aptly demonstrates demand "lock-in," discussed in Sect. 1.4. The industry also shows evidence of postindustrial decline (shrinking profit margins, etc. as discussed in Chap. 1) and thus represents a sector-level analogy of the maturation and decline in growth of economies.

Thinking about the flows of resources, short-lived, and capital materials into the auto industry, we can say that 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 inflows and outflows 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 3.1. Data on the actual flow rates at the industry level is very hard to obtain.[19] 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 [29]. Work is ongoing to characterize the intersectoral flows of these materials [30] which can be analyzed by converting financial data (which is available, as discussed in Sect. 6.6) into physical flow data via knowledge of the entry points of materials into the economy, i.e., via the extraction industries.

Using EW-MFA data on materials, together with financial flows among sectors as a proxy for material flows, researchers could begin to understand the material intensity of different sectors of the economy in an analogous fashion to the manner in which energy input–output (EI–O) methods calculate energy intensities for sectors within the economy; to produce physical input–output (PI–O) tables [33]. Work is being done in this direction with the Environmental Input–Output Life-Cycle Assessment (EIOLCA) models (the model used in studies [27] and [28]), among others [34]. One issue with this approach is the assumption that financial flows are appropriate proxies for physical flows of materials and energy between sectors. Another short-coming of this approach is that materials accumulate within economic sectors. This sector accumulation is ignored by current PI–O methods, a short-coming of this book serves to address.

A number of studies, rather than looking at industry-level activity, have instead looked at the material and energy flows associated with specific or representative vehicle manufacturing *processes* [22–32]. 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[20] in the US [35]. In theory, a representation of the industry-level flows could

[19] The issue of lack of physical flow data is discussed in several places in this book, especially in Chap. 9.

[20] 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.

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. A problem with this product-focused approach is that the studies seldom account for material usage not directly associated with vehicle manufacturing process, for example, materials used in factory construction. That is, accumulation within the sector is neglected, and all inputs to the manufacturing process are incorrectly assumed to be physically embodied in the product [25]. This neglect provides additional impetus for the methodology presented in this book.

3.6 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 nonphysical 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 (Chap. 4) and embodied energy (Chap. 5).

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Chapter 4
Flows of Direct Energy

> *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 Chaps. 1 and 2, we showed that energy consumption is intimately linked to economic activity and deepened the metabolism metaphor for the economy. From the metabolism metaphor, we understand that the economy consists of producers and consumers who exchange goods and services and factors of production while extracting resources from and disposing wastes to the biosphere. In Chap. 3, we established the material basis of economies: economies 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 economic activity within an economy.

All forms of energy provide the potential[1] to do mechanical work.[2] 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 available 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.

[1] The quantification of the mechanical work potential of energy is *exergy*. When energy is "consumed" by an economy, exergy (work potential) is destroyed.

[2] Mechanical work is the product of a force and the distance through which it acts.

M. K. Heun et al., *Beyond GDP*, Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_4

The purpose of this chapter is to develop a framework for accounting energy flows within economies. To do so, we will employ the first law of thermodynamics which tells us that the quantity of energy is conserved in every process.[3] 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 (Chap. 5).

4.1 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 distinguish between "direct" energy and "embodied" energy, which will be discussed in Chap. 5. Examples of direct energy flows include the chemical potential energy of coal into 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 flows is an example of a "transfer in" or a "transfer out," in the language of Sect. 3.1.1. In each case, the material (coal, steam, and CO_2) carries direct energy with it. Figure 4.1 shows a corresponding direct energy flow for each material flow of Fig. 3.1.

For any boundary or control volume (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 ($\dot{Q}_{out}$). As discussed in Sect. 3.1.1, energy is conserved: it is neither created nor destroyed.

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \sum \dot{E} - \sum \dot{Q}_{out}. \tag{4.1}$$

[3] The first law does not speak about the quality of energy—not all forms of energy are equally *useful*. There are several ways to assess the quality of energy. Hammond and Winnett note the importance of the concept of *exergy* to describe the maximum physical work which can be performed by an energy resource as it comes into equilibrium with its environment [2].

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" [3, 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.

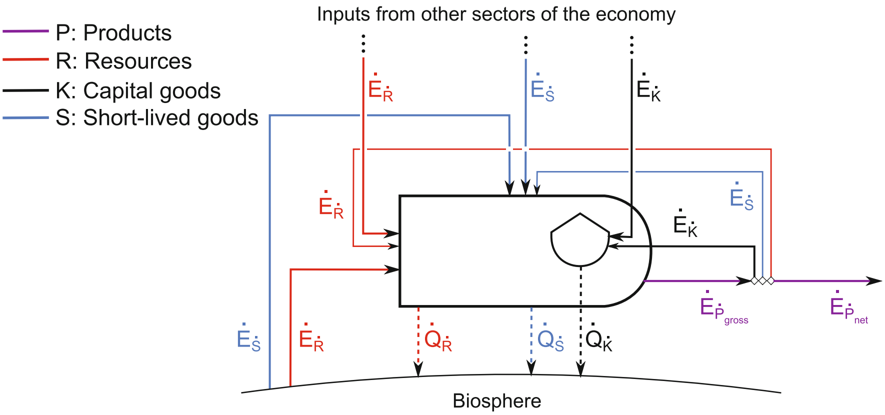

Fig. 4.1 Energy content ($\dot{E}$) of material flows ($\dot{R}$, $\dot{S}$, and $\dot{K}$) from Fig. 3.1

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

$$0 = \sum \dot{E} - \sum \dot{Q}_{out}, \tag{4.2}$$

and outgoing waste heat ($\sum \dot{Q}_{out}$) will balance incoming direct energy ($\sum \dot{E}$).

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 potential energy in steel that could be released upon combustion. However, the direct energy associated with 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 Chap. 5.) 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 Fig. 4.1 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 Fig. 4.1) can be summed to $\dot{E}$ (in Fig. 4.2) such that

$$\dot{E} = \dot{E}_{\dot{R}} + \dot{E}_{\dot{S}} + \dot{E}_{\dot{K}}. \tag{4.3}$$

4.2 Example A: Single-Sector Economy

Aggregated direct energy flows are now applied to Example A, the single-sector economy shown in Fig. 3.2. By summing the direct energy flows associated with each material flow of Fig. 3.2, we obtain a simplified picture of direct energy flows in the economy, as shown in Fig. 4.3.

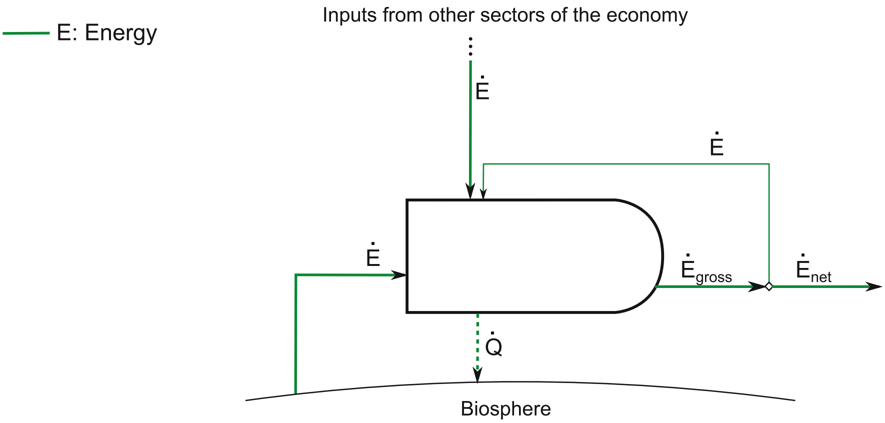

Fig. 4.2 Aggregated direct energy flows ($\dot{E}$) around the producer of Fig. 4.1.

We distinguish useful direct energy inputs to a sector of the economy ($\dot{E}_{01}$ in Fig. 4.3) from wasteful direct energy flows ($\dot{Q}_{10}$ in Fig. 4.3), because $\dot{Q}$ typically denotes thermal energy, and most waste energy is in the form of thermal energy, i.e., waste heat. In Fig. 4.3, 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 Sect. 4.1, 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

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \dot{Q}_{10} - \dot{E}_{01}, \tag{4.4}$$

and

$$\frac{\mathrm{d}E_1}{\mathrm{d}t} = \dot{E}_{01} + \dot{E}_{11} - \dot{E}_1 - \dot{Q}_{10}. \tag{4.5}$$

Note that $\dot{E}_1$ is the gross direct energy production rate of society. For example, firms extract crude oil from the biosphere (a component of $\dot{E}_{01}$) and refine it into petroleum products (which in Fig. 4.3, leave as part of flow $\dot{E}_1$) that are then consumed by society. The direct energy consumption of extraction and refining firms is a component of $\dot{E}_{11}$, that is some of the energy that circulates back into society in flow $\dot{E}_{11}$ is used within the extraction and refining processes to generate flow $\dot{E}_{01}$ from the biosphere.

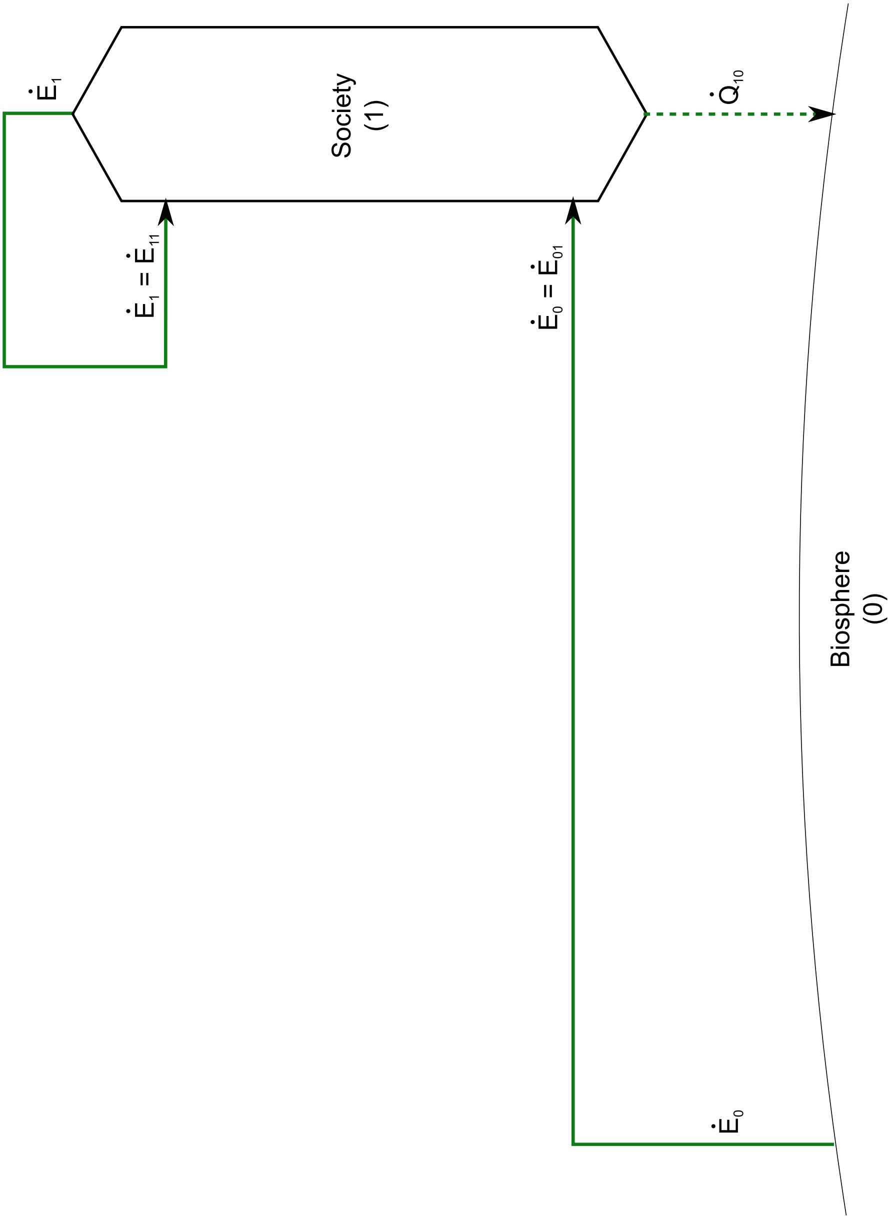

Fig. 4.3 Direct energy flows ($\dot{E}$) a one-sector economy

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.[4] (The world *is*, however, accumulating *embodied* energy in the economy as we shall see in Chap. 5.) Thus, the accumulation rates for direct energy $\left(\frac{dE}{dt}\right)$ in the above equations could be set to zero as follows:

$$0 = \dot{Q}_{10} - \dot{E}_{01}, \tag{4.6}$$

and

$$0 = \dot{E}_{01} + \dot{E}_{11} - \dot{E}_{1} - \dot{Q}_{10}. \tag{4.7}$$

However, we shall see later (in Chap. 5) that keeping direct energy accumulation terms $\left(\frac{dE}{dt}\right)$ provides an advantage when deriving embodied energy accounting equations.

4.3 Example B: Two-Sector economy

For Example B, we split Production (2) from Society (1). Figure 4.4 shows aggregated direct energy flows associated with the material flows of Fig. 3.4.

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

$$\frac{dE_0}{dt} = \dot{Q}_{10} + \dot{Q}_{20} - \dot{E}_{02}, \tag{4.8}$$

and

$$\frac{dE_1}{dt} = \dot{E}_{11} + \dot{E}_{21} - \dot{E}_{1} - \dot{Q}_{10}. \tag{4.9}$$

Note that $\dot{E}_{12}$ represents useful work that people and draft animals contribute to Production (2). Ayres and Warr [4, 5] 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

$$\frac{dE_2}{dt} = \dot{E}_{02} + \dot{E}_{12} + \dot{E}_{22} - \dot{E}_{2} - \dot{Q}_{20}. \tag{4.10}$$

[4] 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.

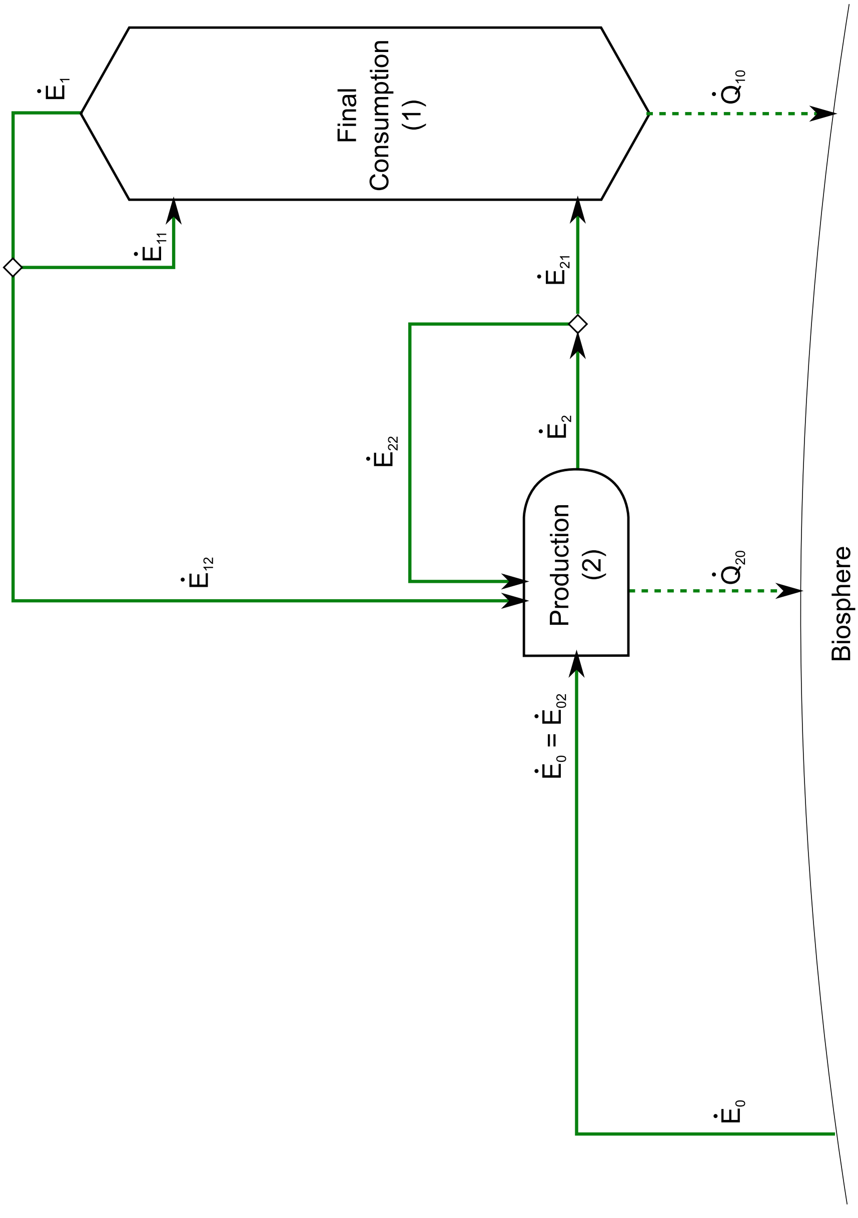

Fig. 4.4 Direct energy flows ($\dot{E}$) for a two-sector economy

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 is given by $\dot{E}_2 - \dot{E}_{12} + \dot{E}_{22}$. The *energy return on investment* (EROI) [6, 7] of the Energy sector (2) is given by

$$EROI_2 = \frac{\dot{E}_2}{\dot{E}_{12} + \dot{E}_{22}}. \tag{4.11}$$

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 many system boundary considerations. These issues are discussed thoroughly by both Murphy et al. [8] and Brandt et al. [9, 10] who outline several EROI ratios according to the factors 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 $\text{EROI}_{2,d}$ [8, Table 1] or GER_γ [11, Table 1], where GER stands for *gross energy ratio* an equivalent metric to EROI.

As discussed in Chap. 3, 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, to build the extra oil rigs necessary to maintain production levels.[5]

Equation (4.8) can be generalized with a sum as

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \sum_{i=1}^{n} \left(\dot{Q}_{i0} - \dot{E}_{0i}\right), \tag{4.12}$$

where n is the number of economic sectors in the accounting framework (in this example, $n = 2$). Similarly, Eqs. (4.9) and (4.10) can generalized with a sum as

$$\frac{\mathrm{d}E_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{E}_{ij} - \dot{E}_j - \dot{Q}_{j0}, \tag{4.13}$$

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

[5] This issue of resource quality will be revisited in Chap. 6.

4.4 Example C: Three-Sector Economy

We can extend Example B, to include a Goods and Services sector (3), thereby obtaining a fuller picture of direct energy flows among sectors (Fig. 4.5).

