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Series Title	Lecture Notes in Energy	
Book Title	Beyond GDP	
Book Sub Title	National Accounting in the Age of Resource Depletion	
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Metadata of the chapter 1 that will be visualized online

Book Title	Beyond GDP																		
Chapter Title	Introduction: The End of an Era																		
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Abstract	<p>In this chapter, we introduce the guiding premise of the book: biophysical limits are becoming binding constraints on mature economies and the data needed for policy makers to understand and manage this reality is not universally available. We discuss the problems that arise from relying solely on the Solow growth model to describe an economy that is deeply interconnected to the biosphere. We point out that mainstream economists forecast low growth rates for mature economies for the foreseeable future because traditional drivers of economic growth (growth rates of capital and labor productivity) have plateaued. We introduce the idea that stalled economic growth may also be the natural outcome of mature economies reaching a limit of the supply of energy, and other forms of natural capital. Thus, mainstream policy recommendations based on the Solow growth model that would spur consumption and investment to invigorate economic growth may actually backfire: expansion of the stock of capital in the economy can contribute to the ultimate slowdown of economic growth! The chapter ends with a call for acknowledging the <i>biophysical</i> reality of the economy and adjusting national accounting accordingly.</p>																		

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Abstract	<p>In this chapter, we describe the development of approaches to the relationship between the economy and the biosphere. The historical development takes place over three eras, the era of abundance, the era of energy constraints, and the age of resource depletion. Each era is defined by a dominant metaphor that guides the economic model and leads to a framework for national accounting that is perceived as relevant to understanding the economy. The metaphor for the economy has evolved from the clockwork mechanism of classical physics (economy isolated from the environment) to an engine (the economy is dependent on an inexhaustible supply of inputs from the environment). The chapter then suggests that the previous metaphors are insufficient for the age of resource depletion and suggests a new metaphor: the economy is society's <i>metabolism</i>. Next, the way in which the metabolism metaphor leads to an expanded understanding of the requirements for national accounting is described. An argument is made for accounting a nation's wealth (manufactured and natural capital) in addition to its income (GDP). The chapter ends with a description of the structure of the rest of the book.</p>																		

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Abstract	<p>In this chapter we will develop a framework for accounting material flows and accumulations within economies. We will begin by looking at accounting in everyday life before using concepts from thermodynamics, such as system boundaries, control volumes as well as the First Law of Thermodynamics, to develop a rigorous accounting procedure. This procedure is applied first to a one-sector then two-sector model of the economy, in order to build up to a general framework for material accounting. We then apply the framework to the real-world example of the US auto industry.</p>																		

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Chapter Title	Flows of Direct Energy																		
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Abstract	In this chapter, we develop equations, assisted by the First Law of Thermodynamics, that describe the flow of direct energy through economies. The equations are applied to example economies with increasing levels of disaggregation. Finally, the energy flows for our running example, the US auto industry, are discussed.																		

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Abstract	This chapter develops equations that describe the accumulation and flow of embodied energy through economies. We noted that waste heat from a sector 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. Finally, we discussed embodied energy in the context of our running example, the US auto industry. We found that there are a few historical estimates of energy embodied within automobiles.																		

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Chapter Title	Stocks and Flows of Economic Value																		
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Abstract	<p>In this chapter, we develop techniques to account for flows of economic value through economies. We employ the prevailing subjective theory of value for our framework, that is, we use the value of market transactions to value physical flows of materials and energy. As part of the methodology section, we discuss the limitations to relying solely on valuations obtainable from market transactions and call for additional nonmarket valuation methods to be employed in national accounting. In particular, we point to the system of environmental economic accounts (SEEA), the international standard developed by the UN¹². We then develop value accounting equations and apply them to example economies A–C. This chapter introduces two new terms to capture value-added (and destroyed) within economic sectors, and demonstrate that these terms capture the value for GDP in national accounts. Finally, we illustrate how our framework can be populated with data from current national accounts to derive inter-sectoral value flows, using national accounting data for the auto industry for illustration. This section of the chapter also contains a discussion of the potential problems with including intangible intellectual property assets in the nations measure of its capital stock.</p>																		

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Book Title	Beyond GDP	
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Abstract	<p>In this chapter, we derive algebraic equations that describe the energy intensity (in units of J/\$) of products of economic sectors. The algebraic equations are applied to Examples A–C to derive a matrix equation for a vector of energy intensities for the entire economy. We review several studies of energy intensity in the literature and note 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/\$.</p>	

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Abstract	<p>In this chapter, we discuss several implications that arise from the detailed development of our dynamic framework for material, energy, and value accounting. The first implications are for the energy I-O method itself. We recommend a physical accounting framework that fully accounts for capital stock and energy input from society (final consumption) to the economy. We then discuss implications for economic "development," namely that 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, including financial capital, physical capital and associated embodied energy, direct energy, resources, and societal inputs. Each, alone, is necessary, but not sufficient, for economic development. We discuss implications for recycling and reuse of materials as well as the concept of dematerialization. Finally, we view the concept of a steady-state economy through the lens of our framework. We find that there are many potential definitions of a steady-state economy, none of which are fully satisfying when compared against the ideal of sustainability.</p>																		

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Chapter Title	Next Steps																		
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Abstract	This chapter briefly summarizes the book and highlights the need for additional data on both inter-sector flows and accumulation of manufactured capital and associated embodied energy. We continue with a call to action, a list containing several tasks that should be undertaken to modify national accounting. Finally, we note that moving forward on these issues will be politically difficult, but necessary, to adapt to the age of resource depletion.																		

¹ **Lecture Notes in Energy**

² Volume 26

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4 study of energy: from science and engineering to the analysis of energy policy. The
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¹⁸ Matthew Kuperus Heun • Michael Carbajales-Dale
¹⁹ Becky Roselius Haney

²⁰ **Beyond GDP**

²¹ National Accounting in the Age of Resource
²² Depletion

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45 “Now! Now!” cried the Queen. “Faster!
46 Faster!” And they went so fast that at last
47 they seemed to skim through the air, hardly
48 touching the ground with their feet, till
49 suddenly, just as Alice was getting quite
50 exhausted, they stopped, and she found
51 herself sitting on the ground, breathless and
52 giddy. The Queen propped her against a tree,
53 and said kindly, “You may rest a little now.
54 ”Alice looked round her in great surprise.
55 “Why, I do believe we’ve been under this tree
56 all the time! Everything’s just as it was!”
57 “Of course it is,” said the Queen: “what
58 would you have it?”
59 “Well, in our country,” said Alice, still
60 panting a little, “you’d generally get to
61 somewhere else—if you ran very fast for a
62 long time, as we’ve been doing.”
63 “A slow sort of country!” said the Queen.
64 “Now, here, you see, it takes all the running
65 you can do, to keep in the same place. If you
66 want to get somewhere else, you must run at
67 least twice as fast as that!”
68 —Lewis Carroll. 1897. *Through the*
69 *Looking-Glass and What Alice Found There.*
70 *Henry Altemus Company, Philadelphia, p. 49.*

71 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.
:

72 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

73 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].

85 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.

88 the poorest nations are “accelerating markedly” [4]. They expect GDP per capita and
89 living standards to grow continuously into the foreseeable future, even under the most
90 pessimistic assumptions [4, p. 170]. The Organisation for Economic Co-operation
91 and Development (OECD), for example, forecasts an average global GDP growth
92 rate of approximately 2 % per year for the next several decades [5, Table A.1].

93 There is a stark contrast between these two visions of the future, because the
94 two groups (scientists and economists) focus on different parts of the economy.
95 Scientists observe the planet’s natural capital dwindling, and foresee declining quality
96 of life. Economists observe the stock of manufactured capital growing, and growing
97 increasingly efficient, and foresee continued improvement in the quality of life.

98 The differences between scientists and economists revolve around the understand-
99 ing and role of capital. Physical scientists often focus on the dependence of our living
100 standards on the availability of natural capital, but ignore the multiplying power of
101 manufactured capital. Conversely, economists place their faith in the ability of man-
102 ufactured capital to continually increase production rates, but ignore constraints of
103 natural capital.

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

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

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

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158 *Matthew Kuperus Heun*
159 *Michael Carbajales-Dale*
160 *Becky Roselius Haney*

161 Prologue

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

166 —William Nordhaus

167 One of the first calls for integrated and comprehensive reporting of environmental-
168 economic data, including natural and manufactured capital,² came from the
169 Brundtland Commission (1983–1987), which recognized the need to devise rig-
170 orous methods for integrating environmental assets into national balance sheets and
171 income statements. In its final report, entitled *Our Common Future*, the commission
172 highlighted the need for all nations to include a full (economic) accounting of the
173 use and development of natural resources in national accounts:

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

185 In response to the call by the Brundtland Commission, economist Peter Bartelmus
186 led an effort at the UN Statistics Division to develop a set of satellite accounts,
187 called the System for Environmental and Economic Accounting (SEEA), which
188 accompanies the UN System of National Accounts framework [3]. The UN published
189 the first Handbook for the SEEA in 1993, and it is now in its third edition [4]. The
190 Philippines served as a pilot study for the new integrated environmental-economic

² We use the phrase “accounting for the environment” as shorthand for the process of gathering, analyzing, and disseminating integrated and comprehensive environmental-economic data that includes natural in addition to manufactured capital.

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 USA.

Unfortunately, progress toward integrated environmental-economic accounting in the USA 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 NASreview 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,

236 should the timber from an old growth forest be harvested? Using data that are limited
237 to income-generating transactions only, the answer is “yes,” because the harvest adds
238 directly to national income. However, the value of foregone “hunting, fishing, and
239 other forms of nonmarket forest recreation” services over time (likely to exceed the
240 value of the harvested timber) cannot be part of the decision unless a system such as
241 the IEESA is in place [1, p. 30].

242 Despite the review panel’s ringing endorsement of the BEA’s work, Congress
243 continued to expressly forbid the BEA’s efforts. Appropriations bills through FY
244 2002 contained the sentence:

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

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

254 We believe that the benefits of accounting for the environment by including both
255 natural and manufactured capital will be worth the political efforts needed to resume
256 the practice. After reading this book, we hope you will agree.

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Contents

280	1 Introduction: The End of an Era	1
282	1.1 (Mis)measuring the Wealth of Nations	4
283	1.2 Nations at Risk	6
284	1.3 Understanding the Biophysical Economy	6
285	1.3.1 Coupling Between Energy and the Economy	7
286	1.3.2 Stalled Growth Is Related to Nonrenewable Stocks	12
287	1.3.3 Stalled Growth Is Related to Capital Stock	16
288	1.4 Consumption-Driven Solutions Are Unsustainable	18
289	1.5 Change Is Needed!	19
290	References	20
291	2 Accounting for the Wealth of Nations	23
292	2.1 Three Eras	24
293	2.1.1 Era of Abundance	24
294	2.1.2 Era of Energy Constraints	27
295	2.1.3 Age of Resource Depletion	30
296	2.2 The Economy is Society's Metabolism	31
297	2.2.1 Anabolism (Capital Formation)	34
298	2.2.2 Catabolism (Energy Production)	34
299	2.2.3 Autophagy (Recycling)	35
300	2.2.4 Issues of Scale	36
301	2.2.5 Benefits of the Metabolism Metaphor	37
302	2.3 New National Accounting	38
303	2.4 Structure of the Book	40
304	References	41
305	Part I Material and Energy	
306	3 Stocks and Flows of Materials	45
307	3.1 Methodology	48
308	3.1.1 Accounting in Everyday Life	48
309	3.1.2 Product, Resource, Short-lived, and Capital Flows	50

310	3.2 Example A: Single-Sector Economy	52
311	3.3 Example B: Two-Sector Economy	59
312	3.4 Example C: Three-Sector Economy	64
313	3.5 Materials in the US Auto Industry	71
314	3.6 Summary	73
315	References	74
316	4 Flows of Direct Energy	77
317	4.1 Methodology	78
318	4.2 Example A: Single-Sector Economy	79
319	4.3 Example B: Two-Sector economy	82
320	4.4 Example C: Three-Sector Economy	85
321	4.5 Direct Energy in the Auto Industry	87
322	4.6 Summary	87
323	References	88
324	5 Stocks and Flows of Embodied Energy	89
325	5.1 Methodology	91
326	5.1.1 Total Energy Accounting	91
327	5.1.2 Embodied Energy Accounting	93
328	5.2 Example A: Single-Sector Economy	94
329	5.2.1 Simplification of the Embodied Energy Accounting Equation	94
330	5.2.2 Substitution of First Law into the Embodied Energy Accounting Equation	96
331	5.2.3 Physical Depreciation	97
332	5.3 Example B: Two-Sector Economy	98
333	5.4 Example C: Three-Sector Economy	101
334	5.5 Embodied Energy in the US Auto Industry	104
335	5.6 Summary	106
336	References	106
339	Part II Economic Value and Energy Intensity	
340	6 Stocks and Flows of Economic Value	111
341	6.1 Subjective Theory of Value	111
342	6.2 Methodology	114
343	6.3 Example A: Single-Sector Economy	115
344	6.3.1 Economic transactions	117
345	6.3.2 Value generation	117
346	6.3.3 Value destruction	118
347	6.3.4 GDP	118
348	6.4 Example B: Two-Sector Economy	119
349	6.5 Example C: Three-Sector Economy	119
350	6.6 Stocks and Flows of Economic Value in the US Auto Industry	122

	Contents	xix
351	6.7 Summary	125
352	References	125
353	7 Energy Intensity	127
354	7.1 Background	127
355	7.2 Methodology	132
356	7.3 Example A: Single-Sector Economy	133
357	7.4 Example B: Two-Sector Economy	134
358	7.5 Example C: Three-Sector Economy	135
359	7.5.1 Total Energy Accounting Equation	135
360	7.5.2 Matrix Formulation	136
361	7.6 What is Endogenous?	139
362	7.7 Choice of Energy Input Vector	140
363	7.8 Energy Intensity in the US Auto Industry	141
364	7.9 Summary	143
365	References	144
366	Part III Implications and Summary	
367	8 Implications	149
368	8.1 Metrics	149
369	8.2 Implications for the I–O Method	150
370	8.2.1 Product-Based vs. Physical Approaches	151
371	8.2.2 Capital Flows and Stock	152
372	8.2.3 Energy Input from Society	157
373	8.2.4 Recommendation	157
374	8.3 Implications for Economic Growth	159
375	8.4 Implications for Recycling, Reuse, and Dematerialization	161
376	8.5 Comparison to a Steady-state Economy	162
377	8.5.1 Constant Level of Capital Stock	163
378	8.5.2 Constant Material Throughput	164
379	8.5.3 Constant GDP	165
380	8.6 Summary	166
381	References	167
382	9 Next Steps	169
383	References	171
384	Appendix A Value Flows for the US Auto Industry	173
385	Appendix B Infinite Series Representation of Energy Intensity	177
386	Appendix C Proof of Eq. 7.31	179
387	Appendix D Estimating the Input–Output Matrix (A)	181

388	Appendix E Column vs. Row Vectors in Energy Intensity Equations	183
389	Glossary	185
390	Bibliography	187
391	Index	199

UNCORRECTED PROOF

392 List of Figures

393 Fig. 1.1	Five-year trailing averages of economic growth, 1965–2013 [4]	2
394 Fig. 1.2	The famous graph from Cleveland et al. [11] showing the strong correlation between energy consumption and economic activity in the USA from 1890 to 1982. © Somebody. Used by permission...	8
395		
396 Fig. 1.3	Gasoline shortages in 1973 [20]	9
397 Fig. 1.4	Oil prices (<i>left axis</i> , data points) and production (<i>right axis</i> , vertical bars). © Rune Likvern, http://www.fractionalflow.com . Used by permission	9
398		
399 Fig. 1.5	Slowing growth in world oil supply [29, Fig.3]. © Gail Tverberg, http://www.ourfiniteworld.com . Used by permission	13
400		
401 Fig. 1.6	Oil company free cash flow [40]. Obtain updated chart from Steve Kopits. © Somebody. Used by permission	16
402		
403 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 [7]	26
404		
405 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	28
406		
407 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	33
408		
409 Fig. 2.4	Vintage autos (“yank tanks”) in Cuba (2011). **** © Larry Cowles, http://lcowlesphotography.wordpress.com . Used by permission. Permission not yet obtained. ****	36
410		
411 Fig. 2.5	Kleiber’s law for metabolic rates (heat production) of different-sized animals [42, p. 530]. Larger animals, as	
412		
413		
414		
415		
416		
417		
418		
419		
420		
421		
422		
423		
424		

425	determined by mass, have a higher metabolic rate, but the	
426	relationship between mass and metabolic rate is not linear	37
427	Fig. 3.1 Material flows into and out of a single sector of the economy.	
428	Resource flows (\dot{R}) enter the sector from the left and are	
429	embodied in products (\dot{P}) which leave from the right. Some waste	
430	resources are leave the sector at the bottom and are returned to the	
431	biosphere. Short-lived material flows (\dot{S}) enter the sector from	
432	above and leave from below to return to the biosphere. Only	
433	capital stock (\dot{K}) may accumulate within the sector, depicted by	
434	the storage tank. These also enter the sector from above.	
435	Depreciated capital leaves the sector from below and is returned	
436	to the biosphere. Energy flows (green lines) are associated with	
437	all flows of materials, but are not drawn explicitly in this diagram.	
438	Flows of energy will be depicted in diagrams in later chapters....	51
439	Fig. 3.2 Flows of materials for a one-sector economy. Resources (\dot{R}_{01}) and	
440	short-lived materials (\dot{S}_{01}) flow into the Society (1) from the	
441	Biosphere (0). Waste resources (\dot{R}_{10}) short-lived materials/goods	
442	(\dot{S}_{10}) and capital goods (\dot{K}_{10}) are returned to the biosphere.....	53
443	Fig. 3.3 Material flows through an economic sector with waste treatment	
444	flows to other economic sectors	58
445	Fig. 3.4 Flows of materials for a two-sector economy.....	60
446	Fig. 3.5 Flows of materials for a three-sector economy	65
447	Fig. 3.6 The matrix of biosphere-economy flows. Note that flow \dot{S}_{00} is not	
448	included within our framework	70
449	Fig. 4.1 Energy content (\dot{E}) of material flows (\dot{R} , \dot{S} , and \dot{K}) from Fig. 3.1	79
450	Fig. 4.2 Aggregated direct energy flows (\dot{E}) around the producer of	
451	Fig. 4.1.....	80
452	Fig. 4.3 Direct energy flows (\dot{E}) a one-sector economy	81
453	Fig. 4.4 Direct energy flows (\dot{E}) for a two-sector economy.....	83
454	Fig. 4.5 Direct energy flows (\dot{E}) for a three-sector economy	86
455	Fig. 4.6 Direct energy flows for the US automobile industry. [12, Table	
456	7.6].....	87
457	Fig. 5.1 Total energy flows (\dot{T}) for a single sector of an economy. For the	
458	sake of clarity, direct (\dot{E}) and embodied (\dot{B}) energy flows are	
459	shown separately for material inflows from other sectors only	91
460	Fig. 5.2 Total energy flows (\dot{T}) in a one-sector economy	95
461	Fig. 5.3 Flows of total energy (\dot{T}) in a two-sector economy	99
462	Fig. 5.4 Flows of total energy (\dot{T}) in a three-sector economy.....	102
463	Fig. 5.5 Embodied energy flows (\dot{B}) for the US automobile industry	105
464	Fig. 6.1 Aggregated flows of value for a single sector, including flows to	
465	and from the biosphere	113
466	Fig. 6.2 Flows of economic value (\dot{X}) for a single sector. The economic	
467	value flows are associated with each of the different material and	
468	energy flows outlined in previous chapters. The <i>dashed lines</i>	

469	represent the equal and opposite flows of the currency used to pay for the material and energy.....	114
470		
471	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 <i>downward arrow</i> flowing into the filled-circle sinks and generation of value, represented by the <i>arrow</i> flowing out of an open-circle source.....	115
472		
473		
474		
475		
476		
477		
478	Fig. 6.4 Flows of value (\dot{X}) for a one-sector economy	116
479	Fig. 6.5 Flows of value (\dot{X}) within a two-sector economy	120
480	Fig. 6.6 Flows of value (\dot{X}) within a three-sector economy.....	121
481		
482	Fig. 6.7 Value of material and energy flows into and out of the US automobile industry (in millions of 2011 US\$).....	123
483		
484	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....	128
485		
486		
487		
488		
489		
490		
491	Fig. 7.2 System boundary for process and I–O analyses. (Adapted from [1]).....	129
492		
493	Fig. 7.3 Advantages (pros) and disadvantages (cons) of “ <i>top-down</i> ,” I–O and “ <i>bottom-up</i> ,” process-based analyses. (Adapted from [19])...	131
494		
495	Fig. 7.4 Units for input–output ratios (a).....	133
496	Fig. 8.1 Coordinates of analysis for implications for the EI–O method	150
497	Fig. B.1 Process flows in a single-sector economy	178

498 List of Tables

499 Table 2.1 Examples used throughout this book	41
500 Table 3.1 List of material input and output flows for the US auto industry 501 (IOC:3361MV) as resources (\dot{R}), short-lived materials (\dot{S}), and 502 capital goods (\dot{K}) using data from [22–25, 27, 28, 31, 32]. This 503 list is illustrative and by no means exhaustive.....	72
504 Table 4.1 Energy inputs to US auto industry (NAICS Code 336111) in 2010. 505 [12, Table 7.6].....	87
506 Table 6.1 Data sources for auto industry (IOC 3361MV) example.....	124
507 Table 7.1 Motor Vehicles and Equipment sector (63) energy intensity values 508 [12].....	142
509 Table 7.2 Selected US economic sector energy intensities, 1972 [12]	142
510 Table 7.3 Automobile manufacturing sector (NAICS 33611x) energy 511 intensity values [23]	143
512 Table 7.4 Selected US economic sector energy intensities, 1997 [23]	143
513 Table 8.1 Manufacturing efficiencies ($\eta_{\dot{R}}$, Eq. 8.10) for selected 514 manufactured goods [9].....	155
515 Table A.1 Data sources and calculations for auto industry (IOC 3361MV) 516 example	173
517 Table A.2 BEA data sources	175

518 List of Symbols

519 *Roman*

520 a	stock of apples [-]
521 a	input output ratio, mixed units
522 a_0	LINEX fitting parameter [-]
523 \dot{a}	apple flow rate [apples/s]
524 A	technology augmentation factor [-]
525 \mathbf{A}	input–output matrix, mixed units
526 B	ecosystem biomass stock [kg]
527 B	embodied energy [MJ]
528 \dot{B}	embodied energy flow rate [MJ/year]
529 \mathbf{B}_K	column vector of energy embodied in capital stock [MJ]
530 $\mathbf{B}_{\dot{W}}$	column vector of waste flows [MJ/year]
531 c_t	LINEX fitting parameter [-]
532 e	indexed energy [-]
533 E	direct energy [MJ]
534 E_s	elasticity of substitution [-]
535 E_s	elasticity of supply [-]
536 \dot{E}	direct energy flow rate [MJ/year]
537 \mathbf{E}_0	column vector of direct energy inputs from the biosphere [MJ/year]
538 $EROI$	Energy return on (energy) invested [-]
539 f_E	energy cost share [-]
540 k	indexed capital stock [-]
541 K	mass of capital goods [kg]
542 \dot{K}	capital goods mass flow rate [kg/year]
543 l	indexed labor [-]
544 m	mass [kg]
545 n	number of sectors in the economy
546 p	a system property
547 P	ecosystem photosynthetic energy production rate [J/year]
548 P	price [\$]
549 P	mass of products [kg]

550	\dot{P}	product mass flow rate [kg]
551	Q	quantity of production or demand [various]
552	q_0	proportionality constant [$\text{W}/\text{kg}^{3/4}$]
553	\dot{Q}	energy consumption rate in Kleiber's Law [W]
554	\dot{Q}	waste heat flow rate [MJ/year]
555	R	mass of resource [kg]
556	\dot{R}	mass flow rate of resources [kg/year]
557	s	stock of steel [kg]
558	\dot{s}	mass flow rate of steel [kg/year]
559	S	mass of short-lived goods [kg]
560	\dot{S}	mass flow rate of short-lived goods [kg/year]
561	t	time [year]
562	T	total energy [MJ]
563	\dot{T}	total energy flow rate [MJ/year]
564	\mathbf{T}_1	column vector of total energy flows (\dot{T}) from society to the economy [MJ/year]
565		
566	\dot{W}	waste flow rate [kg/year]
567	X	stock of economic value [\$]
568	\dot{X}	economic value flow rate, mixed units
569	\mathbf{X}_t	transaction matrix [\$/year]
570	$\hat{\mathbf{X}}$	diagonal matrix of sector outputs in mixed units [\$/year or MJ/year]
571	y	indexed economic output [-]
572	<i>Greek</i>	
573	α	ratio of inflowing capital stock rate to capital stock [1/year]
574	α	output elasticity of capital [-]
575	$\hat{\alpha}$	diagonal matrix of ratios incoming embodied energy in capital [-]
576	β	output elasticity of labor [-]
577	δ_{ij}	Kronecker delta
578	ε	energy intensity [MJ/\$]
579	ε	column vector of sector energy intensities [MJ/\$]
580	η_R	resource efficiency [kg/kg]
581	γ	output elasticity of energy [-]
582	γ	depreciation rate [1/year]
583	$\hat{\gamma}$	diagonal matrix of depreciation rates [1/year]
584	ρ_k	ratio of indexed capital to the average of indexed labor and energy [-]
585	ρ_l	ratio of indexed labor to indexed energy [-]
586	ρ_S	ratio of short-lived material flow rate to resource flow rate [kg/kg]
587	<i>Subscripts</i>	
588	0	Biosphere
589	1	Society (Example A) or Final Consumption (Examples B and C)
590	2	Production sector (Example B) or Energy sector (Example C)
591	3	Goods and Services sector (Example C)
592	a	pertaining to making available to society

593	<i>B</i>	pertaining to embodied energy
594	<i>c</i>	pertaining to consumption
595	<i>dest</i>	destruction
596	<i>gen</i>	generation
597	<i>i</i>	energy type
598	<i>i</i>	economic sector index
599	<i>in</i>	inflow
600	<i>j</i>	economic sector index
601	<i>k</i>	economic sector index
602	<i>K</i>	pertaining to capital stock
603	<i>out</i>	outflow
604	<i>soc</i>	society
605	<i>t</i>	transaction
606	<i>waste</i>	pertaining to waste

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Chapter 1

Introduction: The End of an Era

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

9 —Wendell Berry

10 The world is entering in a new economic era. There is widespread agreement that
11 economic growth in mature economies is unlikely reach the rates seen in the twen-
12 tieth century ever again. Indeed, over the last 50 years, Fig. 1.1 shows that the
13 economic growth rate for the Organisation for Economic Co-operation and Devel-
14 opment (OECD) member states has fallen precipitously. The long-term forecast from
15 the OECD is that mature economies will grow only 1.5–2.0 % annually over the next
16 50 years. Similarly, the US Congressional Budget Office forecasts an average growth
17 rate of 2.2 % for the US economy from 2018 to 2024 [2, 3].

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

27 Is stalled economic growth a problem? Most analysts believe it is. History
28 suggests that GDP growth raises living standards and human well-being, as
29 measured by various indices. Julian Simon’s volume, *The State of Humanity*,
30 catalogues the great improvements in life span, housing, environment, food quality
31 and availability, water cleanliness, etc., that have coincided with economic growth
32 over the last 3 centuries [5].

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

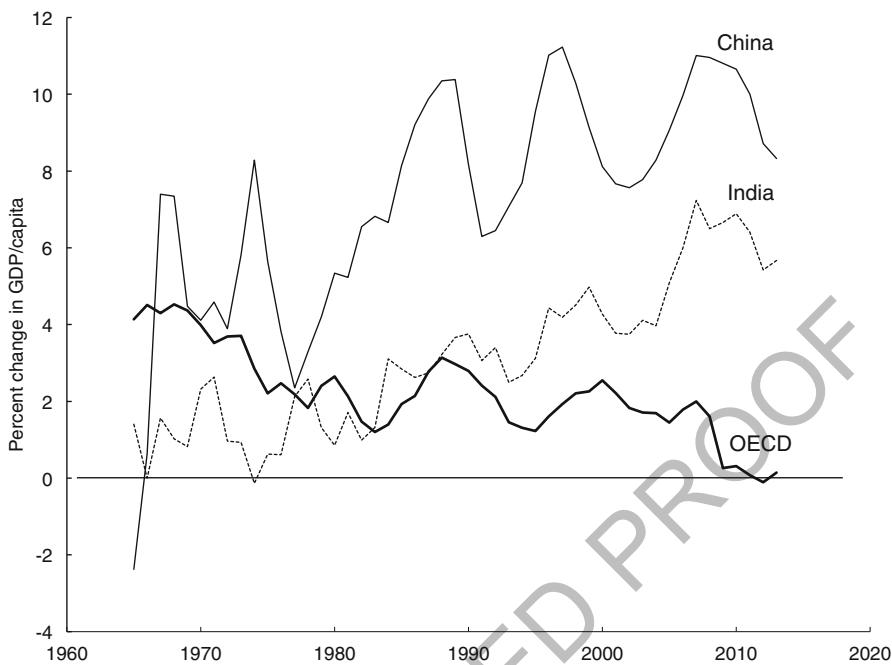


Fig. 1.1 Five-year trailing averages of economic growth, 1965–2013 [4]

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, the economy has 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 rebound [7].

The Cowen and Lindsey analyses represent mainstream explanations for the growth slowdown, and they are based squarely on the assumption that technology

54 augments capital and labor, the inputs to economic growth.¹ If economic slowdown is
55 caused by anything besides technology, capital, or labor, mainstream economic anal-
56 ysis cannot provide any assistance in either diagnosing the problem or prescribing a
57 cure.

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

62 Our approach may be outside the economic mainstream, but we are not alone.
63 There are several interdisciplinary fields (industrial ecology, ecological economics,
64 biophysical economics, and materials flow analysis) where the relationship between
65 the economy and the biosphere is a natural feature of the intellectual landscape,
66 and assessment of patterns of economic growth and economic downturns includes
67 consideration of biophysical limits. This emerging paradigm is taking shape with
68 the leadership of theorists such as Robert Ayres [8], Kenneth Boulding [9], Roger
69 Boyd [10], Robert Costanza [11], Herman Daly [12], Blair Fix [13], Charles Hall
70 [14], Steven Kopits [15], Marina Fischer-Kowalski [16], and others. Throughout this
71 book, we will refer to this approach as a “biophysical” approach to the economy.

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

78 It is difficult to say when, or how, the current economic growth “system” will collapse; it
79 has proved more resilient than many would have predicted. But, unless job-creating growth
80 can be sharply accelerated the choice facing governments is stark: either there will be very
81 sharp and painful cuts in entitlements and social welfare or there will be a financial crisis,
82 probably sudden (like the onset of the Great Depression) and probably within twenty years.
83 The traditional Keynesian job creation mechanisms are ineffective or inapplicable, while
84 trade liberalization and “globalization” are making the unemployment problem worse, not
85 better. Western democracies are, like the passengers on the Titanic, heading “full steam
86 ahead” into extremely dangerous waters. Icy reality lies dead ahead, already dimly visible
87 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.

88 1.1 (Mis)measuring the Wealth of Nations

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

98 A nation's wealth consists of physical *stock*, including both manufactured and
99 natural capital. The word "capital" can be used in many ways, usually referring to
100 assets of one form or another: financial capital, natural capital, human capital, social
101 capital, physical capital, and manufactured capital, to name a few. In this book, we
102 use the term "manufactured capital" or simply "capital" to indicate things such as
103 machines, buildings, roads, vehicles, and computers, all physical items used in and
104 necessary for the production process. Manufactured capital is not normally used
105 up during production of goods and rendering of services, although it depreciates
106 over time. As manufactured capital depreciates, future income is put at risk. We use
107 the term "natural capital" to include oil, coal, and natural gas deposits. But, clean
108 air and water, soils, forests, and natural areas² are counted as natural capital too.
109 Natural capital depletes when consumed (e.g., fossil fuels) or degrades when soils
110 are mistreated, clean air, and water are polluted, and wetlands are contaminated.
111 In a manner similar to manufactured capital, as natural capital dwindles, the future
112 capacity for income generation dwindles.

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

120 Now, let us turn back to GDP as a quantification of economic health. GDP is
121 an estimate of the *income* of an economy. Because firms gain income from the
122 consumption of natural and manufactured capital, estimates of GDP include these
123 transactions. Thus, depletion of natural capital and consumption of manufactured
124 capital (both stocks) are counted as "income" (a flow) in national accounts, and both
125 are "good" for the economy. The focus on GDP as the indicator of economic health
126 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), suggest 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 USA, 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 USA 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 USA, 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.

[AQ1]

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.

167 1.2 Nations at Risk

168 The risk to a nation's living standards from ignoring the effect of economic activity
169 on the nation's balance sheet is borne out in the UN's *Inclusive Wealth Report 2012*
170 [19]. This report sums together all forms of productive capital (natural, human, and
171 manufactured) as a measure of wealth for each nation. This biophysical and social
172 approach to economic measurement reveals that several nations' wealth is currently
173 declining even as their GDP grows. For the years 1990–2008, Saudi Arabia, Russia,
174 Venezuela, South Africa, and Nigeria had declining wealth coincident with income
175 growth, thereby diminishing the productive capacity of future generations in order to
176 support consumption by the current generation. Saudi Arabia's GDP per capita grew
177 at 0.4 % per year, while its wealth declined at a rate of 1.1 % per year, and Nigeria's
178 GDP per capita grew at 2.5 % per year, while its wealth declined at a rate of 1.8 % per
179 year. According to the *Inclusive Wealth Report*, not all nations consume their wealth
180 in pursuit of today's income. However, wealth is growing at a slower rate than income
181 in most countries. For example, GDP per capita for the USA grew on average 1.8 %
182 per year, while the nation's wealth grew at only 0.7 % per year [19, p. 44].

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

190 Given the above, we contend that nations need both income statements and balance
191 sheets to ensure sustainability. Nations must monitor and manage not only the goods
192 and services they produce today, but also their stocks of capital (both natural and
193 manufactured) and the state of that capital. Many questions, such as "How might
194 an economy be affected as an increasing share of production is directed toward
195 replacing degraded ecosystem services," and others enumerated in the next chapter
196 (in Sect. 2.3) are unanswerable without both.

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

200 1.3 Understanding the Biophysical Economy

201 As mentioned above, very little of the discourse about mature economy slowdown in
202 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.

203 considers biophysical factors to be *exogenous* to the economy.⁴

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

212 **1.3.1 Coupling Between Energy and the Economy**

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

217 Because of the high correlation between energy consumption and economic activi-
218 ty, it stands to reason that energy shortage relative to demand will hinder economic
219 activity. Of course, there are degrees of shortage. In extreme cases, and in the ab-
220 sence of price controls, goods become hard to find and prices spike as observed in
221 the USA during 1970s oil crisis (see Fig. 1.3).

222 In mild cases, shortage of any good relative to demand leads to rising prices,
223 even when goods remain available. For example, Fig. 1.4 shows oil prices (line)
224 and worldwide oil production (vertical bars) before, during, and after the Great
225 Recession. Demand for oil increased steadily in the early 2000s due to worldwide
226 economic growth, and production mostly kept pace through early 2005. However,
227 demand continued to increase while production flat lined from early 2005 through
228 late 2007, leading to a steep price increase. From late 2007 through the end of 2008,
229 the small amount of remaining reserve oil production capacity was brought online,
230 but it was too little, too late. Prices spiked above \$130/barrel in mid-2007. The Great
231 Recession reduced demand slightly (by about 2 Mb/day) and the price collapsed to
232 about \$40/barrel. Thereafter, demand and price rose to their previous levels as the
233 world pulled out of the Great Recession. In the years since 2008, oil production has
234 risen slightly past the previous record highs as additional production capacity has
235 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.

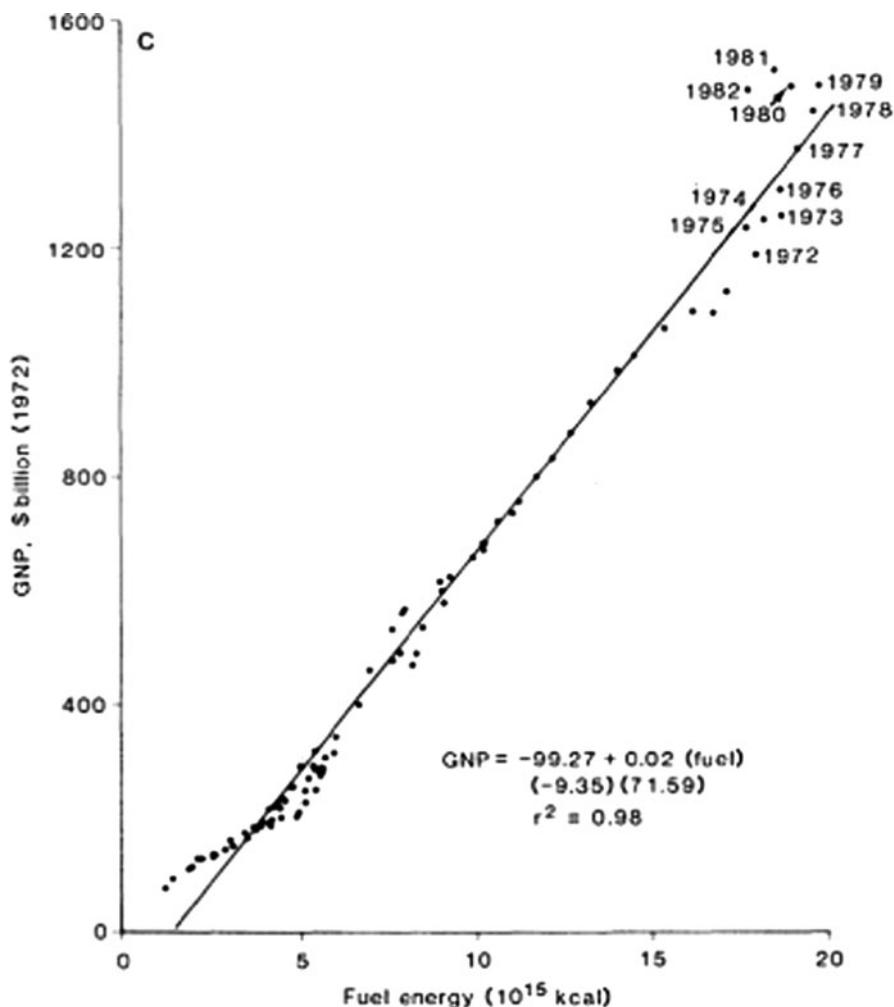


Fig. 1.2 The famous graph from Cleveland et al. [11] showing the strong correlation between energy consumption and economic activity in the USA from 1890 to 1982. © Somebody. Used by permission.

In both cases (1970s and 2000s), significant slowing of economic activity (recessions) followed the oil shortages and price 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



Fig. 1.3 Gasoline shortages in 1973 [20]

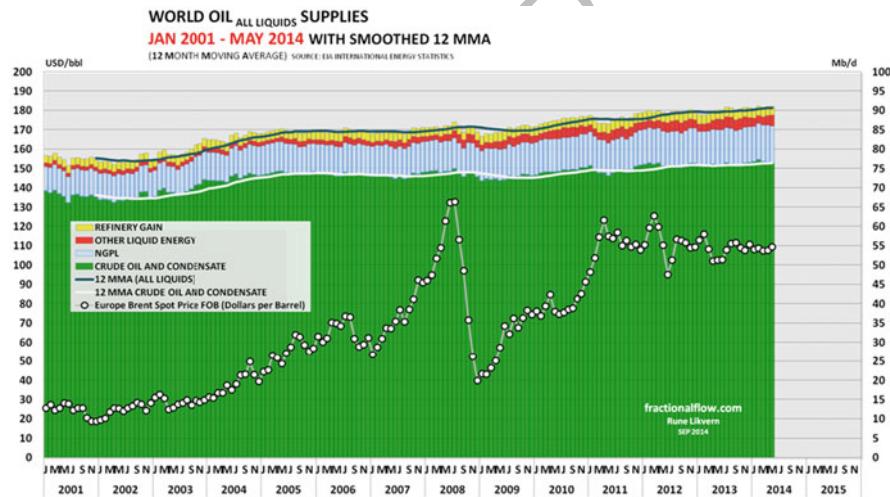


Fig. 1.4 Oil prices (left axis, data points) and production (right axis, vertical bars). © Rune Likvern, <http://www.fractionalflow.com>. Used by permission

244 established firms to increase production. However, the timing of supply and demand
 245 events is crucial. If firms cannot or do not increase production to meet demand, prices
 246 will remain elevated. Even without increased production, falling demand will bring
 247 prices back to earth.

248 In terms of energy, and oil in particular, the *rate* at which production can be
 249 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 the quantity of production, P is the price, and t is the 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

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].

312 a built-in feedback mechanism that enforces alignment between biophysical limits
313 and the economy.

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

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

327 **1.3.2 Stalled Growth Is Related to Nonrenewable Stocks**

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

331 The best-first principle [28] indicates that the economy will extract the easiest-
332 to-obtain stocks of mineral and energy resources first. "Best" and "easiest" can be
333 assessed in several ways, but physical factors that make a resource "best" or "easiest
334 to extract" eventually manifest as lower cost. For example, inexpensive-to-obtain
335 West Texas crude oil was extracted before expensive-to-obtain offshore oil. Surface
336 deposits of gold and diamonds are exhausted before subsurface veins and kimberlite
337 pipes are exploited. High-purity mineral deposits are exploited before low-purity
338 deposits. As a result, it becomes more "difficult" to continually increase extraction
339 rates as time proceeds. To continue with our energy example, historical oil production
340 trends reflect these realities. Through time, the annual rate of increase of worldwide
341 oil production has declined from 7.8 to 0.7 %/year (see Fig. 1.5).

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

350 Application of the best-first principle to the energy production process indicates
351 that it will take more energy to make the same rate of energy available to society
352 as nonrenewable energy resources in the biosphere are depleted. The metric that

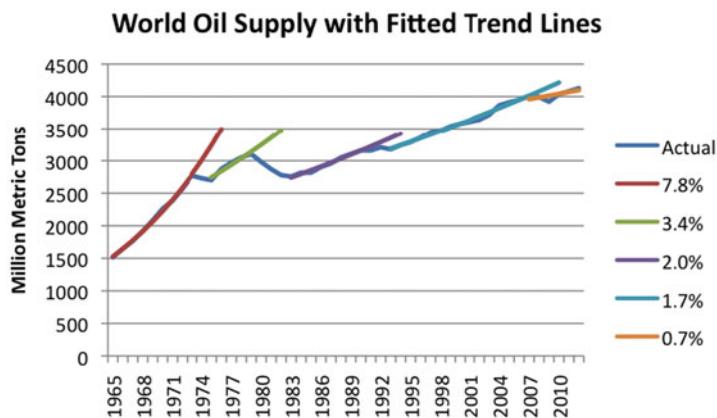


Fig. 1.5 Slowing growth in world oil supply [29, Fig. 3]. © Gail Tverberg, <http://www.ourfiniteworld.com>. Used by permission

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 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. 1.2]. $EROI_{soc}$ for production of oil worldwide has declined from a value of 35 in 1999 to 18 in 2006 [34, Fig. 1.1]. 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 the economic output of the economy. The need to increase productive

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.

capacity 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 clean¹³ and dirty¹⁴ 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.

408 as fast as possible, and high carbon taxes combined with a complete halt of the growth rate
409 of the production of electricity. In this way, according to the model, we may be able to avoid
410 an environmental disaster. [38, p. 25]

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

415 [because all of the] results show elasticity of substitution below unity, none of the factor inputs
416 are perfectly substitutable, and all tend toward complementarity in varying degrees. Such
417 results suggest that transitions from one production or consumption structure to another can
418 be disruptive and that the transitions need to be modeled dynamically to the extent possible
419 [39, p. 8].

420 The challenges of energy substitutions are highlighted when examining the financial
421 situation of oil producers. Figure 1.6 shows that despite the recent increase in oil
422 production rate and continued high prices, the free cash flow¹⁵ of independent oil
423 producers is negative. This situation implies that capital investments are unproductive
424 to date. It remains to be seen how independent producers can continue advancing
425 the oil production rate (which implies capital investment) while their free cash flow
426 is negative. One possible cure for negative free cash flow is higher oil prices. But
427 higher oil prices will lead to increasing energy cost share, and we saw in Sect. 1.3.1
428 that high energy cost share provides recessionary pressure.

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

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

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

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.

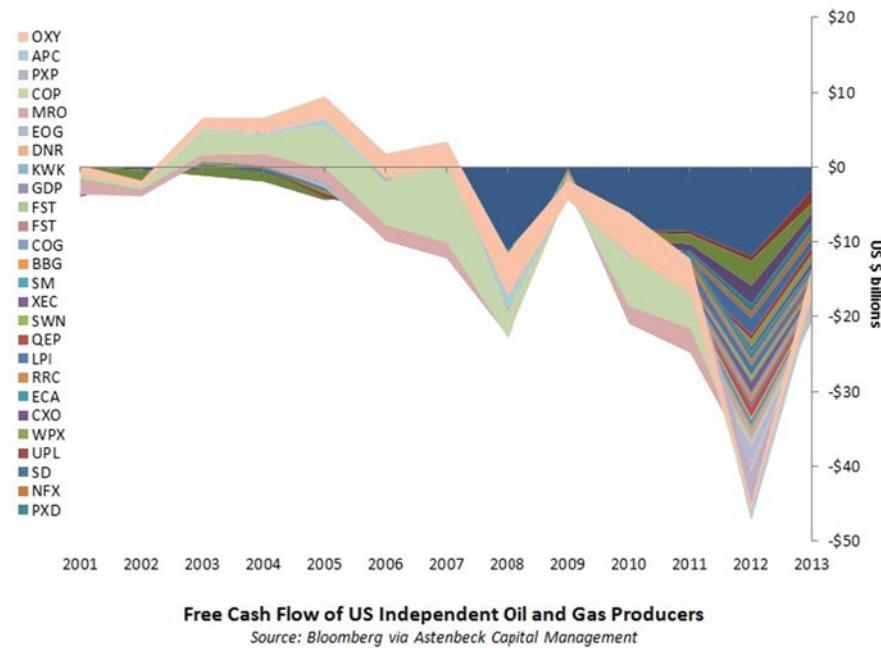


Fig. 1.6 Oil company free cash flow [40]. Obtain updated chart from Steve Kopits. © Somebody. Used by permission

445 1.3.3 Stalled Growth Is Related to Capital Stock

446 Capital is extremely valuable and, in most cases, essential to production processes:
 447 machines reduce per-unit costs of production; buildings provide space to work and
 448 protection for capital; roads provide networks for vehicular transport of raw ma-
 449 terials, finished goods, and capital itself; and computers enhance the efficiency of
 450 workers and enable technological breakthroughs. There are several types of capital
 451 flows to and from its stock in the economy. We use the term “emplacement” to de-
 452 note a flow of capital into the economy, for example, when a new machine is put into
 453 service, when a new building is constructed, or when a new road is opened. “Depre-
 454 ciation” is normal wear-and-tear experienced by capital, a type of outflow of capital
 455 from the economy. Financial depreciation involves the write-off of a percentage of
 456 the value of capital. Physical depreciation involves wear and tear of parts within or
 457 sections of the capital. Financial depreciation usually occurs faster than physical de-
 458 preciation. “Maintenance” is servicing of capital to overcome the effects of physical
 459 depreciation. “Disposal” is the physical outflow of capital from the economy to the
 460 biosphere upon removal from service. Capital “formation” is the rate of net addition
 461 to capital stock in the economy, the difference between inflows and outflows during
 462 a time interval. Traditionally, stocks and flows of capital are measured by currency

463 units, \$ and \$/year, respectively. However, we argue later (Sect. 8.2) that a physical
464 basis for capital accounting is also warranted.

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

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

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

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

499 Given the discussion in Sect. 1.3.2 regarding the economic dynamics of bio-
500 physical limits to raw material and energy extraction, we see that expansion of an
501 economy’s capital stock may increase GDP in the short run, but it also “locks in”
502 future material and energy demands from the biosphere. These “locked in” demands

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

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

503 bring the economy closer to the biophysical extraction limits that will eventually lead
504 to economic slowdown.

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

508 1.4 Consumption-Driven Solutions Are Unsustainable

509 In Sect. 1.3.3 above, we noted that today's consumption-enhancing policies have the
510 side-effect of increasing many material and energy flow rates into the economy. Thus,
511 today's policies also hasten the day when we reach binding biophysical constraints
512 due to resource depletion. Unfortunately, biophysical limits are not included in the
513 mainstream economic thinking and modeling that informs today's policy decisions.¹⁸
514 Three factors, in combination, are vitally important but nearly always ignored: (1) the
515 economy is tightly coupled to the biosphere, (2) there are physical and technological
516 limits to the rate at which materials and energy can be extracted from the biosphere,
517 and (3) today's emplacement of manufactured capital locks in tomorrow's material
518 and energy demands for both operation and maintenance of that capital. Set against
519 the backdrop of Sect. 1.3, we see that consumption-enhancing policies are ineffective,
520 because of the biophysical limits that ultimately constrain the scale of the economy.

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

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

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

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

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

538 1.5 Change Is Needed!

539 The fact that we (as a society) do not include exogenous, biophysical factors in
540 economic decision making indicates that we do not fully understand how the real
541 economy operates. Society is ignorant of the role that natural and manufactured¹⁹
542 capital together play in both sustaining today's economy and constraining future eco-
543 nomic prospects and choices. At present, markets are virtually the only tool at our
544 disposal to help us understand the characteristics of the real economy. What benefits
545 do markets provide? Markets are, at least in economic theory, extremely efficient
546 allocators of resources, provided that all relevant information is available to market
547 participants. Mainstream economic theory holds that prices are the mechanism by
548 which signals of value are communicated to sellers and buyers: sellers receive infor-
549 mation about how goods are valued by consumers, and buyers receive information
550 about the cost of materials accrued by producers.

551 In the age of resource depletion, are price signals sufficient to indicate shortages,
552 especially of important and difficult-to-substitute resources? It appears that some
553 signals are getting through. Heun and de Wit [36] showed that scarcity (as indicated
554 by low $EROI_{soc}$) correlates with higher oil prices. And, higher prices spur energy
555 efficiency improvements [41].

556 However, the market's price mechanism may not be enough. We showed in
557 Sect. 1.3.1 that the physical importance of scarce and difficult-to-substitute re-
558 sources (e.g., oil) far exceeds cost share in the economy, suggesting that prices alone
559 cannot provide comprehensive signals of importance to producers and consumers.
560 Consequently, producers and consumers participate in the market with incomplete
561 information. This is a serious problem, because the allocative efficiency of mar-
562 kets is predicated upon correct and complete information being available to market
563 participants.

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

569 In the age of resource depletion, the allocative efficiency of markets is attractive.
570 Indeed, life would be better if the markets could simply and automatically shift supply
571 and demand away from binding biophysical constraints when they are encountered.
572 But, lack of information in today's markets leads us to argue that they are not up to

¹⁹ Manufactured capital presupposes the existence of significant levels of human and social capital.

573 the task. Today's markets are a poor choice for allocative decisions about scarce and
574 difficult-to-substitute resources (such as oil) or nonproperty goods (such as clean air,
575 clean water, and other ecosystem services).

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

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

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

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

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21 See Sect. 8.2 for our suggested remedy.

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Chapter 2

Accounting for the Wealth of Nations

1 *Essentially, all models are wrong, but some are useful.*

2 [1, p. 424]

3 —George E. P. Box

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

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

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

26 Before exploring these questions, we note that models (economic and otherwise)
27 are informed by metaphors, simplified ways of explaining and framing the world
28 in which we live. Looking back, we note that the Introduction (Chap. 1) contained
29 much metaphorical language.¹ We spoke of “driving” economic growth and of “fueling”
30 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.

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

35 **2.1 Three Eras**

36 There have been three eras of the relationship between the biosphere and the economy
37 in recent human experience. We will call them the era of abundance, the era of energy
38 constraints, and the age of resource depletion. The era of abundance began with the
39 dawn of the industrial revolution and continued to the oil embargoes of the 1970s;²
40 the era of energy constraints covers the time between the oil embargoes and the run-
41 up to the Great Recession;³ and, today, we are entering the age of resource depletion.
42 Each era is associated with a metaphor that explains the economy, an economic
43 model that guides national accounting, and an economic production function that
44 describes output (usually measured by GDP). From one era to the next, there is
45 revision and refinement of the human understanding of the relationship between the
46 biosphere and the economy. Each revision of understanding is informed by a change
47 in the dominant metaphor that explains the economy. Each transition brings changes
48 in national accounting⁵ and modifications to the production function.

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

54 **2.1.1 Era of Abundance**

55 The defining characteristic of the era of abundance was plentiful natural resources
56 relative to economic demand. Society had not moved too far along the path foretold by
57 the best-first principle (Sect. 1.3.2), and materials and energy were easy to obtain from

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 necessarily 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.

58 the biosphere. On the global scale, ecosystem services particularly waste assimilation
 59 were sufficient for the scale of the economy.⁶ In this era, the abundance of natural
 60 resources made industrialization possible in many economies. The binding economic
 61 constraint was the availability of manufactured capital and/or labor. Expanding the
 62 stock of capital or the pool of labor generated, to a greater or lesser extent, economic
 63 growth.

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

69 The traditional model of the economy (Fig. 2.1) was unashamedly mechanistic
 70 and was based on classical physics’ models of mechanical equilibrium which arose
 71 from the “clockwork universe” [4–6]. In the traditional model, goods and services
 72 flow from the production sector to the household sector (consumption) in exchange
 73 for payments (spending). Factors of production are sold by the household sector to the
 74 production sector in exchange for wages and rents (income). Attention is primarily
 75 focused on the circular, clock-like flow of money (dashed line).

76 The traditional model is reflected in the economic production functions that arose
 77 in the era of abundance. Economic output (y) was deemed to be a function of
 78 the factors of production (manufactured capital, k , and labor, l) and augmenting
 79 technology (A) in the Cobb–Douglas equation [8]:

$$y = Ak^\alpha l^\beta, \quad (2.1)$$

80 where α is the output elasticity of capital, β is the output elasticity of labor, and
 81 $\alpha + \beta = 1$ if constant returns to scale are assumed.⁷

82 In the era of abundance, the clockwork metaphor, the traditional model, and the
 83 Cobb–Douglas production function were all, in some sense, appropriate: capital
 84 and labor were the key drivers of economic performance. And, national accounting
 85 reflected the binding constraints of the time. Economist Simon Kuznets led the
 86 development of the first official national accounting tables in response to the extreme

⁶ There are notable *local* exceptions such as the lethal 1952 smog cloud in London, caused by coal-burning power station emissions, that, according to some, claimed as many as 12,000 lives [2, 3]; pollution in the Cuyahoga river and Love Canal; and the legendary smog problems in Los Angeles.

⁷ Constant elasticity of substitution (CES) production functions also appeared in this era. CES production functions have the form

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

where δ_1 is the factor share for capital (k), $\rho \equiv \frac{1}{1-\sigma}$, and σ is the elasticity of substitution between capital (k) and labor (l) [8]. Although the form of the CES model is different from the Cobb–Douglas equation, the functional relationship remains the same: output (y) is a function of manufactured capital (k) and labor (l) only.

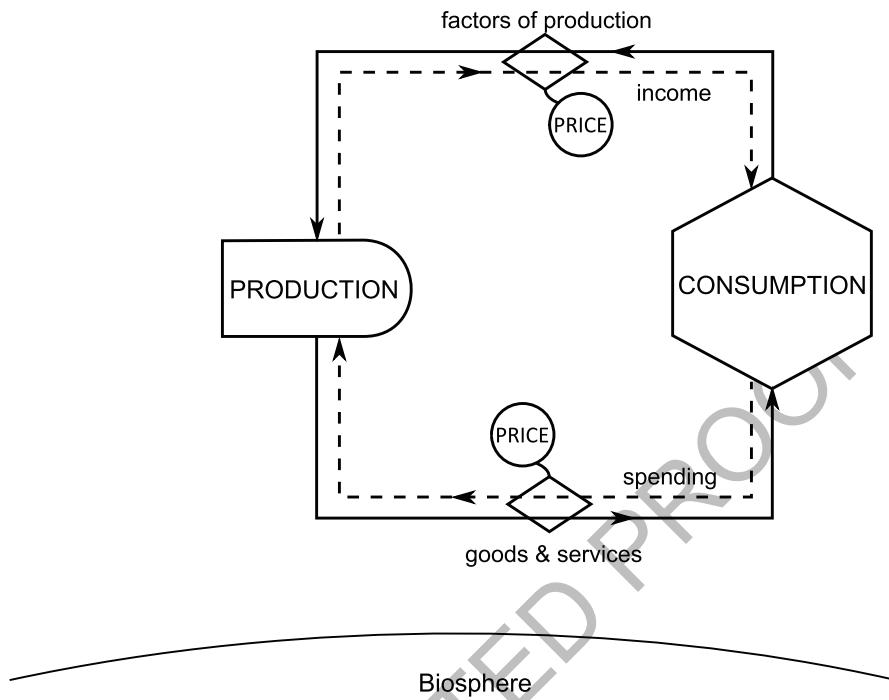


Fig. 2.1 In the traditional economic model, the economy is represented as a circular flow of goods and services between two sectors. Producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers. There are no connections between the economy and the biosphere. We use energy circuit diagrams to represent the flow of materials, energy and information [7]

87 unemployment of the Depression. The first US national accounts (published in 1947)
 88 were focused primarily on financial quantifications of flows of capital and labor
 89 among sectors of the economy.⁸ And, they still are.

90 Today, with the benefit of hindsight, we note that the clockwork metaphor, the
 91 traditional model of the economy, and the first US national accounts precluded any
 92 sort of connection between the economy and the biosphere.⁹ Thus, only the in-
 93 ternal dynamics of the economy were important.¹⁰ By implication, the clockwork

⁸ Natural resources, including energy, were, and still are, included in Systems of National Accounts as *costs*. They are counted in financial units (dollars and yen), not physical units (barrels, tonnes, and gigajoules).

⁹ To this day, the US national accounts still do not include interactions between the economy and the biosphere.

¹⁰ 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 [9].

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 [10].

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

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

2.1.2 Era of Energy Constraints

It came as a severe shock to the economic establishment that energy constraints brought about by the oil embargos of the early 1970s wrought such economic havoc [11, 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.¹¹ 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 objectives¹² or other geopolitical events.¹³

¹¹ 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* [12].

¹² For example, the October 1973–March 1974 oil embargo against Canada, Japan, the Netherlands, the UK, and the USA was a response to the US decision to supply arms to Israel during the Yom Kippur War.

¹³ For example, the 1979 Iranian revolution disrupted oil supply.

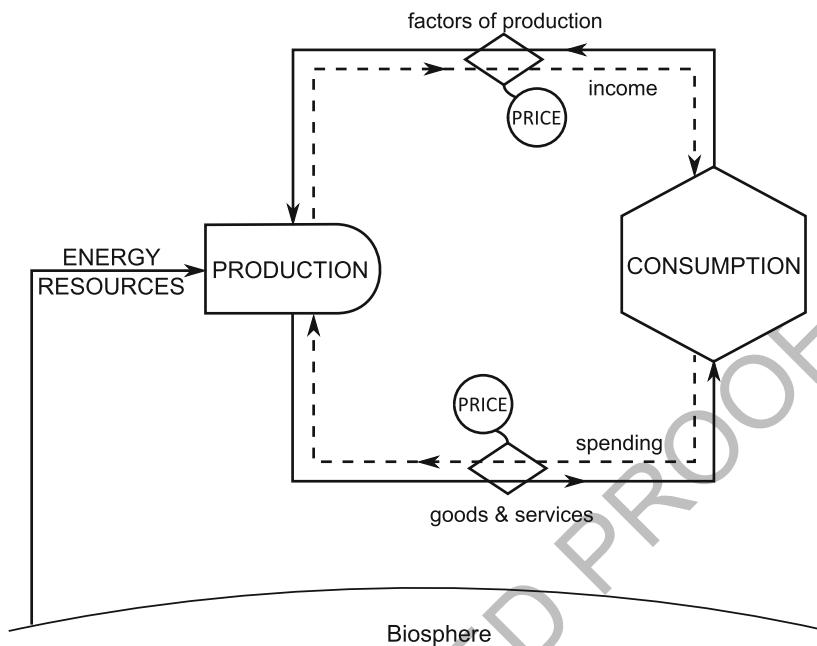


Fig. 2.2 The machine model of the economy includes flows of energy into the economy from the biosphere. This may be considered a perpetual motion machine of the second kind

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 [13, 14]. 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). 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 [15].

In addition to reevaluating the economic metaphor, some researchers reconsidered the production function.¹⁴ Energy augmentation of the Cobb-Douglas production function took several forms [16, Eq. 1], one of which [17, Eq. 3.10] is

$$y = Ak^\alpha l^\beta e^\gamma, \quad (2.2)$$

¹⁴ 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.

142 where e is energy input to the economy,¹⁵ γ is the output elasticity of energy, and
 143 $\alpha + \beta + \gamma = 1$ if constant returns to scale are assumed.¹⁶ In addition, a new production
 144 function, the LINear EXponential (LINEX) function, appeared [22, 25, 26].

$$y = A e \quad (2.3)$$

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

145 In the LINEX function (Eq. 2.3), energy (e) is *the only* factor of production.
 146 $\rho_k \equiv \frac{k}{\frac{1}{2}(1+e)}$ is a measure of capital deepening, and $\rho_l \equiv \frac{l}{e}$ describes the increase
 147 of labor (l) relative to energy (e). When either ρ_k or ρ_l increases, the only factor of
 148 production (energy, e) is augmented (A). a_0 and c_t are fitting parameters, and e in
 149 Eq. 2.4 is the exponential function.

150 In the era of energy constraints, the machine metaphor, the engine model, and
 151 energy-augmented production functions were, arguably, apt for their time: energy
 152 was the binding constraint on the economy. The appearance of energy in the engine
 153 model and energy-augmented production functions (Eqs. 2.2 and 2.3) was mirrored
 154 by international efforts to include energy in national accounting.¹⁷ The International
 155 Energy Agency (IEA) “was founded in response to the 1973/4 oil crisis in order to help
 156 countries co-ordinate a collective response to major disruptions in oil supply” [27].
 157 One of the primary objectives of the IEA was “to operate a permanent information
 158 system on the international oil market” [27]. Today, that “permanent information
 159 system” [28] remains one of the most important sources of economy-level energy
 160 production and consumption statistics in physical units.¹⁸ And, the IEA’s annual
 161 World Energy Outlook series [29] is one of the premier sources of forward-looking
 162 analysis on the relationship between energy and the economy. Although physical
 163 energy statistics and indicators were not inserted into SNA, the dawn of the era of
 164 energy constraints provided the impetus for gathering and disseminating the world’s
 165 energy data.

166 Today, with the benefit of hindsight, we note that the machine metaphor and
 167 the engine model of the economy continued to ignore the flow of wastes from the

¹⁵ There is debate in the literature about quantification of energy input to the economy (e). Most researchers use the thermal equivalent of primary energy [18–21]. Others use useful work obtained by efficiencies from primary exergy [22].

¹⁶ 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) [23, 24]. Three options exist, but a common approach is:

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

¹⁷ 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.

¹⁸ As opposed to financial units (currency). Physical units include barrels of oil, tonnes of coal, and gigajoule energy values.

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.¹⁹ 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.

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

¹⁹ 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 work (useful energy services) without generating any entropy, in violation of the second law of thermodynamics.

204 that moment, aggregate output is no longer constrained by the populations of humans [labor]
205 and their artifacts [manufactured capital] and by the productivity of human effort [A in Equa-
206 tions 2.1 and 2.2]. Rather, the scale of economic activity is constrained by the remaining
207 stock of natural capital and by its productivity. . . . When this moment arrives, a new era of
208 history has begun.[30, p. 430]

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

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

221 All of which raises the question, how should the transition from the era of energy
222 constraints to the age of resource depletion affect (1) society’s dominant metaphors
223 for and models of the economy, (2) the production function, and (3) national ac-
224 counting? In the next section (2.2), we present a new metaphor, and the heart of this
225 book (Chaps. 3–7) provides theoretical grounding for national accounting in the age
226 of resource depletion. The way forward on production functions is beyond the scope
227 of this text.²⁰

228 2.2 The Economy is Society’s Metabolism

229 In our opinion (and that of several others²¹) an apt metaphor for the economy in
230 the age of resource depletion should provide for robust interaction and suggest tight
231 coupling between the biosphere and the economy. Specifically, it should account for
232 the following facts about real economies. Economies:

- 233 1. Intake material and energy from the biosphere;
- 234 2. Exchange materials, energy, and information internally;
- 235 3. Discharge material and energy wastes to the biosphere;
- 236 4. Are affected by energetic costs;
- 237 5. Are affected nonlinearly by scarcity in the face of low substitutability;

²⁰ See England [30] for a starting point.

²¹ An incomplete list of authors who are either (a) progenitors for or (b) directly associated with the metabolism metaphor includes Georgescu-Roegen [31], Odum [32], Daly [33], and Hall [34]. Heijman [35], Haberl [36], Fischer-Kowalski [37], Liu and Hanauer [38], and Giampietro [39].

- 238 6. Can change nonlinearly or in discrete steps with the potential for structural
239 transformation;
240 7. Accumulate embodied energy in material stocks; and
241 8. Maintain organizational structure despite changes in their environment.²²

242 Metabolisms²³ exhibit the characteristics in the list above. Metabolisms and the or-
243 ganisms they support are intimately connected with the biosphere: they withdraw
244 materials and energy from the biosphere (1), transfer materials and energy internally
245 via metabolic processes (2), and discharge wastes back to the biosphere (3); in fact,
246 their very survival depends on these processes. Extending Figs. 2.1 and 2.2 to in-
247 clude the facts in items (1)–(3), we obtain Fig. 2.3. Metabolisms are affected by
248 energetic costs (4): an organism that obtains less energy than it expends is doomed.
249 Withholding life-sustaining resources brings drastic, nonlinear consequences for
250 any metabolism (5). Metabolisms enable nonlinear, structural transformations in
251 their host organisms (e.g., metamorphosis, puberty, and evolution) (6). And, en-
252 ergy absorbed by a metabolism is considered to be “embodied” in the cells of the
253 organism (7). Metabolisms exist in a state of dynamic stability (8), adjusting and
254 readjusting to maintain their internal conditions despite changes in the environment;
255 for a metabolism, equilibrium means death!

256 The economy is society’s metabolism.

257 Although we are not the first to suggest the metabolism metaphor for the econ-
258 omy, we believe that the metabolism metaphor is underutilized on both practical and
259 theoretical levels. On the practical level, the metabolism metaphor is underutilized
260 because SNAs, to date, are built upon the clockwork metaphor and traditional model
261 for the economy (Sect. 2.1.2). This book attempts to correct that oversight by using
262 the metabolism metaphor to develop a rigorous theoretical framework for compre-
263 hensive national accounting (see Chaps. 3–7). On a theoretical level, the metabolism
264 metaphor is underutilized, because, many researchers (with the exception of the au-
265 thors listed in Footnote 21) use the metabolism metaphor merely as framing device
266 for analyses of raw material flows into the economy for the purpose of understand-
267 ing stocks of raw materials in the biosphere.²⁴ Some who employ the metabolism

²² 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.)

²³ The Greek root of metabolism (*metabolē*) means “change.”

²⁴ 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

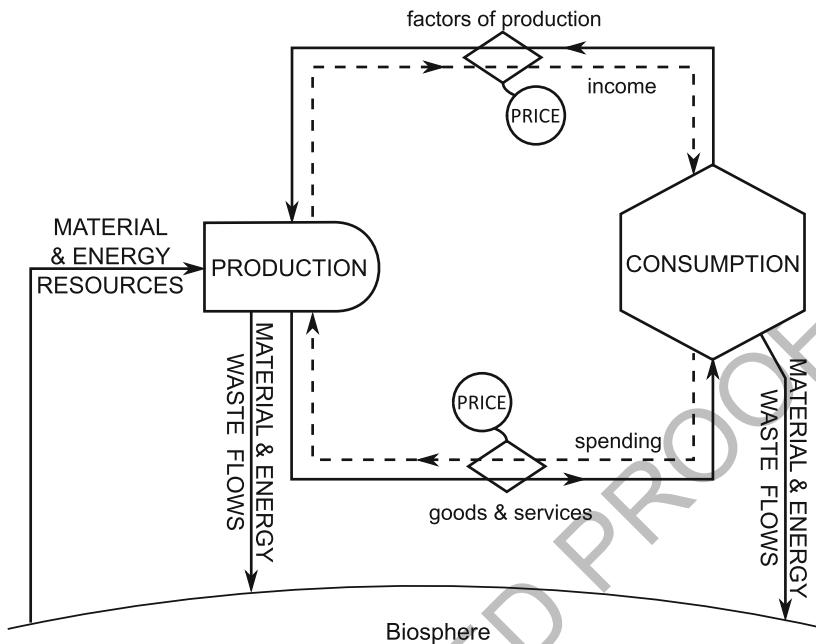


Fig. 2.3 The metabolism model provides a comprehensive view of the economy, fully consistent with the laws of thermodynamics, including degraded resources (waste) expelled to the environment as a necessary consequence of economic activity

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

(buildings), livestock, and people [37, 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 [37, Eq. 1] are almost always written as

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

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

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

thereby focusing on accumulation of stocks within the economy.

275 the physical role of capital stock in the economy, there is little urgency to begin
276 accounting for manufactured capital on a physical (rather than financial) basis.

277 We think that a deeper understanding of the metabolism metaphor can serve to both
278 highlight the important physical roles of both resource extraction and manufactured
279 capital stock and provide the basis for a rigorous theoretical framework for compre-
280 hensive national accounting. In the following sections, we deepen the metabolism
281 metaphor by considering anabolism (capital formation), catabolism (energy produc-
282 tion), autophagy (recycling), and issues of scale.²⁵ Thereafter, we summarize the
283 benefits of the metabolism metaphor for national accounting.

284 **2.2.1 Anabolism (Capital Formation)**

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

291 The economic analog to biological anabolism is capital formation, net addition to
292 the stock of capital (infrastructure, more generally) within a period of time. Tradi-
293 tionally, capital formation is measured in currency units. Thus, capital formation is
294 the financial evidence of the emplacement of manufactured infrastructure. Whereas
295 biological anabolism is fueled by ATP, capital formation is fueled by the energy sec-
296 tor of the economy. The raw material for capital formation comes to the economy
297 from the biosphere.

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

300 **2.2.2 Catabolism (Energy Production)**

301 Catabolic processes break down and destroy material stocks within an organism
302 through an oxidation process. At the cellular level, catabolic oxidation releases chem-
303 ical free energy, some of which synthesizes adenosine triphosphate (ATP), thereby
304 providing fuel to cells. The remainder of the released energy is manifest as waste
305 heat. One of the waste products of cellular catabolism is CO₂. Catabolic processes

²⁵ For the purposes of this discussion, our focus is on metabolic processes as they occur in eukary-
otic animal cells (cells with a nucleus containing genetic material), thereby avoiding complexities
associated with organisms that also perform photosynthesis.

306 are part of a chain of material and energy transformations wherein stored chemical
307 energy is converted to useful energy with waste heat and CO₂ as byproducts.

308 The analogy between catabolic processes and energy transformation processes
309 within the economy is striking. Power plants (fired by coal, oil, natural gas, or
310 refined liquid fuels) in either the energy sector or the final consumption sector break
311 down fossil fuels in an oxidation process (combustion) to produce useful energy
312 (typically, electricity or mechanical drive [22]), thereby providing energy to sectors
313 of the economy. Both waste heat and CO₂ are byproducts of combustion, and O₂ is
314 consumed in the process. Energy production in the economy is a chain of material
315 and energy transformations wherein machines and engines convert stored chemical
316 energy to useful energy with waste heat and CO₂ as byproducts.

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

318 2.2.3 *Autophagy (Recycling)*

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

323 Again, the analogy between cellular metabolism and the economy is striking.
324 Whereas cellular autophagy repurposes proteins and cell organelles for reuse by an
325 organism, recycling repurposes degraded yet economically-valuable materials for
326 reuse by the economy. Furthermore, recycling can also be an adaptive response to
327 reduced material and energy inputs. One famous example can be found on the streets
328 of Cuba. In the face of economic sanctions, government restrictions on vehicle pur-
329 chases, and high import tariffs, automobile imports by Cuba are very low. As a result,
330 Cuba hyper-recycles autos that were imported prior to sanctions and manufactures
331 replacement parts locally. The average lifespan of automobiles has been extended
332 such that an estimated 60,000, pre-1960 cars [40] (so-called “yank tanks”) are in
333 service on the island.²⁶ (See Fig. 2.4.)

334 Its not difficult to imagine that dynamics similar to Cuba’s will emerge if the
335 inflow rate of any important natural but recyclable resource is reduced to a trickle by
336 the effects of depletion.²⁷

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

340 We focus on recycling in Sect. 8.4.

²⁶ Despite the recent change allowing new car purchases by individuals, astronomical import taxes mean that Cuban streets remain populated with vintage 1950s autos [41].

²⁷ See Sect. 1.3.2 for a discussion of depletion of a nonrecyclable natural resource, oil.



Fig. 2.4 Vintage autos (“yank tanks”) in Cuba (2011). **** © Larry Cowles, <http://lcowlesphotography.wordpress.com>. Used by permission. Permission not yet obtained. ***

341 2.2.4 Issues of Scale

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

348 In Fig. 2.5, we see Max Kleiber’s empirically-determined relationship between
 349 metabolic rate (heat production, in kcal/day) and animal mass (in kg) plotted on a
 350 log-log scale for a variety of animals, from mice to whales. Dashed lines represent
 351 theoretical scaling due to either mass (weight) or surface area. The best fit to the data
 352 (thick line) passes between the weight and surface area lines.