The first law of thermodynamics applied to the Biosphere (0), Society (1), and the Energy (2) gives

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \dot{Q}_{10} + \dot{Q}_{20} + \dot{Q}_{30} - \dot{E}_{02} - \dot{E}_{03}, \tag{4.14}$$

$$\frac{\mathrm{d}E_1}{\mathrm{d}t} = \dot{E}_{11} + \dot{E}_{21} + \dot{E}_{31} - \dot{E}_1 - \dot{Q}_{10}, \tag{4.15}$$

and

$$\frac{\mathrm{d}E_2}{\mathrm{d}t} = \dot{E}_{02} + \dot{E}_{12} + \dot{E}_{22} + \dot{E}_{32} - \dot{E}_2 - \dot{Q}_{20}. \tag{4.16}$$

The first law applied to 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

$$\frac{\mathrm{d}E_3}{\mathrm{d}t} = \dot{E}_{03} + \dot{E}_{13} + \dot{E}_{23} + \dot{E}_{33} - \dot{E}_3 - \dot{Q}_{30}. \tag{4.17}$$

Similar to Example B, we can generalize Eqs. (4.14–4.17) with sums to obtain

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{Q}_{i0} - \sum_{i=1}^{n} \dot{E}_{0i} \tag{4.18}$$

and

$$\frac{\mathrm{d}E_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{E}_{ij} - \dot{E}_j - \dot{Q}_{j0}, \tag{4.19}$$

where $j \in [1, n]$. Equations (4.18) and (4.19) are identical to Eqs. (4.12) and 4.13, 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 Eqs. 4.18 and (4.19) will be zero.

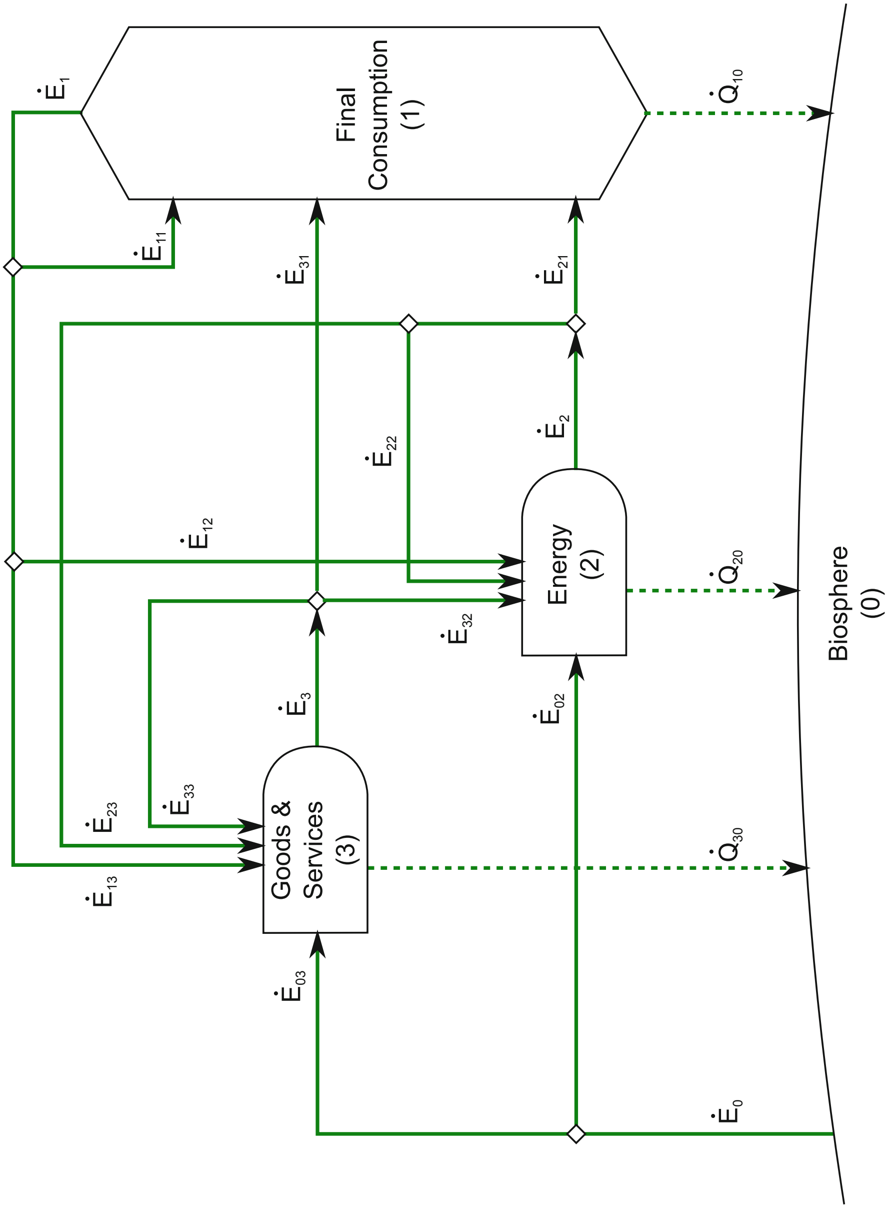

Fig. 4.5 Direct energy flows ($\dot{E}$) for a three-sector economy

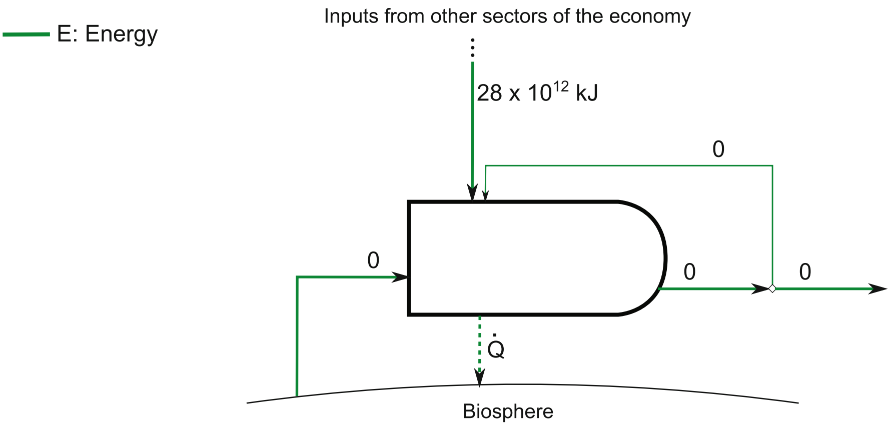

Fig. 4.6 Direct energy flows for the US automobile industry. [12, Table 7.6]

Table 4.1 Energy inputs to US auto industry (NAICS Code 336111) in 2010. [12, Table 7.6]

Source	Quantity	Energy content [kJ]
Electricity	3.0×10^9 kW-hr	10.8×10^{12} [a]
Natural gas	1.5×10^{10} ft^3	16.3×10^{12}
Other	1.0×10^{12} BTU	1.1×10^{12}
Total	2.8×10^{13} kJ (thermal equivalent)	

[a] Nonquality corrected value

4.5 Direct Energy in the Auto Industry

In this section, we discuss inflow of direct energy into the automobile industry as shown in Fig. 4.6. In 2010, the automobile industry purchased 28 trillion kJ of energy in total from all sources. Table 4.1 shows the breakdown of energy by source.

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) [13]. This estimate can be multiplied 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 1532 kg vehicle.

4.6 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 (Sect. 4.1). Examples A–C afforded the opportunity to apply the equations to analyze economies with increasing levels of disaggregation (Sects. 4.2–4.4). Finally, the energy flows for our running example, the US auto industry, were discussed in Sect. 4.5.

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 5
Stocks and Flows of Embodied Energy

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

In Chap. 1, we noted that manufactured capital is a significant driver of material and energy demand from the biosphere and that approaching limits to the extraction rate of materials may have negative effects on the economy. (See Sect. 1.3.2.) Systems of national accounts measure the level of manufactured capital and capital formation in financial terms, but the biophysical perspective shows that it is important to measure the level of capital on a physical basis, too.

One way to assess the level of manufactured capital on a physical basis is to estimate the energy *embodied within* that capital. Because capital is created using output from other economic sectors, it is necessary to estimate the energy embodied in products, too. The energy embodied in products (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. For example, upstream energy consumed by an auto parts supplier to fabricate windows will be embodied in the finished automobile. Embodied energy gives an indication of the energy demand from consumption of goods and services within an economy.

M. K. Heun et al., *Beyond GDP,* Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_5

In most cases, embodied energy is many times higher than the direct energy (Chap. 4) consumed by the final stage of the supply chain. In the case of energy production, the energy embodied in energy products (e.g., fossil fuels and food) can be significantly higher than the direct energy used by the production sector to create the energy product. This is true even for food production, where the embodied energy of processed foods can be about three times larger than its chemical energy content at the point of departure from the factory [2]. Distribution and cooking embody additional energy before it reaches the plate.

To assess the embodied energy of products and economic sectors, we will adapt the first law discussed in Chap. 4.[1]

Fundamentally, nearly all energy on earth comes from or came from the sun. In the framework for embodied energy that we develop below, we consider the embodiment of solar energy *after* its conversion to another energy form, e.g., fossil fuels, hydroelectricity, or solar PV electricity. Other approaches are possible. The *emergy* method counts all material flows in terms of *em*bodied solar en*ergy* [3, 4]. 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 [5]. The decision about solar energy is a boundary choice. Our choice to account post-solar embodied energy is consistent with the direct energy reporting practices of the International Energy Agency (IEA) and the US Energy Information Administration (EIA).

Embodied energy is a very useful way to assess the level of manufactured capital. First, we note that the machines, factories, and stores in which energy becomes embodied are essential for the efficient operation of any economic sector. A sector can't operate without its manufactured capital! Second, to first approximation, embodied energy is a good estimate of the energy that will be needed to replace depreciated capital. Third, we will need to know the embodied energy content of economic products to estimate energy intensity in Chap. 7. Fourth, 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 accumulation and flow 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 (Chap. 7).

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[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 derived from the laws of thermodynamics.

[2] The amount of energy embodied in an entire economy may be an indicator of its level of "development." See Sect. 8.3 for a discussion of several indicators of economic "development."

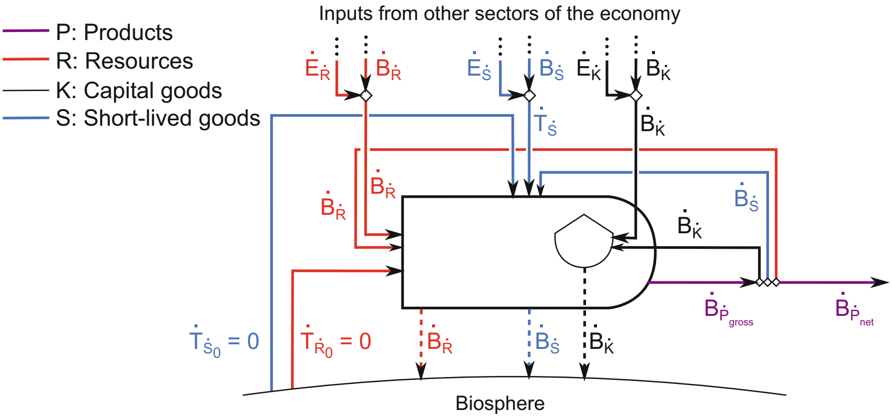

Fig. 5.1 Total energy flows ($\dot{T}$) for a single sector of an economy. For the sake of clarity, direct ($\dot{E}$) and embodied ($\dot{B}$) energy flows are shown separately for material inflows from other sectors only

5.1 Methodology

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

5.1.1 *Total Energy Accounting*

Total energy (T) is defined as the sum of direct energy (E, see Chap. 4) and embodied energy (B), which we will not define at present. This analysis will lead us to a mathematical definition of embodied energy.

$$T \equiv E + B \tag{5.1}$$

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 ($\dot{B}$).

$$\dot{T} = \dot{E} + \dot{B} \tag{5.2}$$

Figure 5.1 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 nonenergy 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 nonenergy 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) 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 [6, 7] applies the following (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:

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\mathrm{d}B}{\mathrm{d}t}. \tag{5.3}$$

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.

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \sum \dot{T} \tag{5.4}$$

By substituting Eqs. 5.2 and 5.3 into Eq. 5.4, we obtain

$$\frac{\mathrm{d}E}{\mathrm{d}t} + \frac{\mathrm{d}B}{\mathrm{d}t} = \sum \left(\dot{E} + \dot{B}\right). \tag{5.5}$$

[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 nonzero.

[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 quickly as we make it available to society.

5.1.2 Embodied Energy Accounting

We note that the definition of total energy (Eq. 5.1) includes direct energy (E) and embodied energy (B) terms. On the other hand, the first law of thermodynamics (Eq. 4.8) 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 (Eq. 4.8) into the total energy accounting equation (Eq. 5.5).

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \sum \dot{B} + \sum \dot{Q}_{out} \tag{5.6}$$

The waste energy terms ($\dot{Q}_{out}$) in Eq. 5.6 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

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \sum \dot{B}_{in} - \sum \dot{B}_{out} + \sum \dot{Q}_{out}. \tag{5.7}$$

In words, the rate of accumulation of embodied energy in a sector of the economy ($\frac{\mathrm{d}B}{\mathrm{d}t}$) 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 Eq. 5.7 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 Eq. 5.7 yields another version of the embodied energy accounting equation: One that illuminates issues related to stages of growth for an economic sector.

$$\sum \dot{B}_{in} + \sum \dot{Q}_{out} = \frac{\mathrm{d}B}{\mathrm{d}t} + \sum \dot{B}_{out} \tag{5.8}$$

From Eq. 5.8, 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 ($\frac{\mathrm{d}B}{\mathrm{d}t}$) 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 5.7 shows

[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.

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 5.7 and 5.8 highlight a contrast between our dynamic analysis and the EI–O literature. The traditional assumption of steady-state conditions in economic sectors is essentially assuming that $\frac{\mathrm{d}B}{\mathrm{d}t} = 0$ in Eqs. 5.7 and 5.8. That assumption precludes analysis of stages of growth and the embodied energy implications thereof.

Equations 5.7 and 5.8 are generalized embodied energy accounting equations that we will see again for Examples A–C in the sections that follow.

5.2 Example A: Single-Sector Economy

Figure 5.2 shows the flows of total energy ($\dot{T}$) through the single-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

$$\frac{\mathrm{d}T_0}{\mathrm{d}t} = \dot{T}_{10} - \dot{T}_{01}, \tag{5.9}$$

and

$$\frac{\mathrm{d}T_1}{\mathrm{d}t} = \dot{T}_{01} + \dot{T}_{11} - \dot{T}_1 - \dot{T}_{10}. \tag{5.10}$$

Substituting Eqs. 5.2 and 5.3 into Eqs. 5.9 and 5.10 yields

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} + \frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{E}_{10} + \dot{B}_{10} - \dot{E}_{01} - \dot{B}_{01} \tag{5.11}$$

and

$$\frac{\mathrm{d}E_1}{\mathrm{d}t} + \frac{\mathrm{d}B_1}{\mathrm{d}t} = \dot{E}_{01} + \dot{B}_{01} + \dot{E}_{11} + \dot{B}_{11} - \dot{E}_1 - \dot{B}_1 - \dot{E}_{10} - \dot{B}_{10}. \tag{5.12}$$

At this point, we can proceed in two directions. The first direction, simplifying Eqs. 5.11 and 5.12, provides an intuitive result. The second direction, substituting the first law of thermodynamics into Eqs. 5.11 and 5.12, provides the advantage of cancelling most of the direct energy terms. We begin with the first approach: simplification.

5.2.1 Simplification of the Embodied Energy Accounting Equation

To simplify Eqs. 5.11 and 5.12, 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

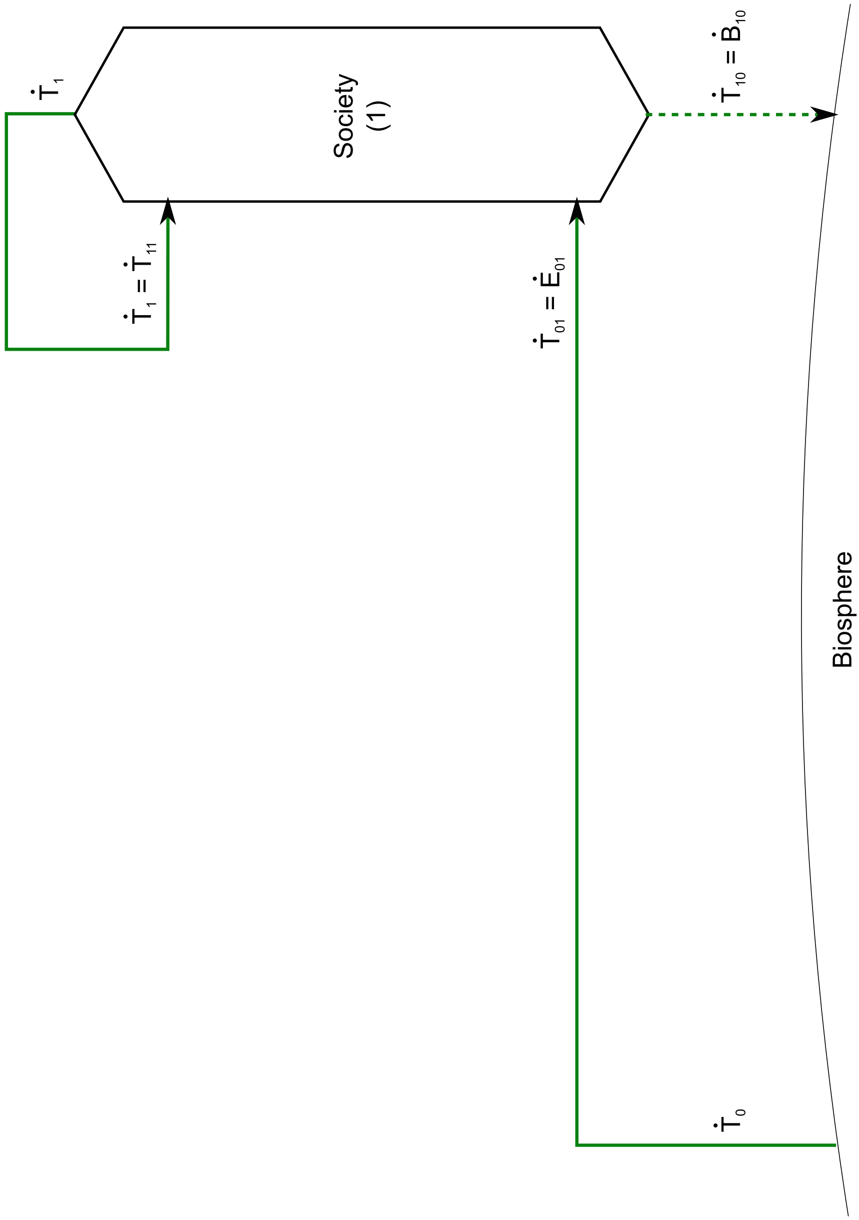

Fig. 5.2 Total energy flows ($\dot{T}$) in a one-sector economy

Fig. 5.2. Second, we can assume that direct energy (E) does not accumulate in the economy such that $\frac{dE_0}{dt} = 0$ and $\frac{dE_1}{dt} = 0$. Finally, we note that $\dot{E}_{10} = 0$, because society does not supply direct energy to the biosphere. Thus, Eqs. 5.11 and 5.12 become

$$\frac{dB_0}{dt} = \dot{B}_{10} - \dot{E}_{01} \tag{5.13}$$

and

$$\frac{dB_1}{dt} = \dot{E}_{01} + \dot{E}_{11} + \dot{B}_{11} - \dot{E}_1 - \dot{B}_1 - \dot{B}_{10}. \tag{5.14}$$

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.