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

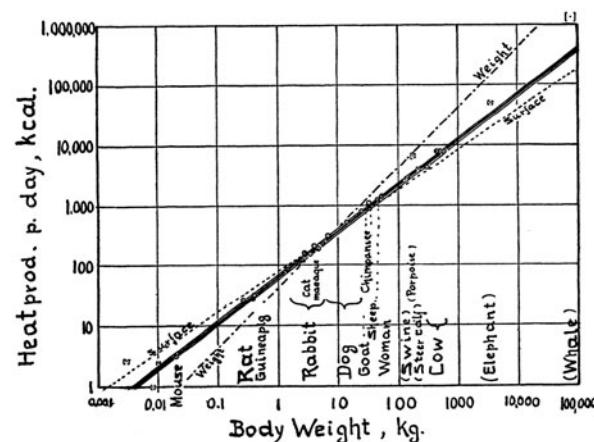
$$\dot{Q} = q_0 m^{3/4} \quad (2.5)$$

354 where \dot{Q} is metabolic rate (heat production), m is the mass of the animal, and q_0 is
 355 a mass-independent normalization constant. From Eq. 2.5, we see that doubling the
 356 mass increases the metabolic rate by $2^{3/4} = 1.68$ times. To compensate for higher
 357 rates of heat loss due to high surface area-to-volume ratio, small animals have higher
 358 metabolic rates and larger food requirements per unit mass.²⁸

²⁸ On a per-unit-mass basis, Kleiber’s Law becomes

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

Fig. 2.5 Kleiber's law for metabolic rates (heat production) of different-sized animals [42, p. 530]. Larger animals, as determined by mass, have a higher metabolic rate, but the relationship between mass and metabolic rate is not linear



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

2.2.5 Benefits of the Metabolism Metaphor

The metabolism metaphor is compelling, because it helps us to see more clearly and understand more deeply how the real, 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): O₂ is consumed as CO₂ 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

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.

380 biosphere, metabolism fails and organisms die. Without materials and energy from
381 the biosphere, the economies collapse and societies fade away. In short, the economy
382 is coupled to the biosphere, because it is utterly and completely dependent upon it.

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

394 Through an understanding of the deep interconnectedness and complexity of or-
395 ganisms and species in the biosphere, we come to appreciate the interdependence
396 among actors within and sectors of the economy. Furthermore, an appreciation of the
397 complex nature of economies leads us to acknowledge the difficulty in discerning
398 precisely which limit(s) is (are) encountered when growth stalls. In fact, there is no
399 single explanation for the slowdown of growth in OECD economies discussed at the
400 outset of Chap. 1. The best explanation to date involves many intertwining factors:
401 slowing growth of energy input rate, decreasing energy return on investment in the
402 liquid fuel sector, problems in the credit markets, etc.

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

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

417 2.3 New National Accounting

418 Society needs to respond to the material and energy shortages that we now face
419 (Chap. 1), and part of that response should involve more-comprehensive national
420 accounting guided by a deeper understanding of the real, biophysical economy gained

421 through the metabolism metaphor (Sect. 2.2). It is imperative that we begin now to
422 help society deal with impending biophysical limits.

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

425 As discussed in the Prologue, the UN System of Environmental-Economic Accou-
426 tинг (SEEA) is a conceptual framework that was developed by a wide range of experts
427 beginning in the early 1990s. This framework has just undergone a third, thorough
428 revision using a global collaborative process. The SEEA are national accounts that
429 capture data related to “interactions between the economy and the environment, and
430 the stocks and changes in stocks of environmental assets” [43, p. 1]. These accounts
431 measure physical as well as financial flows, and are designed to dovetail with the
432 SNA. As such, the UN SEEA represents the state of the art, in terms of account-
433 ing material and energy resource flows through our economies. If implemented, the
434 SEEA allows national governments to answer questions that were previously un-
435 known, such as, “At what rate do we use steel?” or “How much concrete is embodied
436 within our economy?” Indeed, analyses similar to the one presented in Fig. 1.2 (GDP
437 vs. as a function of fuel consumption) might be undertaken for any material (e.g.,
438 iron or water) tracked by the SEEA. Governments gain a great deal of understand-
439 ing about the energetic and material requirements of the country through the use of
440 SEEA.

441 However, because the SEEA framework is defined at the economy-wide (E-W)
442 scale, there are many more important questions that still cannot be answered. One
443 such question is, “What are the material and energetic requirements to scale-up the
444 renewable energy industry?” This is a highly important question for future sustainable
445 development, not just for nations, but for the globe as a whole. Furthermore, the
446 accumulation of materials and embodied energy in the manufactured capital stock of
447 a particular economic sector is impossible to estimate with economy-wide analyses.
448 Such an analysis would require measuring intersectoral (i.e., intra-economy) flows
449 of materials and energy. In the age of resource depletion, we believe obtaining
450 intersectoral flows to be an essential aspect of extended national accounting.

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

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

460 We believe the key to understanding society’s metabolism in the age of resource
461 depletion is to understand how materials, energy, embodied energy, and economic
462 value each interacts with the economy. Specifically, it is important to understand
463 how each accumulates within the economy and how each flows into, within, and out
464 of the economy. The first three items (materials, energy, and embodied energy) are
465 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? [44, p. 221]**
6. **What are the material and energy requirements to scale-up the renewable energy industry?**

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

2.4 Structure of the Book

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

Part I addresses flows of physical matter and energy through the economy. Chap. 3 discusses material flows and accumulation. 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.

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

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

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

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Part I

Material and Energy

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Chapter 3

Stocks and Flows of Materials

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

5 —The Once-ler

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

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

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

31 There are also innumerable material flows between the biosphere and the economy
32 that most of us never observe. The extraction of raw materials generates additional
33 overburden—earth that must be extracted and processed and ultimately discarded
34 without ever entering the economy proper. Other flows cannot be seen with the

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

38 Even services that we consider “nonmaterial” require at least some material in-
39 frastructure. The hairdresser requires scissors (and to a greater or lesser extent some
40 hair) with which to work. Even the internet, often lauded as the exemplar of demate-
41 rialization of the economic process, requires a whole host of infrastructure including
42 uninterrupted electricity supply, data servers, telephone networks, and a computer
43 by which to access it.

44 It almost goes without saying that all materials within the economy (the *econo-*
45 *sphere* [3]) started their “lives” within the biosphere, be they food, water or paper,
46 petroleum, or rock. In fact, the economy is in a continual state of material exchange
47 with its surrounding environment; raw materials are pulled in and wastes are emitted.
48 It is this exchange that intimately couples the two spheres, intertwining their mutual
49 fate.

50 As discussed in the Preface and Chap. 2, researchers are beginning to quantify
51 these material exchanges. Further work, such as that by the United Nations Envi-
52 ronment Programme (UNEP) International Resource Panel (IRP), is attempting to
53 measure the total stock of materials within society [4]. Over the past two centuries,
54 human demand for materials has increased at a phenomenal pace. This demand has
55 driven ever increasing extraction rates of raw materials from the biosphere. Produc-
56 tion of all materials increased from around 12 Gt/yr (10^9 t/yr) to around 35 Gt/yr in
57 the period 1945–1980 and up to 68 Gt/yr by the year 2009 [5]. That is, the flow of
58 materials into the economy from the biosphere has grown over five-fold since the
59 end of the Second World War and has doubled in the last thirty years. But what has
60 driven this incredible growth?

61 An obvious answer to this question is population. The global population has
62 increased by a factor of nearly three during the post-war period [6]. More people
63 obviously leads to greater demand. Living standards have also increased, leading to
64 still greater demands for material possessions. The UNEP-IRP report, *Metal Stocks*
65 *in Society* estimates that if the global in-use per capita stock of metals were to increase
66 to the level of industrialized nations, the total stock might be 3–9 times the present
67 level[4].

68 A less obvious answer comes from social science. In 1980, Schnaiberg [7] intro-
69 duced the concept of the “treadmill of production” to describe the systemic process
70 of ever-increasing capital investment (and thus demand for materials) inherent in
71 capitalist society.¹ The treadmill leads to “higher and higher levels of demand for

¹ The logic of the treadmill is:

1. Capital (production equipment) is accumulating in Western economies as labor is replaced by technologies;
2. These technologies require far more materials and/or energy than the previous, labor-intensive processes;
3. Moreover, unlike labor, the new technologies represent forms of sunk capital;

72 natural resources for a given level of social welfare” [8, p. 297]. The treadmill of
73 production is evident today, driving up demand for many commodities. From an eco-
74 nomic perspective, we may view the treadmill as the striving for productivity from
75 factors of production. In the substitution of capital for labor, total factor productivity
76 (A in Eq. 2.1) is increased. The substitution increases the requirement for natural
77 resources (particularly energy to drive the capital equipment), but these are assumed
78 to be “free” within traditional economic growth models, hence do not count towards
79 productivity; the substitution obtains a free productivity boost from nature.

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

86 When accumulation is not accounted for, the hidden assumption is that all flows
87 in and out balance instantaneously. Imagine a bath tub where the water flowing in
88 through the tap is exactly balanced by the water flowing out the plughole. The state
89 of the system (the amount of water within the bath) is fixed—therefore we say the
90 system is in steady-state. Or, imagine a growing baby. The inputs of food and other
91 materials, though small compared to an adult, exceed the output of excreta (gas, solid,
92 and liquid). While this may be hard for new parents to believe (how can there be
93 possibly be more going in than is coming out!), it is simply this imbalance that induces
94 the growth of the baby. Materials accumulate within the baby’s body. Obviously,
95 this imbalance (and the subsequent growth induced) slows as the child grows up to
96 adulthood. Nevertheless, adults still maintain the ability to accumulate materials. We
97 can gain (or lose) weight; a fact to which any yo-yo dieter will readily attest.

98 Both population and capital equipment are stocks; accumulations of people, ma-
99 chines, equipment, roads, and buildings that have built up over time. As discussed in
100 Sect. 1.3.3, we contend that stocks are the drivers of demand, of flows of materials.
101 People demand food, clothing, shelter, all of the basic necessities of life, as well as
102 all of the trappings of modern life; buildings, vehicles, and computers. The deliv-
103 ery of the material to satisfy human wants requires capital equipment; more stocks
104 which also have needs. They require flows of materials and energy to build, operate,
105 and maintain them. Thus, to properly understand the economic structure and the
106 real drivers of change, we must understand the accumulation of materials within our
107 economies.

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

-
4. 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;
 5. More capital is added to replace further reduced levels of labor [8, p. 296].

113 3.1 Methodology

114 This book is about tracking (accounting) flows through the economy with a focus
115 on counting materials, energy, and value. That an entire academic discipline and
116 industry are focused on counting money (“accounting”) is evidence of its impor-
117 tance in today’s economies. That energy is required to do *anything* is evidence of
118 its importance in the economic activity of our daily lives. And, we believe that the
119 interplay between money and energy has shaped the past and will continue to influ-
120 ence the future. In this section, we define rigorous “counting” methods that will be
121 applied to materials (this chapter), energy (Chap. 4), embodied energy (Chap. 5),
122 and money (Chap. 6) throughout this book.

123 3.1.1 Accounting in Everyday Life

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

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

137 More generally, we may say:

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

138 Notice that, when discussing apples we use the specific terms “grown” and “eaten,”
139 instead of the more general terms “produced” and “consumed.” Later, in Chap. 6,
140 when discussing economic value, we will use the terms “generated” or “added” and
141 “destroyed.” For our purposes, these terms all have equivalent meanings, and we use
142 them interchangeably.

143 After accounting for the stock of apples in a week, we can reframe the question
144 to ask, “at what rate does the stock of apples change ($\frac{da}{dt}$)?” That is, we can examine
145 the rate of change of the apple stock per unit of time relative to the flow of apples
146 (\dot{a}), in which case our accounting equation becomes:

$$\frac{da}{dt} = \dot{a}_{in} - \dot{a}_{out} + \dot{a}_{grown} - \dot{a}_{eaten} \quad (3.3)$$

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

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

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

$$\Delta_{\text{steel}} = \text{steel in} - \text{steel out} \quad (3.4)$$

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:

$$\frac{ds}{dt} = \dot{s}_{\text{in}} - \dot{s}_{\text{out}} \quad (3.5)$$

Again, the last two 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

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

associated act of consumption or destruction. Indeed, within the car industry, inputs of steel, glass, plastic, rubber, etc. are *consumed* in the very process of producing cars, such that *cars* are (literally) *created* within the automobile industry. You 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 destruction³ of cars. Again, focusing on mass flows of the chemical elements avoids this necessity, because mass is *conserved* in physical processes. Any mass entering a control volume (transfer in) must go somewhere, whether it stays within the volume (accumulation) or is transferred out. Conservation of mass is expressed in equations such as the ones above for apples in a home and steel in the auto industry.

Another important conservation principle is the conservation of energy. Similar to the principle of the conservation of mass, the first law of thermodynamics says that *energy can neither be created nor destroyed*. In the discussion that follows (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 materials (\dot{R}) enter the sector from the left. They comprise those materials that are destined to be *embodied* in the goods produced by the sector (\dot{P}), which leave from the right, except for some proportion that is wasted. All wastes depart from the bottom of the sector and are returned to the biosphere. For example, sheet metal, rubber, and glass (as well as many other materials) enter the automobile sector as resources and end up as material parts of the cars that are produced. Some fraction of these resources (\dot{R}) may not make it into the final product, such as

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.

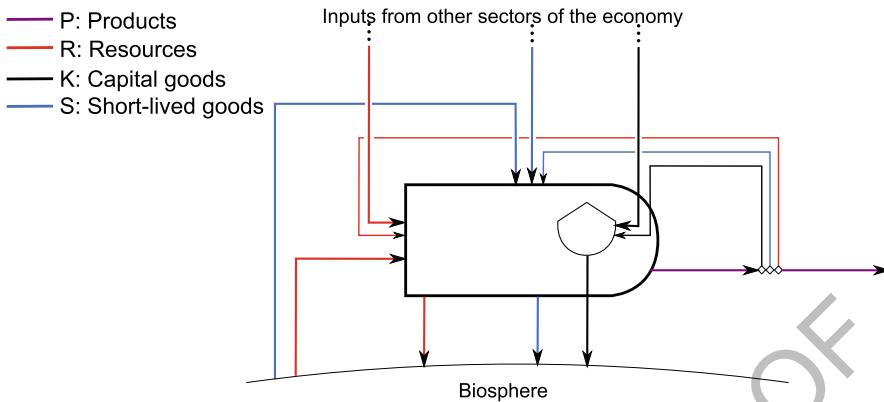


Fig. 3.1 Material flows into and out of a single sector of the economy. Resource flows (\dot{R}) enter the sector from the left and are embodied in products (\dot{P}) which leave from the right. Some waste resources leave the sector at the bottom and are returned to the biosphere. Short-lived material flows (\dot{S}) enter the sector from above and leave from below to return to the biosphere. Only capital stock (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

216 trimming scrap from metal parts stamping, and may be either recycled internally, or
 217 wasted to the biosphere. In this material accounting framework, resource materials
 218 are not accumulated within a sector.

219 Short-lived goods (\dot{S}) include those materials that are necessary for the production
 220 processes of a sector, but are neither accumulated within the sector, nor destined to
 221 become materially part of the product of the sector. They enter the sector from above
 222 and leave the sector from below to return to the biosphere. Examples of these short-
 223 lived flows include energy resources, such as the electricity needed to run automobile
 224 factories and process water used by the sector. Resources and short-lived materials
 225 make up Georgescu-Roegen's "flow" elements⁴ [9] or Daly's "material causes" [10].

226 Many of the material flows into the sector, such as production equipment, are
 227 necessary for the continued operation of a sector but are not counted as short-lived
 228 goods, because the operation of the sector is dependent upon the accumulation of
 229 these materials within the sector. Such flows are counted as capital goods (K). Cap-
 230 ital flows (\dot{K}) also enter from above, but are stored within the sector (represented
 231 by a storage tank) and are returned to the biosphere as physical capital deprecia-
 232 tion. Examples of these capital flows would be the factory and office buildings or
 233 manufacturing equipment within the automobile industry.

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 vehicles or other equipment after depreciation, or recycling of material from capital stock into other goods, e.g., scrap metal. The issue of recycling is discussed in greater detail in 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 (1). In this material accounting framework, energy may be accounted as either an \dot{R} flow or an \dot{S} flow. An example of energy as an \dot{R} flow is crude oil to be converted into gasoline within a refinery: the resource inflow (crude oil) is *literally embodied* (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 from sector j , such that:

$$\dot{W}_{j0} = \dot{R}_{j0} + \dot{S}_{j0} \quad (3.6)$$

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

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

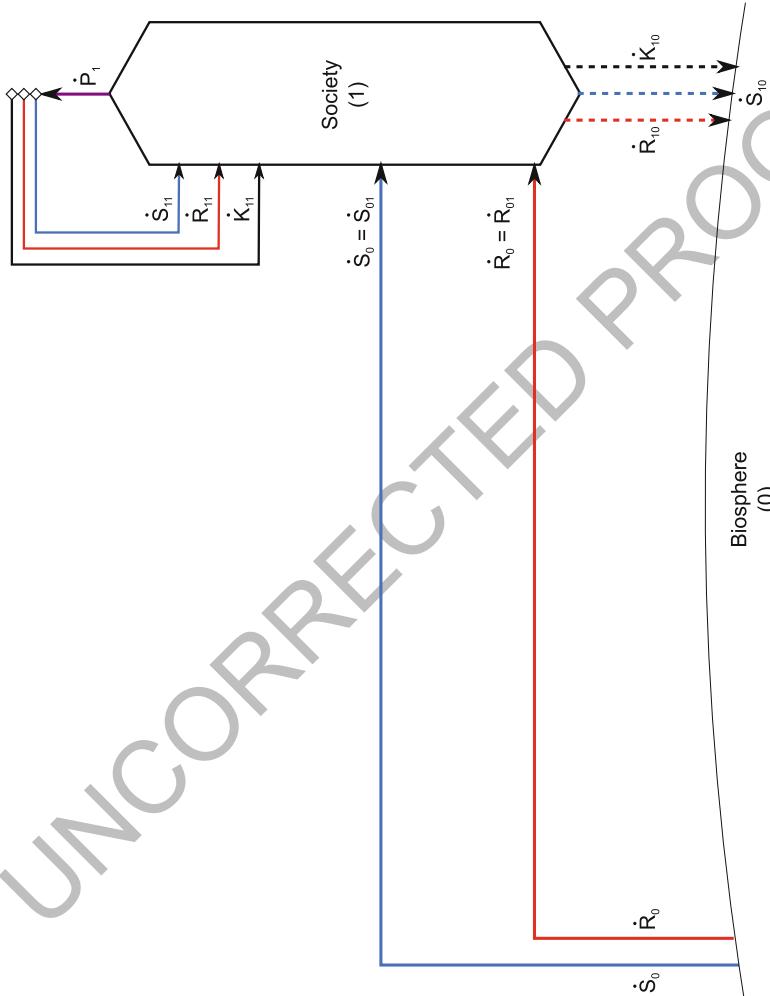


Fig. 3.2 Flows of materials for a one-sector economy. Resources (\dot{R}_{01}) and short-lived materials (\dot{S}_{01}) flow into the Society (1) from the Biosphere (0). Waste resources (\dot{R}_{10}) short-lived materials/goods (\dot{S}_{10}) and capital goods (\dot{K}_{10}) are returned to the biosphere

267 $\frac{dK_1}{dt}$ within the stock of materials within society.⁶ Waste resources (\dot{R}_{10}) and used
 268 short-lived materials/goods (\dot{S}_{10}) are returned to the biosphere without accumulating
 269 in Society (1). Capital goods are returned to the biosphere when they are physically
 270 depreciated (\dot{K}_{10}).

271 Drawing control volumes around both the Biosphere (0) and Society (1) in Fig. 3.2,
 272 we can construct material accounting equations, such that:

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} + \frac{dK_0}{dt} = \dot{R}_{10} + \dot{S}_{10} + \dot{K}_{10} - \dot{R}_0 - \dot{S}_0 \quad (3.7)$$

$$\frac{dR_1}{dt} + \frac{dS_1}{dt} + \frac{dK_1}{dt} = \dot{R}_{01} + \dot{S}_{01} + \dot{R}_{11} + \dot{S}_{11} + \dot{K}_{11} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}. \quad (3.8)$$

273 Because mass is conserved, we find that:

$$\dot{R}_0 = \dot{R}_{01}, \quad (3.9)$$

$$\dot{S}_0 = \dot{S}_{01}, \quad (3.10)$$

$$\dot{P}_1 = \dot{R}_{11} + \dot{S}_{11} + \dot{K}_{11}, \quad (3.11)$$

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

$$\frac{dR_0}{dt} = \dot{R}_{10} - \dot{R}_{01} \neq 0. \quad (3.12)$$

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

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

$$\frac{dR_1}{dt} = 0 \quad (3.13)$$

$$\frac{dS_1}{dt} = 0. \quad (3.14)$$

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

$$\frac{dK_0}{dt} = \dot{K}_{10} \quad (3.15)$$

⁶ See Footnote 8 in Chap. 3 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. $\dot{S}_{11} \ll \dot{S}_{01}$.

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 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:

$$\frac{dR_1}{dt} = \dot{R}_{01} + \dot{R}_{11} - \dot{P}_1 - \dot{R}_{10} = 0, \quad (3.16)$$

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}_{i1}) 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, therefore entailing an EROI of less than unity. Agrarian societies are necessarily constrained by the fact that the energy content of the food delivered *must be* greater than the labor (and draft animal) energy required to produce it.

Another view is that societal capital (K_1) includes only man-made capital, i.e., items manufactured by humans, but not humans themselves. For the purposes of the framework outlined in this book, we favored the latter view. Other researchers favor the opposing view [11]. However, the framework presented in this book is general enough to encompass either point of view.

$$\frac{dS_1}{dt} = \dot{S}_{01} + \dot{S}_{11} - \dot{S}_{10} = 0, \quad (3.17)$$

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

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

307 and

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{01}. \quad (3.19)$$

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

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} = \dot{R}_{10} + \dot{S}_{10} - \dot{R}_{01} - \dot{S}_{01}. \quad (3.20)$$

309 Equation 3.20 states that the rate of “accumulation” (or more accurately depletion)
 310 of natural capital (R_0 and S_0) is dependent on the rates at which society extracts these
 311 materials from the biosphere (\dot{R}_{01} and \dot{S}_{01}) and the rates of disposal of waste materials
 312 back to the biosphere (\dot{R}_{10} and \dot{S}_{10}). Notice however, that although Eq. 3.20 is true
 313 for the total mass of materials, it does not account for the *quality* of these materials.
 314 An intact brick is of higher material quality—is of more use—than the brick dust that
 315 has been eroded by weather and scattered on the wind. Many material stocks or flows
 316 have been concentrated by natural biophysical processes. We do not mine desirable
 317 material from locations with the average abundance of crustal materials. Instead,
 318 society relies heavily on extracted resources from naturally occurring resources that
 319 are far from equilibrium with their surroundings, e.g., fossil fuel reservoirs or seams
 320 of high-grade ore. We may measure the material quality of a resource in reference to
 321 its environment, in this case, the average chemical composition of its environment.
 322 The more concentrated the resource, the further it is from chemical equilibrium with
 323 the environment and the higher the quality. Exergy is a measure of this kind of quality.
 324 The further a resource is from chemical equilibrium with its environment, the higher
 325 the exergetic content.

326 As these high quality material reserves are depleted and society must turn to lower
 327 grade reserves (as predicted by the best-first principle), more total material must flow
 328 through the process (including overburden and tailings—the wasted portion that is
 329 extracted), more productive capital must be deployed and the greater wear and tear on
 330 equipment in order to maintain the same level of production [12, 13]. Additionally, it
 331 takes more energy to process less concentrated resources. This additional processing
 332 requirement entails that we will likely never mine average crustal abundance for
 333 needed materials, or mine gold from seawater.

334 Furthermore, it also entails that recycling—the act of turning low quality materi-
 335 als into high quality resources—requires energy and degrades equipment. The lower
 336 quality the waste, the more energy and degradation occurs such that one hundred per-
 337 cent recycling of materials is almost certainly practically (and possibly theoretically)
 338 impossible.⁹

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 was discussed in reference to our framework in

339 It is likely that the quality of flow \dot{R}_{01} is higher than flow \dot{R}_{10} (e.g., overburden
 340 from mining operations). If this were not the case, \dot{R}_{10} could be easily substituted into
 341 the production process (i.e., recycled) thus offsetting the need for primary resource
 342 extraction.

343 We have here assumed that all waste flows (\dot{W}_{j0}) and depreciated capital
 344 flows (\dot{K}_{j0}) from economic sector j flowed straight to the biosphere. In general,
 345 this is not the case within the economy. The Waste Management and Remediation
 346 Services sector (NAICS 562) has the responsibility, within the US economy, of col-
 347 lecting and disposing of wastes. Additionally, much material is recycled within the
 348 economy (rather than being disposed into the biosphere) and many capital goods
 349 are sold for reuse prior to recycling of materials, for example second-hand cars and
 350 office equipment.

351 We may represent these flows of resources (\dot{R}_j), short-lived goods (\dot{S}_j), and capital
 352 goods (\dot{K}_j) as flows other than the product flow (\dot{P}_j) leaving sector j as in Fig. 3.3.¹¹
 353 In this book we will continue with the assumption that there is only one product
 354 leaving a sector that stays within the economy, i.e. there is no recycling of products.
 355 The issue of recycling is discussed in more detail in Sect. 8.4.

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

$$\frac{dK_1}{dt} = \dot{R}_{01} + \dot{R}_{11} + \dot{K}_{11} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10}. \quad (3.21)$$

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

$$\frac{dK_1}{dt} = \dot{K}_{11} - \dot{K}_{10}, \quad (3.22)$$

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

362 Substituting instead Eq. 3.11 into Eq. 3.21, we obtain:

$$\frac{dK_1}{dt} = \dot{R}_{01} - \dot{R}_{10} - \dot{S}_{11} - \dot{K}_{10}. \quad (3.23)$$

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.¹⁰ Despite the drive to dematerialization and the apparent “unhooking” of the material and energy intensity of GDP, much of the dematerialization of “developed” nations has been by exporting manufacturing to other countries [15]. The material footprint of OECD nations, when weighted by consumption, has increased significantly since 1990 [16].

¹¹ 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.

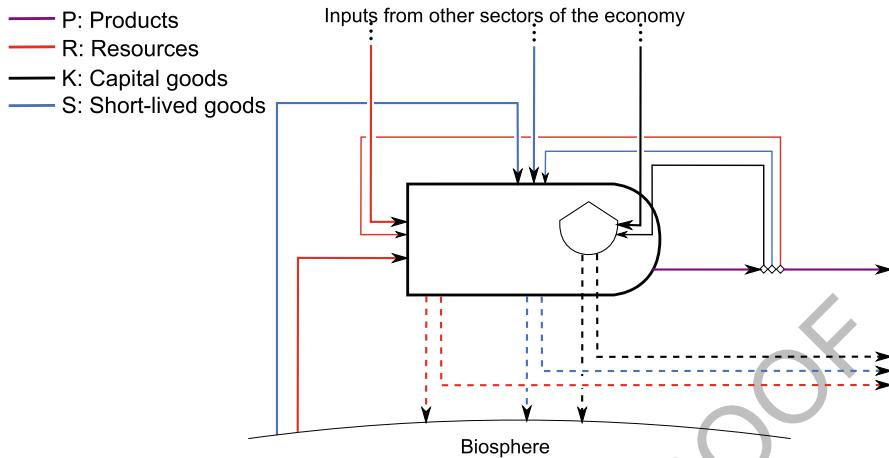


Fig. 3.3 Material flows through an economic sector with waste treatment flows to other economic sectors

363 The last depreciation term (\dot{K}_{10}) may be rewritten as the total stock of man-made
 364 capital (K_1) multiplied by some depreciation rate (γ_{K_1}),¹² where γ_{K_j} is defined as:

$$\gamma_{K_j} \equiv \frac{\dot{B}_{j0}}{B_j}, \quad (3.24)$$

365 i.e., the depreciation *per unit* of capital stock,¹³ such that Eq. 3.23 may be rewritten:

$$\frac{dK_1}{dt} = \dot{R}_{01} - \dot{R}_{10} - \dot{S}_{11} - \gamma_{K_1} K_1. \quad (3.25)$$

366 We may rearrange Eq. 3.25 as:

$$\dot{R}_{01} - \dot{R}_{10} = \frac{dK_1}{dt} + \dot{S}_{11} + \gamma_{K_1} K_1. \quad (3.26)$$

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

$$-\frac{dR_0}{dt} = \frac{dK_1}{dt} + \dot{S}_{11} + \gamma_{K_1} K_1. \quad (3.27)$$

370 Equation 3.27 tells us that depletion of natural resources ($-\frac{dR_0}{dt}$) is used within
 371 society to:

¹² γ_{K_1} has units of inverse time, e.g., 1/year, and is inversely proportional to the average lifetime of man-made capital.

¹³ This depreciation term will be discussed in more depth in Sects. 5.2.3 and 8.2.2.2.

- Build up societal capital stock ($\frac{dK_1}{dt}$),
- 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 capital goods (\dot{K}_{11}) flows.¹⁴ 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.¹⁵

¹⁴ In actuality, both \dot{R}_{11} and \dot{S}_{11} are zero, as will be discussed shortly.

¹⁵ 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).

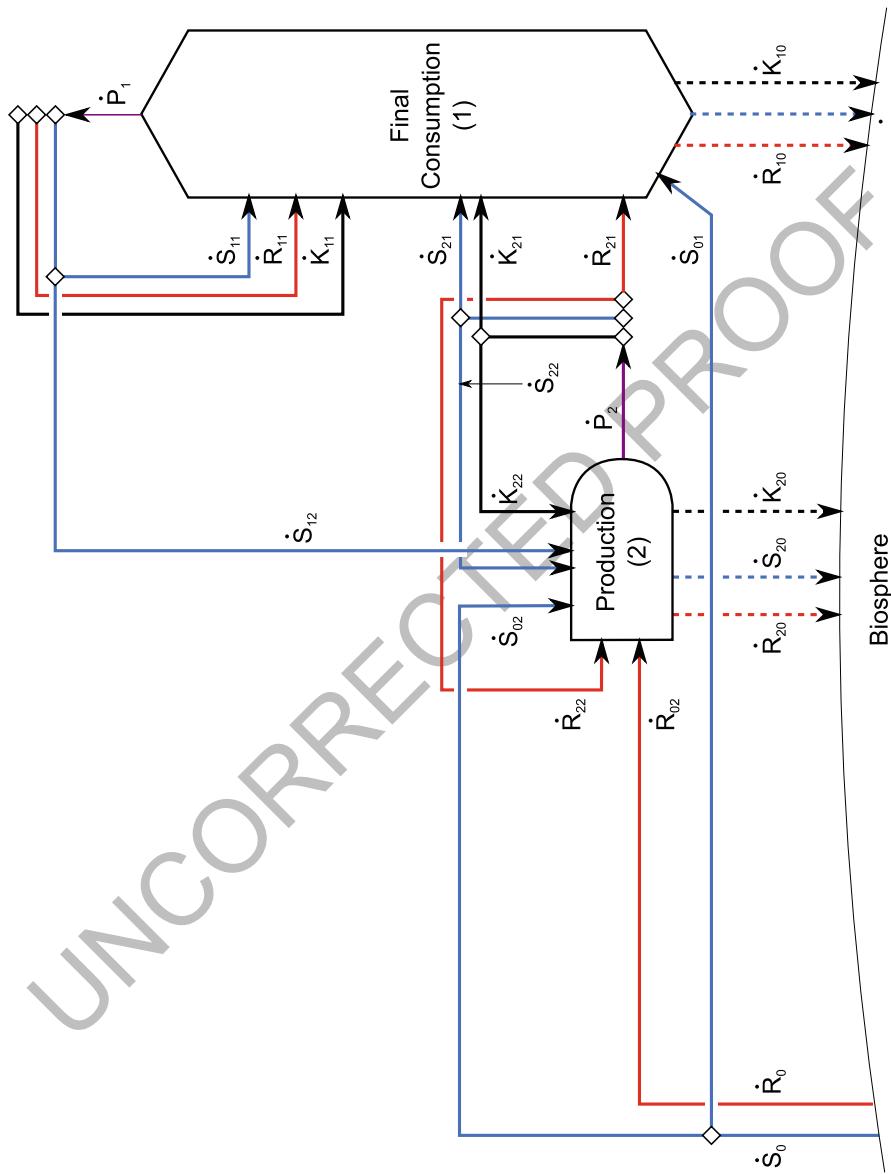


Fig. 3.4 Flows of materials for a two-sector economy

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

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

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} + \frac{dK_0}{dt} = \dot{R}_{10} + \dot{R}_{20} + \dot{S}_{10} + \dot{S}_{20} + \dot{K}_{10} + \dot{K}_{20} - \dot{R}_0 - \dot{S}_0 \quad (3.28)$$

$$\frac{dR_1}{dt} + \frac{dS_1}{dt} + \frac{dK_1}{dt} = \dot{R}_{11} + \dot{R}_{21} + \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} + \dot{K}_{11} + \dot{K}_{21} - \dot{P}_1 - \dot{R}_{10} - \dot{S}_{10} - \dot{K}_{10}, \quad (3.29)$$

$$\frac{dR_2}{dt} + \frac{dS_2}{dt} + \frac{dK_2}{dt} = \dot{R}_{02} + \dot{R}_{22} + \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} + \dot{K}_{22} - \dot{P}_2 - \dot{R}_{20} - \dot{S}_{20} - \dot{K}_{20}, \quad (3.30)$$

413 Because no resources flow directly to Final Consumption (1) from the Bio-
 414 sphere (0),¹⁶ we may say:

$$\dot{R}_0 = \dot{R}_{02}. \quad (3.31)$$

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

$$\dot{S}_0 = \dot{S}_{01} + \dot{S}_{02}. \quad (3.32)$$

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

$$\frac{dR_0}{dt} = \dot{R}_{10} + \dot{R}_{20} - \dot{R}_{02}, \quad (3.33)$$

$$\frac{dS_0}{dt} = \dot{S}_{10} + \dot{S}_{20} - \dot{S}_{01} - \dot{S}_{02}, \quad (3.34)$$

$$\frac{dK_0}{dt} = \dot{K}_{10} + \dot{K}_{20}. \quad (3.35)$$

420 Because we are assuming that only man-made capital (and not human beings them-
 421 selves) are accounted within the physical stock of Final Consumption¹⁷ (K_1) and

¹⁶ 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.

¹⁷ 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 Chap. 3.

422 that the “product” of Final Consumption (1) is labor (a short-lived material flow, \dot{S}),
 423 then we may also state that:

$$\dot{R}_{11} = 0, \quad (3.36)$$

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

$$\dot{K}_{11} = 0, \quad (3.37)$$

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

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

$$\dot{P}_1 = \dot{S}_{11} + \dot{S}_{12}, \quad (3.38)$$

428 and

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

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

$$\frac{dR_1}{dt} = 0, \quad (3.40)$$

$$\frac{dR_2}{dt} = 0, \quad (3.41)$$

$$\frac{dS_1}{dt} = 0, \quad (3.42)$$

431 and

$$\frac{dS_2}{dt} = 0. \quad (3.43)$$

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

$$\frac{dR_1}{dt} = \dot{R}_{21} - \dot{P}_1 - \dot{R}_{10} = 0, \quad (3.44)$$

$$\frac{dS_1}{dt} = \dot{S}_{01} + \dot{S}_{11} + \dot{S}_{21} - \dot{S}_{10} = 0, \quad (3.45)$$

$$\frac{dR_2}{dt} = \dot{R}_{02} + \dot{R}_{22} - \dot{P}_2 - \dot{R}_{20} = 0, \quad (3.46)$$

434 and

$$\frac{dS_2}{dt} = \dot{S}_{02} + \dot{S}_{12} + \dot{S}_{22} - \dot{S}_{20} = 0. \quad (3.47)$$

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

$$\dot{P}_1 = \dot{R}_{21} - \dot{R}_{10} \quad (3.48)$$

$$\dot{S}_{11} = \dot{S}_{10} - \dot{S}_{21}, \quad (3.49)$$

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

436 and

$$\dot{S}_{22} = \dot{S}_{20} - \dot{S}_{02} - \dot{S}_{12}. \quad (3.51)$$

437 Substituting Eqs. 3.31-3.35 into Eq. 3.28, gives

$$\frac{dR_0}{dt} + \frac{dS_0}{dt} = \dot{R}_{10} + \dot{R}_{20} + \dot{S}_{10} + \dot{S}_{20} - \dot{R}_{02} - \dot{S}_{01} - \dot{S}_{02}, \quad (3.52)$$

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

$$\frac{dK_1}{dt} = \dot{R}_{21} + \dot{K}_{21} - \dot{P}_1 - \dot{R}_{10} - \dot{K}_{10} \quad (3.53)$$

439 and

$$\frac{dK_2}{dt} = \dot{R}_{02} + \dot{R}_{22} + \dot{K}_{22} - \dot{P}_2 - \dot{R}_{20} - \dot{K}_{20}, \quad (3.54)$$

440 As in Example A, we again have two definitions for \dot{P}_1 (Eqs. 3.38 and 3.48) and \dot{P}_2

441 (Eqs. 3.39 and 3.50) which may be substituted into Eqs. 3.53 and 3.54, respectively.

442 Let us start by substituting Eqs. 3.48 and 3.50, in which case we obtain:

$$\frac{dK_1}{dt} = \dot{K}_{21} - \dot{K}_{10}, \quad (3.55)$$

443 and

$$\frac{dK_2}{dt} = \dot{K}_{22} - \dot{K}_{20}. \quad (3.56)$$

444 Equations 3.55 and 3.56 tell us that accumulation of man-made capital (K) in each
445 sector (j) is dependent only on inflows of capital goods into that sector (\dot{K}_{2j}) and
446 depreciation of capital to the biosphere from that sector (\dot{K}_{j0}).

447 Now, substituting Eqs. 3.38 and 3.39, we obtain:

$$\frac{dK_1}{dt} = \dot{R}_{21} + \dot{K}_{21} - \dot{S}_{11} - \dot{S}_{12} - \dot{R}_{10} - \dot{K}_{10}, \quad (3.57)$$

448 and

$$\frac{dK_2}{dt} = \dot{R}_{02} - \dot{R}_{21} - \dot{S}_{21} - \dot{S}_{22} - \dot{K}_{21} - \dot{R}_{20} - \dot{K}_{20}, \quad (3.58)$$

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

$$-\dot{R}_{10} = \frac{dK_1}{dt} - \dot{R}_{21} - \dot{K}_{21} + \dot{S}_{11} + \dot{S}_{12} + \gamma_{K_1} K_1, \quad (3.59)$$

451 and

$$\dot{R}_{02} - \dot{R}_{20} = \frac{dK_2}{dt} + (\dot{R}_{21} + \dot{S}_{21} + \dot{K}_{21}) + \dot{S}_{22} + \gamma_{K_2} K_2. \quad (3.60)$$

452 Equation 3.60 tells us that the resources extracted and used by the production
 453 sector ($\dot{R}_{02} - \dot{R}_{20}$) are for the purposes of:

- 454 • Building up capital stock in the production sector ($\frac{dK_2}{dt}$),
- 455 • Providing goods for Final Consumption ($\dot{R}_{21} + \dot{S}_{21} + \dot{K}_{21}$),
- 456 • Providing short-lived goods to support the production sector (\dot{S}_{22}), and
- 457 • Overcoming depreciation of production capital stock ($\gamma_{K_2} K_2$).

458 Adding Eqs. 3.59 and 3.60 together, we obtain:

$$\begin{aligned} -\frac{dR_0}{dt} &= \dot{R}_{02} - \dot{R}_{10} - \dot{R}_{20} \\ &= \frac{dK_1}{dt} + \frac{dK_2}{dt} + \dot{S}_{11} + \dot{S}_{12} + \dot{S}_{21} + \dot{S}_{22} + \gamma_{K_1} K_1 + \gamma_{K_2} K_2. \end{aligned} \quad (3.61)$$

459 which tells us that the depletion of natural resources ($\frac{dR_0}{dt}$) is used within the whole
 460 economy to:

- 461 • Build up capital stock ($\frac{dK_1}{dt} + \frac{dK_2}{dt}$),
- 462 • Produce short-lived goods ($\dot{S}_{11} + \dot{S}_{12} + \dot{S}_{21} + \dot{S}_{22}$), and
- 463 • Overcome depreciation ($\gamma_{K_1} K_1 + \gamma_{K_2} K_2$).

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

466 3.4 Example C: Three-Sector Economy

467 In Example C, we differentiate between two production sectors, sector (2) produces
 468 energy and sector (3) produces other goods and services, as depicted in Fig. 3.5.

469 In this example, we will take a slightly different approach than in the previous
 470 two examples. Instead of discerning whether or not certain flows exist (asking for
 471 example, “is there a flow of resources (\dot{R}_{21}) from Energy (2) to Final Consumption
 472 (1)?”), we shall account for all flows, *even if* those flows are zero. In this way, we
 473 may build up a completely general framework for material accounting within an
 [AQ1] 474 economy of any size.

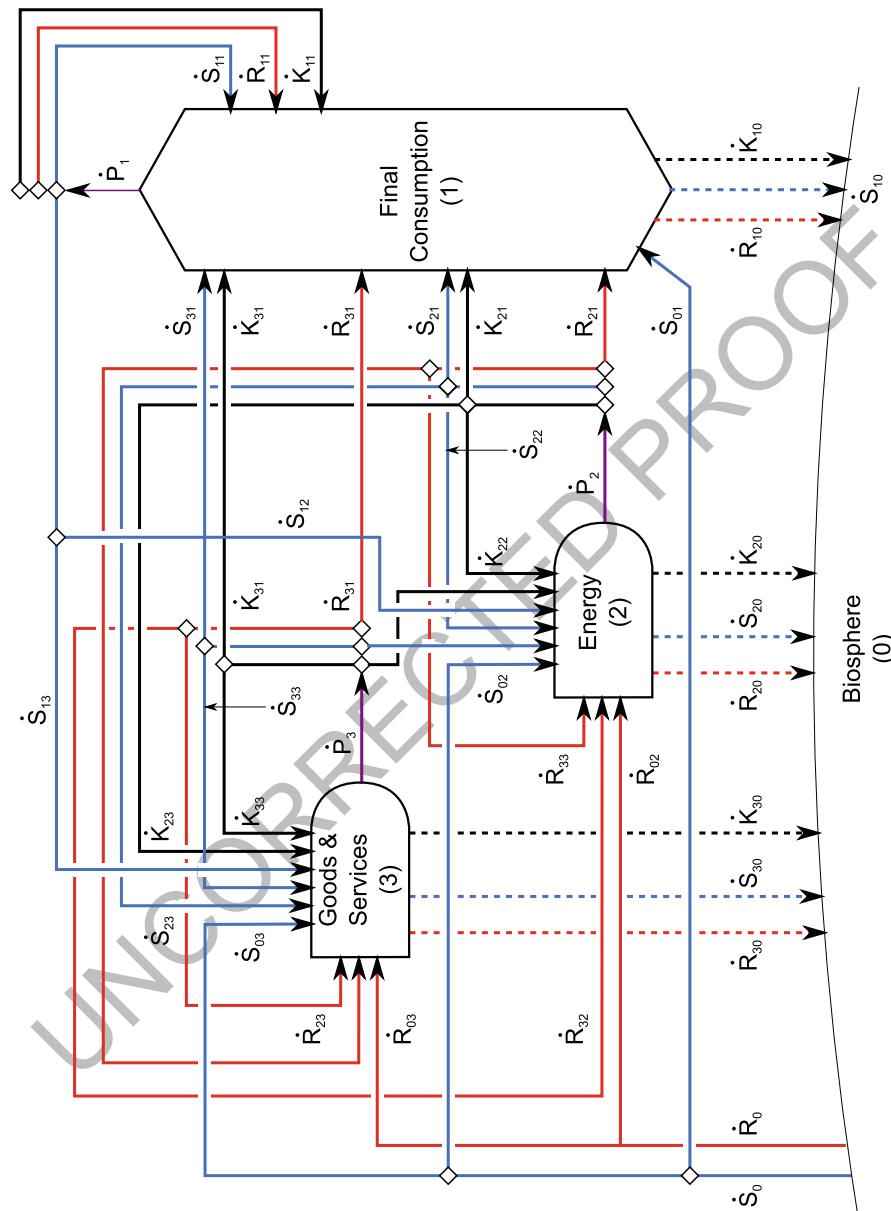


Fig. 3.5 Flows of materials for a three-sector economy

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

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

477 which may be rewritten as:

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

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

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

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

480 and

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

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

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

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

483 and

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

484 which may be rewritten as:

$$\frac{dR_0}{dt} = \sum_{i=1}^3 \dot{R}_{i0} - \sum_{j=1}^3 \dot{R}_{0j}, \quad (3.70)$$

$$\frac{dS_0}{dt} = \sum_{i=1}^3 \dot{S}_{i0} - \sum_{j=1}^3 \dot{S}_{0j}, \quad (3.71)$$

485 and

$$\frac{dK_0}{dt} = \sum_{i=1}^3 \dot{K}_{i0}. \quad (3.72)$$

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

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

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

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

487 As in Example B, Final Consumption (1) provides only labor (represented by \dot{S}
 488 flows) to the other sectors of the economy. The Energy sector (2) provides energy
 489 products (\dot{S}_{2j}) to the other sectors of the economy. It may also provide resources to
 490 itself (\dot{R}_{22}) and to the goods and services sector (3), as in the case of metallurgical
 491 coke or natural gas for fertilizer. The energy sector does not produce capital goods,
 492 hence, for $j \in [1, 3] : \dot{K}_{2j} = 0$. The goods and services sector (3) does not provide
 493 resources for the energy sector (2),¹⁸ hence $\dot{R}_{32} = 0$.

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

$$\frac{dR_j}{dt} = 0, \quad j \in [1, 3], \quad (3.76)$$

$$\frac{dS_j}{dt} = 0, \quad j \in [1, 3]. \quad (3.77)$$

496 As before, we may also define the resource-product and short-lived goods flows
 497 balances separately for each of the sectors of the economy:¹⁹

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

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

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

¹⁸ There may be some exceptions to this, as in the case of energy from industrial waste streams.

¹⁹ It is worth remembering here that $\dot{R}_{01} = \dot{R}_{21} = 0$, because Final Consumption (1) takes resources (in the form of food) from goods and services (3) only and that $R_{32} = 0$ because the goods and services sector (3) does not provide resources to the energy sector (2).

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

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

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

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

$$\dot{P}_1 = \dot{R}_{01} + \dot{R}_{11} + \dot{R}_{21} + \dot{R}_{31} - \dot{R}_{10} \quad (3.84)$$

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

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

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

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

$$\dot{S}_{33} = \dot{S}_{20} - \dot{S}_{03} - \dot{S}_{13} - \dot{S}_{30}. \quad (3.89)$$

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

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

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

501 and

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

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

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

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

504 and

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

3.4 Example C: Three-Sector Economy

69

505 which we may rewrite as the more general result:

$$\frac{dK_j}{dt} = \sum_i \dot{K}_{ij} - \dot{K}_{j0}. \quad (3.96)$$

506 Equation 3.96 states that for any economic sector, j , the accumulation of man-made
 507 capital stock (K_j) is dependent only on inflows of capital stock from other economic
 508 sectors (\dot{K}_{ij}) and depreciation of capital stock back to the biosphere from sector j ,
 509 (\dot{K}_{j0}).

510 Instead, substituting the alternative formulation for \dot{P} from Eqs. 3.73–3.75 into
 511 Eqs. 3.90–3.92, respectively, we obtain:

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

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

512 and

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

513 As before, we can rearrange these equations to obtain:

$$\dot{R}_{01} - \dot{R}_{10} = \frac{dK_1}{dt} - \sum_{i=1}^3 \dot{R}_{i1} - \sum_{i=1}^3 \dot{K}_{i1} + \sum_{j=1}^3 \dot{R}_{1j} + \sum_{j=1}^3 \dot{S}_{1j} + \sum_{j=1}^3 \dot{K}_{1j} + \dot{K}_{10}, \quad (3.100)$$

$$\dot{R}_{02} - \dot{R}_{20} = \frac{dK_2}{dt} - \sum_{i=1}^3 \dot{R}_{i2} - \sum_{i=1}^3 \dot{K}_{i2} + \sum_{j=1}^3 \dot{R}_{2j} + \sum_{j=1}^3 \dot{S}_{2j} + \sum_{j=1}^3 \dot{K}_{2j} + \dot{K}_{20}, \quad (3.101)$$

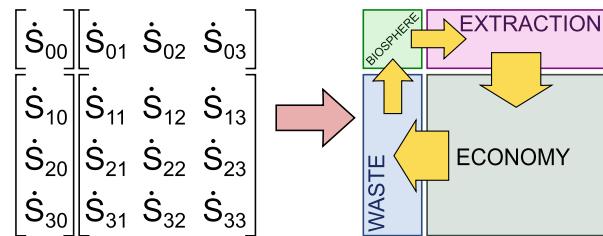
514 and

$$\dot{R}_{03} - \dot{R}_{30} = \frac{dK_3}{dt} - \sum_{i=1}^3 \dot{R}_{i3} - \sum_{i=1}^3 \dot{K}_{i3} + \sum_{j=1}^3 \dot{R}_{3j} + \sum_{j=1}^3 \dot{S}_{3j} + \sum_{j=1}^3 \dot{K}_{3j} + \dot{K}_{30}. \quad (3.102)$$

515 Summing Eqs. 3.100–3.102, we obtain:

$$-\frac{dR_0}{dt} = \sum_{j=1}^3 \dot{R}_{0j} - \sum_{i=1}^3 \dot{R}_{i0}$$

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



$$\begin{aligned}
 &= \frac{dK_1}{dt} + \frac{dK_2}{dt} + \frac{dK_3}{dt} - \sum_{j=1}^3 \sum_{i=1}^3 \dot{R}_{ij} - \sum_{j=1}^3 \sum_{i=1}^3 \dot{K}_{ij} + \sum_{j=1}^3 \sum_{i=1}^3 \dot{R}_{ij} \\
 &+ \sum_{j=1}^3 \sum_{i=1}^3 \dot{S}_{ij} + \sum_{j=1}^3 \sum_{i=1}^3 \dot{K}_{ij} + \dot{K}_{10} + \dot{K}_{20} + \dot{K}_{30}, \tag{3.103}
 \end{aligned}$$

516 which, after substituting for the depreciation term (\dot{K}_{10}), can be simplified to:

$$-\frac{dR_0}{dt} = \sum_{j=1}^3 \frac{dK_j}{dt} + \sum_{j=1}^3 \sum_{i=1}^3 \dot{S}_{ij} + \sum_{j=1}^3 \gamma_{K_j} K_j \tag{3.104}$$

517 or, more generally:

$$-\frac{dR_0}{dt} = \sum_j \frac{dK_j}{dt} + \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j. \tag{3.105}$$

518 Similarly to what we saw in Examples A and B, Eq. 3.105 tells us that depletion of
519 natural resources in the biosphere ($-\frac{dR_0}{dt}$) by the economy is used for the purposes
520 of:

- 521 • Increasing man-made capital stocks within the economy ($\frac{dK_j}{dt}$),
- 522 • Providing short-lived goods exchanged within the economy (\dot{S}_{ij}), and
- 523 • Overcoming depreciation of man-made capital stocks ($\sum_j \gamma_{K_j} K_j$).

524 This implications of this will be discussed in greater detail in Sect. 8.5 concerning
525 sustainable scale of the economy and the concept of a steady-state economy.

526 The exchange of resources (\dot{R}) and short-lived goods (\dot{S}) among each of the
527 four “sectors” (the biosphere and the three economic sectors) may be thought of as
528 four matrices (as depicted in Fig. 3.6 for \dot{S} flows): one 3×3 matrix of flows entirely of
529 within the economy, a 3×1 row vector of flows from the biosphere into the economy
530 (extraction), a 1×3 column vector of flows from the economy into the biosphere
531 (waste), and a 1×1 matrix of flows solely within the biosphere (environment), that
532 do not enter the economy.

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

535 3.5 Materials in the US Auto Industry

536 Throughout the book, we shall be applying the methodology that has been outlined
537 through Examples A–C to the real-world case of the US auto industry. The running
538 example of the US auto industry demonstrates that our dynamic model can be tied
539 into national accounts. The US auto industry example shows where data are:

- 540 • Currently available (e.g., economic value, Chap. 6 and direct energy, Chap. 4),
- 541 • Where it is old (e.g., energy intensity, Chap. 7), and
- 542 • Where it has never been available (e.g., materials, current chapter, and accumu-
543 lated embodied energy, Chap. 5).

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

546 Although our choice for using the auto industry is somewhat arbitrary, there are a
547 number of compelling reasons for its selection. Automobile manufacturing has been
548 used previously in the literature in both process-based [19–25] and Input-Output [26–
549 28] analysis methods. The automobile boom was clearly central to the development of
550 most Western countries during the twentieth Century. Furthermore, the industry still
551 remains a large portion of many industrialized economies. The automobile industry
552 is a large consumer of material resources, some of which are listed below in Table 3.1.
553 The automobile has obvious links with the energy industry, both in the direct demand
554 for energy used in automobile manufacture, and also indirectly for the refined oil
555 products needed to operate vehicles. This dependence aptly demonstrates demand
556 “lock-in,” discussed in Sect. 1.4. The industry also shows evidence of postindustrial
557 decline (shrinking profit margins, etc.) and thus represents a sector-level analogy of
558 the maturation and decline in growth of economies.

559 Thinking about the flows of resources, short-lived, and capital materials into the
560 auto industry, we can say that because the industry does not extract resources directly
561 from the biosphere, the rate of flow of resources (\dot{R}_{0j}) from the biosphere to the auto
562 industry has a zero value. Each of the other inflows and outflows is, in actuality, a
563 vector of hundreds (or even thousands!) of elemental material flows, each of which
564 must be accounted (and balanced) separately.

565 There are a number of key material inputs into the production of automobiles,
566 directly as resources (\dot{R}) as well as short-lived materials (\dot{S}) and capital goods (\dot{K})
567 outlined in Table 3.1. Data on the actual flow rates at the industry level is very hard
568 to obtain.²⁰ In Europe, economy-wide material flow accounts (EW-MFA) have been
569 produced by measurement of the physical flows of materials into and out of economies
570 of each of the member states [29]. Work is ongoing to characterize the intersectoral
571 flows of these materials [30] which can be analyzed by converting financial data
572 (which is available, as discussed in Sect. 6.6) into physical flow data via knowledge
573 of the entry points of materials into the economy, i.e., via the extraction industries.

²⁰ The issue of lack of physical flow data is discussed in several places in this book, especially in Chap. 9.

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, wind shield); rubber (tires); plastic (bodywork, interiors, seals) petroleum (paints, lubricants)
Short-lived from other sectors	\dot{S}_{ij}	Energy (oil, natural gas, electricity) water (process) petroleum (solvents) plastic (packaging) paper (towels, packaging)
Capital from other sectors	\dot{K}_{ij}	Steel (buildings, equipment) concrete (buildings) glass (windows, screens) plastic (fixtures, fittings, equipment) petroleum (paints, lubricants)
Product output	\dot{P}_j	Auto parts and motor vehicles
Resource self-consumption	\dot{R}_{jj}	Auto parts
Short-lived self-consumption	\dot{S}_{jj}	Aone
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

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]. A 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 2010²¹ in the USA [35]. In theory, a representation of the industry-level flows could be “built up” by assuming that the results from these process-based analysis methods represent average processes within the whole industry and scaling the material flows accordingly, with appropriately wide uncertainty bounds. 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 more impetus for the methodology developed herein.

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

²¹ 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.

(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

1 *Living organisms need to be open to a constant flow of*
2 *resources (energy and matter) to stay alive; human organizations need to be open to a flow of mental*
3 *resources (information and ideas), as well as to the flows of energy and materials that are part of the production*
4 *of goods or services. [1, p. 117]*
5 —Fritjof Capra
6
7

8 In Chaps. 1 and 2, we showed that energy consumption is intimately linked to eco-
9 nomic activity and deepened the metabolism metaphor for the economy. From the
10 metabolism metaphor, we understand that the economy consists of producers and
11 consumers who exchange goods and services and factors of production while extract-
12 ing resources from and disposing wastes to the biosphere. In Chap. 3, we established
13 the material basis of economies: economies processes raw resources for the benefit
14 of producers and consumers while generating unavoidable wastes. In this chapter,
15 we describe and analyze the direct energy that is associated with economic activity
16 within an economy.

17 All forms of energy provide the potential¹ to do mechanical work.² Energy (as
18 mechanical work) is an essential aspect of the metabolic economy; with it, materials
19 are refined, shaped, and assembled into useful intermediate and final products; food
20 is made available to people in society; jobs are made easier for workers; human
21 ingenuity is multiplied; and complex systems and civilizations are possible. In the
22 absence of high rates of energy available at low cost, life becomes much more
23 difficult, even impossible, for many people.

24 The analogy for this chapter is this: energy is to thermodynamics as money is
25 to financial accounting. Or, energy is the *currency of thermodynamics*. Just as an
26 accountant understands a firm by watching how and where currency flows through it,
27 so we can understand an economy by watching how and where energy flows through
28 it. Accounting for energy flows through an economy is essential for developing a
29 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.

30 The purpose of this chapter is to develop a framework for accounting energy flows
 31 within economies. To do so, we will employ the first law of thermodynamics which
 32 tells us that the quantity of energy is conserved in every process.³ With an energy
 33 framework in hand, we will be positioned to assess the rate at which consumed
 34 direct energy becomes embodied within the products and services that an economy
 35 provides (Chap. 5).

36 4.1 Methodology

37 We begin by noting that direct energy travels with material through an economy. “Di-
 38 rect” energy refers to forms of energy accounted by the first law of thermodynamics,
 39 including chemical potential energy, nuclear potential energy, gravitational potential
 40 energy, thermal energy, and kinetic energy. We distinguish between “direct” energy
 41 and “embodied” energy, which will be discussed in Chap. 5. Examples of direct en-
 42 ergy flows include the chemical potential energy of coal inflows to an energy sector,
 43 the thermal energy of process steam into a textile plant, and the thermal energy of
 44 CO₂ automobile exhaust. Each of these example flows is an example of a “transfer
 45 in” or a “transfer out,” in the language of Sect. 3.1.1. In each case, the material (coal,
 46 steam, and CO₂) carries direct energy with it. Figure 4.1 shows a corresponding
 47 direct energy flow for each material flow of Fig. 3.1.

48 For any boundary or control volume (around, say, a machine, a plant, a sector
 49 of the economy, or the entire economy itself), the first law of thermodynamics says
 50 that the accumulation rate of direct energy within the boundary ($\frac{dE}{dt}$) is equal to the
 51 sum of the incoming and outgoing direct energy transfer rates (\dot{E}) less outflowing
 52 energy carried by wastes (\dot{Q}_{out}). As discussed in Sect. 3.1.1, energy is conserved: it
 53 be neither created nor destroyed.

$$\frac{dE}{dt} = \sum \dot{E} - \sum \dot{Q}_{out}. \quad (4.1)$$

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.

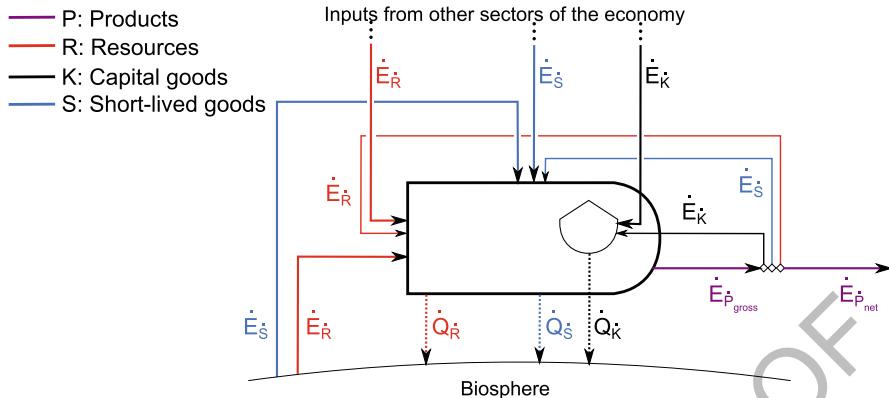


Fig. 4.1 Energy content (\dot{E}) of material flows (\dot{R} , \dot{S} , and \dot{K}) from Fig. 3.1

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

$$0 = \sum \dot{E} - \sum \dot{Q}_{out}, \quad (4.2)$$

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

57 It is important to note that the direct energy associated with some material flows
 58 can be so small as to be negligible compared to other direct energy flows in the
 59 economy. For example, there is a small amount of chemical potential energy in steel
 60 that could be released upon combustion. However, the direct energy associated with
 61 flows of steel within the economy is almost negligible. (The *embodied* energy of
 62 the steel is most certainly *not* negligible, as will be discussed in Chap. 5.) On the
 63 other hand, the direct energy flow rates for fossil fuels (coal, oil, and natural gas)
 64 are typically orders of magnitude larger than any other material flows due to large
 65 chemical potential energy content.

66 To simplify the direct energy analysis, we can aggregate the direct energy flows of
 67 Fig. 4.1 into single arrows when appropriate. For example, the direct energy inputs
 68 from other sectors of the economy (labeled as \dot{E}_R , \dot{E}_S , and \dot{E}_K at the top of Fig. 4.1)
 69 can be summed to \dot{E} (in Fig. 4.2) such that

$$\dot{E} = \dot{E}_R + \dot{E}_S + \dot{E}_K. \quad (4.3)$$

70 4.2 Example A: Single-Sector Economy

71 Aggregated direct energy flows are now applied to Example A, the single-sector economy
 72 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
 73 in the economy, as shown in Fig. 4.3.

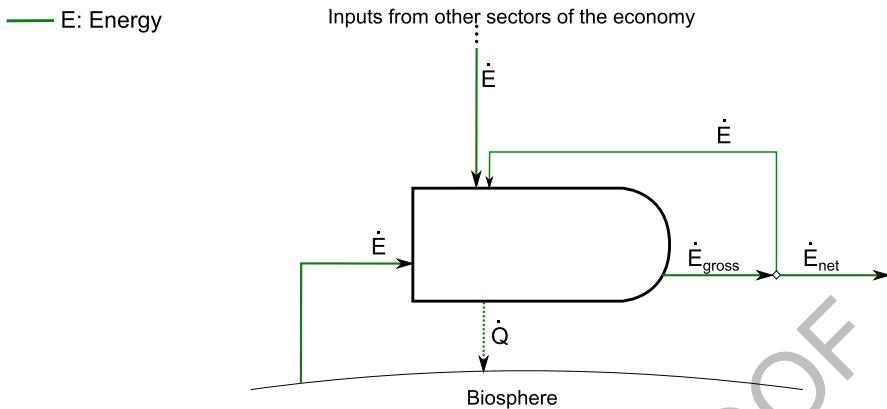


Fig. 4.2 Aggregated direct energy flows (\dot{E}) around the producer of Fig. 4.1.

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

$$\frac{dE_0}{dt} = \dot{Q}_{10} - \dot{E}_{01}, \quad (4.4)$$

and

$$\frac{dE_1}{dt} = \dot{E}_{01} + \dot{E}_{11} - \dot{E}_1 - \dot{Q}_{10}. \quad (4.5)$$

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.

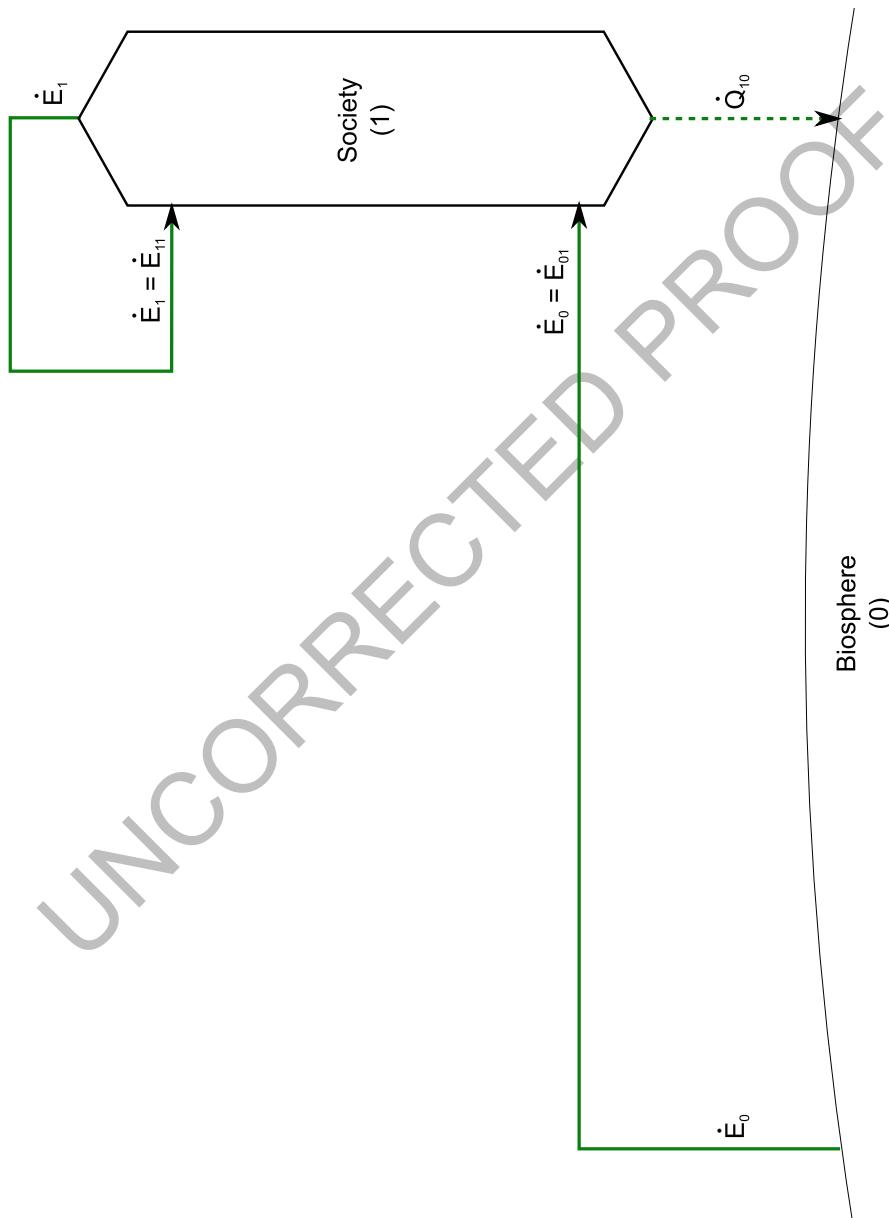


Fig. 4.3 Direct energy flows (\dot{E}) a one-sector economy

93 Aside from, for example, the US Strategic Petroleum Reserve, we are not stock-
 94 piling oil and coal at any meaningful rate, i.e., we consume fossil fuels at a rate equal
 95 to their extraction rate. Thus, the world is not accumulating direct energy in the
 96 economy.⁴ (The world *is*, however, accumulating *embodied* energy in the economy
 97 as we shall see in Chap. 5.) Thus, the accumulation rates for direct energy ($\frac{dE}{dt}$) in
 98 the above equations could be set to zero as follows:

$$0 = \dot{Q}_{10} - \dot{E}_{01}, \quad (4.6)$$

99 and

$$0 = \dot{E}_{01} + \dot{E}_{11} - \dot{E}_1 - \dot{Q}_{10}. \quad (4.7)$$

100 However, we shall see later (in Chap. 4) that keeping direct energy accumula-
 101 tion terms ($\frac{dE}{dt}$) provides an advantage when deriving embodied energy accounting
 102 equations.

103 4.3 Example B: Two-Sector economy

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

106 The first law of thermodynamics requires that both direct energy and waste heat
 107 be conserved around each entity (1 and 2) as well as around the Biosphere (0).

108 First law energy accounting around the Biosphere (0) and Society (1) gives

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

109 and

$$\frac{dE_1}{dt} = \dot{E}_{11} + \dot{E}_{21} - \dot{E}_1 - \dot{Q}_{10}. \quad (4.9)$$

110 Note that \dot{E}_{12} represents useful work that people and draft animals contribute to
 111 Production (2). Ayres and Warr [4, 5] call this “muscle work.” \dot{E}_{11} represents the
 112 muscle work required for consumption. Direct energy (electricity, oil, natural gas,
 113 etc.) required for consumption by final demand is included in \dot{E}_{21} .

114 The first law around Production (2), including the accumulation rate of direct
 115 energy in the sector ($\frac{dE_2}{dt}$), yields

$$\frac{dE_2}{dt} = \dot{E}_{02} + \dot{E}_{12} + \dot{E}_{22} - \dot{E}_2 - \dot{Q}_{20}. \quad (4.10)$$

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.

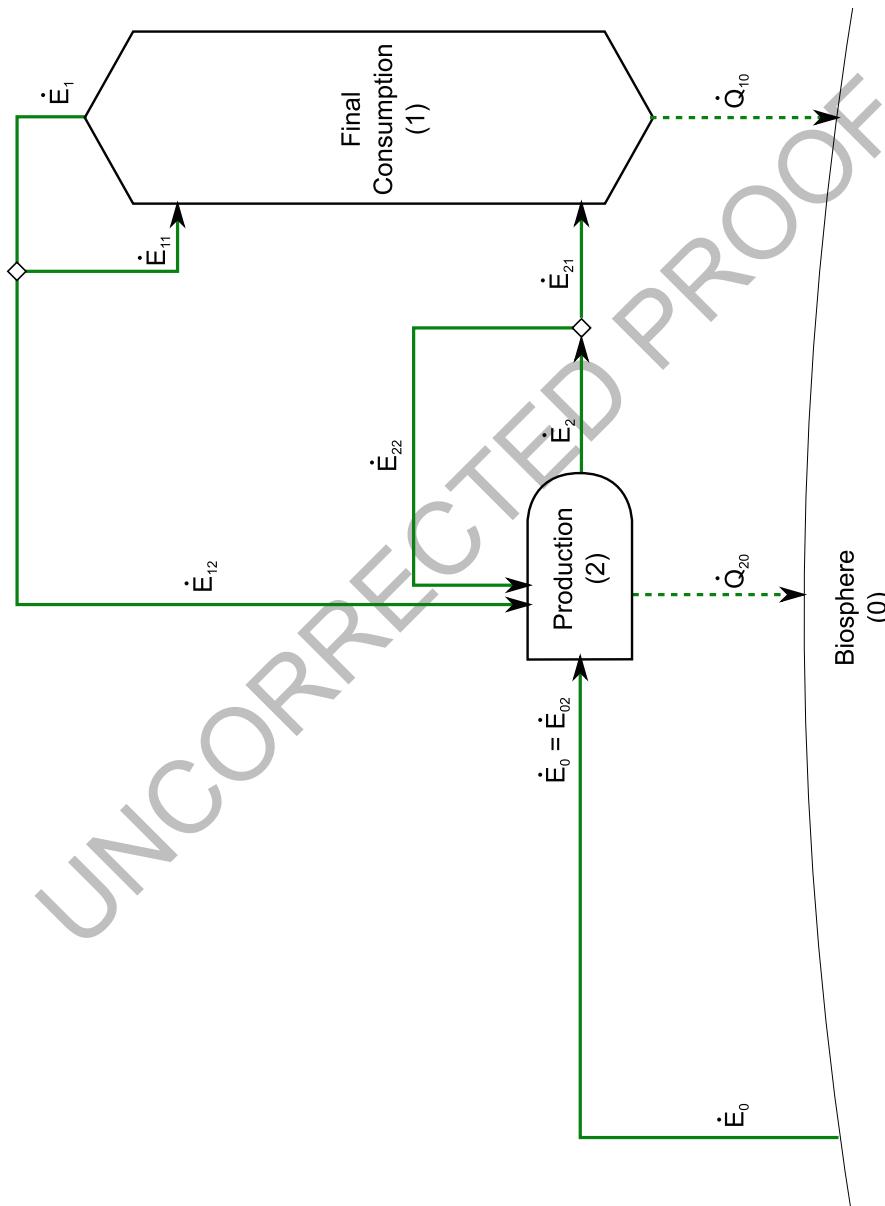


Fig. 4.4 Direct energy flows (\dot{E}) for a two-sector economy

116 It is notable that Production (2) consumes (\dot{E}_{22}) a portion of its gross energy
 117 output (\dot{E}_2): *it takes energy to make energy*. The gross direct energy production
 118 of the Energy sector (2) is \dot{E}_2 , and the direct energy consumption of the Energy
 119 sector (2) is $\dot{E}_{12} + \dot{E}_{22}$. The net direct energy production Energy (2) is given by
 120 $\dot{E}_2 - (\dot{E}_{12} + \dot{E}_{22})$. The *energy return on investment (EROI)* [6, 7] of the Energy
 121 sector (2) is given by

$$122 \quad EROI_2 = \frac{\dot{E}_2}{\dot{E}_{12} + \dot{E}_{22}}. \quad (4.11)$$

122 EROI represents the energy production *per unit* of energy invested by society in
 123 the production process and may be considered a measure of the ease of obtaining
 124 energy resources from the biosphere. Although the definition of *EROI*, as outlined
 125 here, is easy to articulate (essentially, $\frac{\text{energy out}}{\text{energy in}}$), the EROI calculation involves
 126 many system boundary considerations. These issues are discussed thoroughly by
 127 both Murphy et al. [8] and Brandt et al. [9, 10] who outline several EROI ratios
 128 according to the factors included in the calculation. Because we are dealing only
 129 with direct energy in this chapter (and not upstream energy embodied in materials),
 130 the EROI defined here is $EROI_{2,d}$ [8, Table 1] or GER_γ [11, Table 1], where GER
 131 stands for *gross energy ratio* an equivalent metric to EROI.

132 As discussed in Chap. 3, society relies heavily on concentrations of high-quality
 133 material resources. As we mine lower quality material resources we require larger
 134 inputs of energy both directly, to process greater volumes of material, but also in-
 135 directly to build the extra capital equipment necessary to do the processing. The
 136 same is also true of energy resources within the environment. Fossil fuels represent
 137 stocks of solar energy accumulated (in the form of biomass) over many millions of
 138 years. These resources are extremely far from equilibrium with the environment.
 139 EROI can be considered an indicator of energy resource quality. As EROI (and thus
 140 energy quality) declines, more energy is needed to extract and deliver energy from
 141 the environment, both directly, for example, the energy to pump oil from deeper
 142 underground, and indirectly, in order to build the extra oil rigs necessary to maintain
 143 production levels.⁵

144 Equation (4.8) can be generalized with a sum as

$$\frac{dE_0}{dt} = \sum_{i=1}^n (\dot{Q}_{i0} - \dot{E}_{0i}), \quad (4.12)$$

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

$$\frac{dE_j}{dt} = \sum_{i=0}^n \dot{E}_{ij} - \dot{E}_j - \dot{Q}_{j0}, \quad (4.13)$$

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

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

148 **4.4 Example C: Three-Sector Economy**

149 We can extend Example B, to include an Energy sector (2) and a Goods and Services
 150 sector (3), thereby obtaining a fuller picture of direct energy flows among sectors
 151 (Fig. 4.5).