5.2.2 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 (Eqs. 4.4 and 4.5) into the total energy accounting equations (Eqs. 5.11 and 5.12).

$$\frac{dB_0}{dt} = \dot{E}_{10} + \dot{B}_{10} - \dot{B}_{01} - \dot{Q}_{10} \tag{5.15}$$

$$\frac{dB_1}{dt} = \dot{B}_{01} + \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} - \dot{E}_{10} + \dot{Q}_{10} \tag{5.16}$$

This substitution has the advantage of cancelling 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 ($\frac{dE}{dt}$) is zero, because the $\frac{dE}{dt}$ term is cancelled by the substitution.

We can simplify Eqs. 5.15 and 5.16 using the assumptions of Sect. 5.2.1 (namely, that $\dot{B}_{01} = 0$ and $\dot{E}_{10} = 0$) to obtain

$$\frac{dB_0}{dt} = \dot{B}_{10} - \dot{Q}_{10} \tag{5.17}$$

and

$$\frac{dB_1}{dt} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} + \dot{Q}_{10}. \tag{5.18}$$

The material model of this framework (see Chap. 3) indicates that materials are comprised of resources (R), short-lived materials (S), and capital (K). Thus, we can write

$$\frac{dB_1}{dt} = \frac{dB_{R_1}}{dt} + \frac{dB_{S_1}}{dt} + \frac{dB_{K_1}}{dt}, \tag{5.19}$$

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

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \frac{\mathrm{d}B_{K_1}}{\mathrm{d}t}. \tag{5.20}$$

We can substitute Eq. 5.20 into Eq. 5.18 to obtain

$$\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} + \dot{Q}_{10}. \tag{5.21}$$

Equations 5.17 and 5.21 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 Sect. 5.2.1), because of the benefit of cancelling direct energy flow terms ($\dot{E}$).

5.2.3 Physical Depreciation

The term $\dot{B}_{10}$ in Eq. 5.21 represents the disposal rate of embodied energy from Society (1) to the Biosphere (0), i.e., depreciated physical assets. Figure 3.2 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

$$\dot{B}_{10} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \dot{B}_{\dot{K}_{10}}. \tag{5.22}$$

The term $\dot{B}_{\dot{K}_{10}}$ represents the energy embodied in depreciated physical assets. In this framework, 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

$$\dot{B}_{\dot{K}_{10}} = \gamma_{B_1} B_{K_1}, \tag{5.23}$$

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

[8] Note that γ_B will, in general, be different from γ_K defined in Sect. 3.2. 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.

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 5.23 can be substituted into Eq. 5.22 to obtain

$$\dot{B}_{10} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{B_1} B_{K_1}. \tag{5.24}$$

Equation 5.24 can be substituted into Eqs. 5.17 and 5.21 to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{B_1} B_{K_1} - \dot{Q}_{10} \tag{5.25}$$

and

$$\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{\dot{R}_{10}} - \dot{B}_{\dot{S}_{10}} - \gamma_{B_1} B_{K_1} + \dot{Q}_{10}. \tag{5.26}$$

Equation 5.26 indicates that the accumulation rate of embodied energy in an economic sector ($\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t}$) 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 ($\gamma_{B_1} B_{K_1}$).

As discussed in previous chapters, natural resource quality has a direct impact on both material and energy intensity of economic processes. The best-first principle (Sect. 1.3.2) indicates that 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 increase in the material and energy intensity of upstream sectors.[9] We turn now to Example B, a two-sector economy.

5.3 Example B: Two-Sector Economy

For the two-sector economy of Figs. 3.4 and 4.4, we again follow the EI–O literature by assuming that total energy (T) is conserved. Figure 5.3 shows total energy flows for the two-sector economy.

[9] This issue of resource quality will be revisited in Chap. 6.

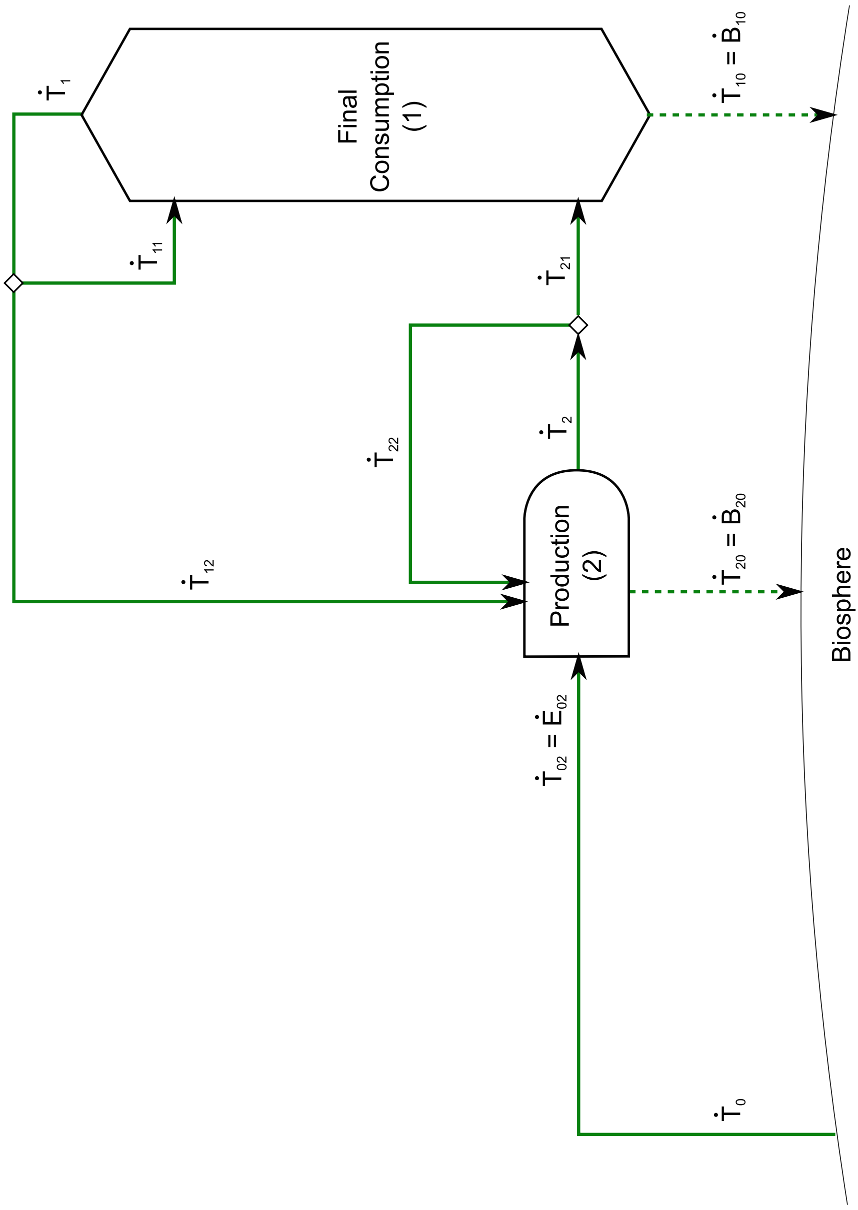

Fig. 5.3 Flows of total energy ($\dot{T}$) in a two-sector economy

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

$$\frac{\mathrm{d}T_0}{\mathrm{d}t} = \dot{T}_{10} + \dot{T}_{20} - \dot{T}_{02}, \tag{5.27}$$

$$\frac{\mathrm{d}T_1}{\mathrm{d}t} = \dot{T}_{11} + \dot{T}_{21} - \dot{T}_1 - \dot{T}_{10}, \tag{5.28}$$

and

$$\frac{\mathrm{d}T_2}{\mathrm{d}t} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} - \dot{T}_2 - \dot{T}_{20}. \tag{5.29}$$

Substituting Eqs. 5.2 and 5.3 into Eqs. 5.27 through 5.29 gives

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} + \frac{\mathrm{d}E_0}{\mathrm{d}t} = \dot{E}_{10} + \dot{B}_{10} + \dot{E}_{20} + \dot{B}_{20} - \dot{E}_{02} - \dot{B}_{02}, \tag{5.30}$$

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} + \frac{\mathrm{d}E_1}{\mathrm{d}t} = \dot{E}_{11} + \dot{B}_{11} + \dot{E}_{21} + \dot{B}_{21} - \dot{E}_1 - \dot{B}_1 - \dot{E}_{10} - \dot{B}_{10}, \tag{5.31}$$

and

$$\frac{\mathrm{d}B_2}{\mathrm{d}t} + \frac{\mathrm{d}E_2}{\mathrm{d}t} = \dot{E}_{02} + \dot{B}_{02} + \dot{E}_{12} + \dot{B}_{12} + \dot{E}_{22} + \dot{B}_{22} - \dot{E}_2 - \dot{B}_2 - \dot{E}_{20} - \dot{B}_{20}. \tag{5.32}$$

As in Example A, we can substitute the first law of thermodynamics (Eqs. 4.8–4.10) into the total energy accounting equations (Eqs. 5.30–5.32) and employ the assumptions that $\dot{E}_{i0} = 0$ and $\dot{B}_{0j} = 0$ to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \dot{B}_{10} + \dot{B}_{20} - \dot{Q}_{10} - \dot{Q}_{20}, \tag{5.33}$$

$$\frac{\mathrm{d}B_1}{\mathrm{d}t} = \dot{B}_{11} + \dot{B}_{21} - \dot{B}_2 - \dot{B}_{10} + \dot{Q}_{10}, \tag{5.34}$$

and

$$\frac{\mathrm{d}B_2}{\mathrm{d}t} = \dot{B}_{12} + \dot{B}_{22} - \dot{B}_2 - \dot{B}_{20} + \dot{Q}_{20}. \tag{5.35}$$

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 5.33–5.35 can be simplified using sums:

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{i0} - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{5.36}$$

and

$$\frac{\mathrm{d}B_j}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{ij} - \dot{B}_j - \dot{B}_{j0} + \dot{Q}_{j0}, \tag{5.37}$$

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 Eqs. 5.36 and 5.37 to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \sum_{i=1}^{n} \left(\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K_i}\right) - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{5.38}$$

and

$$\frac{\mathrm{d}B_{K,j}}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{ij} - \dot{B}_j - \left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j}\right) + \dot{Q}_{j0}. \tag{5.39}$$

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

5.4 Example C: Three-Sector Economy

Again, we begin with a diagram showing total energy ($\dot{T}$) flows among the economic sectors of Example C (Fig. 5.4).

Accounting for accumulation of total energy and applying the assumption that total energy is conserved, we can write the following equations. We start with the derivation in Sect. 5.3 and utilize sums for each equation below:

$$\frac{\mathrm{d}T_0}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{T}_{i0} - \sum_{j=1}^{n} \dot{T}_{0j} \tag{5.40}$$

and

$$\frac{\mathrm{d}T_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{T}_{ij} - \dot{T}_j - \dot{T}_{j0}. \tag{5.41}$$

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

Substituting Eqs. 5.2 and 5.3 into Eqs. 5.40 and 5.41 gives

$$\frac{\mathrm{d}E_0}{\mathrm{d}t} + \frac{\mathrm{d}B_0}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{E}_{i0} + \sum_{i=1}^{n} \dot{B}_{i0} - \sum_{j=1}^{n} \dot{E}_{0j} - \sum_{j=1}^{n} \dot{B}_{0j} \tag{5.42}$$

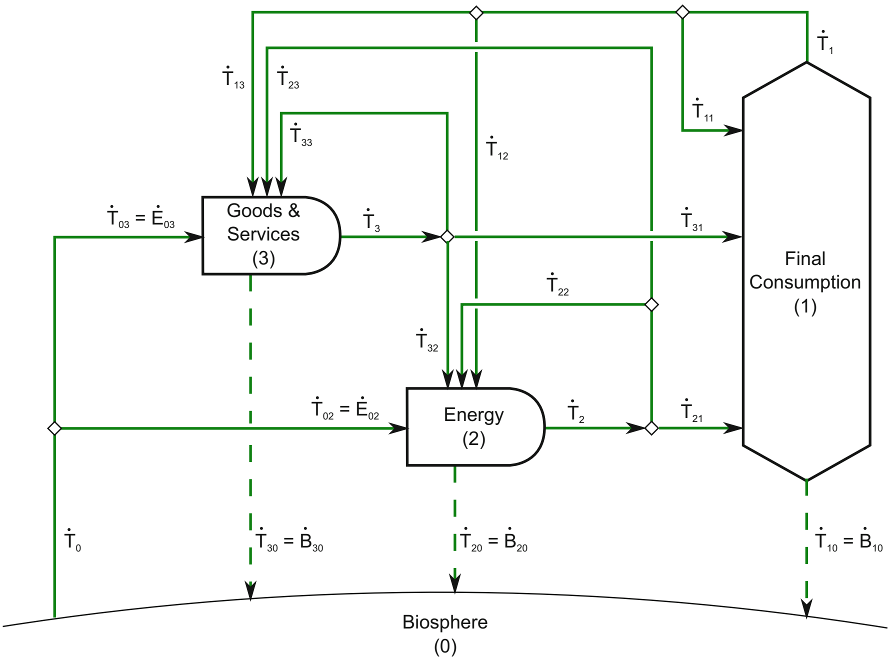

Fig. 5.4 Flows of total energy ($\dot{T}$) in a three-sector economy

and

$$\frac{\mathrm{d}E_j}{\mathrm{d}t} + \frac{\mathrm{d}B_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{E}_{ij} + \sum_{i=0}^{n} \dot{B}_{ij} - \dot{E}_j - \dot{B}_j - \dot{E}_{j0} - \dot{B}_{j0}. \tag{5.43}$$

Substituting the first law of thermodynamics (Eqs. 4.8 and 4.10) into the total energy accounting equations (Eqs. 5.42 and 5.43) 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:

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{i0} - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{5.44}$$

$$\frac{\mathrm{d}B_j}{\mathrm{d}t} = \sum_{i=0}^{n} \dot{B}_{ij} - \dot{B}_j - \dot{B}_{j0} + \dot{Q}_{j0} \tag{5.45}$$

As in Example B, we can disaggregate the accumulation and waste embodied energy terms and express physical waste of capital stock as depreciation in Eqs. 5.44 and 5.45 to obtain

$$\frac{\mathrm{d}B_0}{\mathrm{d}t} = \sum_{i=1}^{n} \left(\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K_i}\right) - \sum_{i=1}^{n} \dot{Q}_{i0} \tag{5.46}$$

and

$$\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{ij} - \dot{B}_j - \left(\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j}\right) + \dot{Q}_{j0}, \tag{5.47}$$

which are same as Eqs. 5.38 and 5.39, indicating that we have successfully generalized the embodied energy equations to an arbitrarily-large economy.

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})

$$\alpha_{B,j} \equiv \frac{\sum\limits_{i=1}^{n} \dot{B}_{ij}}{B_{K_j}} \tag{5.48}$$

and resource and short-lived material flows as waste

$$\dot{B}_{\dot{W}_j} \equiv \dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}}. \tag{5.49}$$

With the above definitions, Eq. 5.47 can be expressed as

$$\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t} = (\alpha_{B_j} - \gamma_{B_j})B_{K_j} - \dot{B}_{\dot{W}_j} - \dot{B}_j + \dot{Q}_{j0}. \tag{5.50}$$

With Eq. 5.50, we see that the rate of accumulation of embodied energy in the capital stock of an economic sector ($\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t}$) 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 ($\dot{Q}_{j0}$).

5.5 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 Fig. 5.5. As in Sect. 3.5, we face difficulties due to lack of data. We know that some flows will have zero value, as shown in Fig. 5.5. 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 Fig. 5.5) and capital flows ($\dot{K}$, black in Fig. 5.5) will have no direct energy ($\dot{E}$) associated with them,[10] because (a) energy" products enter the industry as short-lived flows ($\dot{S}$, blue in Fig. 5.5) and (b) 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.

[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.

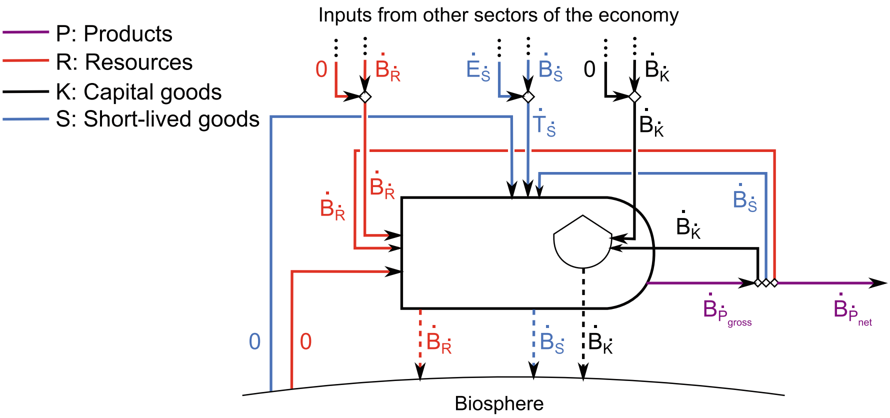

Fig. 5.5 Embodied energy flows ($\dot{B}$) for the US automobile industry

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–output analysis), to find that the energy cost of automobile manufacturing[11] in the US was 37,275 kW-hr (134 GJ or 134 $\times$ 10^9 J) per vehicle [8, 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 itself 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 [9, 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 within the auto sector) per vehicle [10, Fig. 2], which they compare with contemporaneous estimates from Sullivan of 81 GJ per vehicle [11] and Volkswagen of 62 GJ per vehicle [12].

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 [13–15].

[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 automobiles/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 Sect. 7.1 for details.

5.6 Summary

This chapter relies upon the results from Chap. 4 to develop equations that describe the flow of *embodied* energy ($\dot{B}$) through economies (Sect. 5.1). 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 Sects. 5.2–5.4. Finally, we discussed embodied energy in the context of our running example, the US auto industry (Sect. 5.5). We found that there are few historical estimates of energy embodied within automobiles, with a range of 62–134 GJ/vehicle.

In Chap. 6, we develop theory and equations to account for value flows though economies, leading (in Chap. 7) to techniques to estimate energy intensity of economic products.

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Part II
Economic Value and Energy Intensity

Chapter 6
Stocks and Flows of Economic Value

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

—Donella Meadows

In Chaps. 4 and 5, we noted that energy is the currency of thermodynamics, and we developed accounting equations for flows and accumulation of direct ($\dot{E}$ and $\frac{dE}{dt}$) and embodied ($\dot{B}$ and $\frac{dB}{dt}$) energy through an economy. In this chapter, we develop a framework for accounting value flows ($\dot{X}$) through economies. Accounting for flows and accumulation of economic value is routinely done in systems of national accounts, however, this chapter demonstrates that such accounting fits comfortably within the framework we have developed thus far (Chaps. 3–5). Accounting flows of value within our framework is a necessary step along the path to developing equations (in Chap. 7) to estimate the energy intensity (ε) of intermediate and final products within an economy.

6.1 Subjective Theory of Value

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 economic 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 (though imperfect) proxy for the value of the material and energy that exchanges hands from seller to buyer. Market transactions are easily documented, and the data to estimate the economic value of these flows is available in most countries [2].