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

$$\frac{dE_0}{dt} = \dot{Q}_{10} + \dot{Q}_{20} + \dot{Q}_{30} - \dot{E}_{02} - \dot{E}_{03}, \quad (4.14)$$

154

$$\frac{dE_1}{dt} = \dot{E}_{11} + \dot{E}_{21} + \dot{E}_{31} - \dot{E}_1 - \dot{Q}_{10}, \quad (4.15)$$

155 and

$$\frac{dE_2}{dt} = \dot{E}_{02} + \dot{E}_{12} + \dot{E}_{22} + \dot{E}_{32} - \dot{E}_2 - \dot{Q}_{20}. \quad (4.16)$$

156 The first law applied to the Goods and Services sector (3) including, for now, the
 157 accumulation rate of direct energy in the sector ($\frac{dE_3}{dt}$) yields

$$\frac{dE_3}{dt} = \dot{E}_{03} + \dot{E}_{13} + \dot{E}_{23} + \dot{E}_{33} - \dot{E}_3 - \dot{Q}_{30}. \quad (4.17)$$

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

$$\frac{dE_0}{dt} = \sum_{i=1}^n \dot{Q}_{i0} - \sum_{i=1}^n \dot{E}_{0i} \quad (4.18)$$

159 and

$$\frac{dE_j}{dt} = \sum_{i=0}^n \dot{E}_{ij} - \dot{E}_j - \dot{Q}_{j0}, \quad (4.19)$$

160 where $j \in [1, n]$. Equations (4.18) and (4.19) are identical to Eqs. (4.12) and 4.13,
 161 indicating that we have successfully generalized the framework to any number of
 162 sectors.

163 In this economy, the purpose of Goods and Services (3) is to produce goods and
 164 provide services, it provides no direct energy to society. The purpose of Energy (2) is
 165 to make direct energy (\dot{E}) available to the economy and society in a useful form. We
 166 may simplify the above equations by realizing that (a) $\dot{E}_3 = \dot{E}_{3i} = 0$, because Goods
 167 and Services (3) is assumed to produce no direct energy, and (b) $\dot{E}_{03} = 0$, because
 168 Goods and Services (3) receives no direct energy from the Biosphere (0), except via
 169 the Energy sector (2). Thus, several terms in the sums of Eq. (4.19) will be zero.

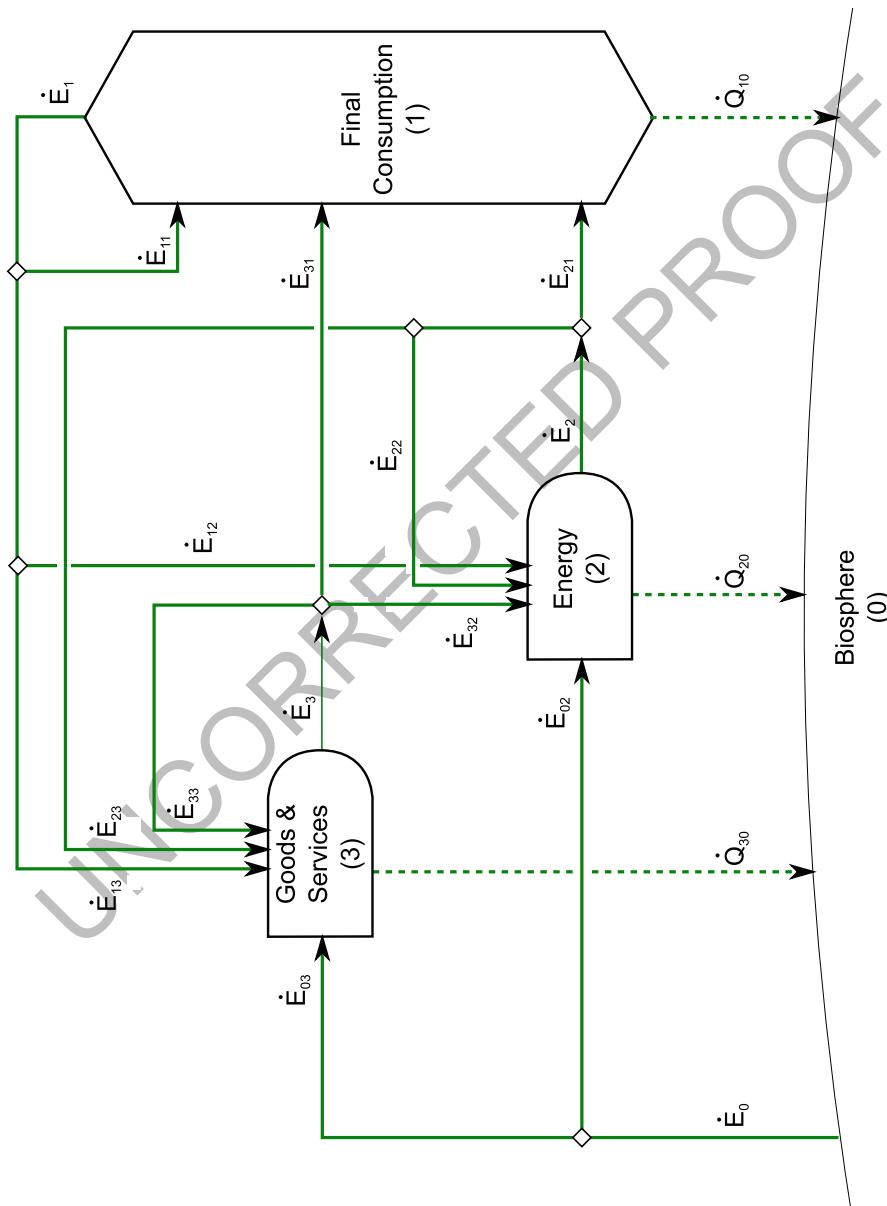


Fig. 4.5 Direct energy flows (\dot{E}) for a three-sector economy

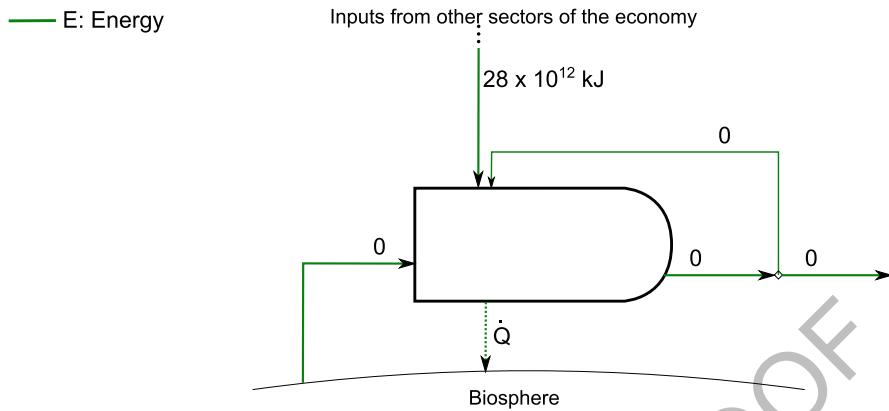


Fig. 4.6 Direct energy flows for the US automobile industry. [12, Table 7.6]

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	$10.8 \times 10^{12} {}^a$
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

170 4.5 Direct Energy in the Auto Industry

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

174 Total energy use can also be estimated by summing the energy use of the under-
 175 lying detailed processes in manufacturing automobiles. Sullivan et al. arrive at an
 176 estimate of the “gate-to-gate” energy used in the process of creating one automobile
 177 (the direct energy used within the automobile manufacturing process only) [13]. This
 178 estimate can be multiplied by the number of vehicles manufactured in a given year to
 179 obtain total energy use by the automobile industry. Sullivan estimated a total direct
 180 energy use of 34,000 MJ for a generic 1532 kg vehicle.

181 4.6 Summary

182 In this chapter, we have developed equations, assisted by the first law of thermody-
 183 namics, that describe the flow of direct energy (\dot{E}) through economies (Sect. 4.1).
 184 Examples A–C afforded the opportunity to apply the equations to analyze economies

185 with increasing levels of disaggregation (Sects. 4.2–4.4). Finally, the energy flows
186 for our running example, the US auto industry, were discussed in Sect. 4.5.

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

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216 hicle and component manufacturing. Technical report, Argonne National Laboratory (ANL);
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Chapter 5

Stocks and Flows of Embodied Energy

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

16 —David MacKay

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

23 One way to assess the level of manufactured capital on a physical basis is to
24 estimate the energy *embodied within* that capital. Because capital is created using
25 output from other economic sectors, it is necessary to estimate the energy embodied
26 in products (\dot{P}), too. The energy embodied in products (e.g., energy embodied in
27 the automobiles produced by the automotive sector) is related to the sum of all
28 direct energy consumed in the manufacture of its products, including all upstream
29 processing stages. For example, the upstream energy consumed by an auto parts
30 supplier to fabricate windows will be embodied in the finished automobile. Embodied
31 energy gives an indication of the energy demand from consumption of goods and
32 services within an economy.

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

41 To assess the embodied energy of products and economic sectors, we will adapt
42 the first law discussed in Chap. 4.¹

43 Fundamentally, nearly all energy on earth comes from or came from the sun.
44 In the framework for embodied energy that we develop below, we consider the
45 embodiment of solar energy *after* its conversion to another energy form, e.g., fossil
46 fuels, hydroelectricity, or solar PV electricity. Other approaches are possible. The
47 *emergy* method counts all material flows in terms of embodied solar energy [3, 4].
48 The basic unit of measure is the *emjoule* which is often given in terms of flows of
49 solar energy embodied in the energy (or material)—the solar emjoule—per unit of
50 resource, abbreviated to seJ/J for energy resources, or seJ/kg for materials. As such,
51 even fossil fuels, e.g., coal, extracted from the earth have an embodied energy of
52 around 67,000 seJ/J [5]. The decision about solar energy is a boundary choice. Our
53 choice to account post-solar embodied energy is consistent with the direct energy
54 reporting practices of the International Energy Agency (IEA) and the US Energy
55 Information Administration (EIA).

56 Embodied energy is a very useful way to assess the level of manufactured capital.
57 First, we note that the machines, factories, and stores in which energy becomes em-
58 bodied are essential for the efficient operation of any economic sector. A sector can't
59 operate without its manufactured capital! Second, to first approximation, embodied
60 energy is a good estimate of the energy that will be demanded to replace depreciated
61 capital. Furthermore, we will need to know the embodied energy content of eco-
62 nomic products to estimate energy intensity in Chap. 7. Third, the amount of energy
63 embodied in the sector is an indicator of the complexity of the sector.²

64 The purpose of this chapter is to develop a framework for accounting embodied
65 energy accumulation and flow within economies. With an embodied energy account-
66 ing framework in hand, we will be positioned to develop a method for analyzing the
67 energy intensity of goods and services within an economy (Chap. 7).

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."

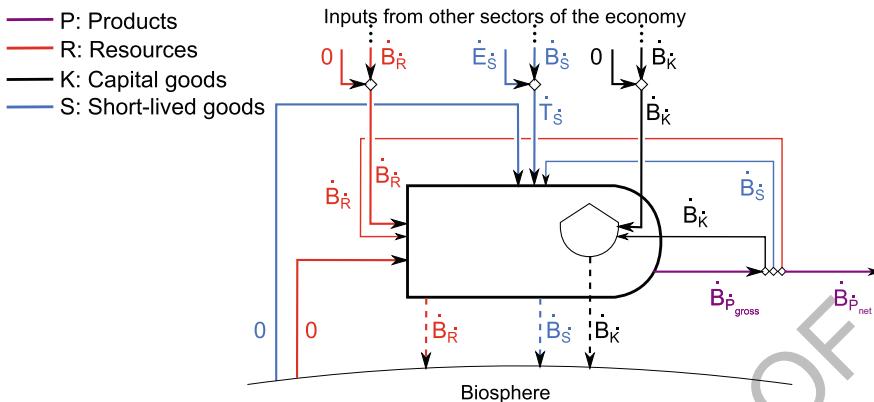


Fig. 5.1 Total energy flows (\dot{T}) for a single sector of an economy. For the sake of clarity, direct (\dot{E}) and embodied (\dot{B}) energy flows are shown separately for material inflows from other sectors only

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.

$$T \equiv E + B \quad (5.1)$$

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}).

$$\dot{T} = \dot{E} + \dot{B} \quad (5.2)$$

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 (and often unstated) assumptions:

- Flows of total energy (\dot{T}) are conserved,⁴
- Total energy does not accumulate in economic sectors,
- There is never a flow of embodied energy to the biosphere, and
- All total energy inflow to a sector is allocated to the products of that sector (i.e., there is no “waste” of total energy).

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

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

$$\frac{dT}{dt} = \frac{dE}{dt} + \frac{dB}{dt}. \quad (5.3)$$

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.

$$\frac{dT}{dt} = \sum \dot{T} \quad (5.4)$$

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

$$\frac{dE}{dt} + \frac{dB}{dt} = \sum (\dot{E} + \dot{B}). \quad (5.5)$$

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 fast 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).

$$\frac{dB}{dt} = \sum \dot{B} + \sum \dot{Q}_{out} \quad (5.6)$$

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

$$\frac{dB}{dt} = \sum \dot{B}_{in} - \sum \dot{B}_{out} + \sum \dot{Q}_{out}. \quad (5.7)$$

In words, the rate of accumulation of embodied energy in a sector of the economy ($\frac{dB}{dt}$) 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.

$$\sum \dot{B}_{in} + \sum \dot{Q}_{out} = \frac{dB}{dt} + \sum \dot{B}_{out} \quad (5.8)$$

From Eq. 5.8, we see that incoming embodied energy (\dot{B}_{in}) and waste heat⁷ (\dot{Q}_{out}) can be used to increase either (a) the embodied energy within a sector of the economy ($\frac{dB}{dt}$) 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 $\frac{dB}{dt}$ 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 $\frac{dB}{dt}$ 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 $\frac{dB}{dt}$ 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 tantamount to assuming that $\frac{dB}{dt} = 0$ 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

$$\frac{dT_0}{dt} = \dot{T}_{10} - \dot{T}_{01}, \quad (5.9)$$

and

$$\frac{dT_1}{dt} = \dot{T}_{01} + \dot{T}_{11} - \dot{T}_1 - \dot{T}_{10}. \quad (5.10)$$

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

$$\frac{dE_0}{dt} + \frac{dB_0}{dt} = \dot{E}_{10} + \dot{B}_{10} - \dot{E}_{01} - \dot{B}_{01} \quad (5.11)$$

and

$$\frac{dE_1}{dt} + \frac{dB_1}{dt} = \dot{E}_{01} + \dot{B}_{01} + \dot{E}_{11} + \dot{B}_{11} - \dot{E}_1 - \dot{B}_1 - \dot{E}_{10} - \dot{B}_{10}. \quad (5.12)$$

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

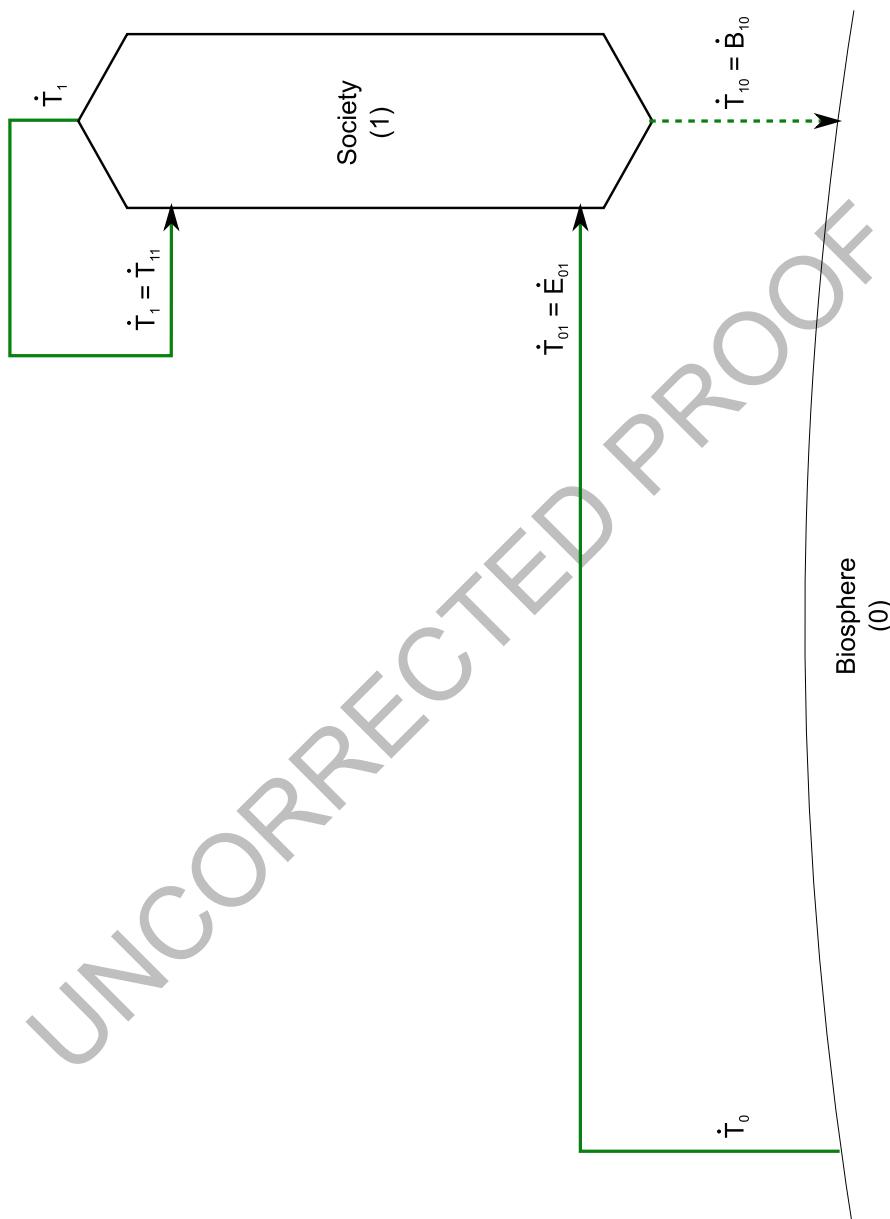


Fig. 5.2 Total energy flows (\dot{T}) in a one-sector economy

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

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

171 and

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

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

175 5.2.2 Substitution of First Law into the Embodied Energy 176 Accounting Equation

177 The second approach to the derivation of embodied energy accounting equations is
 178 to substitute the first law (Eqs. 4.4 and 4.5) into the total energy accounting equations
 179 (Eqs. 5.11 and 5.12).

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

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

180 This substitution has the advantage of cancelling most of the direct energy terms
 181 from the embodied energy accounting equations. And, it is no longer necessary to
 182 assume that the accumulation rate of direct energy ($\frac{dE}{dt}$) is zero, because the $\frac{dE}{dt}$ term
 183 is cancelled by the substitution.

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

$$\frac{dB_0}{dt} = \dot{B}_{10} - \dot{Q}_{10} \quad (5.17)$$

186 and

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

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

$$\frac{dB_1}{dt} = \frac{dB_{R_1}}{dt} + \frac{dB_{S_1}}{dt} + \frac{dB_{K_1}}{dt}, \quad (5.19)$$

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

$$\frac{dB_1}{dt} = \frac{dB_{K_1}}{dt}. \quad (5.20)$$

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

$$\frac{dB_{K_1}}{dt} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{10} + \dot{Q}_{10}. \quad (5.21)$$

193 Equations 5.17 and 5.21 are the embodied energy accounting equations for
194 Example A.

195 In Examples B and C following, we will choose the approach of this section,
196 namely substitution of the first law of thermodynamics into the total energy ac-
197 counting equation (instead of simplifying the total energy equation as discussed in
198 Sect. 5.2.1), because of the benefit of cancelling direct energy flow terms (\dot{E}).

199 5.2.3 Physical Depreciation

200 The term \dot{B}_{10} in Eq. 5.21 represents the disposal rate of embodied energy from Society
201 (1) to the Biosphere (0), i.e., depreciated physical assets. Figure 3.2 shows that the
202 outgoing material flow from Society (1) is comprised of resources (\dot{R}_{10}), short-lived
203 materials (\dot{S}_{10}), and capital (\dot{K}_{10}). Each of these material flows will have associated
204 embodied energy such that

$$\dot{B}_{10} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \dot{B}_{\dot{K}_{10}}. \quad (5.22)$$

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

$$\dot{B}_{\dot{K}_{10}} = \gamma_B B_{K_1}, \quad (5.23)$$

212 where γ_B represents the depreciation rate of embodied energy in units of inverse
213 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., $\gamma_B = 0.05/\text{year}$). 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

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

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

$$\frac{dB_0}{dt} = \dot{B}_{\dot{R}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{B_1} B_{K_1} - \dot{Q}_{10} \quad (5.25)$$

and

$$\frac{dB_{K_1}}{dt} = \dot{B}_{11} - \dot{B}_1 - \dot{B}_{\dot{R}_{10}} - \dot{B}_{\dot{S}_{10}} - \gamma_{B_1} B_{K_1} + \dot{Q}_{10}. \quad (5.26)$$

Equation 5.26 indicates that the accumulation rate of embodied energy in an economic sector ($\frac{dB_{K_1}}{dt}$) 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 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.

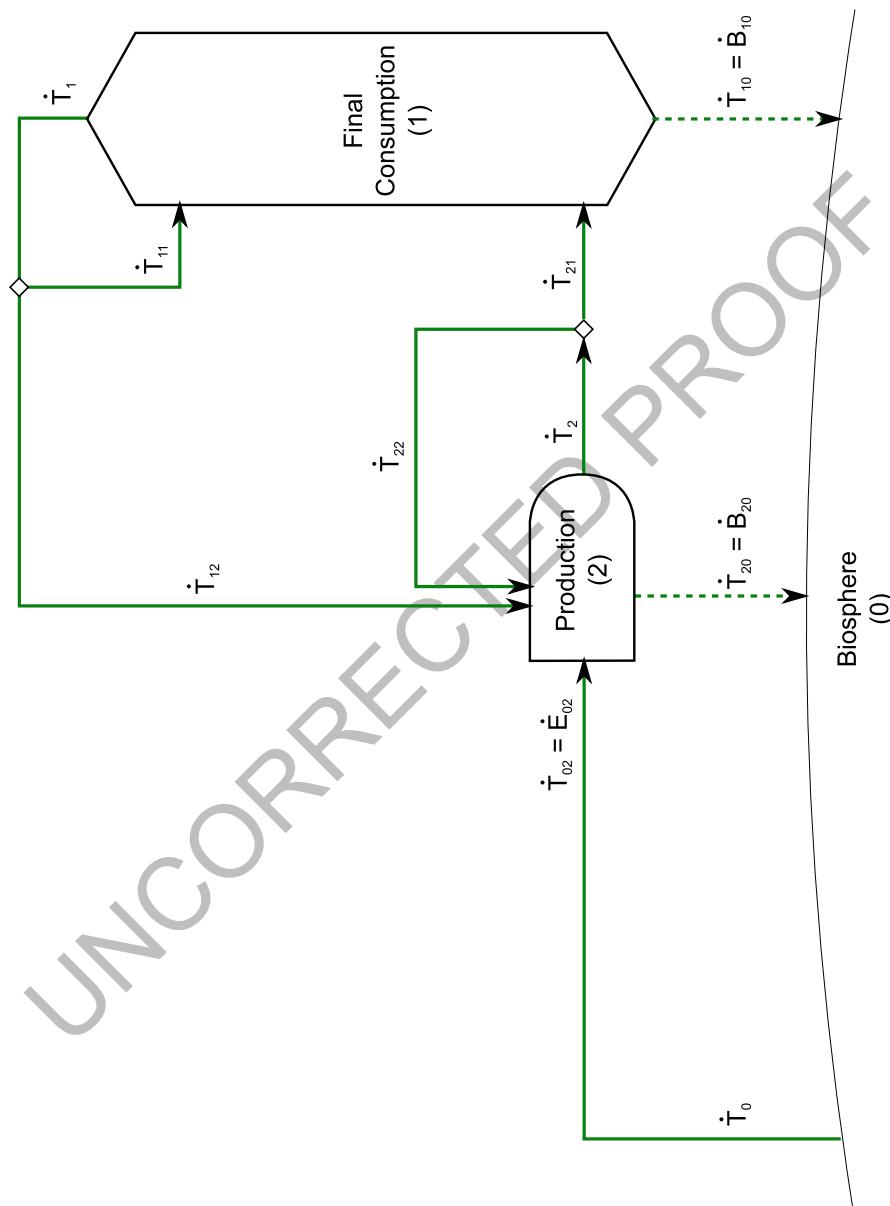


Fig. 5.3 Flows of total energy (\dot{T}) in a two-sector economy

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

$$\frac{dT_0}{dt} = \dot{T}_{10} + \dot{T}_{20} - \dot{T}_{02}, \quad (5.27)$$

$$\frac{dT_1}{dt} = \dot{T}_{11} + \dot{T}_{21} - \dot{T}_1 - \dot{T}_{10}, \quad (5.28)$$

244 and

$$\frac{dT_2}{dt} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} - \dot{T}_2 - \dot{T}_{20}. \quad (5.29)$$

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

$$\frac{dB_0}{dt} + \frac{dE_0}{dt} = \dot{E}_{10} + \dot{B}_{10} + \dot{E}_{20} + \dot{B}_{20} - \dot{E}_{02} - \dot{B}_{02}, \quad (5.30)$$

$$\frac{dB_1}{dt} + \frac{dE_1}{dt} = \dot{E}_{11} + \dot{B}_{11} + \dot{E}_{21} + \dot{B}_{21} - \dot{E}_1 - \dot{B}_1 - \dot{E}_{10} - \dot{B}_{10}, \quad (5.31)$$

246 and

$$\frac{dB_2}{dt} + \frac{dE_2}{dt} = \dot{E}_{02} + \dot{B}_{02} + \dot{E}_{12} + \dot{B}_{12} + \dot{E}_{22} + \dot{B}_{22} - \dot{E}_2 - \dot{B}_2 - \dot{E}_{20} - \dot{B}_{20}. \quad (5.32)$$

247 As in Example A, we can substitute the first law of thermodynamics (Eqs. 4.8–
 248 4.10) into the total energy accounting equations (Eqs. 5.30–5.32) and employ the
 249 assumptions that $\dot{E}_{i0} = 0$ and $\dot{B}_{0j} = 0$ to obtain

$$\frac{dB_0}{dt} = \dot{B}_{10} + \dot{B}_{20} - \dot{Q}_{10} - \dot{Q}_{20}, \quad (5.33)$$

$$\frac{dB_1}{dt} = \dot{B}_{11} + \dot{B}_{21} - \dot{B}_1 - \dot{B}_{10} + \dot{Q}_{10}, \quad (5.34)$$

250 and

$$\frac{dB_2}{dt} = \dot{B}_{12} + \dot{B}_{22} - \dot{B}_2 - \dot{B}_{20} + \dot{Q}_{20}. \quad (5.35)$$

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

255 Equations 5.33–5.35 can be simplified using sums:

$$\frac{dB_0}{dt} = \sum_{i=1}^n \dot{B}_{i0} - \sum_{i=1}^n \dot{Q}_{i0} \quad (5.36)$$

256 and

$$\frac{dB_j}{dt} = \sum_{i=1}^n \dot{B}_{ij} - \dot{B}_j - \dot{B}_{j0} + \dot{Q}_{j0}, \quad (5.37)$$

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

258 As in Example A, we can disaggregate the accumulation and waste embodied
259 energy terms and express physical waste of capital stock as depreciation in Eqs. 5.36
260 and 5.37 to obtain

$$\frac{dB_0}{dt} = \sum_{i=1}^n (\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K_i}) - \sum_{i=1}^n \dot{Q}_{i0} \quad (5.38)$$

261 and

$$\frac{dB_{K,j}}{dt} = \sum_{i=1}^n \dot{B}_{ij} - \dot{B}_j - (\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j}) + \dot{Q}_{j0}. \quad (5.39)$$

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

264 5.4 Example C: Three-Sector Economy

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

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

$$\frac{dT_0}{dt} = \sum_{i=1}^n \dot{T}_{i0} - \sum_{j=1}^n \dot{T}_{j0} \quad (5.40)$$

270 and

$$\frac{dT_j}{dt} = \sum_{i=0}^n \dot{T}_{ij} - \dot{T}_j - \dot{T}_{j0}. \quad (5.41)$$

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

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

$$\frac{dE_0}{dt} + \frac{dB_0}{dt} = \sum_{i=1}^n \dot{E}_{i0} + \sum_{i=1}^n \dot{B}_{i0} - \sum_{j=1}^n \dot{E}_{0j} - \sum_{j=1}^n \dot{B}_{0j} \quad (5.42)$$

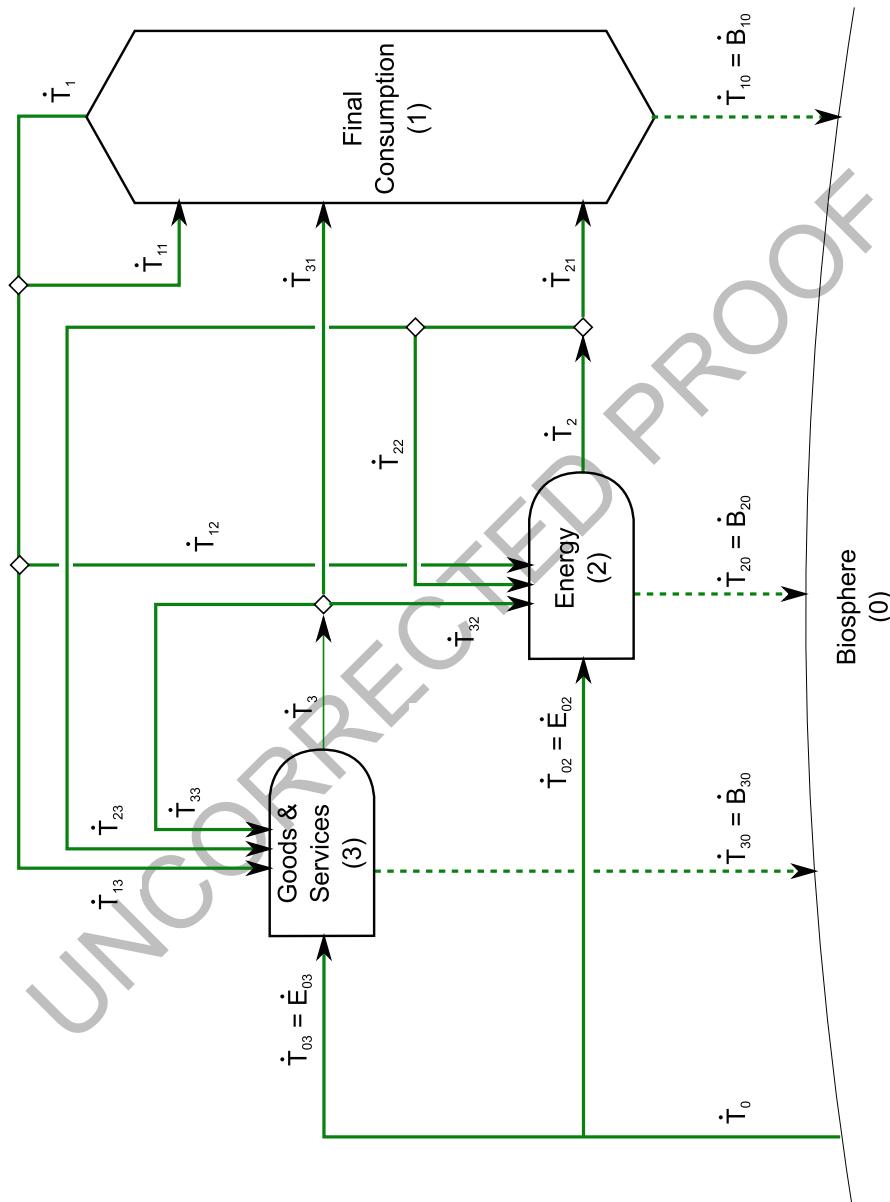


Fig. 5.4 Flows of total energy (\dot{T}) in a three-sector economy

273 and

$$\frac{dE_j}{dt} + \frac{dB_j}{dt} = \sum_{i=0}^n \dot{E}_{ij} + \sum_{i=0}^n \dot{B}_{ij} - \dot{E}_j - \dot{B}_j - \dot{E}_{j0} - \dot{B}_{j0}. \quad (5.43)$$

274 Substituting the first law of thermodynamics (Eqs. 4.8 and 4.10) into the total energy
 275 accounting equations (Eqs. 5.42 and 5.43) and recognizing that $\dot{B}_{0j} = 0$ for $j \in [1, n]$
 276 and $\dot{E}_{i0} = 0$ for $i \in [1, n]$ gives embodied energy accounting equations for
 277 Example C:

$$\frac{dB_0}{dt} = \sum_{i=1}^n \dot{B}_{i0} - \sum_{i=1}^n \dot{Q}_{i0} \quad (5.44)$$

$$\frac{dB_j}{dt} = \sum_{i=0}^n \dot{B}_{ij} - \dot{B}_j - \dot{B}_{j0} + \dot{Q}_{j0} \quad (5.45)$$

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

$$\frac{dB_0}{dt} = \sum_{i=1}^n (\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K_i}) - \sum_{i=1}^n \dot{Q}_{i0} \quad (5.46)$$

281 and

$$\frac{dB_{Kj}}{dt} = \sum_{i=1}^n \dot{B}_{ij} - \dot{B}_j - (\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j}) + \dot{Q}_{j0}, \quad (5.47)$$

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

284 To verify the above derivation, we sum Eqs. 5.46 and 5.47 for all sectors of the
 285 economy ($j \in [1, n]$) to obtain

$$\begin{aligned} \frac{dB_0}{dt} + \sum_{j=1}^n \frac{dB_{Kj}}{dt} &= \sum_{i=1}^n (\dot{B}_{\dot{R}_{i0}} + \dot{B}_{\dot{S}_{i0}} + \gamma_{B_i} B_{K,i}) - \sum_{i=1}^n \dot{Q}_{i0} \\ &\quad + \sum_{j=1}^n \sum_{i=1}^n \dot{B}_{ij} - \sum_{j=1}^n \dot{B}_j \\ &\quad - \sum_{j=1}^n (\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K,j}) + \sum_{j=1}^n \dot{Q}_{j0}. \end{aligned} \quad (5.48)$$

286 Using the identities

$$\dot{B}_j = \sum_{k=1}^n \dot{B}_{jk} \quad (5.49)$$

287 and

$$\sum_{j=1}^n \dot{B}_j = \sum_{j=1}^n \sum_{k=1}^n \dot{B}_{jk} = \sum_{i=1}^n \sum_{k=1}^n \dot{B}_{ik} = \sum_{i=1}^n \sum_{j=1}^n \dot{B}_{ij} = \sum_{j=1}^n \sum_{i=1}^n \dot{B}_{ij}, \quad (5.50)$$

288 Equation 5.48 becomes

$$\frac{dB_0}{dt} + \sum_{j=1}^n \frac{dB_j}{dt} = 0, \quad (5.51)$$

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

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

$$\alpha_{B,j} \equiv \frac{\sum_{i=1}^n \dot{B}_{ij}}{B_{K_j}} \quad (5.52)$$

294 and resource and short-lived material flows as waste

$$\dot{B}_{\dot{W}_j} \equiv \dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}}. \quad (5.53)$$

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

$$\frac{dB_{K_j}}{dt} = (\alpha_{B,j} - \gamma_{B,j}) B_{K_j} - \dot{B}_{\dot{W}_j} - \dot{B}_j + \dot{Q}_{j0}. \quad (5.54)$$

296 With Eq. 5.54, we see that the rate of accumulation of embodied energy in the capital
297 stock of an economic sector ($\frac{dB_{K_j}}{dt}$) is affected by the balance between the inflow
298 ($\alpha_{B,j}$) and depreciation ($\gamma_{B,j}$) rates, the rate of wasting embodied energy ($\dot{B}_{\dot{W}_j}$), the
299 rate at which embodied energy leaves with the products of the sector (\dot{B}_j), and the
300 waste heat that leaves the sector (\dot{Q}_{j0}).

301 5.5 Embodied Energy in the US Auto Industry

302 In this section, we apply the framework developed above to flows of total energy in
303 the US auto industry, as depicted in Fig. 5.5. As in Sect. 3.5, we face difficulties due to
304 lack of data. We know that some flows will have zero value, as shown in Fig. 5.5. For
305 instance, there is zero energy content (direct or embodied) associated with flows from
306 the biosphere into the auto industry. Furthermore, we may assume that the resource
307 flows (\dot{R} , red in Fig. 5.5) and capital flows (\dot{K} , black in Fig. 5.5) will have no direct

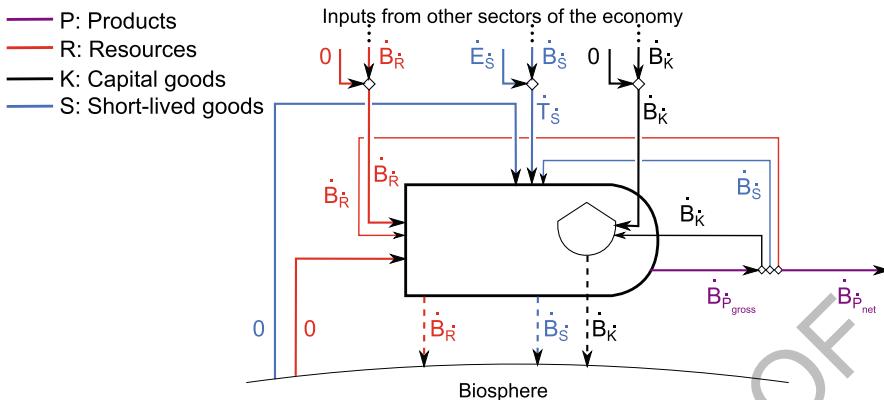


Fig. 5.5 Embodied energy flows (\dot{B}) for the US automobile industry

308 energy (\dot{E}) associated with them.¹⁰ First, because energy products enter the industry
 309 as short-lived flows (\dot{S} , blue in Fig. 5.5) and second, because energy products are not
 310 stored as capital within the sector. In fact, we can assume that all flows, other than
 311 inputs of short-lived goods (\dot{S}), will have no direct energy content (\dot{E}) associated
 312 with them.