Although the market price is readily available and conveys important information (such as scarcity and usefulness of the good to fulfill human wants relative to potential substitutes), we note that market price is subjective. Value is based on the agreement of a mutually acceptable price by the human trading partners. The market price is not a measure of any *intrinsic* value of the goods (e.g., for biodiversity 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].

M. K. Heun et al., *Beyond GDP,* Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_6

The subjective theory of value, while convenient and prevalent, does not provide market participants with complete information, a particularly troubling fact in the age of resource depletion. (See Sect. 1.5). The limitations of the subjective theory of value have been a philosophical concern to economists, and others, since the beginning of economics. Throughout history, economists (particularly the classicals) and noneconomists alike have searched for an invariant, objective, *intrinsic* determinant of value, one that is not reliant solely on human wants at a particular point in time.[1] Adam Smith, Karl Marx, David Ricardo, and neo-Ricardian Piero Sraffa, for example, have 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 as a numeraire, a way to measure value across the entire spectrum of goods and services in commensurate units.

More recently, some have proposed an *energy* theory of value. Costanza [4], in particular, 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]

Mainstream economics rejected the energy theory of value, as well as all earlier alternative theories of value, in favor of the subjective theory of value. However, as discussed in Sect. 1.5, the information and signals provided by markets and prices may not be sufficient for national accounting in the age of resource depletion. To paraphrase Herman Daly, national accounting focuses on measuring value-added, but it ignores "that to which value is being added" [5, p. 453]. Ignoring the value provided by natural capital distorts the measures of economic value provided by the subjective theory of value. In particular, ignoring "that to which value is being added" tends to overestimate gross domestic product (GDP). When easily accessible forms of energy (e.g., oil extracted from the Texas panhandle) are depleted and more difficult locations must be tapped (e.g., Alaskan north slope or the Gulf of Mexico), the economy appears to grow. The "value-added" by human and manufactured capital increases as humans must do more work to extract increasingly marginal energy resources. However, what is actually happening is that the stock of natural resources is diminishing in both quantity and quality, and the drawdown of natural capital is (mis)measured by GDP as an increase in income [3, p. 66 and 75].

As discussed in Chap. 1, when the level of the stock of "that to which value is added" (natural capital) declines, the economy begins to reach binding material

[1] Following the ecological economics literature, we use the term *intrinsic* in the sense of "objective." Costanza [4] notes that a better term would be objective, thereby avoiding 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 Chap. 5 for further discussion of the concept of *emergy*.

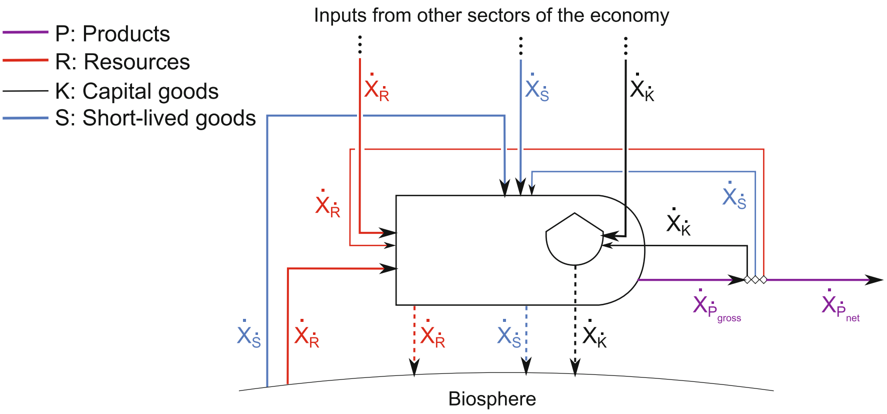

Fig. 6.1 Aggregated flows of value for a single sector, including flows to and from the biosphere

and energy constraints, and economic growth suffers. Thus, identifying the right economic scale—as represented by the rate at which materials are put through the economy—becomes an optimization problem. If the material throughput rate is too small, economies do not provide enough goods and services for society. If the material throughput rate is too high, the biosphere cannot replenish natural resources fast enough and binding constraints are reached with dire economic consequences. Unfortunately, this is an optimization problem that the market alone cannot solve.

Despite the considerable drawbacks to the subjective theory of value, using market transactions to confer economic value on flows of energy and material goods is widely accepted and understood, and better measures of value are difficult to implement. Thus, in the development of our framework, we use market prices at the time of transaction to determine the value of material and energy flows. However, we do so for pragmatic, rather than philosophical, reasons.

That being said, we also believe that our framework demonstrates the urgent need for additional valuation methods to be used alongside market prices to provide the information needed for national accounting in the age of resource depletion. The UN System of Environmental-Economic Accounting (SEEA)[3] provides a rigorous methodology to estimate the value of material and energy flows between the biosphere and the economy (see Fig. 6.1). Such a system should be used consistently by all nations to estimate the value of these flows, as depicted in the accounting framework

[3] As of this printing, the System of Environmental-Economic Accounting (SEEA) [6] is in its third edition, having been thoroughly reviewed and revised by a global consultation process. The SEEA contains internationally agreed-upon standards for quantifying the value of flows of material and energy between the economy and the biosphere. The SEEA is a system that is designed to work hand in hand with the System of National Accounts (SNA), the international standard for measuring economic value creation consistently across nations, and several OECD member states currently use the SEEA alongside their national accounting.

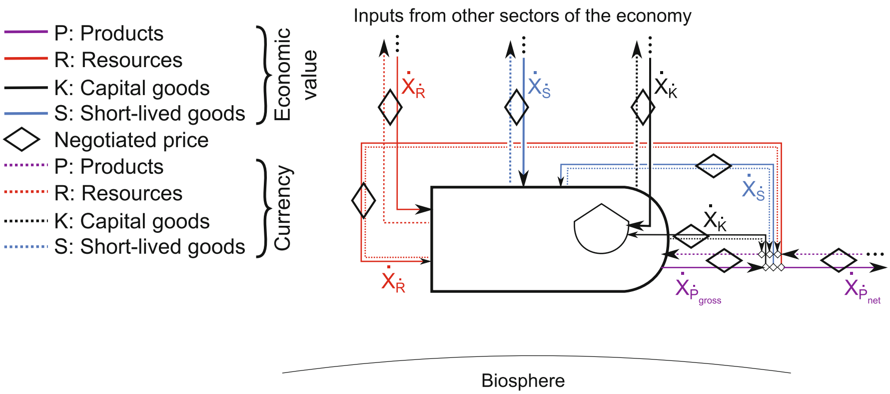

Fig. 6.2 Flows of economic value ($\dot{X}$) for a single sector. The economic value flows are associated with each of the different material and energy flows outlined in previous chapters. The *dashed lines* represent the equal and opposite flows of the currency used to pay for the material and energy

below. Without SEEA, or something similar,[4] these flows cannot be valued. Thus, those flows are conspicuously absent from the model for the flow of economic value presented in the next section (See, e.g., Fig. 6.2).

6.2 Methodology

Because the basic unit of analysis in our framework is the economic sector, flows of value within the economy are based on the prices from intersectoral market transactions. The flows of value that accompany material and energy flows in and out of one sector in an economy are depicted in Fig. 6.2. The solid lines represent flows of economic value whose direction is the same as the flow of material and energy. The dashed lines represent the equal and opposite flows of currency used to pay for the material and energy.[5] The negotiated price diamonds (also seen in Figs. 2.1, 2.2, and 2.3) indicate that the economic value of material and energy flows is set by agreement between buyers and sellers, the subjective theory of value.

As mentioned in the discussion of the subjective theory of value in Sect. 6.1, today's national accounting focuses on measuring value-added. We denote creation and destruction of value within a sector using the notion of "source" and "sink." In Fig. 6.3, the open circle, "source," inside the economic sector represents the

[4] As described in the Prologue, the US BEA developed its analogous methodology in the early 1990s, the Integrated Environmental Economic System of Accounts (IEESA), but has been politically hamstrung for over 20 years from publishing the data.

[5] Because the currency lines clutter the diagram, we will omit currency flows from all following diagrams in this chapter.

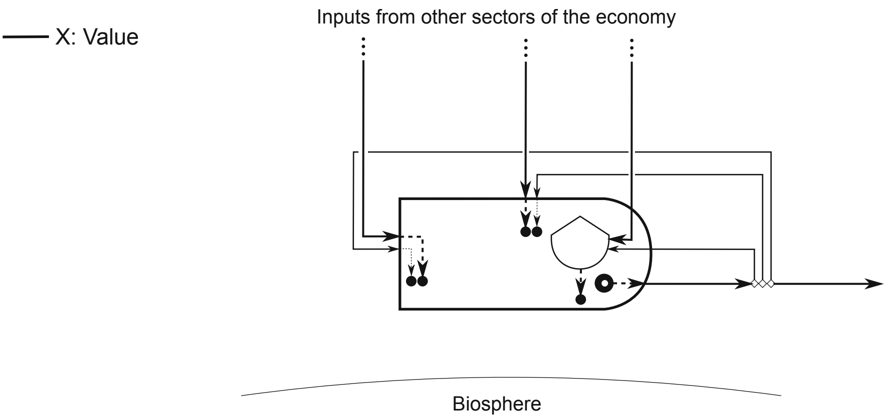

Fig. 6.3 Aggregated flows of value ($\dot{X}$) for a single sector. Distinction is made between value flows that enter the sector and are accumulated (i.e., capital goods) and value flows that are not accumulated. Within the sector there is destruction of value $\dot{X}_{dest}$, represented by the *downward arrow* flowing into the filled-circle sinks and generation of value, represented by the *arrow* flowing out of an open-circle source

value-added, that is, the value that is created by the economic processes within that sector. Flows of economic value from a value-source are denoted $\dot{X}_{gen}$. Similarly, filled circles represent the value "sinks" where value is destroyed by economic processes or natural disasters. Flows of economic value into a value-sink 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 Sect. 6.3.2.

6.3 Example A: Single-Sector Economy

Figure 6.4 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 an extraction industry. Value flows are independent from wastes, because wastes, by definition, have no economic value upon leaving the economy.

The contrast between the biophysical picture (as represented in Figs. 3.2 and 4.3) on the one hand, and the conventional viewpoint of economics (as represented in Fig. 6.4) on the other, is striking. The biophysical picture of material and energy flows in Figs. 3.2 and 4.3 emphasizes interaction with and dependence upon the biosphere that is not reflected in the typical economic model of value flows depicted in Fig. 6.4. As discussed in Sect. 6.1, the isolation of the value flows from the

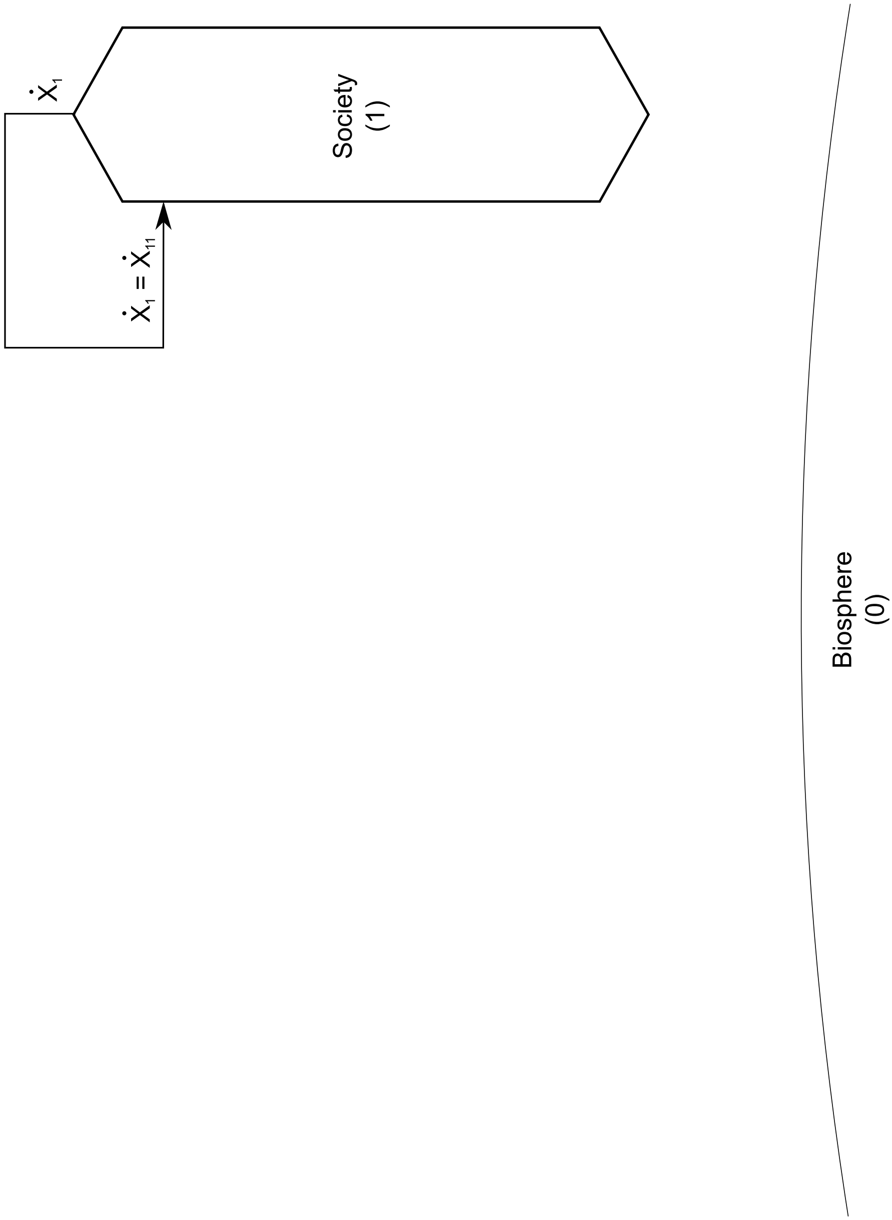

Fig. 6.4 Flows of value ($\dot{X}$) for a one-sector economy

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 6.1 describes the accumulation of value (X) in Society (1).

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = \dot{X}_{11} - \dot{X}_1 + \dot{X}_{gen,1} - \dot{X}_{dest,1} \tag{6.1}$$

The following subsections discuss the terms in Eq. 6.1.

6.3.1 Economic Transactions ($\dot{X}_{11}$ and $\dot{X}_1$)

The returning arrow in Fig. 6.4 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 (Sect. 6.1) posits that buyers and sellers agree on value at the time of the transaction. Thus, $\dot{X}_1 = \dot{X}_{11}$, and Eq. 6.1 simplifies to

$$\frac{\mathrm{d}X_1}{\mathrm{d}t} = \dot{X}_{gen,1} - \dot{X}_{dest,1}, \tag{6.2}$$

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.

6.3.2 Value Generation ($\dot{X}_{gen}$)

In Eq. 6.1, the value generation term ($\dot{X}_{gen}$) is akin to growing apples. The term $\dot{X}_{gen}$ 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.

Much of the value added that is attributed to the manufacturing process was actually value provided by natural capital, at no monetary cost to producers. For example, in Sect. 3.1, the apples that are produced would be counted in national accounting as value added by capital and labor, when in reality, the value is provided by the biosphere and natural capital, including:

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

6.3.3 Value Destruction ($\dot{X}_{dest}$)

In Eq. 6.1, 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 Sect. 3.1). 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.

$\dot{X}_{dest}$ is accounted as depreciation, or "consumption 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].

6.3.4 GDP

If Society (1) in Fig. 6.4 represents the economy of an entire country, $\dot{X}_1$ is its GDP in units of \$/year. Although GDP is often considered a stock, it is not. It is a flow. 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 measured directly by money.

6.4 Example B: Two-Sector Economy

Figure 6.5 shows flows of value ($\dot{X}$) within a two-sector economy. Again, we note the isloation of the economy from the biosphere.

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

$$\frac{dX_1}{dt} = \dot{X}_{11} + \dot{X}_{21} - \dot{X}_1 + \dot{X}_{gen,1} - \dot{X}_{dest,1}, \tag{6.3}$$

and

$$\frac{dX_2}{dt} = \dot{X}_{12} + \dot{X}_{22} - \dot{X}_2 + \dot{X}_{gen,2} - \dot{X}_{dest,2}. \tag{6.4}$$

Equations 6.3 and 6.4 can be generalized as

$$\frac{dX_j}{dt} = \sum_{i=1}^{n} \dot{X}_{ij} - \dot{X}_j + \dot{X}_{gen,j} - \dot{X}_{dest,j}, \tag{6.5}$$

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

6.5 Example C: Three-Sector Economy

Figure 6.6 shows flows of value ($\dot{X}$) within a three-sector economy.

The equations representing flows of value in Example C are:

$$\frac{dX_j}{dt} = \sum_{i=1}^{n} \dot{X}_{ij} - \dot{X}_j + \dot{X}_{gen,j} - \dot{X}_{dest,j}, \tag{6.6}$$

where n is the number of sectors in the economy, and $j \in [1, n]$. Equation 6.6 is identical to Eq. 6.5. If we sum the value accounting equations for the entire economy, we obtain

$$\sum_{j=1}^{n} \frac{dX_j}{dt} = \sum_{j=1}^{n}\sum_{i=1}^{n} \dot{X}_{ij} - \sum_{j=1}^{n} \dot{X}_j + \sum_{j=1}^{n} \dot{X}_{gen,j} - \sum_{j=1}^{n} \dot{X}_{dest,j}. \tag{6.7}$$

With the identities

$$\dot{X}_j = \sum_{k=1}^{n} \dot{X}_{jk} \tag{6.8}$$

and

$$\sum_{j=1}^{n} \dot{X}_j = \sum_{j=1}^{n}\sum_{k=1}^{n} \dot{X}_{jk} = \sum_{i=1}^{n}\sum_{k=1}^{n} \dot{X}_{ik} = \sum_{i=1}^{n}\sum_{j=1}^{n} \dot{X}_{ij} = \sum_{j=1}^{n}\sum_{i=1}^{n} \dot{X}_{ij}, \tag{6.9}$$

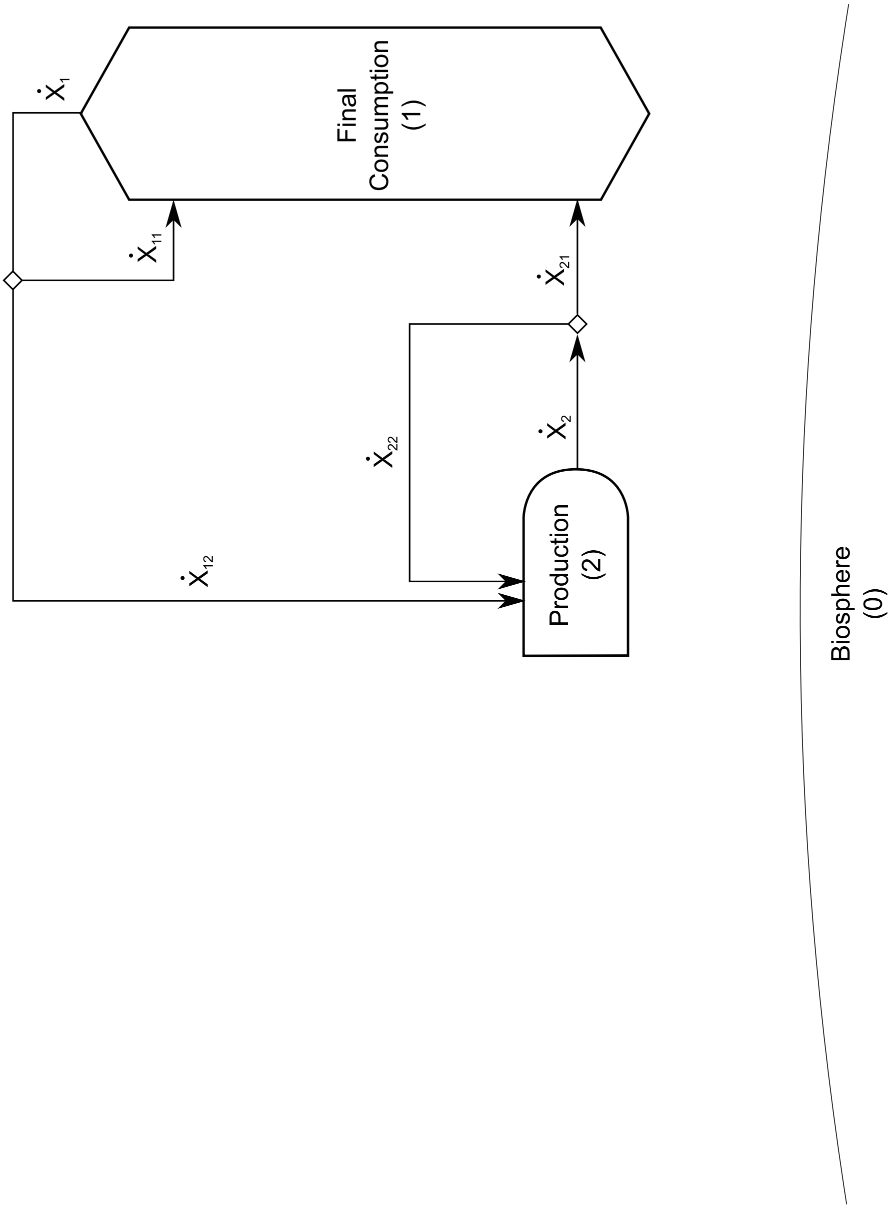

Fig. 6.5 Flows of value ($\dot{X}$) within a two-sector economy

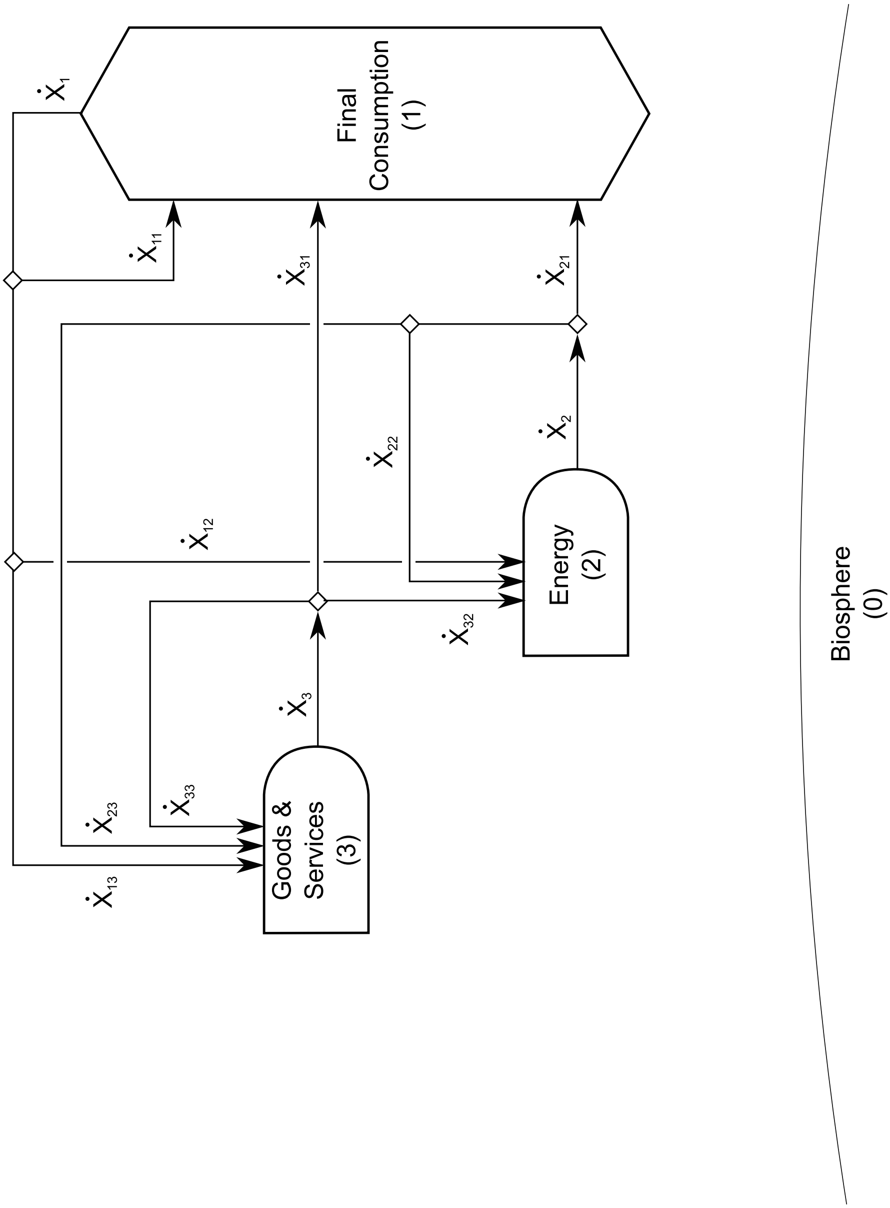

Fig. 6.6 Flows of value ($\dot{X}$) within a three-sector economy

Eq. 6.7 becomes

$$\sum_{j=1}^{n} \frac{\mathrm{d}X_j}{\mathrm{d}t} = \sum_{j=1}^{n} \dot{X}_{gen,j} - \sum_{j=1}^{n} \dot{X}_{dest,j}, \tag{6.10}$$

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 6.10 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].

6.6 Stocks and Flows of Economic Value in the US Auto Industry

To estimate value flows through the automobile industry, we use publicly available data from the US BEA.[6] The tables needed to estimate dynamic value flows and capital accumulation within the economy are primarily the KLEMS[7] intermediate use tables and the fixed asset, nonresidential 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.

The KLEMS intermediate use data are categorized in the same way as the input flows in our framework. The total material inputs into the auto industry (IOC 3361 MV) 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 ($\dot{X}_{\dot{P}_{net}}$).

The capital flow ($\dot{X}_{\dot{K}}$) values represent the flows of physical capital which are calculated as the sum of the equipment and structures categories from the fixed assets tables. The first number is the value for physical capital flows only; the number in parentheses, and denoted "w/ R&D," adds in flows of intangible capital assets from the intellectual property category on the fixed assets table. The importance of this distinction is discussed below.

Figure 6.7 populates the flows of economic value figure with these data for the US auto industry. This example illustrates that our framework can be combined with national accounting data to provide estimates of the flows of economic value for a typical industrial sector. In general, all of the data needed to calculate the matrix

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

[7] KLEMS is an acronym for capital (K), Labor, Energy, Materials, and Services.

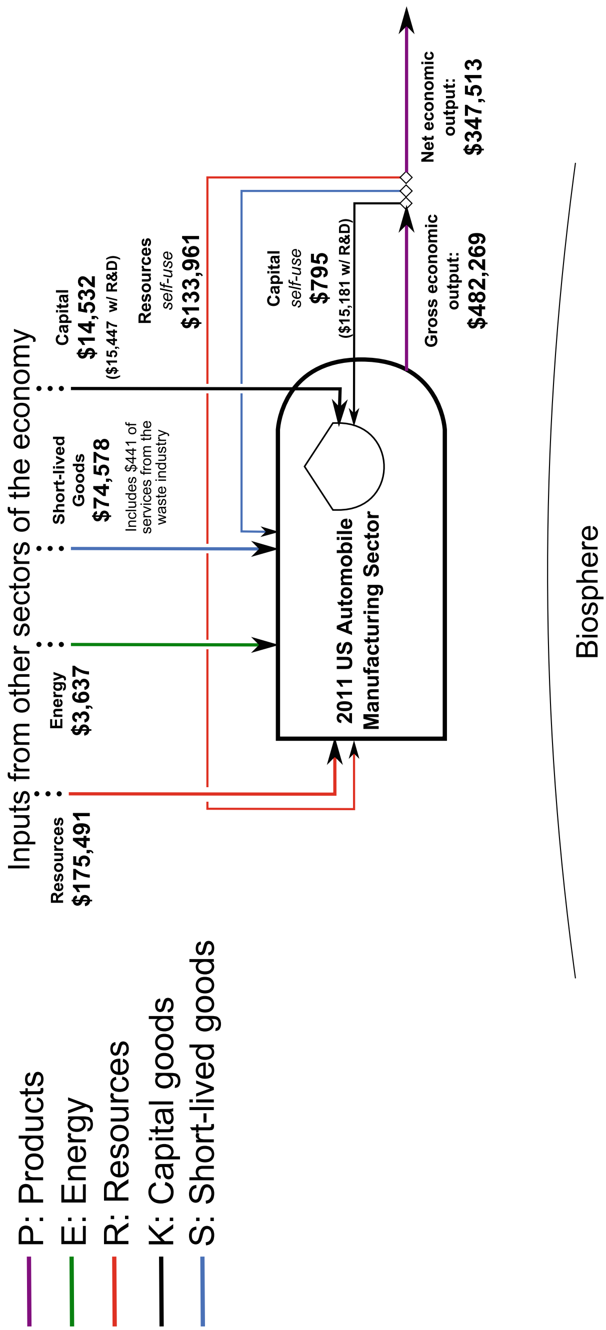

Fig. 6.7 Value of material and energy flows into and out of the US automobile industry (in millions of 2011 US$)

Table 6.1 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	3,367	2011 KLEMS total energy inputs
Short-lived goods	74,578	2011 KLEMS total services inputs
Capital	14,532	2011 Fixed assets 2011 (nonresidential detailed estimates)
Gross economic output	482,269	2011 Input-output use tables
Resources (self-use)	133,961	2011 Input-output use tables
Short-lived goods (self-use)	0	2011 Input-output use tables
Capital (self-use)	795	2011 Fixed assets (nonresidential detailed estimates)
Net economic output	347,513	Authors' calculations

of intersectoral flows of economic value for the economy are publicly accessible, and the mapping from the national accounts to our framework is straightforward. Table 6.1 contains a brief summary of the data sources that were used to obtain the values in Fig. 6.7. Appendix A contains detailed calculations and sources of data.

Another issue that the auto industry example in Fig. 6.7 highlights is the evolution of the treatment of capital in national accounts. Note the difference between the two values for self-use capital flows: $ 795 million in flows of physical capital only and $ 15,181 million in flows that include research and development (R&D). In the case of the auto industry, and most industries in general, this difference is an order of magnitude. The larger figure ($ 15,181 million) includes intellectual property assets and is consistent with the current official definition of Fixed Assets in the US national accounts.

The expansion of the definition of fixed assets by the BEA reveals a continual evolution away from physical capital to intangible capital in the BEA's measurement of US capital stock. Until the mid-1990s, fixed assets included only manufactured, physical assets: equipment and structures. In 1996, the BEA expanded the definition to include software. Doing so added about $ 174 billion to the nation's private fixed asset account and $ 56 billion to the nation's public fixed asset account, less than 1% of $ 23.8 trillion in stock of fixed assets at the time [11, p. 20].

In 2013, the BEA fundamentally revised the definition of fixed assets again to include R&D, as well as production of creative works, such as art, music, and long-running television shows. These types of assets, along with software, were combined together into a sub-category in the fixed assets account labeled "Intellectual Property" [12]. The fixed assets tables were revised retrospectively to conform to the new definition. In 2012, intellectual property accounts for approximately 11 % of the nonresidential, private fixed investment ($ 3.4 trillion (line 20) out of $ 32.1 trillion total private and government nonresidential fixed assets (line17)). For comparison, the $ 3.4 trillion in value the US places on intellectual property is more than half the value the nation ascribes to its stock of Equipment for the same year ($ 6.6 trillion (line 18)) [13].

We are concerned that the evolution of the definition of capital assets is indicative of an ill-timed tendency for national accounting to be revised toward measurement of intangible assets. Does this reflect an underlying belief that the country can invent its way out of having to face biophysical limits to the economy? If so, we believe that this approach will lead to the inability to both (a) assess the biophysical reality of the economy and (b) develop effective policies in the age of resource depletion.

Today, the limited, and dwindling, budget allocated toward national accounting in the US is being steered toward rigorous and time-consuming valuation of intangible (albeit financially valuable) assets and away from assessment of biophysical reality. The satellite accounts that once captured estimates of environmental economic data were shelved by order of Congress (see the Prologue) and replaced by R&D satellite accounts, which have been permanently integrated into national accounts. The evolution of the definition of capital assets in US national accounting is not commensurate with a direction that will lead to effective policy in the age of resource depletion.

6.7 Summary

In this chapter, we developed techniques to account for flows of economic value ($\dot{X}$) through economies (Sect. 6.2). 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 Sects. 6.3–6.5. 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 industry (Sect. 6.6).

It is important to note at this point that, in contrast to materials and energy, we found that there is no lack of data on value flows to and from industry sectors available from the US BEA. The value flows are relatively easily derived from the data captured at the point of sale in market transactions. However, the US BEA has no values for material and energy flows *to and from the biosphere*, and we are concerned that the evolution of the definition of capital assets will not lead to effective policy for the age of resource depletion.

In Chap. 7, we combine results from Chaps. 4, 5, and 6 to develop techniques to estimate the energy intensity of economic products.

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Chapter 7
Energy Intensity

Accounting systems change behavior.
—unknown NASA JPL accountant

At the end of Chap. 1, we noted that in the age of resource depletion, routine dissemination of information regarding energy, embodied energy, and energy intensity would provide firms and consumers with better information to navigate the age of resource depletion. To that end, we developed equations that describe the flow and accumulation of direct energy, embodied energy, and economic value within an economy in Chaps. 4, 5, and 6. In this chapter, we merge energy and economic value together to estimate the energy intensity (ε) of economic sectors, measured in joules per dollar.[1]

7.1 Background

Input–output (I–O) analysis, developed by Wassilly Leontief in the 1930s as an extension to the work of Quesnay and Walras [2], is of primary importance in national accounting. The method allows for the investigation of economic interdependencies within the economy, i.e., how much economic activity in each sector of the economy is used to generate a product consumed by "final demand." The traditional Leontief method relies upon financial quantifications of flows of value through an economy.

The basic premise of the I–O method, as depicted in Fig. 7.1a, is that each economic sector takes in factors of production from other sectors (and possibly itself) to produce an economic good at some rate.[2] For example, the automotive sector takes in steel, rubber, glass, etc., and produces a number of cars per year. In contrast to high-level economic growth models that include only a few factors of production (such

[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."

[2] Note that Fig. 7.1a is similar to the clockwork metaphor and traditional model of the economy discussed in relation to the era of abundance in Sect. 2.1.1.

M. K. Heun et al., *Beyond GDP,* Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_7

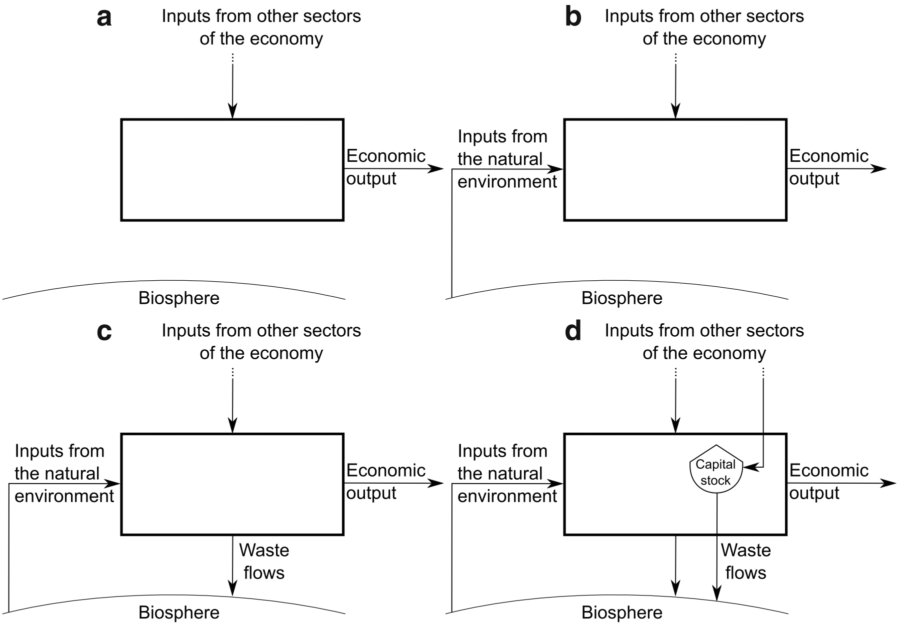

Fig. 7.1 The basic unit of input–output analysis: **a** the standard economic approach includes only transactions among sectors of the economy, **b** the energy input–output (EI–O) method allows inputs from the natural environment to be factors of production, **c** including waste flows to the environment makes the model physically consistent, and **d** the framework developed and presented herein accounts also for accumulation in capital stock (K) of embodied energy within materials in economic sectors

as land, capital, and labor),[3] the I–O analysis technique allows many differentiated factors of production and raw material feedstocks [3]. This is important, because, in reality, each economic process exists in a complex network of interacting processes that comprise 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" [1, p. 281]. Figure 7.2 shows that every process calls on every other process within the economy, even if only minutely and indirectly at many steps removed.

As discussed in Chap. 2, the oil shocks of the 1970s spurred great interest in the important role of energy in economic production. In addition to the productive services provided by stocks of capital and labor, a flow of energy[4] is required for economic activity. These energy flows originate from the biosphere, recognition of

[3] The traditional primary factors of production (land, capital, and labor) are not *flows* into the production processes. Rather, they are *stocks* that, when present, allow factors of production (steel, rubber, and glass) to be transformed into final products (automobiles). The quantity and quality of these stocks determine the quantity and quality of their flow of productive services.

[4] Or, more precisely, the degradation of an exergetic gradient/destruction of exergy.