313 Historically, very few estimates of embodied energy of automobiles have been
 314 made. In 1973, Berry and Fels, used a process-based analysis (rather than an input–
 315 output analysis), to find that the energy cost of automobile manufacturing¹¹ in the
 316 US was 37,275 kW-hr (134 GJ or 134×10^9 J) per vehicle [8, Table 2]. Of this,
 317 100 GJ was (upstream) energy embodied in the materials (\dot{B}_R) and the remaining
 318 was (direct) energy used within the auto industry to manufacture, assemble, and
 319 transport the automobile.

320 Two decades later (1995), Stodolsky et al. estimated the energy consumed in
 321 materials and manufacturing automobiles to be 79 GJ per vehicle for a conventional
 322 automobile and 66 GJ per vehicle for an aluminum intensive vehicle, both under a
 323 maximum-recycling scenario [9, p. 11]. Three years later (1998), MacLean and Lave
 324 estimated the embodied energy for an automobile to be 113.6 MBTU (120 GJ, of
 325 which 13 GJ were consumed upstream and 107 GJ were consumed direct in the auto
 326 sector) per vehicle [10, Fig. 2], which they compare with contemporaneous estimates
 327 from Sullivan of 81 GJ per vehicle [11] and Volkswagen of 62 GJ per vehicle [12].

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.

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 production rate (in automobiles/year) gives the rate of gross embodied energy outflow in the product stream of the auto sector ($\dot{B}_{P_{gross}}$). A limitation of the process-based approach employed by Berry and Fels is truncation error for upstream energy demand. See Sect. 7.1 for details.

Estimates of vehicle embodied energy are related to contemporary debates on whether electric vehicles (EVs) reduce CO₂ 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].

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 through 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

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Chapter 6

Stocks and Flows of Economic Value

1 We try to measure what we value. We come to value what we
2 measure. [1, p. 2]
3 —Donella Meadows

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

14 6.1 Subjective Theory of Value

15 We begin by explicitly stating what we mean by value. We follow the mainstream
16 approach of using the market price at the time of an exchange to determine the
17 economic value of the flows of products (goods, services, and capital). As materials
18 and energy flow in one direction between sectors, currency flows in the opposite
19 direction. The monetary flow is an easy and logical (though imperfect) proxy for the
20 value of the material and energy that exchanges hands from seller to buyer. Market
21 transactions are easily documented, and the data to estimate the economic value of
22 these flows is available in most countries [2].

23 Although the market price is readily available and conveys important information
24 (such as relative scarcity of the good and relative usefulness of the good to fulfill
25 human wants), we note that market price is *subjective*. Value is based on the agreement
26 of a mutually acceptable price by the human trading partners. The market price is
27 not a measure of any *intrinsic* value of the goods (e.g., for biodiversity or ecosystem
28 services). Market prices ignore the costs and benefits that accrue to other parties
29 (externalities), including the impact of trade on the quality of human relations, just
30 distribution of resources, or sustainable scale of the economy [3, p. 55].

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 used up 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*.

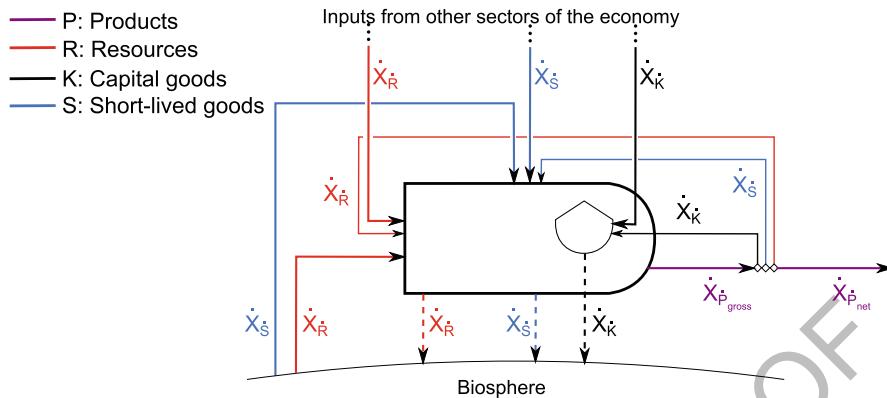


Fig. 6.1 Aggregated flows of value for a single sector, including flows to and from the biosphere

and energy constraints, and economic growth suffers. Thus, identifying the right economic scale—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 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.

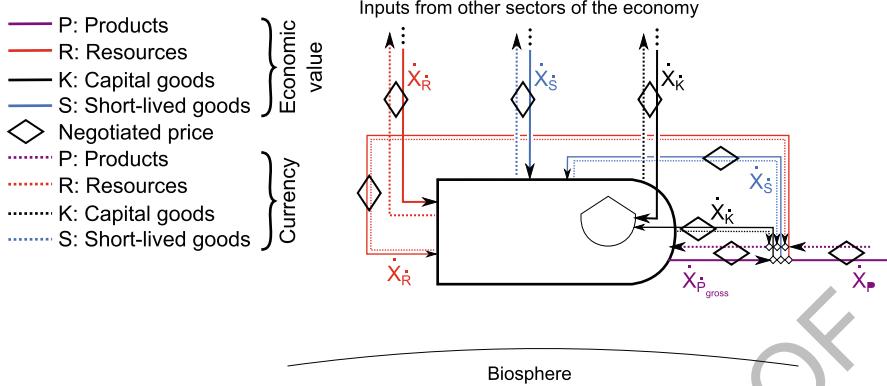


Fig. 6.2 Flows of economic value (\dot{X}) for a single sector. The economic value flows are associated with each of the different material and energy flows outlined in previous chapters. The dashed lines represent the equal and opposite flows of the currency used to pay for the material and energy

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.

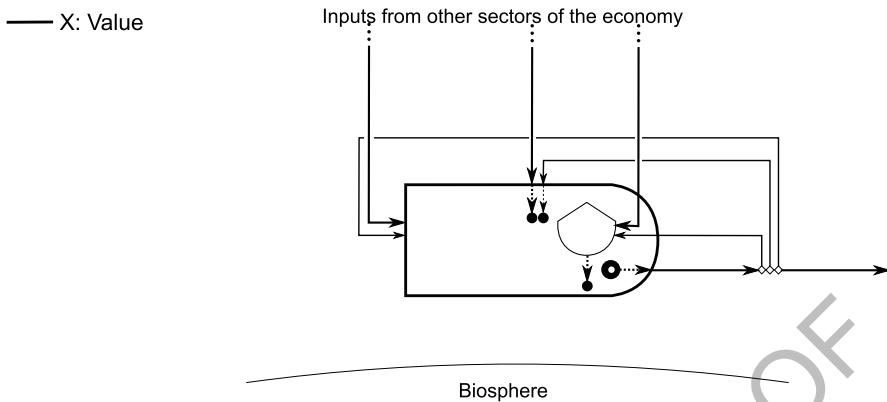


Fig. 6.3 Aggregated flows of value (\dot{X}) for a single sector. Distinction is made between value flows that enter the sector and are accumulated (i.e., capital goods) and value flows that are not accumulated. Within the sector there is destruction of value \dot{X}_{dest} , represented by the downward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

106 value-added, that is, the value that is created by the economic processes within that
 107 sector. Flows of economic value from a value-source are denoted \dot{X}_{gen} . Similarly,
 108 filled circles represent the value “sinks” where value is destroyed by economic pro-
 109 cesses or natural disasters. Flows of economic value into a value-sink are denoted
 110 \dot{X}_{dest} . Although we do not define the value creation and destruction processes any
 111 further (mathematically), we discuss what is meant by the underlying processes in
 112 Sect. 6.3.2.

113 6.3 Example A: Single-Sector Economy

114 Figure 6.4 shows flows of value in the single-sector economy. Following typical
 115 assumptions in economic modeling, the economy is *completely isolated* from the
 116 biosphere in terms of both material inputs and wastes. In other words, the value flows
 117 of an economy are *independent* from material inputs and wastes. Value flows are
 118 independent from material inputs, because raw materials have no economic value
 119 until they have been removed from the biosphere by an extraction industry. Value
 120 flows are independent from wastes, because wastes, by definition, have no economic
 121 value upon leaving the economy.

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

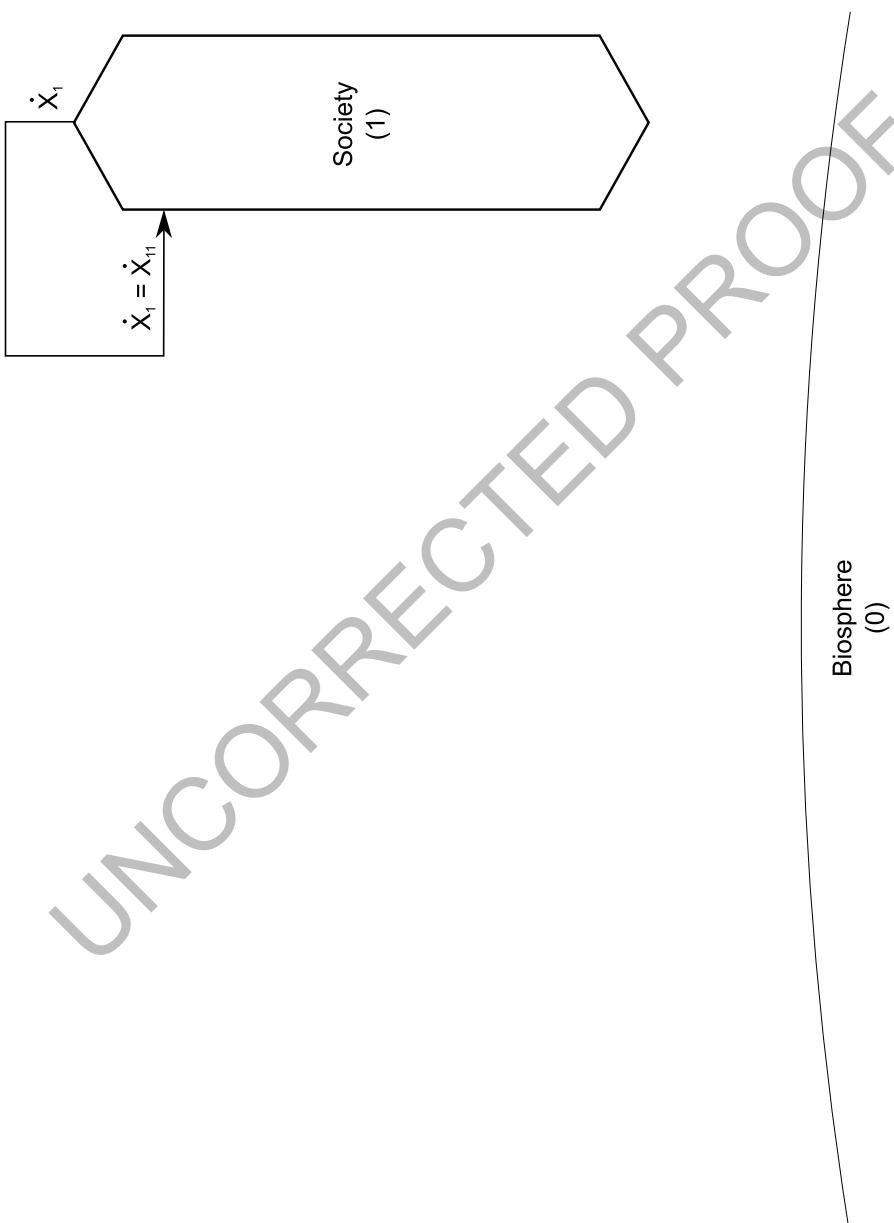


Fig. 6.4 Flows of value (\dot{X}) for a one-sector economy

128 biosphere is a consequence of the subjective theory of value that underpins modern
 129 economics. The biosphere is akin to a third party with no voice in determining the
 130 value of a transaction: it is neither buyer nor seller.

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

$$\frac{dX_1}{dt} = \dot{X}_{11} - \dot{X}_1 + \dot{X}_{gen,1} - \dot{X}_{dest,1}. \quad (6.1)$$

132 The following subsections discuss the terms in Eq. 6.1.

133 6.3.1 Economic Transactions (\dot{X}_{11} and \dot{X}_1)

134 The returning arrow in Fig. 6.4 represents transactions between

- 135 • Buyers (who receive things of value, \dot{X}_{11} , in exchange for currency) and
- 136 • Sellers (who give up things of value, \dot{X}_1 , in exchange for currency).

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

141 The subjective theory of value (Sect. 6.1) posits that buyers and sellers agree on
 142 value at the time of the transaction. Thus, $\dot{X}_1 = \dot{X}_{11}$, and Eq. 6.1 simplifies to

$$\frac{dX_1}{dt} = \dot{X}_{gen,1} - \dot{X}_{dest,1}, \quad (6.2)$$

143 indicating that value accumulates in the economy ($\frac{dX_1}{dt}$) due to value generation
 144 ($\dot{X}_{gen,1}$) and destruction ($\dot{X}_{dest,1}$) processes only.

145 6.3.2 Value Generation (\dot{X}_{gen})

146 In Eq. 6.1, the value generation term (\dot{X}_{gen}) is akin to growing apples. The term \dot{X}_{gen}
 147 is accounted as “value added” to an industry in national accounts. It is calculated
 148 as the difference between gross economic output of the industry and the cost of its
 149 intermediate inputs [7]. A simple way to think of value added is the increase in value
 150 of the raw materials from the work performed on them by workers and manufactured
 151 capital.

152 Much of the value added that is attributed to the manufacturing process was
 153 actually value provided by natural capital, at no monetary cost to producers. For
 154 example, in Sect. 3.1, the apples that are produced would be counted in national
 155 accounting as value added by capital and labor, when in reality, the value is provided
 156 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 capital, and any other “wealth” that cannot be exchanged for money.

189 **6.4 Example B: Two-Sector Economy**

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

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

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

193 and

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

194 Equations 6.3 and 6.4 can be generalized as

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

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

196 **6.5 Example C: Three-Sector Economy**

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

198 The equations representing flows of value in Example C are:

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

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

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

202 With the identities

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

203 and

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

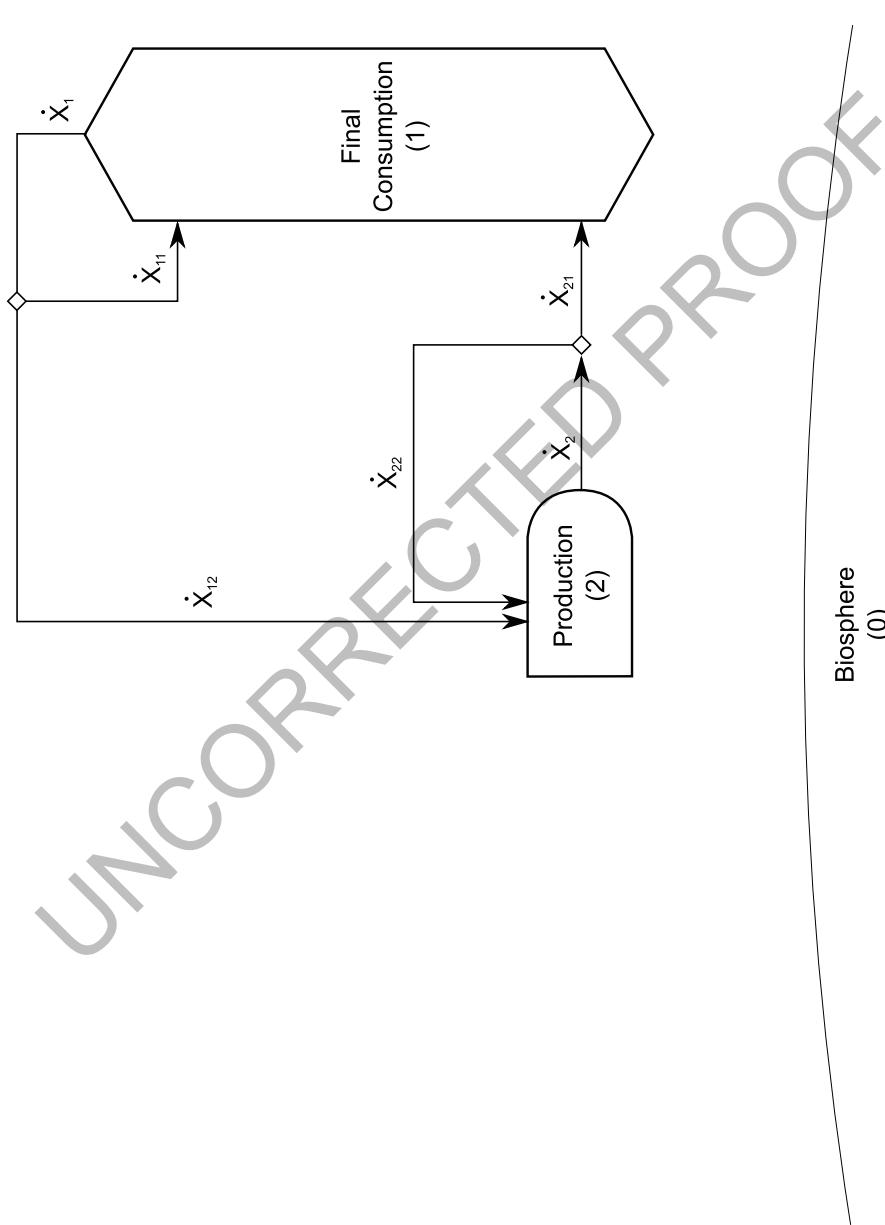


Fig. 6.5 Flows of value (\dot{X}) within a two-sector economy

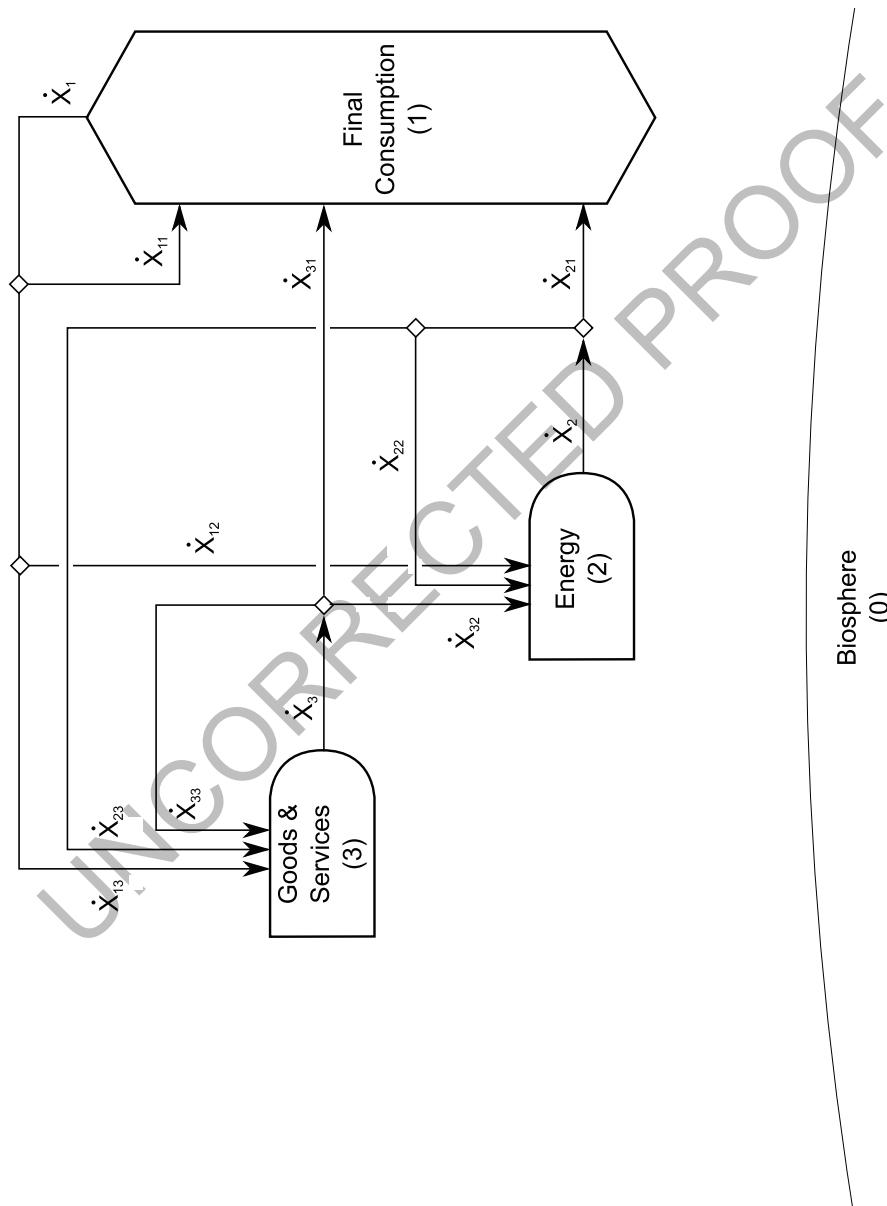


Fig. 6.6 Flows of value (\dot{X}) within a three-sector economy

204 Equation 6.7 becomes

$$\sum_{j=1}^n \frac{dX_j}{dt} = \sum_{j=1}^n \dot{X}_{gen,j} - \sum_{j=1}^n \dot{X}_{dest,j}, \quad (6.10)$$

205 for $j \in [1, n]$, indicating that value generation ($\dot{X}_{gen,j}$) and destruction ($\dot{X}_{dest,j}$) are
 206 the only mechanisms by which value is accumulated or lost ($\frac{dX_j}{dt}$) within the econ-
 207 omy. Equation 6.10 is a mathematical representation of the value-added approach to
 208 measuring GDP. The sum of the value-added across all industries is equivalent to
 209 the total value of final produced goods [9, p. 196].

210 6.6 Stocks and Flows of Economic Value in the US Auto Industry

211 To estimate value flows through the automobile industry, we use publicly available
 212 data from the US BEA.⁶ The tables needed to estimate dynamic value flows and
 213 capital accumulation within the economy are primarily the KLEMS⁷ intermediate
 214 use tables and the fixed asset, nonresidential detail table. The KLEMS data tables are
 215 based on the input-output (I-O) tables, but are at a lower level of aggregation, and
 216 the inputs are categorized into three broad types: energy, materials, and services.

217 The KLEMS intermediate use data are categorized in the same way as the in-
 218 put flows in our framework. The total material inputs into the auto industry (IOC
 219 3361 MV) represents the value of resource flows (\dot{X}_R). Similarly, the total direct
 220 energy inputs into the auto industry represents the value of energy flows (\dot{X}_E), and
 221 the total service inputs into the auto industry represents short-lived goods (\dot{X}_S). The
 222 fixed asset accounts are used to estimate capital value flows (\dot{X}_K) as well as self-use
 223 of capital. The I-O tables are used to determine gross economic output of the auto in-
 224 dustry ($\dot{X}_{P_{Gross}}$). And subtracting self-use capital and resources from gross economic
 225 output yields net economic output ($\dot{X}_{P_{net}}$).

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

232 Figure 6.7 populates the flows of economic value figure with these data for the
 233 US auto industry. This example illustrates that our framework can be combined with
 234 national accounting data to provide estimates of the flows of economic value for a
 235 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.

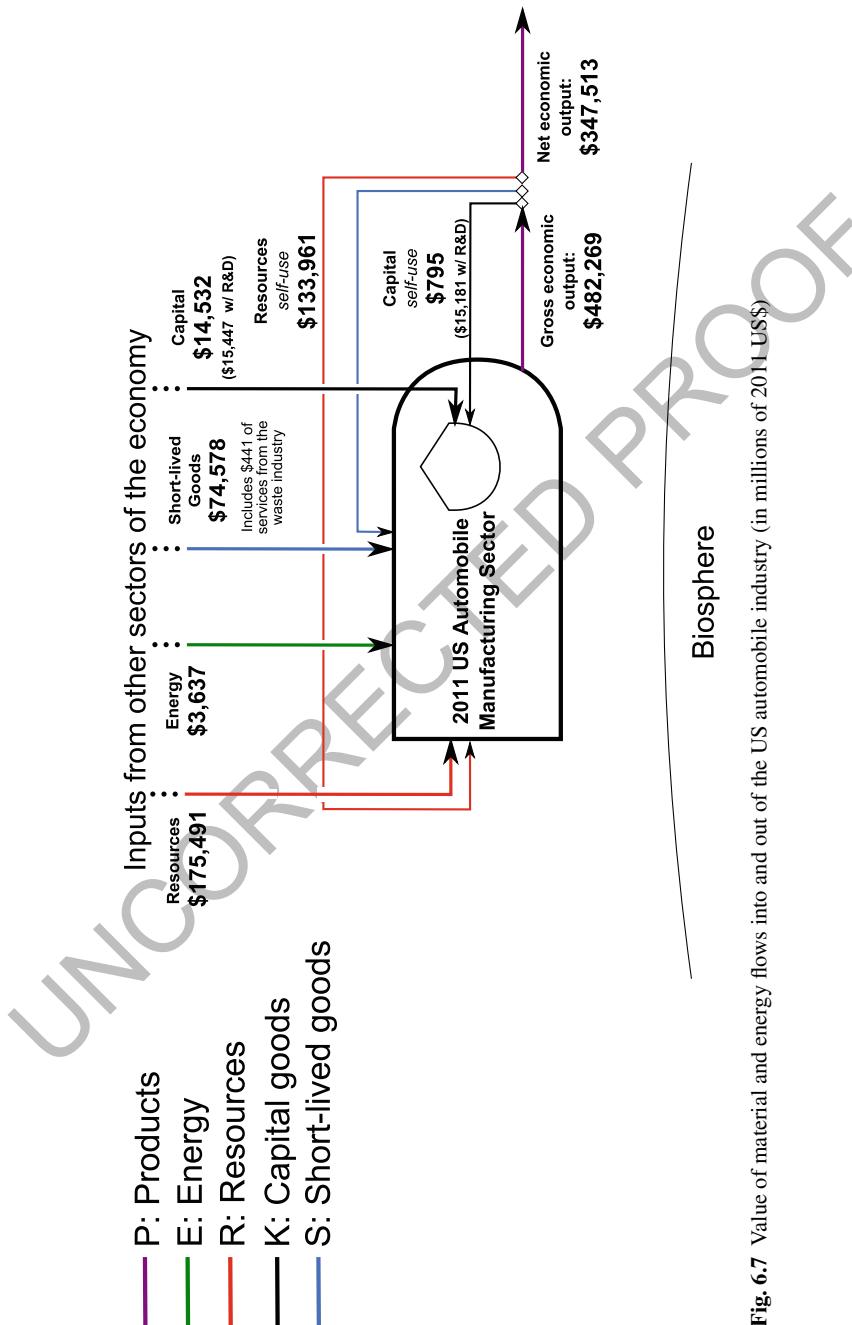


Fig. 6.7 Value of material and energy flows into and out of the US automobile industry (in millions of 2011 US\$)

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	3637	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

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

240 Another issue that the auto industry example in Fig. 6.7 highlights is the evolution
 241 of the treatment of capital in national accounts. Note the difference between the two
 242 values for self-use capital flows: \$ 795 million in flows of physical capital only and
 243 \$ 15,181 million in flows that include research and development (R&D). In the case
 244 of the auto industry, and most industries in general, this difference is an order of
 245 magnitude. The larger figure (\$ 15,181 million) includes intellectual property assets
 246 and is consistent with the current official definition of fixed Assets in the US national
 247 accounts.

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

255 In 2013, the BEA fundamentally revised the definition of fixed assets again to
 256 include R&D, as well as production of creative works, such as art, music, and long-
 257 running television shows. These types of assets, along with software, were combined
 258 together into a sub-category in the fixed assets account labeled "Intellectual Property"
 259 [12]. The fixed assets tables were revised retrospectively to conform to the new
 260 definition. In 2012, intellectual property accounts for approximately 11 % of the
 261 nonresidential, private fixed investment (\$ 3.4 trillion (line 20) out of \$ 32.1 trillion
 262 total private and government nonresidential fixed assets (line17)). For comparison,
 263 the \$ 3.4 trillion in value the US places on intellectual property is more than half the

264 value the nation ascribes to its stock of Equipment for the same year (\$ 6.6 trillion
 265 (line 18)) [13].

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

[AQ1]

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

281 6.7 Summary

282 In this chapter, we developed techniques to account for flows of economic value (\dot{X})
 283 through economies (Sect. 6.2). We began with a discussion about theories of value
 284 and settled on the prevailing subjective theory of value for our framework. Thereafter,
 285 value accounting equations were developed and applied to example economies A–C
 286 in Sects. 6.3–6.5. We noted the need for terms that describe creation and destruction
 287 of value (\dot{X}_{gen} and \dot{X}_{dest} , respectively) within economic sectors. Finally, we explored
 288 value flows to and from the US auto economy (Sect. 6.6).

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

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

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[AQ2]

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Chapter 7

Energy Intensity

1 *Accounting systems change behavior.*
2 —unknown NASA JPL accountant

3 At the end of Chap. 1, we noted that in the age of resource depletion, routine dis-
4 semination of information regarding energy, embodied energy, and energy intensity
5 would provide firms and consumers with better information to navigate the era of
6 resource depletion. To that end, we developed equations that describe the flow and
7 accumulation of direct energy, embodied energy, and economic value within an econ-
8 omy in Chaps. 4, 5, and 6. In this chapter, we merge energy and economic value
9 together to estimate the energy intensity (ε) of economic sectors, measured in joules
10 per dollar.¹

11 7.1 Background

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

19 The basic premise of the I–O method, as depicted in Fig. 7.1a, is that each eco-
20 nomic sector takes in factors of production from other sectors (and possibly itself) to

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.”

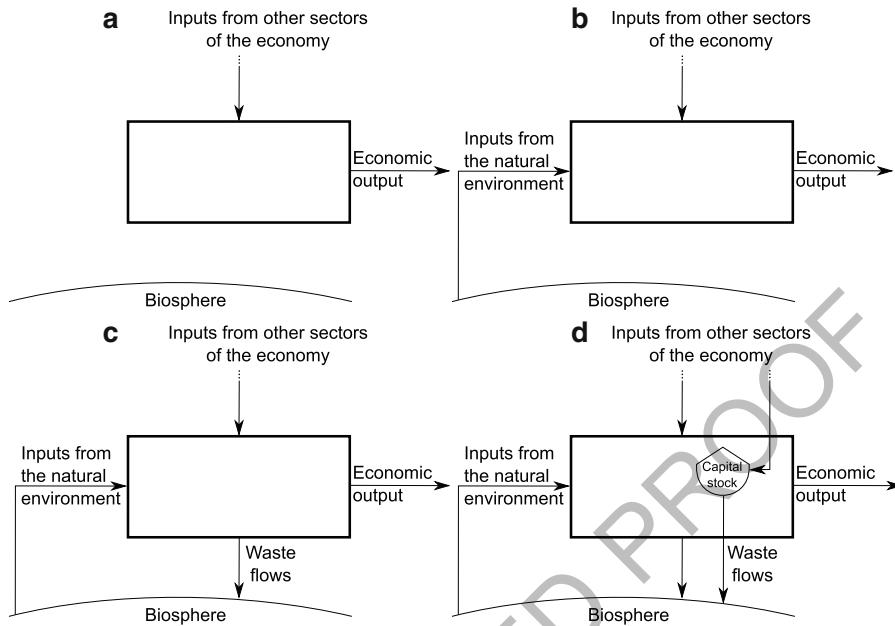


Fig. 7.1 The basic unit of input–output analysis: **a** the standard economic approach includes only transactions among sectors of the economy, **b** the energy input–output (EI–O) method allows inputs from the natural environment to be factors of production, **c** including waste flows to the environment 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

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 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

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.

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,

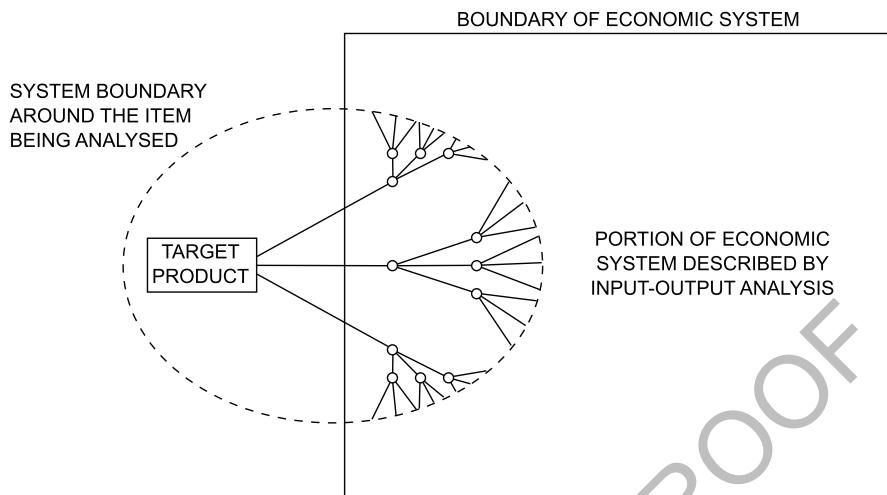


Fig. 7.2 System boundary for process and I-O analyses. (Adapted from [1])

34 services provided by stocks of capital and labor, a flow of energy⁴ is required for
 35 economic activity. These energy flows originate from the biosphere, recognition of
 36 which prompted researchers from the field of net energy analysis (NEA) to extend
 37 the traditional Leontief input–output method to include important energy flows from
 38 the environment, developing an energy input–output (EI–O) method as depicted in
 39 Fig. 7.1b⁵ [3–10]. While the Leontief input–output method relies exclusively on
 40 monetary units to represent flows of economic value among sectors of an economy,
 41 the EI–O method relies upon physical units (especially energy units of joules) to
 42 represent some of the flows among economic sectors. In doing so, energy intensities
 43 (ε) of products can be estimated in a manner that includes the “upstream” energy
 44 consumed in the supply chain.

45 When applying the EI–O method, it is important to clearly define what counts
 46 for energy input to a sector of the economy. The early pioneers of the EI–O method
 47 counted only postsolar (i.e., fossil fuel) energy inputs to the economy, in a manner
 48 similar to our approach as discussed in the introduction to Chap. 5. About a decade
 49 later, Costanza [11] included an option to consider solar energy as an input to the
 50 economy, thereby significantly increasing the energy intensity of agricultural sectors
 51 and other sectors that depend upon agricultural outputs. However later work by
 52 Costanza [3, 12] did not include solar input to the economy.

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.

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.

53 Whether solar input to the economy should be included in an EI-O analysis
54 within a materials, energy, and economic value accounting framework is probably
55 dependent upon the objectives of the analysis. The motivation for this particular book
56 is primarily the effects of declining energy natural resource quality on industrialized
57 economies in the age of resource depletion. As such, inclusion of solar flows is prob-
58 ably unnecessary. However, expanding the framework to include nonindustrialized
59 or agrarian societies may require accounting for solar energy flows.⁶

60 The early EI-O method assumed that each economic sector makes a single product
61 (\dot{P}) [13]. In later years, the EI-O method was extended in the literature to include
62 coproducts for each economic sector [8, 12]. To do so, both *make* and *use* data
63 must be employed.⁷ For the purposes of simplicity, we decided to leverage the
64 older, single-product formulation of the EI-O method. The materials, energy, and
65 value accounting framework presented herein is more easily understood without the
66 additional complexity of the make-use formulation of the EI-O method. Recent
67 work has shown that converting between the single-product and make-use forms of
68 the EI-O method is possible [14].

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

82 Both the original Leontief input–output method (Fig. 7.1a) and the EI-O extension
83 cited above (Fig. 7.1b) assume steady-state conditions in an economy, i.e., flows of

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 (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 EIO 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 method individually [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	<ul style="list-style-type: none"> * Comprehensiveness * Economy-wide analysis * System-level comparison * Publicly available data * Reproducible results * Assessment of future product development 	<ul style="list-style-type: none"> * Aggregated data * Process analysis difficult * Reliance on financial data * Imports treated as domestic products * Lack of physical data * Data uncertainty
BOTTOM-UP	<ul style="list-style-type: none"> * Detail and specificity * Comparison of specific products or processes * Identifies process improvements * Assessment of future product development 	<ul style="list-style-type: none"> * 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

84 economic value and material into and out of each economic sector are in balance.
 85 Wastes are not present, and dynamic or transient behavior of the economic system
 86 is not considered. Thus, in the EI–O analysis technique, there is no accumulation of
 87 economic factors or embodied energy within any of the sectors.

88 The EI–O approach provides “snapshots” of economic activity at an instant in time,
 89 but its model is incomplete. Figures 7.1c and d show that wastes exist and materials
 90 can accumulate in economic sectors as manufactured capital.⁹ In fact, assuming no
 91 accumulation of materials, within economic sectors or society itself, is tantamount
 92 to assuming that *all* material flows through the economy are directed toward the
 93 production of nondurable goods. However, evidence of the durability of goods and
 94 the accumulation of materials surrounds us. Furthermore, energy was required to both
 95 fabricate and emplace the durable goods and infrastructure of modern economies.¹⁰
 96 As Georgescu-Roegen notes, “in the everyday world one cannot possibly cross a
 97 river only on the flow of maintenance materials of a non-existent bridge” [20].