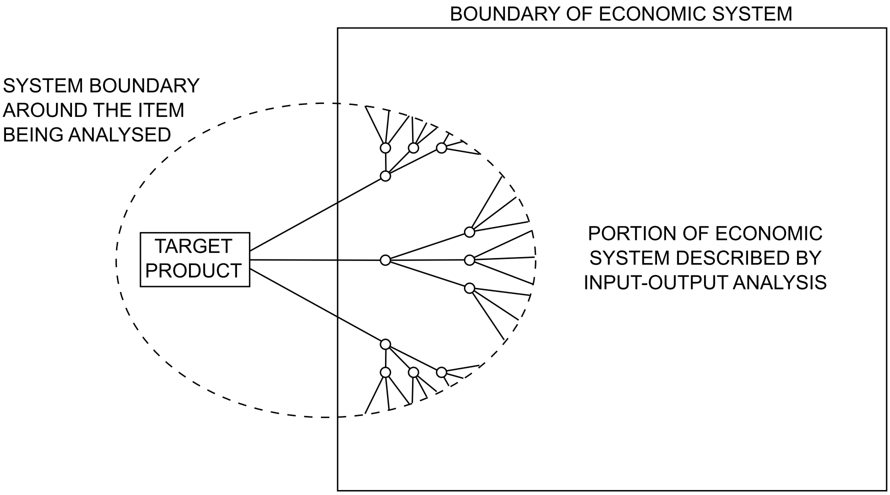

Fig. 7.2 System boundary for process and I–O analyses. (Adapted from [1])

which prompted researchers from the field of net energy analysis (NEA) to extend the traditional Leontief input–output method to include important energy flows from the environment, developing an energy input–output (EI–O) method as depicted in Fig. 7.1b[5] [3–10]. While the Leontief input–output method relies exclusively on monetary units to represent flows of economic value among sectors of an economy, the EI–O method relies upon physical units (especially energy units of joules) to represent some of the flows among economic sectors. In doing so, energy intensities (ε) of products can be estimated in a manner that includes the "upstream" energy consumed in the supply chain.

When applying the EI–O method, it is important to clearly define what counts for energy input to a sector of the economy. The early pioneers of the EI–O method counted only post-solar (i.e., fossil fuel) energy inputs to the economy, in a manner similar to our approach as discussed in the introduction to Chap. 5. About a decade later, Costanza [11] 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 [3, 12] did not include solar input to the economy.

Whether solar input to the economy should be included in an EI–O analysis within a materials, energy, and economic value accounting framework is dependent upon the objectives of the analysis. The motivation for this particular book is primarily the effects of declining energy natural resource quality on industrialized economies in the age of resource depletion. As such, inclusion of solar flows is probably

[5] Note that Fig. 7.1b is similar to the machine metaphor and engine model from the era of energy constraints discussed in Sect. 2.1.2.

unnecessary. However, expanding the framework to include nonindustrialized or agrarian societies may require accounting for solar energy flows.[6]

The early EI–O method assumed that each economic sector makes a single product ($\dot{P}$) [13]. In later years, the EI–O method was extended in the literature to include coproducts for each economic sector [8, 12]. To do so, both *make* and *use* data must be employed.[7] For the purposes of simplicity, we decided to leverage the older, single-product formulation of the EI–O method. 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. Recent work has shown that converting between the single-product and make-use forms of the EI–O method is possible [14].

The EI–O method can be considered a "top-down" analysis approach for estimating energy intensity. An alternative, "bottom-up" approach, that we will discuss here briefly but not employ in this book, consists of detailed, process-based analysis of specific economic processes. Process analysis calculates the energetic and material flows associated with the process under study by disaggregating the process into several components or subprocesses. Model specification and data collection for process analysis is arduous, time-consuming, and costly. Obviously, the time, effort, and cost involved with trying to model and measure all of the flows in process analysis becomes daunting for even low numbers of interacting processes. The decision of where to draw the boundary of a process analysis is known in the lifecycle assessment literature as the *truncation problem* [15]. A comparison of the top-down and bottom-up approaches is provided in Fig. 7.3. For the purposes simplicity, we focus on top-down EI–O methods in this book.[8]

Both the original Leontief input–output method (Fig. 7.1a) and the EI–O extension cited above (Fig. 7.1b) assume steady-state conditions in an economy, i.e., flows of material, energy, and economic value into and out of each economic sector are in balance. Wastes are not present, and dynamic or transient behavior of the economic system is not considered. Thus, in the EI–O analysis technique, there is no accumulation of economic factors or embodied energy within any of the sectors.

The EI–O approach provides "snapshots" of economic activity at an instant in time, but its model is incomplete. Figures 7.1c and d show that wastes exist and materials

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[6] In our framework, solar energy flows could be accounted as short-term ($\dot{S}$) flows for agricultural and forestry sectors and for 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. See the introduction to Chap. 5 for a short discussion of another approach: emergy.

[7] The *make-use* method is sometimes also called the *supply-use* method.

[8] It is possible to pursue hybrid top-down and bottom-up analysis methods. The hybrid approach utilizes data from an EI–O analysis to supplement the missing data from truncation of a 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 [1]. A variety of other hybrid methods exist which also aim to overcome the limitations of either process or I–O methods [1, 15–18].

Fig. 7.3 Advantages (pros) and disadvantages (cons) of "*top-down*," I–O and "*bottom-up*," process-based analyses. (Adapted from [19].)

	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

can accumulate in economic sectors as manufactured capital.[9] In fact, assuming no accumulation of materials, within economic sectors or society itself, is tantamount to assuming that *all* material flows through the economy are directed toward the production of nondurable goods. However, evidence of the durability of goods and the accumulation of materials surrounds us. Furthermore, energy was required to both fabricate and emplace the durable goods and infrastructure of modern economies.[10] As Georgescu-Roegen notes, "in the everyday world one cannot possibly cross a river only on the flow of maintenance materials of a non-existent bridge" [20].

Historically, many mainstream economists have spurned analyses aimed at determining energy intensity, because energy intensity and the EI–O method were significant features of the proposal for an energy theory of value[11] [21]. However, we recognize that all economic activity requires energy. Thus, we contend that society needs to understand well the way energy flows through economies. And, we argue that energy intensity does not necessarily lead to an energy theory of value. Rather, it is an inherently useful metric that describes the energy associated with the pathways traveled by products through an economy. We view energy intensity as a key piece of information that will help consumers and firms alike make wise consumption and investment decisions in the age of resource depletion.

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[9] Note that Figs. 7.1c and d are similar to the metabolic metaphor that we propose for the age of resource depletion as discussed in Sect. 2.1.3.

[10] The energy it took to create and emplace durable goods and infrastructure can be considered "embodied" within the built environment, a point to which we will return in detail later.

[11] See Sect. 6.1 for a discussion of theories of value.

The steady-state EI–O techniques of Bullard, Herendeen, and others [5, 7] offer a starting point toward determining energy intensity. But, we need to move toward a fuller picture of the role of energy and manufactured capital in the economy; we need to move toward Figs. 7.1c and d. In the sections below, we utilize the results from Chaps. 3–6 and extend the steady-state EI–O techniques to estimate energy intensity given the existence of wastes and the accumulation of embodied energy.

7.2 Methodology

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

$$\varepsilon_j \equiv \frac{\dot{T}_j}{\dot{X}_j}, \tag{7.1}$$

and ε is in units of J/$.[12] Energy intensity ($\varepsilon_j$) represents the total energy demanded by sector j (both for sector j itself and the energy required to create the inputs to sector j) per dollar of output from sector j. Equation 7.1 includes the embodied energy of products in the numerator ($\dot{T}_j$) term. A narrower definition of 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 Eq. 7.1 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

$$\varepsilon_j = \frac{\dot{T}_{jk}}{\dot{X}_{jk}} \tag{7.2}$$

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.[13]

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.

$$a_{ij} \equiv \frac{\dot{X}_{ij}}{\dot{X}_j} \tag{7.3}$$

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

[13] If this approach is unsatisfactory, the sector may be divided into subsectors each with its own energy intensity.

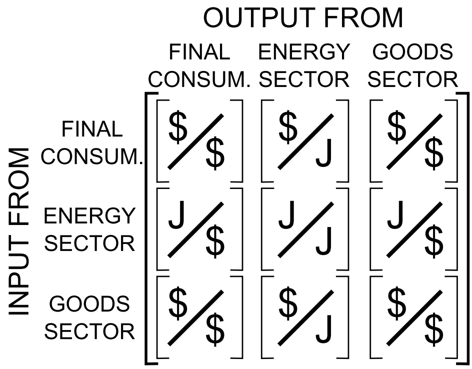

Fig. 7.4 Units for input–output ratios (a)

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

$$a_{ij} = \frac{\dot{X}_{\dot{R}_{ij}} + \dot{X}_{\dot{S}_{ij}} + \dot{X}_{\dot{K}_{ij}}}{\dot{X}_{\dot{R}_j} + \dot{X}_{\dot{S}_j} + \dot{X}_{\dot{K}_j}}, \tag{7.4}$$

where R represents resources, S represents short-lived materials, and K represents capital, as discussed in Chap. 3.

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 Fig. 7.4.

Equations 7.2 and 7.3 can be combined to give

$$\dot{T}_{jk} = \varepsilon_j a_{jk} \dot{X}_k. \tag{7.5}$$

That is, the flow of total energy from sector j into sector k ($\dot{T}_{jk}$), is given by the energy intensity of sector j (ε_j) multiplied by the amount of input good j required to produce a unit of output from sector k (a_{jk}) multiplied by the output flow of value from sector k ($\dot{X}_k$).

7.3 Example A: Single-Sector Economy

With reference to Figs. 4.3, 5.2, and 6.4, the energy intensity (ε_1) of a single-sector economy is calculated by

$$\varepsilon_1 = \frac{\dot{T}_1}{\dot{X}_1} = \frac{\dot{T}_{11}}{\dot{X}_{11}}. \tag{7.6}$$

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.

7.4 Example B: Two-Sector Economy

With reference to Figs. 4.4, 5.3, and 6.5, the energy intensity (ε_2) of the production sector is given by

$$\varepsilon_2 = \frac{\dot{T}_2}{\dot{X}_2} = \frac{\dot{T}_{22}}{\dot{X}_{22}}. \tag{7.7}$$

Thus,

$$\dot{T}_2 = \varepsilon_2 \dot{X}_2. \tag{7.8}$$

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

$$a_{22} = \frac{\dot{X}_{22}}{\dot{X}_2}, \tag{7.9}$$

thus

$$\dot{T}_{22} = \varepsilon_2 a_{22} \dot{X}_2. \tag{7.10}$$

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

$$\frac{\mathrm{d}T_2}{\mathrm{d}t} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} - \dot{T}_2 - \dot{T}_{20} \tag{5.29}$$

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 do not 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,[14] 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 Sect. 5.2.3.

If we substitute Eqs. 7.8 and 7.10 into Eq. 5.29, we obtain

$$\frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} = \dot{E}_{02} + \dot{T}_{12} + \varepsilon_2 a_{22} \dot{X}_2 - \varepsilon_2 \dot{X}_2 - \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}\right). \tag{7.11}$$

Equation 7.11 can be solved for energy intensity (ε_2) to obtain

$$\varepsilon_2 = (1 - a_{22})^{-1} \dot{X}_2^{-1} \left[\dot{E}_{02} + \dot{T}_{12} - \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} - \dot{B}_{\dot{R}_{20}} - \dot{B}_{\dot{S}_{20}} - \gamma_{B_2} B_{B_2}\right] \tag{7.12}$$

To extend Eq. 7.12 to a matrix formulation, we turn to Example C.

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

7.5 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 (Eq. 5.41) 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.

7.5.1 *Total Energy Accounting Equation*

We apply Eq. 5.41 to the three-sector economy shown in Figs. 4.5, 5.4, and 6.6 to obtain the following total energy accounting equations for the Energy (2) and Goods and Services (3) sectors of Example C:

$$\frac{\mathrm{d}T_2}{\mathrm{d}t} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} + \dot{T}_{32} - \dot{T}_2 - \dot{T}_{20} \tag{7.13}$$

and

$$\frac{\mathrm{d}T_3}{\mathrm{d}t} = \dot{T}_{03} + \dot{T}_{13} + \dot{T}_{23} + \dot{T}_{33} - \dot{T}_3 - \dot{T}_{30}. \tag{7.14}$$

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 do not 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 Sect. 5.2.3.

to obtain

$$\frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} = \dot{E}_{02} + \dot{T}_{12} + \varepsilon_2 \dot{X}_{22} + \varepsilon_3 \dot{X}_{32} - \varepsilon_2 \dot{X}_2 - \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}\right) \tag{7.15}$$

and

$$\frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} = \dot{E}_{03} + \dot{T}_{13} + \varepsilon_2 \dot{X}_{23} + \varepsilon_3 \dot{X}_{33} - \varepsilon_3 \dot{X}_3 - \left(\dot{B}_{\dot{R}_{30}} + \dot{B}_{\dot{S}_{30}} + \gamma_{B,3} B_{K_3}\right). \tag{7.16}$$

7.5.2 Matrix Formulation

Equations 7.15 and 7.16 can be rewritten in vector notation as

$$\begin{Bmatrix} \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} \\ \frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} \end{Bmatrix} = \begin{Bmatrix} \dot{E}_{02} \\ \dot{E}_{03} \end{Bmatrix} + \begin{Bmatrix} \dot{T}_{12} \\ \dot{T}_{13} \end{Bmatrix} + \begin{bmatrix} \dot{X}_{22} & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}$$
$$- \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} - \begin{Bmatrix} \dot{B}_{\dot{R}_{20}} \\ \dot{B}_{\dot{R}_{30}} \end{Bmatrix} - \begin{Bmatrix} \dot{B}_{\dot{S}_{20}} \\ \dot{B}_{\dot{S}_{30}} \end{Bmatrix} - \begin{bmatrix} \gamma_{B_2} & 0 \\ 0 & \gamma_{B,3} \end{bmatrix} \begin{Bmatrix} B_{K_2} \\ B_{K_3} \end{Bmatrix}. \tag{7.17}$$

If we define the following matrices and vectors:

$$\mathbf{B}_K \equiv \begin{Bmatrix} B_{K_2} \\ B_{K_3} \end{Bmatrix}, \tag{7.18}$$

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} \equiv \begin{Bmatrix} \frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} \\ \frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} \end{Bmatrix}, \tag{7.19}$$

$$\mathbf{E}_0 \equiv \begin{Bmatrix} \dot{E}_{02} \\ \dot{E}_{03} \end{Bmatrix}, \tag{7.20}$$

$$\mathbf{T}_1 \equiv \begin{Bmatrix} \dot{T}_{12} \\ \dot{T}_{13} \end{Bmatrix}, \tag{7.21}$$

$$\mathbf{X}_t \equiv \begin{bmatrix} \dot{X}_{22} & \dot{X}_{23} \\ \dot{X}_{32} & \dot{X}_{33} \end{bmatrix}, \tag{7.22}$$

$$\boldsymbol{\varepsilon} \equiv \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}, \tag{7.23}$$

$$\mathbf{B}_{\dot{W}} = \begin{Bmatrix} \dot{B}_{\dot{W}_{20}} \\ \dot{B}_{\dot{W}_{30}} \end{Bmatrix} = \begin{Bmatrix} \dot{B}_{\dot{R}_{20}} \\ \dot{B}_{\dot{R}_{30}} \end{Bmatrix} + \begin{Bmatrix} \dot{B}_{\dot{S}_{20}} \\ \dot{B}_{\dot{B}_{30}} \end{Bmatrix}, \tag{7.24}$$

$$\hat{\mathbf{X}} \equiv \delta_{ij}\dot{X}_j = \begin{Bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{Bmatrix}, \tag{7.25}$$

and

$$\hat{\boldsymbol{\gamma}}_B \equiv \delta_{ij}\gamma_{B_j} = \begin{bmatrix} \gamma_{B_2} & 0 \\ 0 & \gamma_{B_3} \end{bmatrix}, \tag{7.26}$$

with the "Kronecker delta" (δ_{ij}), being a function of two integer variables (i and j) that has value of 1 if i and j are equal and zero otherwise;

$$\delta_{ij} \equiv \begin{cases} 0 & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}, \tag{7.27}$$

we can rewrite Eq. 7.17 compactly in matrix notation as

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + \mathbf{X}_t^{\mathrm{T}}\boldsymbol{\varepsilon} - \hat{\mathbf{X}}\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K. \tag{7.28}$$

Equation 7.28 can be simplified to

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + (\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}})\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K. \tag{7.29}$$

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

$$\mathbf{A} \equiv \begin{bmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{bmatrix}. \tag{7.30}$$

Appendix C shows that

$$\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I}), \tag{7.31}$$

which allows Eq. 7.29 to be recast as

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K. \tag{7.32}$$

Equation 7.32 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 7.17 applies for the three-sector economy of Example C, but the equivalent matrix formulation (Eq. 7.32) can be extended to any desired level of economic and energy sector disaggregation by expanding the vectors and matrices in Eqs. 7.18–7.26, and 7.30 to include all sectors ($2 \ldots n$) of an n – 1-sector economy [1, 8].

Equation 7.32 provides a means to estimate the embodied energy accumulation rate in economic sectors $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$ 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 7.32 can be rearranged to obtain

$$\hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\boldsymbol{\varepsilon} = \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1 \tag{7.33}$$

and

$$\boldsymbol{\varepsilon} = \left[\hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\right]^{-1} \left[\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1\right]. \tag{7.34}$$

We apply the matrix identity [22, Formula 6.2, p. 308]

$$(\mathbf{FGH})^{-1} = \mathbf{H}^{-1}\mathbf{G}^{-1}\mathbf{F}^{-1} \tag{7.35}$$

to the right side of Eq. 7.34 to obtain

$$\boldsymbol{\varepsilon} = (\mathbf{A}^{\mathrm{T}} - \mathbf{I})^{-1}\hat{\mathbf{X}}^{-1} \left[\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1\right]. \tag{7.36}$$

Finally, we can multiply both parenthetical terms[15] on the right side of Eq. 7.36 by -1 to obtain

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1}\hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 + \mathbf{T}_1 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right]. \tag{7.37}$$

Equation 7.37 is the key energy intensity equation in this section. In words, it says that the energy intensity of economic sector output ($\boldsymbol{\varepsilon}$) is a function of the energy input from the biosphere ($\mathbf{E}_0$), the energy input from society ($\mathbf{T}_1$), less the rate at which energy is embodied in the sector $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$, less the rate at which energy embodied in resource and short-lived material streams ends up as waste ($\mathbf{B}_{\dot{W}}$), less the rate at which embodied energy is discarded from the sector in depreciated capital ($\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K$).

Comparison of Eqs. 7.37 and 7.12 shows that the matrix form is an extension of the algebraic form of the energy intensity equation.

Equation 7.37 provides a means to estimate energy intensity ($\boldsymbol{\varepsilon}$) of the sectors of the economy, under the assumption that Final Consumption (1) is exogenous to the economy (Sectors $2 \ldots n$). We discuss Eq. 7.37 further in Sect. 8.2. But first, we address a few methodological issues followed by an examination of energy intensity in the context of our running example, the US auto industry.

[15] The parenthetical terms on the right side of Eq. 7.36 are $(\mathbf{A}^{\mathrm{T}} - \mathbf{I})$ and $\left[\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1\right]$.

7.6 What is Endogenous?

There is debate in the literature about whether government and households (Final Consumption (1) in Fig. 3.4) should be endogenous to economic models. This debate is fundamentally a discussion about the appropriate analysis boundary. Costanza [3] 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 [3] 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 above (Eq. 7.37) was derived under the assumption that Final Consumption (1) is exogenous to energy intensity calculation. However, Eq. 7.37 could be re-derived to endogenize Final Consumption (1).