98 Historically, many mainstream economists have spurned analyses aimed at
 99 determining energy intensity, because energy intensity and the EI–O method were
 100 significant features of the proposal for an energy theory of value¹¹ [21]. However,
 101 we recognize that all economic activity requires energy. Thus, we contend that

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.

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.

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 to 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 ,

$$\varepsilon_j \equiv \frac{\dot{T}_j}{\dot{X}_j}, \quad (7.1)$$

and ε is in units of J/\$.¹² Energy intensity (ε_j) represents the total energy demanded by sector j (both for sector j itself and the energy required to create the inputs to sector j) per dollar of output from sector j . Equation 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

$$\varepsilon_j = \frac{\dot{T}_{jk}}{\dot{X}_{jk}}. \quad (7.2)$$

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

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)

		OUTPUT FROM		
		FINAL ENERGY SECTOR	CONSUM. SECTOR	GOODS SECTOR
INPUT FROM		FINAL CONSUM.	\$ / J	\$ / \$
	FINAL ENERGY SECTOR	J / \$	J / J	J / \$
	GOODS SECTOR	\$ / \$	\$ / J	\$ / \$

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

$$a_{ij} \equiv \frac{\dot{X}_{ij}}{\dot{X}_j} \quad (7.3)$$

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

$$a_{ij} = \frac{\dot{X}_{Rij} + \dot{X}_{Sij} + \dot{X}_{Kij}}{\dot{X}_{Rj} + \dot{X}_{Sj} + \dot{X}_{Kj}}. \quad (7.4)$$

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

135 Input–output ratios (a_{ij}) are given in mixed units, depending on both the purpose
 136 of each sector of the economy and the type of input as shown in Fig. 7.4.

137 Equations 7.2 and 7.3 can be combined to give

$$\dot{T}_{jk} = \varepsilon_j a_{jk} \dot{X}_k. \quad (7.5)$$

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

142 7.3 Example A: Single-Sector Economy

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

$$\varepsilon_1 = \frac{\dot{T}_1}{\dot{X}_1} = \frac{\dot{T}_{11}}{\dot{X}_{11}}. \quad (7.6)$$

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

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

150 7.4 Example B: Two-Sector Economy

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

$$\varepsilon_2 = \frac{\dot{T}_2}{\dot{X}_2} = \frac{\dot{T}_{22}}{\dot{X}_{22}}. \quad (7.7)$$

153 Thus,

$$\dot{T}_2 = \varepsilon_2 \dot{X}_2. \quad (7.8)$$

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

$$a_{22} = \frac{\dot{X}_{22}}{\dot{X}_2}, \quad (7.9)$$

155 thus

$$\dot{T}_{22} = \varepsilon_2 a_{22} \dot{X}_2. \quad (7.10)$$

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

$$\frac{dT_2}{dt} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} - \dot{T}_2 - \dot{T}_{20} \quad (5.29)$$

157 using energy intensity by realizing that:

- 158 • $\frac{dE_2}{dt} = 0$ meaning that $\frac{dT_2}{dt} = \frac{dB_2}{dt}$, because direct energy does not accumulate
 159 within economic sectors,
- 160 • $\frac{dB_2}{dt} = \frac{dB_{K2}}{dt}$, because resources (R) and short-lived materials (S) do not
 161 accumulate at appreciable rates in economic sectors,
- 162 • $\dot{B}_{02} = 0$ meaning that $\dot{T}_{02} = \dot{E}_{02}$, because flows from the biosphere have yet to
 163 have any energy from society embodied in them,
- 164 • $\dot{E}_{20} = 0$ meaning that $\dot{T}_{20} = \dot{B}_{20}$, because direct energy is not wasted to the
 165 biosphere at any significant rate,¹⁴ and

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

- 166 • $\dot{B}_{20} = (\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \dot{B}_{K_{20}}) = (\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2})$, as shown in Sect. 5.4.

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

$$\frac{dB_{K_2}}{dt} = \dot{E}_{02} + \dot{T}_{12} + \varepsilon_2 a_{22} \dot{X}_2 - \varepsilon_2 \dot{X}_2 - (\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}). \quad (7.11)$$

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

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

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

170 7.5 Example C: Three-Sector Economy

171 The three-sector economy of Example C affords the opportunity to develop a matrix
 172 version of the total energy accounting Eq. (5.41) and to develop an equation that
 173 estimates the energy intensity of economic sectors. We begin by deriving a matrix
 174 version of the total energy accounting equation.

175 7.5.1 Total Energy Accounting Equation

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

$$\frac{dT_2}{dt} = \dot{T}_{02} + \dot{T}_{12} + \dot{T}_{22} + \dot{T}_{32} - \dot{T}_2 - \dot{T}_{20} \quad (7.13)$$

179 and

$$\frac{dT_3}{dt} = \dot{T}_{03} + \dot{T}_{13} + \dot{T}_{23} + \dot{T}_{33} - \dot{T}_3 - \dot{T}_{30}. \quad (7.14)$$

180 Similar to Example B, we realize that:

- 181 • $\frac{dE_i}{dt} = 0$ meaning that $\frac{dT_i}{dt} = \frac{dB_i}{dt}$, because direct energy does not accumulate
 182 within economic sectors,
- 183 • $\frac{dB_i}{dt} = \frac{dB_{K_i}}{dt}$, because resources (R) and short-lived materials (S) do not accumulate
 184 at appreciable rates in economic sectors,
- 185 • $\dot{B}_{0j} = 0$ meaning that $\dot{T}_{0j} = \dot{E}_{0j}$, because flows from the biosphere have yet to
 186 have any energy from society embodied in them,
- 187 • $\dot{E}_{j0} = 0$ meaning that $\dot{T}_{j0} = \dot{B}_{j0}$, because direct energy is not wasted to the
 188 biosphere at any significant rate, and

189 • $\dot{B}_{j0} = (\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \dot{B}_{\dot{K}_{j0}}) = (\dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}} + \gamma_{B_j} B_{K_j})$, as shown in Sec-
190 tion 5.4.

191 to obtain

$$\frac{dB_{K_2}}{dt} = \dot{E}_{02} + \dot{T}_{12} + \varepsilon_2 \dot{X}_{22} + \varepsilon_3 \dot{X}_{32} - \varepsilon_2 \dot{X}_2 - (\dot{B}_{\dot{R}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{B_2} B_{K_2}) \quad (7.15)$$

192 and

$$\frac{dB_{K_3}}{dt} = \dot{E}_{03} + \dot{T}_{13} + \varepsilon_2 \dot{X}_{23} + \varepsilon_3 \dot{X}_{33} - \varepsilon_3 \dot{X}_3 - (\dot{B}_{\dot{R}_{30}} + \dot{B}_{\dot{S}_{30}} + \gamma_{B,3} B_{K_3}). \quad (7.16)$$

193 7.5.2 Matrix Formulation

194 Equations 7.15 and 7.16 can be rewritten in vector notation as

$$\begin{aligned} \left\{ \begin{array}{l} \frac{dB_{K_2}}{dt} \\ \frac{dB_{K_3}}{dt} \end{array} \right\} &= \left\{ \begin{array}{l} \dot{E}_{02} \\ \dot{E}_{03} \end{array} \right\} + \left\{ \begin{array}{l} \dot{T}_{12} \\ \dot{T}_{13} \end{array} \right\} + \begin{bmatrix} \dot{X}_{22} & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} \end{bmatrix} \left\{ \begin{array}{l} \varepsilon_2 \\ \varepsilon_3 \end{array} \right\} - \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \\ \left\{ \begin{array}{l} \varepsilon_2 \\ \varepsilon_3 \end{array} \right\} &- \left\{ \begin{array}{l} \dot{B}_{\dot{R}_{20}} \\ \dot{B}_{\dot{R}_{30}} \end{array} \right\} - \left\{ \begin{array}{l} \dot{B}_{\dot{S}_{20}} \\ \dot{B}_{\dot{S}_{30}} \end{array} \right\} - \begin{bmatrix} \gamma_{B_2} & 0 \\ 0 & \gamma_{B,3} \end{bmatrix} \left\{ \begin{array}{l} B_{K_2} \\ B_{K_3} \end{array} \right\}. \end{aligned} \quad (7.17)$$

195 If we define the following matrices and vectors:

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

$$\frac{d\mathbf{B}_K}{dt} \equiv \begin{Bmatrix} \frac{dB_{K_2}}{dt} \\ \frac{dB_{K_3}}{dt} \end{Bmatrix}, \quad (7.19)$$

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

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

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

$$\boldsymbol{\varepsilon} \equiv \begin{Bmatrix} \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix}, \quad (7.23)$$

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

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

¹⁹⁷ and

$$\hat{\boldsymbol{\gamma}}_B \equiv \delta_{ij} \gamma_{B_j} = \begin{bmatrix} \gamma_{B_2} & 0 \\ 0 & \gamma_{B_3} \end{bmatrix}; \quad (7.26)$$

¹⁹⁸ with the “Kronecker delta” (δ_{ij}), being a function of two integer variables (i and j)
¹⁹⁹ that has value of 1 if i and j are equal and zero otherwise;

$$\delta_{ij} \equiv \begin{cases} 0 & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}; \quad (7.27)$$

²⁰⁰ we can rewrite Eq. 7.17 compactly in matrix notation as

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

²⁰¹ Equation 7.28 can be simplified to

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

²⁰² We can define the input–output matrix (\mathbf{A}) as

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

203 Appendix C shows that

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

204 which allows Eq. 7.29 to be recast as

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

205 Equation 7.32 is the matrix version of the total energy accounting equation written
 206 in terms of embodied energy (\mathbf{B}), energy intensities ($\boldsymbol{\varepsilon}$), and input–output ratios (\mathbf{A}).
 207 Equation 7.17 applies for the three-sector economy of Example C, but the equivalent
 208 matrix formulation (Eq. 7.32) can be extended to any desired level of economic and
 209 energy sector disaggregation by expanding the vectors and matrices in Eqs. 7.19,
 210 7.18, and 7.30 to include all sectors ($2 \dots n$) of an n -sector economy [1, 8].

211 Equation 7.32 provides a means to estimate the embodied energy accumulation
 212 rate in economic sectors ($\frac{d\mathbf{B}_K}{dt}$) knowing only direct energy inputs to the economy
 213 from the biosphere (\mathbf{E}_0), total energy inputs from society to the economy (\mathbf{T}_1), sector
 214 outputs ($\hat{\mathbf{X}}$), sector input–output ratios (\mathbf{A}), sector energy intensities ($\boldsymbol{\varepsilon}$), energy em-
 215 bodied in wastes from the economy ($\mathbf{B}_{\dot{W}}$), and physical depreciation rates of capital
 216 stock ($\hat{\boldsymbol{\gamma}}_B \mathbf{B}_K$). In theory, the transaction matrix (\mathbf{X}_t) is not required if the input–
 217 output matrix (\mathbf{A}) is known, though in practice, knowledge of input–output matrix
 218 (\mathbf{A}) would be derived from the transaction matrix (\mathbf{X}_t), as shown in Appendix D.

219 Equation 7.32 can be rearranged to obtain

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

220 and

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

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

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

222 to the right side of Eq. 7.34 to obtain

$$\boldsymbol{\varepsilon} = (\mathbf{A}^T - \mathbf{I})^{-1} \hat{\mathbf{X}}^{-1} \left[\frac{d\mathbf{B}_K}{dt} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1 \right]. \quad (7.36)$$

223 Finally, we can multiply both parenthetical terms¹⁵ on the right side of Eq. 7.36 by
 224 –1 to obtain

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^T)^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 + \mathbf{T}_1 - \frac{d\mathbf{B}_K}{dt} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K \right]. \quad (7.37)$$

¹⁵ The parenthetical terms on the right side of Eq. 7.36 are $(\mathbf{A}^T - \mathbf{I})$ and $\left[\frac{d\mathbf{B}_K}{dt} + \mathbf{B}_{\dot{W}} + \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K - \mathbf{E}_0 - \mathbf{T}_1 \right]$.

Equation 7.37 is the key energy intensity equation in this section. In words, it says that the energy intensity of economic sector output (ϵ) is a function of the energy input from the biosphere (E_0), the energy input from society (T_1), less the rate at which energy is embodied in the sector ($\frac{d\mathbf{B}_K}{dt}$), less the rate at which energy embodied in resource and short-lived material streams end up as waste ($\dot{\mathbf{B}}_W$), less the rate at which embodied energy is discarded from the sector in depreciated capital ($\hat{\mathbf{y}}_B \mathbf{B}_K$).

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 (ϵ) of the sectors of the economy, under the assumption that Final Consumption (1) is exogenous to the economy (Sectors 2 ... 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.

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

$$\frac{dB_{K_1}}{dt} = \dot{E}_{01} + \varepsilon_1 \dot{X}_{11} + \varepsilon_2 \dot{X}_{21} + \varepsilon_3 \dot{X}_{31} - \varepsilon_1 \dot{X}_1 - (\dot{B}_{\dot{K}_{10}} + \dot{B}_{\dot{S}_{10}} + \gamma_{K,1} B_{K_1}). \quad (7.38)$$

Furthermore, Eqs. 7.15 and 7.16 can be rewritten as

$$\frac{dB_{K_2}}{dt} = \dot{E}_{02} + \varepsilon_1 \dot{X}_{12} + \varepsilon_2 \dot{X}_{22} + \varepsilon_3 \dot{X}_{32} - \varepsilon_2 \dot{X}_2 - (\dot{B}_{\dot{K}_{20}} + \dot{B}_{\dot{S}_{20}} + \gamma_{K,2} B_{K_2}) \quad (7.39)$$

and

$$\frac{dB_{K_3}}{dt} = \dot{E}_{03} + \varepsilon_1 \dot{X}_{13} + \varepsilon_2 \dot{X}_{23} + \varepsilon_3 \dot{X}_{33} - \varepsilon_3 \dot{X}_3 - (\dot{B}_{\dot{K}_{30}} + \dot{B}_{\dot{S}_{30}} + \gamma_{K,3} B_{K_3}). \quad (7.40)$$

256 Following the derivation of Chap. 7, we can obtain an updated version of Eq. 7.37:

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^T)^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 - \frac{d\mathbf{B}_K}{dt} - \mathbf{B}_{\dot{W}} - \hat{\boldsymbol{\gamma}}_B \mathbf{B}_K \right], \quad (7.41)$$

257 wherein

- 258 • the vectors and matrices of Eqs. 7.18–7.26 and 7.30 have been extended to include
259 Final Consumption (1) and
 - 260 • Final Consumption (1) has been endogenized (the \mathbf{T}_1 term of Eq. 7.37 has been
261 subsumed into the $(\mathbf{I} - \mathbf{A}^T)^{-1} \hat{\mathbf{X}}^{-1}$ term of Eq. 7.41).
- 262 Future work could estimate energy intensity ($\boldsymbol{\varepsilon}$) using Eqs. 7.37 and 7.41 with updated
263 economic data for a wider range of countries.¹⁶ Doing so could provide further insight
264 on Costanza's result [3] that endogenizing Final Consumption (1) reduces variation
265 of energy intensity ($\boldsymbol{\varepsilon}$) across all sectors of the economy.

266 7.7 Choice of Energy Input Vector

267 There is discussion in the literature about the \mathbf{E}_0 vector and how it should be applied
268 to the economy. Costanza and Herendeen [12] counted fossil fuel input from the
269 biosphere to the economy at both

- 270 1. the points where direct energy physically enters the economy from the biosphere,
271 typically energy-producing sectors (called the DIRECT method), and
- 272 2. the points of conversion to useful work, typically all energy *consuming* sectors
273 (called the direct energy conversion (DEC) method).

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

281 The primary energy sectors functions [*sic*] are like the transportation sectors, which also [*sic*]
282 require special treatment in I-O analysis based on the difference between the services they
283 provide and their physical inputs and outputs. If a strictly physical interpretation were applied
284 to the transportation sectors, they would receive almost all goods produced in the whole
285 economy as inputs and redistribute them as output, masking information on transfers of
286 goods between sectors. For this reason, the transportation sectors in I-O analysis are thought
287 of as providing transportation services that are purchased by the producing sector, preserving
288 the connection between the producing and consuming sector but adding a 'transportation
289 margin.' For analogous reasons, the primary energy sectors should be thought of as providing

¹⁶ Costanza's analysis [3] was conducted using the US data for 1963, 1967, and 1972.

290 a ‘transportation service’ in moving primary energy from nature to the consuming sectors.
 291 The DEC energy input vector incorporates this interpretation. [12, p. 151]

292 The derivation of the materials, energy, and value accounting framework presented
 293 herein counts energy flows from the biosphere to the economy at the point of physical
 294 inflow to the economy. That is, elements of the energy input vector (\mathbf{E}_0) are nonzero
 295 only for those sectors that receive energy directly from the biosphere. So, for example,
 296 in Fig. 4.5 from Example C, $\dot{E}_{03} = 0$ and $\dot{E}_{02} \geq 0$. Our approach is equivalent to
 297 Costanza’s DIRECT method. We believe that the DIRECT approach is correct and
 298 that the DEC method is unwarranted.

299 Justification for our position comes from the detailed derivation of the materials,
 300 energy, and value framework presented in Chaps. 3–6.

- 301 1. First, \mathbf{E}_0 was defined as a flow from the biosphere to economic sectors into which
 302 direct energy *physically* flows. It is inappropriate to route the energy elsewhere.
- 303 2. Second, Costanza and Herendeen’s concern [12, p. 130 and 138] about flow-
 304 through of direct energy is unfounded, because direct energy outflows from a
 305 sector are *never* counted against the sector with the DIRECT method. We see this
 306 fact in the following terms:
 - 307 a) $-\dot{E}_1$ in Eq. 5.12,
 - 308 b) $-\dot{E}_j$ in Eq. 5.43,
 - 309 c) $-\left[\begin{array}{cc} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{array} \right] \left\{ \begin{array}{c} \varepsilon_2 \\ \varepsilon_3 \end{array} \right\}$ in Eq. 7.17, and
 - 310 d) $-\hat{\mathbf{X}}\mathbf{e}$ in Eq. 7.28.
- 311 3. Third, further proof that the DEC approach is unwarranted comes from equations
 312 that show waste heat (\dot{Q}_{j0}) as counting toward the accumulation of embodied
 313 energy within an economic sector. Equation 5.16 of Sect. 5.2.2 is an example.
 314 It is the waste heat (\dot{Q}_{10}), i.e. the energy *burned within* the sector, that counts
 315 against the sector.

316 The DIRECT approach *already always* provides the effect that Costanza and
 317 Herendeen [12] desired from the DEC approach. Because the DEC approach is un-
 318 warranted, we quote DIRECT energy intensity values only when discussing energy
 319 intensities in the following Sect. (7.8).

320 7.8 Energy Intensity in the US Auto Industry

321 Equation 7.37 shows that it is possible to estimate the energy intensity of products of
 322 the economic sectors using the EI–O analysis method.¹⁷ Several studies have used
 323 similar energy-based, input–output methods (EI–O) to estimate the energetic cost of

¹⁷ For a discussion of differences between Eq. 7.37 and similar equations in the literature, see Appendix E.

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

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

In 1980, Costanza [3] estimated the energy intensity of all economic sectors of the US economy using the I-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 and Lave [19] and allows computation of the energy flows through the economy based on the US national accounts data from 1992, 1997, and 2002.²⁰ Using the tool with the 2002 producer price model, we

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

¹⁸ See Sect. 5.5 for discussion of the Berry and Fels [30] paper.

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.

Table 7.3 Automobile manufacturing sector (NAICS 33611x) 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)

345 find that \$1M of output from the automobile manufacturing industry (NAICS sector
 346 336111) generates a total flow of 8.33 TJ (10^{12} J) of energy through the economy,
 347 2.19 TJ from the power generation and supply sector (221100) and 1.25 TJ from the
 348 iron and steel mills sector (331110) (Table 7.4).

349 All of these estimates use product-focused accounting frameworks. In Sect. 8.2.1,
 350 we recommended a physical accounting framework. It would be interesting to know
 351 how the above energy intensity results vary (a) if a physical accounting framework
 352 is employed, (b) with time, and (c) across economies at different stages of industrialization.
 353 However, we know of no longitudinal estimates of the energy intensity of
 354 automobiles using the EI–O method. In fact, the current account records, upon which
 355 the estimates of energy intensity values above are based, are no longer maintained
 356 by the US government. So, we could not update the results presented in this section,
 357 even if we wanted to. Furthermore, few countries maintain and publish records with
 358 enough detail to perform these analyses. In Chap. 9, we discuss further the need for
 359 additional data.

360 7.9 Summary

361 In this chapter, we derived algebraic equations, based on the top-down EI–O method,
 362 that describe the energy intensity (in units of J/\$) of products of economic sectors.
 363 The algebraic equations were applied to Examples A–C to derive a matrix equation

Table 7.4 Selected US economic sector energy intensities, 1997 [23]

Sector	Energy intensity [kJ/\$]
Coal mining (212100)	1.11×10^4
Air transportation (481000)	2.62×10^4
Manufacturing and industrial buildings (230210)	0.76×10^4
Automobile and light truck manufacturing (336110)	0.76×10^4
Automotive repair and maintenance, except car washes (8111A0)	0.52×10^4

364 for a vector of energy intensities for the entire economy (ϵ). We then reviewed several
365 studies in the literature of energy intensity of the US auto industry and noted a wide
366 range of results from one study to the next. The estimates of energy intensity also
367 vary with time. The range of energy intensities for the auto sector is 0.83×10^4 kJ/\$
368 to 11.6×10^4 kJ/\$.

369 In the next chapter, we draw several implications from the material, energy, and
370 value accounting framework presented in Chaps. 3–7.

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1
2

Part III

Implications and Summary

UNCORRECTED PROOF

Chapter 8

Implications

1 *Development without growth beyond the earth's carrying
2 capacity is true progress.* [1]
3 —Herman Daly

[AQ1]

4 Several implications can be drawn from the detailed development of our framework
5 for materials, energy, and value accounting (in Chaps. 3–7). In the sections below, we
6 discuss implications for the development of important economic metrics, the energy
7 input–output (EI–O) method itself, implications for economic growth, implications
8 for recycling, reuse, and dematerialization, and comparisons between our framework
9 and the notion of a steady-state economy. We begin by discussing metrics.

10 8.1 Metrics

11 Our framework highlights the value that could be derived from continuous monitoring
12 and reporting of several important metrics by national accounting agencies, including

- 13 • Energy intensity of products of economic sectors (Chap. 7),
14 • Total accumulation of material (Chap. 3) and embodied energy (Chap. 5) in
15 economic sectors,
16 • The flow rate of energy from the biosphere into economic sectors (Chap. 4),
17 • The flow rate of materials from economic sectors to the biosphere (Chap. 3), and
18 • The flow rate of embodied energy from economic sectors to the biosphere
19 (Chap. 5).

20 In the age of resource depletion, it would be very helpful if these metrics were
21 available for sectors and/or firms on a regular basis.

22 Both initial conditions and periodic reporting of important data are essential for
23 the ongoing tracking of important economic indicators. Because initial conditions
24 are not known and periodic reporting is not done, the dynamics of the accumula-
25 tion of materials and embodied energy in economic sectors are not discernible at
26 this time. For example, depreciation of some material from an economic sector will
27 require replacement. The replacement material will have embodied energy. Produc-
28 tion of the replacement places an energy drain on the economy. We have no way
29 of quantifying that drain at the present time. If our model were implemented and

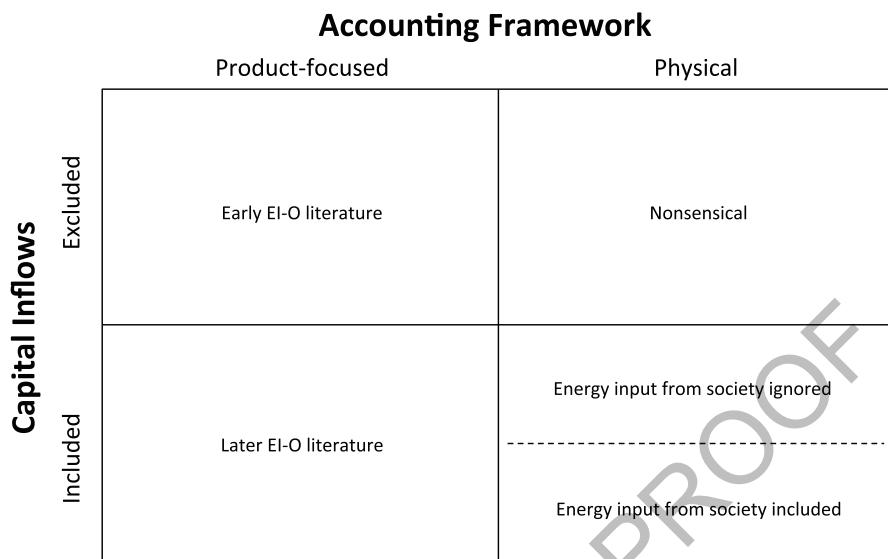


Fig. 8.1 Coordinates of analysis for implications for the EI-O method

30 periodic updates were available, society would better understand the costs (in terms
 31 of both dollars *and* energy) of maintaining capital. And, society would understand
 32 how those maintenance flows constrain economic growth.

33 **8.2 Implications for the I-O Method**

34 Extension of the Leontief input–output method for energy analysis has allowed en-
 35 ergy analysts to estimate the energy intensity of economic products (ϵ). As discussed
 36 in Sect. 6.2, we do not take the ability to estimate energy intensity as a license to
 37 declare an intrinsic “energy theory of value.” Rather, we believe that energy inten-
 38 sity (ϵ) is an important and useful metric that can assess the energy performance of
 39 economies, even within the prevailing subjective theory of value that underlies mod-
 40 ern economics. It is important to consider the assumptions behind the literature’s
 41 presentation of the EI–O method for estimating the energy intensity of economic
 42 output before drawing implications from our framework.

43 As we investigate, we will use the following coordinates of analysis: product-
 44 based vs. physical accounting frameworks, whether capital stock is included in the
 45 accounting framework, and whether energy input from society to the economy is
 46 included (see Fig. 8.1). We will end with our recommendation for how best to estimate
 47 energy intensity (ϵ) within a materials, energy, and value accounting framework.

48 8.2.1 Product-Based vs. Physical Approaches

49 The distinction between product-focused and physical accounting frameworks is
 50 located in the columns of Fig. 8.1. A *physical accounting* framework strictly follows
 51 materials through the economy. Embodied energy is allocated to the material stock
 52 or material flow in which it resides—wherever it goes, so goes the embodied energy.
 53 When the material is scrapped, so is its embodied energy. For example, energy
 54 embodied within wastes ($\dot{B}_{\dot{W}}$) is not assigned to economic products. Rather, the
 55 energy embodied in wastes flows out of sectors into the biosphere *with the waste*
 56 *material*.

57 In contrast, a *product-focused accounting* framework assigns energy embodied
 58 in wastes to the products of the sector. Both product-based and physical accounting
 59 frameworks assign direct energy (\dot{E}) consumed by each sector to the products of
 60 each sector.

61 Equation 8.1 below describes the outflow of embodied energy from sector j for a
 62 physical accounting system that neglects both capital stock accumulation and capital
 63 inflow (upper right quadrant of Fig. 8.1).¹

$$64 \dot{B}'_j = \sum_{i=1}^n \dot{B}'_{ij} - \dot{B}_{\dot{W}_j} + \dot{Q}_{j0} \quad (8.1)$$

65 Terms written with a “prime” (e.g., \dot{B}'_j) indicate definitions and terms that exclude
 66 input capital flows (\dot{K}) and capital stock (K). The term $\dot{B}_{\dot{W}_j}$ represents the energy
 67 embodied within wasted resource (\dot{R}_{j0}) and short-lived (\dot{S}_{j0}) material flows. The
 68 $\dot{B}_{\dot{W}_j}$ term is subtracted, because waste material flows *out of* the sector. In a physical
 69 accounting framework, the energy embodied in waste flows ($\dot{B}_{\dot{W}_j}$) is not assigned to
 70 the product (\dot{B}'_j).

71 In contrast, Eq. 8.2 describes the outflow of embodied energy from sector j ,
 72 exclusive of capital stock, for a product-focused accounting framework (upper left
 73 quadrant of Fig. 8.1).

$$74 \dot{B}'_j = \sum_{i=1}^n \dot{B}'_{ij} + \dot{Q}_{j0} \quad (8.2)$$

75 Notice that Eq. 8.2 does not subtract the energy embodied in waste resource and short-
 76 lived material flows ($\dot{B}_{\dot{W}_j}$) on the right side of the equation, because product-focused
 77 accounting systems assign energy embodied in wastes to products. The magnitude
 78 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.

77 sector, the value of \dot{B}'_j is different between a physical accounting framework (Eq. 8.1)
 78 and a product-focused accounting framework (Eq. 8.2).

79 8.2.2 Capital Flows and Stock

[AQ2] 80 The rows of Fig. 8.1 represent the role of capital flows and stock in an accounting
 81 framework. The Bureau of Economic Analysis (BEA) Industry Accounts include
 82 capital flows in the “make” tables for each industry [2, Table 1], but capital inflows
 83 are accounted separately from intermediate uses as “Private fixed investment” [2,
 84 Table 2]. During the earliest years of the EI-O method (prior to the mid-1970s) both
 85 capital inflows to economic sectors and stocks of capital were ignored. In essence, the
 86 state of the art was located in the upper left quadrant of Fig. 8.1. In time, Kirkpatrick
 87 [3], Bullard and Herendeen [4], and Casler [5] attempted to include inflows of capital
 88 in a product-focused accounting framework, thereby moving the state of the art to
 89 the lower left quadrant of Fig. 8.1.

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

94 In 1969, Odum outlined a number of defining characteristics of both *develop-*
 95 *mental* (growing) and *mature* (stable) ecosystems in terms of key properties of the
 96 system [6]. Ecosystems cannot grow indefinitely in their (photosynthetic) produc-
 97 tion rate (P) due to the necessity of increasing maintenance demands as the stock of
 98 biomass (B) increases. Eventually, all production is used in this manner and growth
 99 ceases ($\frac{d}{dt}(P) = 0$).

100 In the early stages of ecosystem development, the energy production rate per unit
 101 of biomass stock ($\frac{P}{B}$) is high. As the ecosystem approaches maturity, this ratio de-
 102 creases. Put another way, the biomass stock (maintained) per unit of energy produced
 103 (the inverse ratio, $\frac{B}{P}$) starts low and asymptotically increases to a maximum when
 104 growth (in both P and B) has ceased. The value of $\frac{B}{P}$ at the asymptote may be high
 105 or low² and may therefore be considered a measure of the “efficiency” to which the
 106 ecosystem applies energy production toward the goal of maintaining biomass stock.

107 Turning back to economies, Daly has, in our view, correctly applied this concept to
 108 societal patterns of economic consumption [7]. Our framework analogously suggests
 109 that as capital stock (\mathbf{B}_K) increases, an increasing flow of energy supply (\mathbf{E}_0) will be
 110 needed to maintain that stock.³ Thus, it is important to account for capital stock in a
 111 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

$$a'_{ij} \equiv \frac{\dot{X}_{\dot{R}_{ij}} + \dot{X}_{\dot{S}_{ij}}}{\dot{X}_{\dot{R}_j} + \dot{X}_{\dot{S}_j} + \dot{X}_{\dot{K}_j}} = \frac{\dot{X}'_{ij}}{\dot{X}'_j}. \quad (8.3)$$

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

$$\mathbf{A}' = \begin{bmatrix} a'_{22} & a'_{23} \\ a'_{32} & a'_{33} \end{bmatrix}. \quad (8.4)$$

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

$$\boldsymbol{\varepsilon}' = (\mathbf{I} - \mathbf{A}'^T)^{-1} (\dot{\mathbf{X}})^{-1} \mathbf{E}_0. \quad (8.5)$$

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:

$$\boldsymbol{\varepsilon} = [\mathbf{I} - (\mathbf{A}'^T + \mathbf{A}_K^T)]^{-1} (\hat{\mathbf{X}})^{-1} \mathbf{E}_0 \quad (8.6)$$

with

$$\mathbf{A}_K \equiv \begin{bmatrix} a_{\dot{K}_{22}} & a_{\dot{K}_{23}} \\ a_{\dot{K}_{32}} & a_{\dot{K}_{33}} \end{bmatrix} \quad (8.7)$$

and

$$a_{\dot{K}_{ij}} \equiv \frac{\dot{X}_{\dot{K}_{ij}}}{\dot{X}_j}. \quad (8.8)$$

Bullard and Herendeen counted embodied energy from incoming capital stock in \mathbf{A}_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 (ϵ) 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 (**B_K**). And, the stock of embodied energy (**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.

$$\epsilon = (\mathbf{I} - \mathbf{A}^T)^{-1} (\hat{\mathbf{X}})^{-1} \left[\mathbf{E}_0 - \frac{d\mathbf{B}_K}{dt} - \mathbf{B}_{\dot{W}} - \hat{\gamma}_B \mathbf{B}_K \right]. \quad (8.9)$$

Differences between Eqs. 8.9 and 8.6 include:

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

- Equation 8.9 includes \mathbf{A} while Eq. 8.6 splits \mathbf{A} into \mathbf{A}' and $\mathbf{A}_{\dot{K}}$ (a difference in appearance only),
- Equation 8.9 subtracts accumulation ($\frac{d\mathbf{B}_K}{dt}$) 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 ($\hat{\gamma}_B \mathbf{B}_K$) of energy embodied in capital stock, because energy embodied in depreciated capital ($\dot{B}_{K_{j0}}$) 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.

179 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:

$$\eta_{\dot{R}_j} \equiv \frac{\dot{P}_j}{\sum_{i=1}^n \dot{R}_{ij}}. \quad (8.10)$$

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

$$\rho_{\dot{S}_j} \equiv \frac{\dot{S}_{j0}}{\sum_{i=1}^n \dot{R}_{ij}} = \frac{\sum_{i=1}^n \dot{S}_{ij}}{\sum_{i=1}^n \dot{R}_{ij}}. \quad (8.11)$$

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

$$\dot{R}_{j0} + \dot{S}_{j0} = (1 - \eta_{\dot{R}_j} + \rho_{\dot{S}_j}) \sum_{i=1}^n \dot{R}_{ij}. \quad (8.12)$$

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

$$\dot{B}_{\dot{W}_j} = \dot{B}_{\dot{R}_{j0}} + \dot{B}_{\dot{S}_{j0}}. \quad (8.13)$$

194 Simplification via Capital Stock Accounting Equation

195 A possible simplification to Eq. 8.9 can be obtained from a control volume around
 196 the stock of capital in sector j :

$$\frac{dB_{K_j}}{dt} = \sum_{i=1}^n \dot{B}_{\dot{K}_{ij}} - \gamma_{B_j} B_{K_j}. \quad (8.14)$$

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

$$\alpha_{B_j} \equiv \frac{\sum_{i=1}^n \dot{B}_{\dot{K}_{ij}}}{B_{K_j}} \quad (8.15)$$

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

$$\hat{\alpha}_B \equiv \delta_{ij} \alpha_{B_j} = \begin{bmatrix} \alpha_{B_2} & 0 \\ 0 & \alpha_{B_3} \end{bmatrix}. \quad (8.16)$$

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

$$\frac{d\mathbf{B}_K}{dt} = \hat{\alpha}_B \mathbf{B}_K - \hat{\gamma}_B \mathbf{B}_K. \quad (8.17)$$

202 Rearranging slightly gives

$$\hat{\alpha}_B \mathbf{B}_K = \frac{d\mathbf{B}_K}{dt} + \hat{\gamma}_B \mathbf{B}_K, \quad (8.18)$$

203 which says that the incoming capital ($\hat{\alpha}_B \mathbf{B}_K$) can be used to either increase the stock
 204 of capital in the economy ($\frac{d\mathbf{B}_K}{dt}$) or overcome depreciation ($\hat{\gamma}_B \mathbf{B}_K$). Substituting
 205 Eq. 8.18 into Eq. 8.9 gives

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^T)^{-1} \hat{\mathbf{X}}^{-1} [\mathbf{E}_0 - \hat{\alpha}_B \mathbf{B}_K - \mathbf{B}_{\dot{W}}]. \quad (8.19)$$

206 8.2.3 Energy Input from Society

207 In Sects. 8.2.1 and 8.2.2 above, we implicitly assumed that Society (1) (final con-
 208 sumption, in example economies A–C) contributes negligible energy to the economy.
 209 Thus, all vectors and matrices in Eq. 8.9 involve Sectors 2– n , but not Sector 1.

210 Energy input from society to the economy (\mathbf{T}_1) is “muscle work” supplied by
 211 working humans and draft animals [10–12]. This muscle work term (\mathbf{T}_1) should
 212 include all upstream energy required to make the labor available.⁴ Equation 7.37
 213 adds the effect of energy input from society to the economy, effectively moving from
 214 the top half to the lower half of the lower right quadrant in Fig. 8.1.

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^T)^{-1} \hat{\mathbf{X}}^{-1} \left[\mathbf{E}_0 + \mathbf{T}_1 - \frac{d\mathbf{B}_K}{dt} - \mathbf{B}_{\dot{W}} - \hat{\gamma}_B \mathbf{B}_K \right]. \quad (7.37)$$

215 For industrialized economies, the direct energy component (\mathbf{E}_1) of muscle work
 216 (\mathbf{T}_1) is likely to provide only a small fraction of the energy input from fossil fuels (\mathbf{E}_0).
 217 But, the embodied energy of the muscle work (\mathbf{B}_1) is likely to be large. For agrarian
 218 and developing economies, \mathbf{T}_1 and \mathbf{E}_0 could be on the same order of magnitude.
 219 For both industrial and agrarian economies, neglecting \mathbf{T}_1 could cause errors in
 220 estimates of $\boldsymbol{\varepsilon}$. To the extent that \mathbf{T}_1 is significantly relative to \mathbf{E}_0 , neglecting \mathbf{T}_1 will
 221 underpredict the energy intensity of economic output. Energy input from society is
 222 discussed further in Sect. 7.6.