The total energy accounting equation for Final Consumption (1) in Fig. 5.4 can be written analogously to Eqs. 7.15 and 7.16 as

$$\frac{\mathrm{d}B_{K_1}}{\mathrm{d}t} = \dot{E}_{01} + \varepsilon_1 \dot{X}_{11} + \varepsilon_2 \dot{X}_{21} + \varepsilon_3 \dot{X}_{31} - \varepsilon_1 \dot{X}_1 - \left(\dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{K,1} B_{K_1}\right). \tag{7.38}$$

Furthermore, Eqs. 7.15 and 7.16 can be rewritten as

$$\frac{\mathrm{d}B_{K_2}}{\mathrm{d}t} = \dot{E}_{02} + \varepsilon_1 \dot{X}_{12} + \varepsilon_2 \dot{X}_{22} + \varepsilon_3 \dot{X}_{32} - \varepsilon_2 \dot{X}_2 - \left(\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{K,2} B_{K_2}\right) \tag{7.39}$$

and

$$\frac{\mathrm{d}B_{K_3}}{\mathrm{d}t} = \dot{E}_{03} + \varepsilon_1 \dot{X}_{13} + \varepsilon_2 \dot{X}_{23} + \varepsilon_3 \dot{X}_{33} - \varepsilon_3 \dot{X}_3 - \left(\dot{B}_{\dot{R}_{30}} + \dot{B}_{\dot{S}_{30}} + \gamma_{K,3} B_{K_3}\right). \tag{7.40}$$

Following the derivation of Chap. 7, we can obtain an updated version of Eq. 7.37:

$$\boldsymbol{\varepsilon} = \left(\mathbf{I} - \mathbf{A}^{\mathrm{T}}\right)^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right], \tag{7.41}$$

wherein

- the vectors and matrices of Eqs. 7.18–7.26 and 7.30 have been extended to include Final Consumption (1) and
- Final Consumption (1) has been endogenized (the $\mathbf{T}_1$ term of Eq. 7.37 has been subsumed into the $\left(\mathbf{I} - \mathbf{A}^{\mathrm{T}}\right)^{-1} \hat{\mathbf{X}}^{-1}$ term of Eq. 7.41).

Future work could estimate energy intensity ($\boldsymbol{\varepsilon}$) using Eqs. 7.37 and 7.41 with updated economic data for a wider range of countries and years.[16] Doing so could provide

[16] Costanza's analysis [3] was conducted using US data for 1963, 1967, and 1972.

further insight on Costanza's result [3] that endogenizing Final Consumption (1) reduces variation of energy intensity ($\boldsymbol{\varepsilon}$) across all sectors of the economy.

7.7 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 [12] 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
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 DEC approach on both thermodynamic and economic grounds. The thermodynamic justification is 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. [12, 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 nonzero only for those sectors that receive energy directly from the biosphere. So, for example, in Fig. 4.5 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 Chaps. 3–6.

1. First, $\mathbf{E}_0$ 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. Second, Costanza and Herendeen's concern [12, p. 130 and 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 Eq. 5.12,
   b) $-\dot{E}_j$ in Eq. 5.43,
   c) $-\begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}$ in Eq. 7.17, and
   d) $-\hat{\mathbf{X}}\boldsymbol{\varepsilon}$ in Eq. 7.28.
3. Third, 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 5.16 of Sect. 5.2.2 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 [12] desired from the DEC approach. Because the DEC approach is unwarranted, we quote DIRECT energy intensity values only when discussing energy intensities in the following section (7.8).

7.8 Energy Intensity in the US Auto Industry

Equation 7.37 shows that it is possible to estimate the energy intensity of products of the economic sectors using the EI–O analysis method.[17] 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 [3, 5, 7, 12, 19, 23–29]. 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 [5]. 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 [30] 2 years earlier.[18]

[17] For a discussion of differences between Eq. 7.37 and similar equations in the literature, see Appendix E.

[18] See Sect. 5.5 for discussion of the Berry and Fels [30] paper.

Table 7.1 Motor Vehicles and Equipment sector (63) energy intensity values [12]

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

Table 7.2 Selected US economic sector energy intensities, 1972 [12]

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

Table 7.3 Automobile manufacturing sector energy intensity values [23]

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)

In 1980, Costanza [3] estimated the energy intensity of all economic sectors of the US economy using the EI–O method. Unfortunately, the energy intensity of the Motor Vehicles and Equipment sector (63) was not reported in [3]. Later, Costanza and Herendeen [12] reestimated 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 7.1 and 7.2.[19]

The economic input–output life cycle assessment (EIOLCA) online tool [23] is based on the framework outlined by Hendrickson Lave and Matthews [19] and allows computation of the energy intensity of all sectors of the economy based on the US national accounts data from 1992, 1997, and 2002.[20] (See Table 7.3.) 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

[19] Values from Costanza and Herendeen's DIRECT method are provided here. See Sect. 7.7 for discussion of the differences between DIRECT and DEC methods and justification for reporting DIRECT method values only.

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

(10^{12} J) of energy through the economy, 2.19 TJ from the power generation and supply sector (221100) and 1.25 TJ from the iron and steel mills sector (331110).

It would be interesting to know how the above energy intensity results vary (a) with time, and (b) 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 Chap. 9, we discuss further the need for additional data.

7.9 Summary

In this chapter, we derived algebraic equations, based on the top-down EI–O method, 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 Chaps. 3–7.

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Part III
Implications and Summary

Chapter 8
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 Chaps. 3–7). In the sections below, we discuss implications for the development of important economic metrics, the energy input–output (EI–O) method itself, implications for economic growth, implications for recycling, reuse, and dematerialization, and comparisons between our framework and the notion of a steady-state economy. We begin by discussing metrics.

8.1 Metrics

Our framework highlights the value that could be derived from continuous monitoring and reporting of several important metrics by national accounting agencies, including

- Energy intensity of products of economic sectors (Chap. 7),
- Total accumulation of material (Chap. 3) and embodied energy (Chap. 5) in economic sectors,
- The flow rate of energy from the biosphere into economic sectors (Chap. 4),
- The flow rate of materials from economic sectors to the biosphere (Chap. 3), and
- The flow rate of embodied energy from economic sectors to the biosphere (Chap. 5).

In the age of resource depletion, 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 relevant 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 framework were implemented and periodic

M. K. Heun et al., *Beyond GDP*, Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7_8

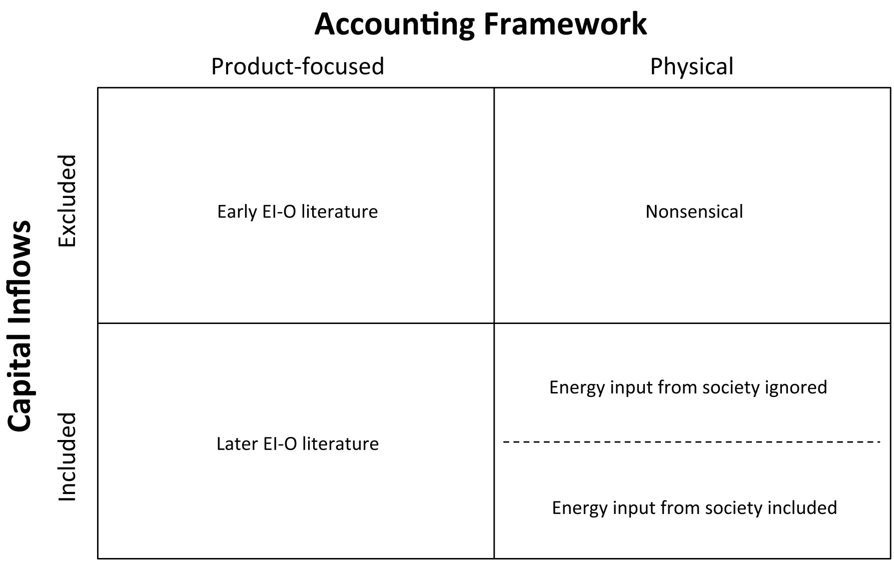

Fig. 8.1 Coordinates of analysis for implications for the EI–O method

updates were available, society would better understand the costs (in terms of both dollars *and* energy) of maintaining capital. And, society would understand how those maintenance flows constrain economic growth.

8.2 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 Sect. 6.2, we do not take the ability to estimate energy intensity as a license to declare an intrinsic “energy theory of value.” Rather, we believe 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 Fig. 8.1). We will end with our recommendation for how best to estimate energy intensity ($\boldsymbol{\varepsilon}$) within a materials, energy, and value accounting framework.

8.2.1 Product-Based vs. Physical Approaches

The distinction between product-focused and physical accounting frameworks is located in the columns of Fig. 8.1. 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 8.1 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 Fig. 8.1).[1]

$$\dot{B}_j' = \sum_{i=1}^{n} \dot{B}_{ij}' - \dot{B}_{\dot{W}_j} + \dot{Q}_{j0} \tag{8.1}$$

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, Eq. 8.2 describes the outflow of embodied energy from sector j, exclusive of capital stock, for a product-focused accounting framework (upper left quadrant of Fig. 8.1).

$$\dot{B}_j' = \sum_{i=1}^{n} \dot{B}_{ij}' + \dot{Q}_{j0} \tag{8.2}$$

Notice that Eq. 8.2 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. The magnitude of $\dot{B}_{\dot{W}_j}$ relative to the $\sum_{i=1}^{n} \dot{B}_{ij}'$ and $\dot{Q}_{j0}$ terms determines whether, for any particular

[1] Equation 8.1 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 Fig. 8.1 (physical accounting framework that neglects capital) is labeled as nonsensical.

sector, the value of $\dot{B}'_j$ is different between a physical accounting framework (Eq. 8.1) and a product-focused accounting framework (Eq. 8.2).

8.2.2 Capital Flows and Stock

The rows of Fig. 8.1 represent the role of capital flows and stock in an accounting framework. The Bureau of Economic Analysis (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 Fig. 8.1. 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 Fig. 8.1.

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.

[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

To see the effect of the move from the upper left to the lower left quadrant of Fig. 8.1, 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, which include capital flows on the output, but do not include capital flows on the input. Thus, this early literature implicitly assumes that

$$a_{ij}^{'} \equiv \frac{\dot{X}_{\dot{R}_{ij}} + \dot{X}_{\dot{S}_{ij}}}{\dot{X}_{\dot{R}_j} + \dot{X}_{\dot{S}_j} + \dot{X}_{\dot{K}_j}} = \frac{\dot{X}_{ij}^{'}}{\dot{X}_j}. \tag{8.3}$$

Comparison between Eqs. 7.4 and 8.3 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

$$\mathbf{A}^{'} = \begin{bmatrix} a_{22}^{'} & a_{23}^{'} \\ a_{32}^{'} & a_{33}^{'} \end{bmatrix}. \tag{8.4}$$

The implicit assumptions of the early energy I–O literature are consistent with the upper left quadrant of Fig. 8.1, and the energy intensity equation found in most of the early literature is

$$\boldsymbol{\varepsilon}^{'} = \left(\mathbf{I} - \mathbf{A}^{'\mathrm{T}}\right)^{-1} \left(\hat{\mathbf{X}}\right)^{-1} \mathbf{E}_0. \tag{8.5}$$

Bullard and Herendeen [4], following Kirkpatrick [3], added flows of capital as inputs to each sector [4, Fig. 5], and, in so doing, changed Eq. 8.5 to Eq. 8.6:

$$\boldsymbol{\varepsilon} = \left[\mathbf{I} - \left(\mathbf{A}^{'\mathrm{T}} + \mathbf{A}_{\dot{K}}^{\mathrm{T}}\right)\right]^{-1} \left(\hat{\mathbf{X}}\right)^{-1} \mathbf{E}_0 \tag{8.6}$$

with

$$\mathbf{A}_{\dot{K}} \equiv \begin{bmatrix} a_{\dot{K}_{22}} & a_{\dot{K}_{23}} \\ a_{\dot{K}_{32}} & a_{\dot{K}_{33}} \end{bmatrix} \tag{8.7}$$

and

$$a_{\dot{K}_{ij}} \equiv \frac{\dot{X}_{\dot{K}_{ij}}}{\dot{X}_j}. \tag{8.8}$$

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

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 $\left(\frac{\mathbf{B}_K}{\mathbf{E}_0}\right)$.

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 instead that half of the incoming capital went toward replacement. These early researchers moved from the upper left quadrant to the lower left quadrant of Fig. 8.1. And, Eq. 8.6 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 Fig. 8.1). 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 Fig. 8.1. 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 capital stock becomes an important driver of both financial and natural resource demands, as illustrated by the following 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 the industrialization process. 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 Fig. 8.1), 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 Fig. 8.1) is described by Eq. 8.9.

$$\boldsymbol{\varepsilon} = \left(\mathbf{I} - \mathbf{A}^{\mathrm{T}}\right)^{-1} \left(\hat{\mathbf{X}}\right)^{-1} \left[\mathbf{E}_0 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right]. \tag{8.9}$$

Differences between Eqs. 8.9 and 8.6 include:

- Equation 8.9 includes **A** while Eq. 8.6 splits **A** into $\mathbf{A}'$ and $\mathbf{A}_{\dot{K}}$ (a difference in appearance only),
- Equation 8.9 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 8.9 subtracts waste $(\mathbf{B}_{\dot{W}})$, because energy embodied in waste products is not assigned to products of the sector, and
- Equation 8.9 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 Eq. 8.9 that are worthy of consideration: waste flows and an accounting equation for capital stock.

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:

$$\eta_{\dot{R}_j} \equiv \frac{\dot{P}_j}{\sum\limits_{i=1}^{n} \dot{R}_{ij}}. \tag{8.10}$$

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 estimate manufacturing efficiencies for metals. The data are summarized in Table 8.1.

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:

$$\rho_{\dot{S}_j} \equiv \frac{\dot{S}_{j0}}{\sum\limits_{i=1}^{n} \dot{R}_{ij}} = \frac{\sum\limits_{i=1}^{n} \dot{S}_{ij}}{\sum\limits_{i=1}^{n} \dot{R}_{ij}}. \tag{8.11}$$

Table 8.1 Manufacturing efficiencies ($\eta_{\dot{R}}$, Eq. 8.10) 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

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

$$\dot{R}_{j0} + \dot{S}_{j0} = (1 - \eta_{\dot{R}_j} + \rho_{\dot{S}_j}) \sum_{i=1}^{n} \dot{R}_{ij}. \tag{8.12}$$

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

$$\dot{B}_{\dot{W}_j} = \dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}}. \tag{8.13}$$

Simplification via Capital Stock Accounting Equation

A possible simplification to Eq. 8.9 can be obtained from a control volume around the stock of capital in sector j:

$$\frac{\mathrm{d}B_{K_j}}{\mathrm{d}t} = \sum_{i=1}^{n} \dot{B}_{\dot{K}_{ij}} - \gamma_{B_j} B_{K_j}. \tag{8.14}$$

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

$$\alpha_{B_j} \equiv \frac{\sum\limits_{i=1}^{n} \dot{B}_{\dot{K}_{ij}}}{B_{K_j}} \tag{8.15}$$

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

$$\hat{\boldsymbol{\alpha}}_B \equiv \delta_{ij}\alpha_{B_j} = \begin{bmatrix} \alpha_{B_2} & 0 \\ 0 & \alpha_{B_3} \end{bmatrix}. \tag{8.16}$$

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

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \hat{\boldsymbol{\alpha}}_B \mathbf{B}_K - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K. \tag{8.17}$$

Rearranging slightly gives

$$\hat{\boldsymbol{\alpha}}_B \mathbf{B}_K = \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K, \tag{8.18}$$

which says that the 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 Eq. 8.17 into Eq. 8.9 gives

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^{\mathrm{T}})^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 - \hat{\boldsymbol{\alpha}}_B \mathbf{B}_K - \mathbf{B}_{\dot{W}}\right]. \tag{8.19}$$

8.2.3 Energy Input from Society

In Sects. 8.2.1 and 8.2.2 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 Eq. 8.9 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 7.37 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 Fig. 8.1.

$$\boldsymbol{\varepsilon} = \left(\mathbf{I} - \mathbf{A}^{\mathrm{T}}\right)^{-1}\hat{\mathbf{X}}^{-1}\left[\mathbf{E}_0 + \mathbf{T}_1 - \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B\mathbf{B}_K\right]. \tag{7.37}$$

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 significantly large relative to $\mathbf{E}_0$, neglecting $\mathbf{T}_1$ will underpredict the energy intensity of economic output. See Sect. 7.6 for more about energy in put from society.

8.2.4 Recommendation

Sections 8.2.1–8.2.3 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 Fig. 8.1.

At this point, it is instructive to look back at the product-focused vs. physical discussion in Sect. 8.2.1. We understand the argument for including capital stock in a product-focused accounting framework (lower left quadrant of Fig. 8.1): 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 Fig. 8.1) masks structural aspects of

[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 … n), and upstream energy consumption needs to be included manually. However, in Sect. 7.6, 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.

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 metabolism metaphor (Chap. 2) provides guidance here. If we were to create a model of an organism that neglects tissues that accumulate embodied energy, the organism (in the model) has nothing with which to absorb, process, waste, or otherwise exchange material with the biosphere. The organism does not 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 Fig. 8.1). 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 Chap. 9.

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 Fig. 8.1. So, the state of the art has moved from the nascent energy I–O literature located in the upper left quadrant of Fig. 8.1 as represented by Eq. 8.5 through the lower left quadrant of Fig. 8.1 as represented by Eq. 8.6 to the lower half of the bottom right quadrant of Fig. 8.1 as represented by Eq. 7.37.

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 (in addition 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 Eq. 7.37 instead of Eq. 8.5 or Eq. 8.6 for estimating energy intensity ($\boldsymbol{\varepsilon}$) of economic sectors within an economy.

Of course, whether or not any particular flow of embodied energy is included in or excluded from analyses or whether the product-focused or physical form of the framework is adopted is less important than beginning to account for embodied energy and routinely reporting energy intensity values in the first place. Deciding to do so will require an understanding that such analyses are important (see Chaps. 1 and 2) and the courage to make some movement in the right direction (see Chap. 9).

8.3 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 dimensions. Viewing these dimensions through the lens of our framework illustrates some important points about measures of economic growth and well-being, including whether it be measured by a stock or a flow, and the roles of currency, capital stock, energy, natural resources, and labor in economic processes.

With reference to Fig. 6.6, GDP is calculated by summing value-added across all industry sectors:

$$GDP = \sum_{j=1}^{n} \dot{X}_j \tag{8.20}$$

where n is the number of sectors in the economy. Equation 8.20 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:

$$X_j(t) = X_j(0) + \int_{t=0}^{t=t} \frac{\mathrm{d}X_j}{\mathrm{d}t}\mathrm{d}t, \tag{8.21}$$

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 8.22 indicates how accumulated embodied energy in the capital stock of an economy ($\mathbf{B}_K$) could be calculated:

$$\mathbf{B}_K(t) = \mathbf{B}_K(0) + \int_{t=0}^{t=t} \frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\mathrm{d}t, \tag{8.22}$$

[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 the well-being by 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 compilation of survey and other data related to nine factors: ecological diversity and resilience, psychological well-being, health, education, culture, 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 can be similarly criticized.

where $\mathbf{B}_K$ is given by Eq. 7.18. Equation 8.22 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), Eq. 7.32 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.

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 $\mathbf{B}_K$ does not. 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 $X_{2 \ldots n}$) 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 and complementary 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 areas of inquiry, and we encourage further research in all of these areas.

8.4 Implications for Recycling, Reuse, and Dematerialization

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 from both short-lived goods $\left(\mathbf{B}_{\dot{W}}\right)$ and depreciated capital stock $\left(\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K\right)$ that would otherwise have been discarded to the biosphere.[7]

In Chap. 7, 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:

$$\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t} = \mathbf{E}_0 + \mathbf{T}_1 + \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I})\boldsymbol{\varepsilon} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K \tag{7.32}$$

One effect of recycling is to reduce the magnitude of the waste $\left(\mathbf{B}_{\dot{W}}\right)$ and depreciation $\left(\hat{\boldsymbol{\gamma}}_B\right)$ terms. As can be seen in Eq. 7.32, 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 $\left(\hat{\boldsymbol{\gamma}}_B\right)$ 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 $\left(\frac{\mathrm{d}\mathbf{B}_K}{\mathrm{d}t}\right)$.

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[7] 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].

The possibility of technology to reduce material and energetic inputs (dematerialization) has caused some cornucopian "techno-optimists" [27] (techno-copians) to speculate on the potential of human ingenuity to endlessly overcome physical resource constraints. If technology can reduce the need for materials and energy (dematerialization), prices will decline. This view should be contrasted with a neo-Ricardian (or doomsayer, or peaknik [28]) perspective which believes that physical constraints are binding and that prices for materials will, all other things being equal, increase in the long run.

The two sides clashed in a famous bet between (techno-copian) economist Julian Simon and (peaknik) biologist Paul Ehrlich (plus colleagues John Harte and John Holdren) on whether the price of five metals (copper, chromium, nickel, tin, and tungsten) would increase or decrease over the 10 year period from 1980–1990 [29, 30]. Simon believed that technological innovation would outpace declining ore grade (and allow substitution), thereby reducing prices. Ehrlich believed that rising demand (mainly due to increasing population) and finite resources would cause prices to increase. Simon won the bet in 1990 and Ehrlich (and friends) paid Simon the difference in price for the five metals.

Many were quick to see Simon's win as a resounding validation of the techno-copian perspective. However, were the bet still running today (in 2014), Simon would be losing (as he would have done for most of the 10-year periods during the past century). Were the wager expanded to include all important commodities, Simon would have lost severely [29, 30].

What was special about the period 1980–1990? As discussed in Chap. 1, the oil crises of the 1970s had caused large increases in the price of oil. In the run-up to the start of the wager period, the effects of the embargoes had raised prices on all commodities, including the five metals in the wager. During the 1980s, the return to normal supply rates of oil and recovery from the recessions of the 1970s caused the decline of prices for most commodities. As such, Simon won the bet more by luck than by judgment.

8.5 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]

As discussed in Chap. 1, the human economy is a subset of the biosphere, a finite, nongrowing system. Thus, the human economy cannot physically grow indefinitely. The concept of a nongrowing 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 $\frac{\mathrm{d}p}{\mathrm{d}t} = 0$. 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 [31, p. 32]. This definition is consistent with zero rate of accumulation of capital stock within the economy and society. 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" [31, 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 our framework. The issue of human population as part of society's capital stock is addressed in Footnote 8 of Chap. 3.

8.5.1 Constant Level of Capital Stock

Chapter 3 includes Eq. 3.105:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_j \frac{\mathrm{d}K_j}{\mathrm{d}t} + \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j . \tag{3.105}$$

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 human-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 manufactured 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 $\left(\sum_j \frac{\mathrm{d}K_j}{\mathrm{d}t} = 0\right)$,[8] we can see that Eq. 3.105 reduces to:

$$-\frac{\mathrm{d}R_0}{\mathrm{d}t} = \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j . \tag{8.23}$$

A number of interesting concepts may be understood via Eq. 8.23. First, 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.

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

Second, 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 biosphere $\left(\sum_j \gamma_{K_j} K_j\right)$. Equation 8.23 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 Chap. 3, 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 Eq. 8.23). 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).[9] 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.

Third, 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.

8.5.2 Constant Material Throughput

Herman Daly has placed great emphasis on a steady-state economy as having a constant rate of material throughput [31, 32] 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, nongrowing biosphere of which it is a sub-system? Growth of the human

[9] While computers and software can be considered capital investment by businesses, consumer electronics such as laptops and cell phones, are considered consumption expenditures in the BEA national accounts.

economy must either displace other natural ecosystems (replacing old growth forest with cultivated crops) or deplete natural capital stocks, be they renewable (fisheries) or nonrenewable (fossil fuels). As shown in Fig. 3.5, 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:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{R}_0\right) = 0, \tag{8.24}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{S}_0\right) = 0, \tag{8.25}$$

and

$$\sum_i \left[\frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{R}_{i0}\right) + \frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{S}_{i0}\right) + \frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{K}_{i0}\right)\right] = 0. \tag{8.26}$$

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.

8.5.3 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.[10] Within our framework, a condition of constant GDP would be characterized by the following equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}(GDP) = \sum_j \frac{\mathrm{d}}{\mathrm{d}t}\left(\dot{X}_j\right) = 0. \tag{8.27}$$

---

[10] 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”’ [31, p. 32].

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 $\left(\frac{\mathrm{d}}{\mathrm{d}t}\,(GDP) \le 0\right)$. 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 [33–37] for two main reasons:

- First, that the costs of growth in GDP (e.g., externalities and defensive expenditures) outweigh any benefit that comes from increasing GDP; and
- Second, that increased GDP increases relative income inequality, which decreases welfare for both rich and poor alike [36].

Indeed, it may be the case that at the margin an increase in GDP produces more "illth" than "wealth," resulting in "uneconomic" growth [36, 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.[11] 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" [36].

8.6 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. Finally, we viewed the concept of a steady-state economy through

[11] 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.

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.

In the next chapter, we suggest some next steps towards implementing our framework.

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Chapter 9
Next Steps

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 indicated at the outset (Chaps. 1 and 2) that this book would be about counting and change; counting materials, energy, and economic value, so that we can manage the upcoming energy transition and navigate our way through the age of resource depletion. Our motivation for counting more carefully is mounting evidence (discussed in Chap. 1) that scarcity of materials, energy, and assimilation capacity of the biosphere is limiting the potential for continued economic growth in mature economies, thereby affecting us all. We need to 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. But, before collecting data to describe society's metabolism, we argued that we, as a society, need a rigorous theoretical framework for better systems of national accounts, one that goes beyond gross domestic product (GDP) and one that is relevant to the age of resource depletion.

To develop such an accounting framework guided by the metabolism metaphor, we applied thermodynamic control volume accounting equations (Chaps. 3–6) to economic sectors that are *open* to their surroundings, that is they are open to both inflows and outflows of both materials and energy. Application of our framework shows that national accounting should gather and disseminate a great deal of additional physical, material data on real economies. The business axiom "you can't manage what you don't measure" reminds us that we need this additional data if we are to navigate successfully through the age of resource depletion. In short, we need balance sheets in addition to income statements! We need accounting in physical units in addition to financial units. Work to account such flows is starting to be undertaken at the economy-wide level, particularly within Europe. It needs to continue, but subeconomy, intersector material and energy accounts need to be developed, too.

The need for rigorous and accurate data is all the more pressing in light of the need, as demonstrated in Chap. 7, to track the accumulation of manufactured capital and associated embodied energy within sectors of the economy. There is a critical need for systematic collection and public dissemination of such data by a centralized agency. However, as discussed in the Prologue, such accounting is currently nonexistent in the US. The Bureau for Economic Analysis (BEA) was expressly forbidden

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DOI 10.1007/978-3-319-12820-7_9

by congress to collect such data after the first Integrated Environmental-Economic Satellite Accounts (IEESA) tables were published in 1994.

Thus, we add our voices to those encouraging governments and institutions worldwide to collect and disseminate high-quality data on material and energy stocks and flows. It will be impossible to make wise decisions about which materials to use, which energy sources to develop, and which products and services to incentivize without such data.

To that end, we offer the following suggestions as a way to move forward.

1. National accounting agencies worldwide should seek and be given mandates to estimate and disseminate information on the value of transactions that occur outside of the market. In the US, the BEA should seek authorization to restart the IEESA (see the Prologue.) Doing so will allow accounting for material and energy resources that are currently outside of the market. (See Sects. 1.3.1 and 1.5.)
2. National accounting agencies worldwide should develop and maintain balance sheets of both natural and manufactured capital in addition to national income statements. Doing so will allow countries to assess whether they are at risk of drawing down their wealth to produce today's income, thereby jeopardizing future quality of life. (See the Prologue and Sect. 1.1.)
3. All stocks and intersector flows should be provided in physical as well as financial units. At present, national accounting disseminates data in financial units, not physical units such as kilograms and kilojoules. Doing so will allow analysis of the true *biophysical* nature of the economy.
4. In the US, the BEA should restart *detailed* Capital, Labor, Energy, Material, and Services (KLEMS) reporting. Until January 2014, KLEMS data were estimated and disseminated by the BEA in a matrix that revealed source and destination industries for each flow. However, due to budget cuts, only economy-wide aggregate values are captured and reported today. The previous level of detail is needed to obtain sector-level information on material and energy flows in financial units. Doing so will provide a better picture of the structure of materials and energy dependencies among economic sectors.
5. National accounting agencies should provide additional detail for waste flows. At present, only two value flows related to waste are published, and both figures are aggregates of different types of waste: "Waste Management Services" and "Water & Sewage." These streams should be disaggregated and reported in physical units as well. Doing so will allow for analysis of opportunities for recycling and reuse within economies. (See Sects. 2.2.3 and 8.4.)
6. All data on stocks and intersector flows should be reported by a single, centralized agency. This will require synchronizing and reconciling data sets that are now reported by several different organizations. And, it may require gathering and dissemination of new data. In the US, for example, the Energy Information Agency (EIA) and the BEA should combine their respective energy data. The Environmental Protection Agency (EPA) and the BEA should combine

their respective waste data. Perhaps more than any other proposed change, centralized reporting in both physical and financial units would demonstrate the interconnectedness of the economy and the biosphere.

7. National accounting agencies should routinely estimate the energy intensity of economic products using a physical accounting framework, as discussed in Sect. 8.2. Doing so will provide consumers and firms alike with important information for sound consumption and investment decisions.
8. All of the above should be estimated and disseminated on an annual basis. Doing so will allow for assessment of trends in the material and energy structures of economies.

There should be no illusion that this agenda will be easy to implement; in many places, it will be politically difficult to undertake these changes. But, if we, as a society, can begin collecting these data, perhaps we can begin to also utilize the analytical tools, metrics, and knowledge needed to go beyond GDP and make wise choices for the future.

Our deepest hope is that this book makes a positive contribution in that direction.

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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. Counterpoint, Berkely, California, p. 89.

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 Chap. 6. 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).[a] 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, $ 1182)
Energy	3,367	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.[a] 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	14,532	2011 Fixed Assets (non-residential detailed estimates). The value of Equipment and Structures purchased by the Auto Industry ($ 15,327), less the value of the equipment that was produced within the Auto Industry itself ($ 795). These figures exclude Intellectual Property, as explained in the calculation of Capital (self-use) below

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DOI 10.1007/978-3-319-12820-7

Table A.1 (continued)

Value flow	2011 USD (millions)	Data calculations
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 http://www.bea.gov for the Automobile Industry (IOC 3361MV)
Resources (self-use)	133,961	2011 Input–Output accounts. Self-use of Resources that were made in the automobile industry (IOC 3361MV used by IOC 3361MV, $ 133,961)
Capital (self-use)	795	2011 Fixed Assets (nonresidential detailed estimates). The authors designated capital flows as "self-use" if the Equipment was an item that would be produced within the Automobile Industry: autos, internal combustion engines, light trucks, other trucks, buses and truck trailers. Note: Intellectual property is not counted as a (physical) capital flow in our framework, thus $ 14,133 of R&D developed by the auto industry (as well as custom software made within the Auto industry) is excluded from this flow, even though it is considered a capital investment in US national accounting and is part of the total capital investment as calculated in the US Fixed Assets table. Section 6.6 contains further discussion about the implications of including intellectual property as part of the national measure of capital stock
Net economic output	347,513	2011 Input–Output accounts. The use of commodities by industries before redefinitions. (Producers' Prices). Total industry output, less capital (self-use) ($ 795) and resources (self-use) (IOC 3361MV used by IOC 3361MV, $ 133,961)[b]

[a] Two commodities categorized in the KLEMS data as "Material" intermediate inputs are "Wholesale Trade" (IOC 4200, $ 26,580) and "Truck Transportation." (IOC 4840, $ 5552). 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"

[b] 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 (above) 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	Capital (K), Labor, Energy, Materials, and 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
	Important note: As of January 2014, the 1998–2011 KLEMS tables that were used for the analyses in Chap. 6 are no longer available online. They have been archived and replaced with the 2005–2012 revised format KLEMS dataset. Due to budget cuts, the new KLEMS only contains the Energy, Materials, and Service value flow *totals*. It no longer captures the underlying detail sources. Thus, the authors' calculations for self-use of materials, and re-categorization of some material inputs to service inputs are not possible with the revised data. The original dataset used for these analyses are available by request from the BEA. For more information on the KLEMS revison, see [4] and [5]
	The authors hope, of course, that a reinviorated focus on the importance of these details for national accounting will provide justification for the BEA to return to making publicly available the underyling detailed KLEMS data
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" [6, 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 Figs 3.4, 4.4, 5.3, and 6.5 can be re-drawn as shown in Fig. B.1.

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

$$\varepsilon_2 = (1 - a_{22})^{-1}\dot{X}^{-1}\dot{E}_{02}. \tag{B.5}$$

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DOI 10.1007/978-3-319-12820-7

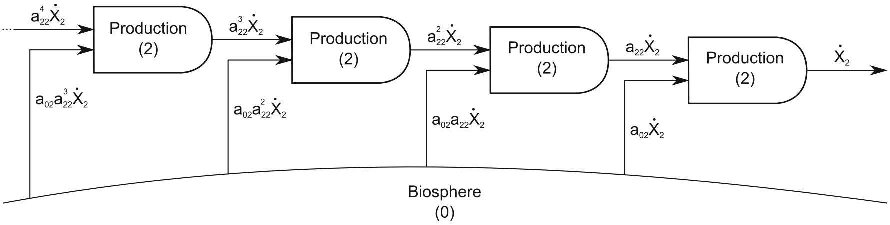

Fig. B.1 Process flows in a single-sector economy

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 ($\frac{\mathrm{d}B_2}{\mathrm{d}t} = 0$), and physical depreciation ($\gamma_{B_2} B_2 = 0$), Eq. 7.37 and B.5 are identical, indicating that the EI–O approach accounts for the infinite recursion of energy demand by the economy.

Appendix C
Proof of Eq. 7.31

We begin with a restatement of Eq. 7.31.

$$\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I}) \tag{7.31}$$

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 Eq. 7.3) 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.

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Appendix D
Estimating the Input–Output Matrix (A)

Using Eq. 7.31, which is proved in Appendix C

$$\mathbf{X}_t^{\mathrm{T}} - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^{\mathrm{T}} - \mathbf{I}); \tag{7.31}$$

we can derive an expression for estimating the Input–Output matrix (**A**) given sector outputs ($\hat{\mathbf{X}}$) and the transaction matrix ($\mathbf{X}_t$). Premultiplying both sides of Eq. 7.31 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

$$\mathbf{A} = \mathbf{X}_t(\hat{\mathbf{X}}^{-1})^{\mathrm{T}}. \tag{D.6}$$

Both $\hat{\mathbf{X}}$ and $\hat{\mathbf{X}}^{-1}$ are diagonal matrices. Therefore, $(\hat{\mathbf{X}}^{-1})^{\mathrm{T}} = \hat{\mathbf{X}}^{-1}$, and Eq. D.6 becomes

$$\mathbf{A} = \mathbf{X}_t\hat{\mathbf{X}}^{-1}. \tag{D.7}$$

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Expanding the matrices of Eq. 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 Eq. 7.3:

$$a_{ij} \equiv \frac{\dot{X}_{ij}}{\dot{X}_j}. \tag{7.3}$$

Thus, Eq. D.7 provides a method of estimating the input-output matrix (**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 Eqs. 7.23, 7.20, and 7.21, respectively), because it natural to solve a system of equations for a column vector rather than a row vector. And, Eq. 7.17 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, Eqn. (7.37).

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 (Eq. 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 Eqs. 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

$$\begin{bmatrix} \dot{X}_{11} & \dot{X}_{21} \\ \dot{X}_{12} & \dot{X}_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \tag{E.4}$$

[1] Equation E.1 is written according to the variable conventions in this manuscript. The literal Eq. 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 Eq. E.2.

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Substituting $\dot{X}_{ij} = a_{ij}\dot{X}_j$ (from Eq. 7.3) gives

$$\begin{bmatrix} a_{11}\dot{X}_1 & a_{21}\dot{X}_1 \\ a_{12}\dot{X}_2 & a_{22}\dot{X}_2 \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \tag{E.5}$$

Expanding Eq. 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 Eqs. 7.25, 7.30, 7.20, and 7.23, respectively, we can rewrite Eq. 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 Eqs. E.1 and E.8 are due to the choice of row vectors (for Eq. E.1) or column vectors (for Eq. E.8) only. Note that Eq. E.8 is similar to Eq. 7.37. A detailed discussion of the differences between Eqs. E.8 and 7.37 can be found in Sect. 8.2.

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Glossary

ATP	Adenosine Triphosphate
BEA	Bureau of Economic Analysis, US Department of Commerce (http://www.bea.gov)
CES	Constant Elasticity of Substitution
DEC	Direct Energy Conversion
EIA	Energy Information Administration
EI-O	Energy Input-Output
EIOLCA	Economic Input-Output Life Cycle Assessment (http://www.eiolca.net)
EROI	Energy Return on (Energy) Invested
EW-MFA	Economy-Wide Materials Flow Accounts
GDP	Gross Domestic Product
GER	Gross Energy Ratio
GHG	Greenhouse Gas
GNH	Gross National Happiness
GPI	Genuine Progress Indicator
HDI	Human Development Index
IE	Industrial Ecology
IEA	International Energy Agency
IEESA	Integrated Environmental-Economic System of Accounts
I-O	Input-Output
IRP	International Resource Panel
ISEW	Index of Sustainable Economic Welfare
KLEMS	Capital (K), Labor (L), Energy (E), Materials (M), and Services (S)
LCA	Life Cycle Assessment
LINEX	LINear Exponential
MDGPI	Maryland Genuine Progress Indicator
MFA	Material Flow Analysis
NAICS	North American Industry Classification System
NEA	Net Energy Analysis
OICA	International Organization of Motor Vehicle Manufacturers
OPEC	Organization of the Petroleum Exporting Countries
PI-O	Physical Input-Output

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SEEA	System of Environmental-Economic Accounting
SNA	Systems of National Accounts
UK	United Kingdom
UN	United Nations
UNEP	United Nations Environmental Programme
US	United States

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M. K. Heun et al., *Beyond GDP,* Lecture Notes in Energy 26,
DOI 10.1007/978-3-319-12820-7