223 8.2.4 Recommendation

224 Sections 8.2.1–8.2.3 discussed three factors that affect the form of the energy intensity
 225 equation: product-focused vs. physical accounting frameworks, whether capital stock
 226 is included, and whether energy input from society is included. The three factors are
 227 summarized in Fig. 8.1.

228 At this point, it is instructive to look back at the product-focused vs. physical
 229 discussion in Sect. 8.2.1. We understand the argument for including capital stock in a
 230 product-focused accounting framework (lower left quadrant of Fig. 8.1): capital stock
 231 and waste exist solely due to product demand, therefore energy embodied in capital
 232 and waste should be assigned to products. However, a product-focused framework
 233 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.

234 economies that we believe are essential to fully understanding how and why energy
235 flows through economies, namely the accumulation of capital and associated energy
236 embodied within sectors.

237 The metabolism metaphor (Chap. 2) provides guidance here. If we were to create
238 a model of an organism that neglects tissues that accumulate embodied energy,
239 the organism (in the model) has nothing with which to absorb, process, waste, or
240 otherwise exchange material with the biosphere. The organism does not physically
241 exist (in the model)! Neglecting to account for the stock of capital (and its embodied
242 energy) is tantamount to assuming that economic production occurs out of nothing!
243 Accounting for capital stock is essential.

244 For our framework, we chose a physical accounting approach (which puts us in
245 the right column of Fig. 8.1). We chose the physical approach primarily because
246 of our belief that capital is an important aspect of economies, and the physical
247 accounting framework properly includes a stock of capital for each sector of the
248 economy. Product-based accounting frameworks mask crucial aspects of why and
249 how energy flows through economies. We acknowledge that the choice of a physical
250 accounting framework necessitates careful tracking of capital flows (and associated
251 embodied energy) through the economy. For more on data needs, see Chap. 9.

252 Finally, we suggest that accounting for energy input from society to the economy
253 is important, and we need to be in the lower half of the bottom right quadrant of
254 Fig. 8.1. So, the state of the art has moved from the nascent energy I–O literature
255 located in the upper left quadrant of Fig. 8.1 as represented by Eq. 8.5 through the
256 lower left quadrant of Fig. 8.1 as represented by Eq. 8.6 to the lower half of the
257 bottom right quadrant of Fig. 8.1 as represented by Eq. 7.37.

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

- 260 • Conversion to a physical accounting framework such as the one we propose herein,
- 261 • Physical (as opposed to financial) tracking of accumulated capital stock within
262 economic sectors,
- 263 • Redefinition of A and ϵ to include embodied energy on inflows of material, and
- 264 • Use of Eq. 7.37 instead of Eq. 8.5 or Eq. 8.6 for estimating energy intensity (ϵ)
265 of economic sectors within an economy.

266 Of course, whether or not any particular flow of embodied energy is included in
267 or excluded from analyses or whether the product-focused or physical form of the
268 framework is adopted is less important than beginning to account for embodied
269 energy and routinely reporting energy intensity values in the first place. Deciding to
270 do so will require an understanding that such analyses are important (see Chaps. 1
271 and 2) and the courage to make some movement in the right direction (see Chap. 9).

272 8.3 Implications for Economic Growth

273 Across the world, economic health and well-being is measured almost exclusively
 274 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
 275 dimensions. Viewing these dimensions through the lens of our framework illustrates
 276 some important points about measures of economic growth and well-being, includ-
 277 ing whether it be measured by a stock or a flow, and the roles of currency, capital
 278 stock, energy, natural resources, and labor in economic processes.

280 With reference to Fig. 6.6, GDP is calculated by summing value-added across all
 281 industry sectors:

$$282 \quad GDP = \sum_{j=1}^n \dot{X}_j \quad (8.20)$$

282 where n is the number of sectors in the economy. Equation 8.20 clearly shows that
 283 GDP is a *flow* of value in units of \$/year.

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

$$285 \quad X_j(t) = X_j(0) + \int_{t=0}^{t=t} \frac{dX_j}{dt} dt, \quad (8.21)$$

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

287 As an economy grows, sectors within the economy accumulate capital stock (K ,
 288 typically expressed in units of dollars) and associated embodied energy (B_K , ex-
 289 pressed in units of joules). If we turn this around, accumulation of embodied energy
 290 in economic sectors and society could be considered a *proxy* for growth.⁶ Equa-
 291 tion 8.22 indicates how accumulated embodied energy in the capital stock of an
 292 economy (\mathbf{B}_K) could be calculated:

$$293 \quad \mathbf{B}_K(t) = \mathbf{B}_K(0) + \int_{t=0}^{t=t} \frac{d\mathbf{B}_K}{dt} dt, \quad (8.22)$$

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 are open to similar criticism.

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 $\frac{d\mathbf{B}_K}{dt}$ 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 (E_0) are required to maintain capital stock in the sectors of the economy to offset the effects of depreciation ($\hat{\gamma}_B \mathbf{B}_K$), assuming that $\frac{d\mathbf{B}_K}{dt} \geq 0$ 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 occurred 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 $X_{2\dots n}$) 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 (R) to feed the capital, and
- Pay workers (represented by societal energy input to the economy, 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 T_1) is necessary, but not sufficient, for economic growth.

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

341 8.4 Implications for Recycling, Reuse, and Dematerialization

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

346 In Chap. 7, we defined the rate of accumulation of embodied energy within the
 347 economy ($\frac{d\mathbf{B}_K}{dt}$) by the following equation:

$$\frac{d\mathbf{B}_K}{dt} = \mathbf{E}_0 + \mathbf{T}_1 + \hat{\mathbf{X}}(\mathbf{A}^T - \mathbf{I})\boldsymbol{\epsilon} - \mathbf{B}_W - \hat{\gamma}_B \mathbf{B}_K \quad (7.32)$$

348 One effect of recycling is to reduce the magnitude of the waste (\mathbf{B}_W) and depreciation
 349 ($\hat{\gamma}_B$) terms. As can be seen in Eq. 7.32, reducing both \mathbf{B}_W and $\hat{\gamma}_B$, puts *upward*
 350 pressure on the accumulation of energy embodied in capital stock ($\frac{d\mathbf{B}_K}{dt}$), all other
 351 things being equal.

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

362 If recycling produces a net reduction in energy demand (\mathbf{E}_0), the upward pressure
 363 on growth ($\frac{d\mathbf{B}_K}{dt}$) from decrease in depreciation ($\hat{\gamma}_B$) and waste (\mathbf{B}_W) and the down-
 364 ward pressure on growth from net reduction in energy demand (\mathbf{E}_0) can offset each
 365 other. Under those conditions, the accumulation rate of energy embodied in capital
 366 stock ($\frac{d\mathbf{B}_K}{dt}$) will remain near zero and total embodied energy (\mathbf{B}_K) will remain con-
 367 stant. In that scenario, dematerialization can occur: Reduced material and energy
 368 input (\mathbf{E}_0) can be accompanied by no change in the growth of the economy ($\frac{d\mathbf{B}_K}{dt}$).

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 technocopian 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 the (Chap. 1 “Introduction”), 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.

398 8.5 Comparison to a Steady-state Economy

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

403 As discussed in Chap. 1, the human economy is a subset of the biosphere, a finite,
404 nongrowing system. Thus, the human economy cannot physically grow indefinitely.
405 The concept of a nongrowing or “steady-state” economy has existed for centuries.

406 There are a number of different conditions that may characterize a system as
407 steady-state. In thermodynamics, steady state is characterized by unchanging system
408 properties (p), such that $\left(\frac{dp}{dt}\right) = 0$. In ecological economics, a steady-state economy
409 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:

$$-\frac{dR_0}{dt} = \sum_j \frac{dK_j}{dt} + \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j. \quad (3.105)$$

which indicates that natural resources in the biosphere ($-\frac{dR_0}{dt}$) are depleted by the economy for the purposes of:

- Increasing man-made capital stocks within the economy ($\frac{dK_j}{dt}$),
- Providing short-lived goods exchanged within the economy (\dot{S}_{ij}), and
- Overcoming depreciation of manufactured capital stocks ($\gamma_{K_j} K_j$).

Assuming, first, that a steady-state economy exists when the level of capital stock remains constant ($\sum_j \frac{dK_j}{dt} = 0$),⁸ we can see that Eq. 3.105 reduces to:

$$-\frac{dR_0}{dt} = \sum_{i,j} \dot{S}_{ij} + \sum_j \gamma_{K_j} K_j. \quad (8.23)$$

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 ($\frac{dR_0}{dt}$) had better be at some rate lower than the biosphere can replenish those stocks. In reality, $\frac{dR_0}{dt}$ 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.

438 Second, the steady state condition $\left(\sum_j \frac{dK_j}{dt} = 0\right)$ says nothing about the trans-
 439 fer rates of short-lived goods within in the economy $\left(\sum_{i,j} \dot{S}_{ij}\right)$ or the depreciation
 440 of capital stock back to the biosphere $\left(\sum_j \gamma_{K_j} K_j\right)$. Equation 8.23 indicates that
 441 the higher the rates of these flows, the greater the rate of depletion of natural re-
 442 sources, and the more difficult it will be to meet the sustainability condition (that
 443 the withdrawal rate of natural resources from the biosphere is lower than the bio-
 444 sphere replenishment rate). Within industrial society, the flow of short-lived goods
 445 (packaging, paper products, disposable tableware, cutlery, and napkins) is large and
 446 presumably, attaining a sustainable steady-state economy will be difficult. This def-
 447 inition of steady state, constant capital stock $\left(\sum_j \frac{dK_j}{dt} = 0\right)$, does not necessarily
 448 coincide with sustainability.

449 As discussed in Chap. 3, the rate of depreciation (γ_K) is inversely proportional
 450 to the average lifetime of capital stock—as the average lifetime of capital stock
 451 decreases, the rate of depreciation of capital stock increases thereby increasing the
 452 draw on natural resources (by Eq. 8.23). It is likely that the average lifetime of
 453 capital stock has decreased over the last century, due to a decrease in durability of
 454 capital stock (the average table built today is not as durable as the average table built
 455 in the early twentieth century) and also due to increasing proportions of consumer
 456 electronics with short lifetimes (cell phones, laptops, tablets).⁹ Decreasing lifetime
 457 causes higher rates of flow for replacement materials. In the absence of extreme
 458 recycling of materials, these large replacement flows place large demands on natural
 459 resources.

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

466 8.5.2 Constant Material Throughput

467 Herman Daly has placed great emphasis on a steady-state economy as having a
 468 constant rate of material throughput [31, 32] which, as discussed above, should be
 469 below biophysical limits if sustainability is to be achieved. This is often referred to as
 470 the “scale” issue—how large is the (currently growing) human economy in relation
 471 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.

472 economy must either displace other natural ecosystems (replacing old growth forest
 473 with cultivated crops) or deplete natural capital stocks, be they renewable (fisheries)
 474 or nonrenewable (fossil fuels). As shown in Fig. 3.5, material throughput is composed
 475 of two distinct processes: exchange of material *from* the biosphere *into* the economy
 476 (extraction) and exchange of material *from* the economy *into* biosphere (waste and
 477 depreciation). We may characterize constant material throughput as either constant
 478 rate of extraction, constant rate of waste disposal, or both. In the language of our
 479 framework, we could write:

$$\frac{d}{dt} (\dot{R}_0) = 0, \quad (8.24)$$

$$\frac{d}{dt} (\dot{S}_0) = 0, \quad (8.25)$$

480 and

$$\sum_i \left[\frac{d}{dt} (\dot{R}_{i0}) + \frac{d}{dt} (\dot{S}_{i0}) + \frac{d}{dt} (\dot{K}_{i0}) \right] = 0. \quad (8.26)$$

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

492 8.5.3 Constant GDP

493 Although one definition of a steady-state economy is based upon constant levels of
 494 *material* throughput, it is possible to examine the implications of constraining the
 495 *value* of GDP to be constant.¹⁰ Within our framework, a condition of constant GDP
 496 would be characterized by the following equation:

$$\frac{d}{dt} (GDP) = \sum_j \frac{d}{dt} (\dot{X}_j) = 0. \quad (8.27)$$

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 ($\frac{d}{dt}(GDP) \leq 0$). 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 dematerialization. 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.

532 the lens of our framework. We found that there are many potential definitions of a
533 steady-state economy, none of which are fully satisfying when compared against the
534 ideal of sustainability.

535 In the next chapter, we suggest some next steps towards implementing our
536 framework.

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[AQ6]

Chapter 9

Next Steps

1 Only a crisis—actual or perceived—produces real change.
2 When that crisis occurs, the actions that are taken depend on the
3 ideas that are lying around. [1, p. ix]
4 —Milton Friedman

5 We indicated at the outset (Chaps. 1 and 2) that this book would be about counting and
6 change; counting materials, energy, and economic value, so that we can manage the
7 upcoming energy transition and navigate our way through the age of resource deple-
8 tion. Our motivation for counting more carefully is mounting evidence (discussed in
9 Chap. 1) that scarcity of materials, energy, and assimilation capacity of the biosphere
10 is limiting the potential for continued economic growth in mature economies, thereby
11 affecting us all. We need to know precisely *how* and *at what rate* we are using our
12 material and energy resources today if we are to undertake the necessary transition to
13 a more sustainable global economy. But, before collecting data to describe society’s
14 metabolism, we argued that we, as a society, need a rigorous theoretical framework
15 for better systems of national accounts, one that goes beyond gross domestic product
16 (GDP) and one that is relevant to the age of resource depletion.

17 To develop such an accounting framework guided by the metabolism metaphor,
18 we applied thermodynamic control volume accounting equations (Chaps. 3–6) to
19 economic sectors that are *open* to their surroundings, that is they are open to both
20 inflows and outflows of both materials and energy. Application of our framework
21 shows that national accounting should gather and disseminate a great deal of ad-
22 ditional physical, material data on real economies. The business axiom “you can’t
23 manage what you don’t measure” reminds us that we need this additional data if we
24 are to navigate successfully through the age of resource depletion. In short, we need
25 balance sheets in addition to income statements! We need accounting in physical
26 units in addition to financial units. Work to account such flows is starting to be un-
27 dertaken at the economy-wide level, particularly within Europe. It needs to continue,
28 but subeconomy, intersector material ,and energy accounts need to be developed, too.

29 The need for rigorous and accurate data is all the more pressing in light of the need,
30 as demonstrated in Chap. 7, to track the accumulation of manufactured capital and
31 associated embodied energy within sectors of the economy. There is a critical need for
32 systematic collection and public dissemination of such data by a centralized agency.
33 However, as discussed in the Prologue, such accounting is currently nonexistent
34 in the USA. The Bureau for Economic Analysis (BEA) was expressly forbidden

35 by congress to collect such data after the first Integrated Environmental-Economic
36 System of Accounts (IEESA) tables were published in 1994.

37 Thus, we add our voices to those encouraging governments and institutions world-
38 wide to collect and disseminate high-quality data on material and energy stocks and
39 flows. It will be impossible to make wise decisions about which materials to use,
40 which energy sources to develop, and which products and services to incentivize
41 without such data.

42 To that end, we offer the following suggestions as a way to move forward.

- 43 1. National accounting agencies worldwide should seek and be given mandates
44 to estimate and disseminate information on the value of transactions that occur
45 outside of the market. In the USA, the BEA should seek authorization to restart
46 the IEESA (see the Prologue.) Doing so will allow accounting for material and
47 energy resources that are currently outside of the market (see Sects. 1.3.1 and 1.5.)
- 48 2. National accounting agencies worldwide should develop and maintain balance
49 sheets of both natural and manufactured capital in addition to national income
50 statements. Doing so will allow countries to assess whether they are at risk of
51 drawing down their wealth to produce today's income, thereby jeopardizing future
52 quality of life (see the Prologue and Sect. 1.1.)
- 53 3. All stocks and intersector flows should be provided in physical as well as financial
54 units. At present, national accounting disseminates data in financial units, not
55 physical units such as kilograms and kilojoules. Doing so will allow analysis of
56 the true *biophysical* nature of the economy.
- 57 4. In the USA, the BEA should restart detailed Capital, Labor, Energy, Material, and
58 Services (KLEMS) reporting. Until January 2014, KLEMS data were estimated
59 and disseminated by the BEA in a matrix that revealed the source and destination
60 industries for each flow. However, due to budget cuts, only economy-wide aggregate
61 values are captured and reported today. The previous level of detail is needed
62 to obtain sector-level information on material and energy flows in financial units.
63 Doing so will provide a better picture of the structure of materials and energy
64 dependencies among economic sectors.
- 65 5. National accounting agencies should provide additional detail for waste flows. At
66 present, only two value flows related to waste are published, and both figures are
67 aggregates of different types of waste: "Waste Management Services" and "Water
68 & Sewage." These streams should be disaggregated and reported in physical units
69 as well. Doing so will allow for analysis of opportunities for recycling and reuse
70 within economies (see Sects. 2.2.3 and 8.4.)
- 71 6. All data on stocks and intersector flows should be reported by a single, central-
72 ized agency. This will require synchronizing and reconciling data sets that
73 are now reported by several different organizations. And, it may require gather-
74 ing and dissemination of new data. In the USA, for example, the Energy
75 Information Agency (EIA) and the BEA should combine their respective energy
76 data. The Environmental Protection Agency (EPA) and the BEA should com-
77 bine their respective waste data. Perhaps more than any other proposed change,

- 78 centralized reporting in both physical and financial units would demonstrate the
79 interconnectedness of the economy and the biosphere.
- 80 7. National accounting agencies should routinely estimate the energy intensity
81 of economic products using a physical accounting framework, as discussed
82 in Sect. 8.2. Doing so will provide consumers and firms alike with important
83 information for sound consumption and investment decisions.
- 84 8. All of the above should be estimated and disseminated on an annual basis. Doing
85 so will allow for assessment of trends in the material and energy structures of
86 economies.

87 There should be no illusion that this agenda will be easy to implement; in many
88 places, it will be politically difficult to undertake these changes. But, if we, as a
89 society, can begin collecting these data, perhaps we can begin to also utilize the
90 analytical tools, metrics, and knowledge needed to go beyond GDP and make wise
91 choices for the future.

92 Our deepest hope is that this book makes a positive contribution in that direction.

93 If we apply our minds directly and competently to the needs of the earth, then we will have
94 begun to make fundamental and necessary changes in our minds. We will begin to understand
95 and to mistrust and to change our wasteful economy, which markets not just the produce
96 of the earth, but also the earth's ability to produce. We will see that beauty and utility are
97 alike dependent upon the health of the world. But we will also see through the fads and the
98 fashions of protest. We will see that war and oppression and pollution are not separate issues,
99 but are aspects of the same issue. Amid the outcries for the liberation of this group or that,
100 we will know that no person is free except in the freedom of other persons, and that man's
101 only real freedom is to know and faithfully occupy his place—a much humbler place than
102 we have been taught to think—in the order of creation.

103 —Wendell Berry. 2002. *The Art of the Commonplace: The Agrarian
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1 Appendix A

2 Value Flows for the US Auto Industry

3 This appendix describes the calculations used to estimate the value flows to and from
 4 the US Auto Industry in Chap. 6. The details of the calculations and assumptions
 5 made to calculate each of the value flows is described in Table A.1. The data sources
 6 are described in Table A.2. These data are free and available for download from
 7 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	3637	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

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 industry's compensation to labor from value added, and the capital cost category (K) includes the industry's 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 <i>totals</i> . 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 revision, see [4] and [5]
	The authors hope, of course, that a reinvigorated focus on the importance of these details for national accounting will provide justification for the BEA to return to making publicly available the underlying 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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UNCORRECTED PROOF

²² **Appendix B**
²³ **Infinite Series Representation of Energy**
²⁴ **Intensity**

²⁵ In this appendix, we show that the EI–O method accounts for the infinite recursion
²⁶ of energy demands for production.

²⁷ The single-sector economy of Figs 3.4, 4.4, 5.3, and 6.5 can be re-drawn as shown
²⁸ in Fig. B.1.

If we consider the Biosphere (0) to be producing a valuable product, namely energy, we can say

$$\dot{X}_{02} = \dot{E}_{02} \quad (\text{B.1})$$

and

$$a_{02} \equiv \frac{\dot{E}_{02}}{\dot{X}_2}. \quad (\text{B.2})$$

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 ($\dot{E}_{\text{demand,tot}}$) is an infinite sum.

$$\dot{E}_{\text{demand,tot}} = a_{02}\dot{X}_2 + a_{02}a_{22}\dot{X}_2 + a_{02}a_{22}^2\dot{X}_2 + \dots \quad (\text{B.3})$$

The energy intensity of the economy (ε_2) is

$$\varepsilon_2 = \frac{\dot{E}_{\text{demand,tot}}}{\dot{X}_2} = a_{02}(1 + a_{22} + a_{22}^2 + \dots) = a_{02} \sum_{n=0}^{\infty} a_{22}^n. \quad (\text{B.4})$$

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

$$\varepsilon_2 = (1 - a_{22})^{-1} \dot{X}^{-1} \dot{E}_{02}. \quad (\text{B.5})$$

²⁹

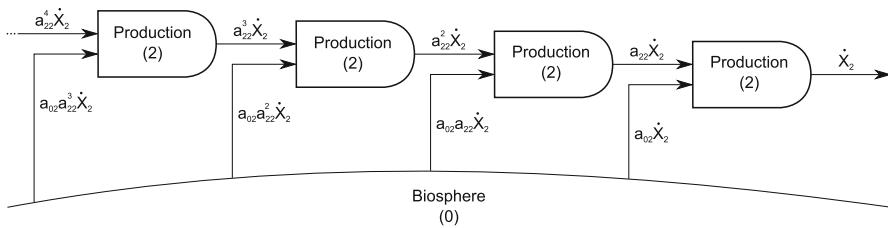


Fig. B.1 Process flows in a single-sector economy

30 Accounting for the differences between scalar and matrix equations and neglecting
31 energy flows from society to the economy ($\dot{T}_{12} = 0$), accumulation of embodied
32 energy in the economy ($\frac{dB_2}{dt} = 0$), and physical depreciation ($\gamma_{B_2} B_2 = 0$), Eq. 7.37
33 and **B.5** are identical, indicating that the EI-O approach accounts for the infinite
34 recursion of energy demand by the economy.

³⁵ **Appendix C**
³⁶ **Proof of Eq. 7.31**

We begin with a restatement of Eq. 7.31.

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

We expand the matrices to obtain

$$\begin{bmatrix} \dot{X}_{22} & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} \end{bmatrix} - \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} = \begin{bmatrix} \dot{X}_2 & 0 \\ 0 & \dot{X}_3 \end{bmatrix} \begin{bmatrix} a_{22} - 1 & a_{32} \\ a_{23} & a_{33} - 1 \end{bmatrix}. \quad (\text{C.1})$$

Subtracting and multiplying matrices gives

$$\begin{bmatrix} \dot{X}_{22} - \dot{X}_2 & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} - \dot{X}_3 \end{bmatrix} = \begin{bmatrix} \dot{X}_2 a_{22} - \dot{X}_2 & \dot{X}_2 a_{32} \\ \dot{X}_3 a_{23} & \dot{X}_3 a_{33} - \dot{X}_3 \end{bmatrix}. \quad (\text{C.2})$$

Using $\dot{X}_j a_{ij} = \dot{X}_{ij}$ (see Eq. 7.3) gives

$$\begin{bmatrix} \dot{X}_{22} - \dot{X}_2 & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} - \dot{X}_3 \end{bmatrix} = \begin{bmatrix} \dot{X}_{22} - \dot{X}_2 & \dot{X}_{32} \\ \dot{X}_{23} & \dot{X}_{33} - \dot{X}_3 \end{bmatrix} \quad (\text{C.3})$$

³⁷ to complete the proof.

³⁸ **Appendix D**
³⁹ **Estimating the Input–Output Matrix (A)**

Using Eq. 7.31, which is proved in Appendix C

$$\mathbf{X}_t^T - \hat{\mathbf{X}} = \hat{\mathbf{X}}(\mathbf{A}^T - \mathbf{I}); \quad (7.31)$$

we can derive an expression for estimating the Input–Output matrix (\mathbf{A}) given sector outputs ($\hat{\mathbf{X}}$) and the transaction matrix (\mathbf{X}_t). Premultiplying both sides of Eq. 7.31 by $\hat{\mathbf{X}}^{-1}$ gives

$$\hat{\mathbf{X}}^{-1} (\mathbf{X}_t^T - \hat{\mathbf{X}}) = \mathbf{A}^T - \mathbf{I} \quad (D.1)$$

Further rearranging gives

$$\mathbf{A}^T = \hat{\mathbf{X}}^{-1} (\mathbf{X}_t^T - \hat{\mathbf{X}}) + \mathbf{I}, \quad (D.2)$$

$$\mathbf{A}^T = \hat{\mathbf{X}}^{-1} \mathbf{X}_t^T - \hat{\mathbf{X}}^{-1} \hat{\mathbf{X}} + \mathbf{I}, \quad (D.3)$$

$$\mathbf{A}^T = \hat{\mathbf{X}}^{-1} \mathbf{X}_t^T - \mathbf{I} + \mathbf{I}, \quad (D.4)$$

$$\mathbf{A}^T = \hat{\mathbf{X}}^{-1} \mathbf{X}_t^T, \quad (D.5)$$

and

$$\mathbf{A} = \mathbf{X}_t (\hat{\mathbf{X}}^{-1})^T. \quad (D.6)$$

Both $\hat{\mathbf{X}}$ and $\hat{\mathbf{X}}^{-1}$ are diagonal matrices. Therefore, $(\hat{\mathbf{X}}^{-1})^T = \hat{\mathbf{X}}^{-1}$, and Eq. D.6 becomes

$$\mathbf{A} = \mathbf{X}_t \hat{\mathbf{X}}^{-1}. \quad (D.7)$$

Expanding the matrices of Eq. D.7 gives

$$\mathbf{A} = \begin{bmatrix} \dot{X}_{11} & \dot{X}_{12} & \dots \\ \dot{X}_{21} & \dot{X}_{22} & \dots \\ \vdots & \vdots & \ddots \end{bmatrix} \begin{bmatrix} \frac{1}{\dot{X}_1} & 0 & \dots \\ 0 & \frac{1}{\dot{X}_2} & \dots \\ \vdots & \vdots & \ddots \end{bmatrix} = \begin{bmatrix} \frac{\dot{X}_{11}}{\dot{X}_1} & \frac{\dot{X}_{12}}{\dot{X}_2} & \dots \\ \frac{\dot{X}_{21}}{\dot{X}_1} & \frac{\dot{X}_{22}}{\dot{X}_2} & \dots \\ \vdots & \vdots & \ddots \end{bmatrix}, \quad (\text{D.8})$$

as expected given the definition of the Input–Output ratio (a) in Eq. 7.3:

$$a_{ij} \equiv \frac{\dot{X}_{ij}}{\dot{X}_j}. \quad (7.3)$$

⁴⁰ Thus, Eq. D.7 provides a method of estimating the Input–Output matrix (\mathbf{A}) using
⁴¹ the transaction matrix (\mathbf{X}_t) and sector outputs ($\dot{\mathbf{X}}$).

42 **Appendix E**
 43 **Column vs. Row Vectors in Energy Intensity**
 44 **Equations**

45 In this manuscript, we choose to define energy intensity (ε) and energy input
 46 (\mathbf{E}_0 and \mathbf{T}_1) as a column vectors (see Eqs. 7.23, 7.20, and 7.21, respectively), because
 47 it natural to solve a system of equations for a column vector rather than a row vector.
 48 And, Eq. 7.17 could not be written as neatly if ε and \mathbf{E}_0 were row vectors.

49 In contrast, the EI–O literature (see, e.g., [1] and [2]) defines energy intensity
 50 and energy input as row vectors. The row vs. column difference is manifest in the
 51 appearance of the energy intensity matrix equation.

To demonstrate that our column vector formulation is equivalent to the literature's
 row vector formulation, this appendix derives a column vector version of the energy
 intensity equation that is often found in the literature. The point of comparison is
 Casler.[1] Casler's energy intensity (Eq. 6) was derived from row vectors as¹

$$\varepsilon = \mathbf{E} \hat{\mathbf{X}}^{-1} (\mathbf{I} - \mathbf{A})^{-1}. \quad (\text{E.1})$$

We begin with Eqs. 3 and 4 from Casler [1], converted to overdot notation for rates.

$$\varepsilon_1 \dot{X}_{11} + \varepsilon_2 \dot{X}_{21} = \varepsilon_1 \dot{X}_1 \quad (\text{E.2})$$

$$\varepsilon_1 \dot{X}_{12} + \varepsilon_2 \dot{X}_{22} + \dot{E}_{02} = \varepsilon_2 \dot{X}_2 \quad (\text{E.3})$$

Adding an \dot{E}_{01} term² and utilizing matrix notation with column vectors (instead of
 row vectors) gives

$$\begin{bmatrix} \dot{X}_{11} & \dot{X}_{21} \\ \dot{X}_{12} & \dot{X}_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \quad (\text{E.4})$$

¹ Equation E.1 is written according to the variable conventions in this manuscript. The literal Eq. 6 in Casler [1] is $\varepsilon = \mathbf{E} \hat{\mathbf{X}}^{-1} (\mathbf{I} - \mathbf{A})^{-1}$.

² Note that $\dot{E}_{01} = 0$ for Casler [1], so \dot{E}_{01} can be included without changing Eq. E.2.

Substituting $\dot{X}_{ij} = a_{ij}\dot{X}_j$ (from Eq. 7.3) gives

$$\begin{bmatrix} a_{11}\dot{X}_1 & a_{21}\dot{X}_1 \\ a_{12}\dot{X}_2 & a_{22}\dot{X}_2 \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \quad (\text{E.5})$$

Expanding Eq. E.5 gives

$$\begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{bmatrix} a_{11} & a_{21} \\ a_{12} & a_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix} + \begin{Bmatrix} \dot{E}_{01} \\ \dot{E}_{02} \end{Bmatrix} = \begin{bmatrix} \dot{X}_1 & 0 \\ 0 & \dot{X}_2 \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{Bmatrix}. \quad (\text{E.6})$$

With the definitions of $\hat{\mathbf{X}}$, \mathbf{A} , $\boldsymbol{\varepsilon}$, and \mathbf{E}_0 from Equations 7.25, 7.30, 7.20, and 7.23, respectively, we can rewrite Eq. E.6 as

$$\hat{\mathbf{X}}\mathbf{A}^T\boldsymbol{\varepsilon} + \mathbf{E}_0 = \hat{\mathbf{X}}\boldsymbol{\varepsilon}. \quad (\text{E.7})$$

Solving for $\boldsymbol{\varepsilon}$ gives

$$\boldsymbol{\varepsilon} = (\mathbf{I} - \mathbf{A}^T)^{-1}\hat{\mathbf{X}}^{-1}\mathbf{E}_0. \quad (\text{E.8})$$

52 The differences between Eqs. E.1 and E.8 are due to the choice of row vectors (for
 53 Eq. E.1) or column vectors (for Eq. E.8) only. Note that Eq. E.8 is similar to Eq. 7.37.
 54 A detailed discussion of the differences between Eqs. E.8 and 7.37 can be found in
 55 Sect. 8.2.

56 If we apply our minds directly and competently to the needs of the earth, then we will have
 57 begun to make fundamental and necessary changes in our minds. We will begin to understand
 58 and to mistrust and to change our wasteful economy, which markets not just the produce
 59 of the earth, but also the earth's ability to produce. We will see that beauty and utility are
 60 alike dependent upon the health of the world. But we will also see through the fads and the
 61 fashions of protest. We will see that war and oppression and pollution are not separate issues,
 62 but are aspects of the same issue. Amid the outcries for the liberation of this group or that,
 63 we will know that no person is free except in the freedom of other persons, and that man's
 64 only real freedom is to know and faithfully occupy his place—a much humbler place than
 65 we have been taught to think—in the order of creation.

66 —Wendell Berry. 2002. *The Art of the Commonplace: The Agrarian Essays*.
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73 Glossary

74	ATP	Adenosine Triphosphate
75	BEA	Bureau of Economic Analysis, US Department of Commerce (http://www.bea.gov)
76	CES	Constant Elasticity of Substitution
77	DEC	Direct Energy Conversion
78	EIA	Energy Information Administration
79	EI-O	Energy Input-Output
80	EIOLCA	Economic Input-Output Life Cycle Assessment (http://www.eiolca.net)
81	EROI	Energy Return on (Energy) Invested
82	EW-MFA	Economy-Wide Materials Flow Accounts
83	GDP	Gross Domestic Product
84	GER	Gross Energy Ratio
85	GHG	Greenhouse Gas
86	IE	Industrial Ecology
87	IEA	International Energy Agency
88	IEESA	Integrated Environmental-Economic System of Accounts
89	I-O	Input-Output
90	IRP	International Resource Panel
91	KLEMS	Capital (K), Labor (L), Energy (E), Materials (M), and Services (S)
92	LCA	Life Cycle Assessment
93	LINEX	LINear Exponential
94	MFA	Material Flow Analysis
95	NAICS	North American Industry Classification System
96	NEA	Net Energy Analysis
97	OICA	International Organization of Motor Vehicle Manufacturers
98	OPEC	Organization of the Petroleum Exporting Countries
99	PI-O	Physical Input-Output
100	SEEA	System of Environmental-Economic Accounting
101	SNA	Systems of National Accounts
102	UK	United Kingdom
103	UN	United Nations
104	UNEP	United Nations Environmental Programme
105	US	United States

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Index

A

- Accumulation
 - of apples, 48–50
 - of capital, 57, 158, 163
 - of direct energy, 79, 82, 92, 96, 134
 - of economic factors, 131
 - of economic value, 40
 - of embodied energy, 32, 93, 104, 132, 158, 161, 178
 - of goods, 54, 59
 - of materials, 39, 47, 74, 97, 131
 - of natural capital, 30, 56
 - of natural resources, 58
 - of resources, 5
 - of short-lived capital, 67
 - of total energy, 100, 101
- Anabolism, 34
- Autophagy, 34, 35, 38

B

- Best-First Principle, 12–14, 24, 30, 56, 98
- Biomass energy, 84, 130
- Biomass stock, 152
- Biophysical, 3–7, 10–12, 18, 19, 37–39, 56, 115, 125, 164, 170
- Biosphere, 3, 5, 7, 10–13, 15–20, 24–28, 30–32, 34, 37, 38, 40, 46, 47, 50–57, 59, 61, 63, 66, 69–72, 80, 82, 84, 85, 91, 92, 94, 96, 97, 104, 113, 115, 117–119, 125, 129, 134, 135, 138–141, 149, 151, 158, 161–166
- Boulding, Kenneth, 3
- Bullard, Clark, 128, 132, 142, 152–154
- Bureau of Economic Analysis (BEA), 122, 124, 125, 142, 152, 153, 169, 170

C

- Capital depreciation, 54
- Capital goods, 50–55, 57, 59, 61–63, 67, 71, 72, 92, 115
- Catabolism, 34, 35
- CES, 25, 29
- China, 1, 5
- Chemical energy, 90
- Clockwork metaphor. *See* Metaphor: clockwork
- Clockwork universe, 25
- Co-products, 130
- Coal, 4, 25, 35, 40, 52, 55, 78, 79, 82, 90, 92
- Cobb-Douglas, 3, 25, 28
- Congressional Budget Office, 1
- Control volume, 32, 48–50, 73, 78, 156, 169
- Cuba, 35

D

- Daly, Herman, 3, 112, 152, 154, 164
- DEC method. *See* Direct energy conversion
- Development
 - economic, 163
- Depreciation, 50, 52, 57–59, 63, 64, 69, 70, 94, 98, 101, 103, 104, 118, 138, 149, 154, 155, 156, 160, 161, 163–165, 178
- capital. *See* Capital depreciation
- financial. *See* Financial depreciation
- embodied energy. *See* Embodied energy
 - depreciation
 - physical. *See* Physical depreciation
- Direct (DIRECT) method, 140–142
- Direct energy conversion, 140–142
- Direct energy
 - flow-through of, 81, 83, 86

E

- Economic development, 163

- Economic value, 39, 40, 48, 50, 71, 78, 111–115, 118, 122, 124, 125, 129–131
- Economic value
destruction of, 50, 114
flow of, 114
- Ecosphere, 46
- Economy
agrarian, 61, 157
developing, 37, 157
- EI-O. *See* Energy input-output
- Elasticity of substitution, 15, 25, 29
- Embodied energy
depreciation of, 94, 97
- Emergy, 90, 112, 130
- Emjoule, 90
- Embargo
oil, 24, 27, 162
- Energy
biomass. *See* Biomass energy
chemical. *See* Chemical energy
direct. *See* Direct energy
embodied. *See* Embodied energy
gravitational. *See* Gravitational energy
hydro. *See* Hydro energy
kinetic. *See* Kinetic energy
nuclear. *See* Nuclear energy
ocean thermal. *See* Ocean thermal energy
renewable. *See* Renewable energy
solar. *See* Solar energy
solar thermal. *See* Solar thermal energy
thermal. *See* Thermal energy
total. *See* Total energy
- Energy input-output (EI-O), 32, 73, 92, 128, 129
- Energy intensity, 127–143
- Energy resources, 7, 12, 13, 15, 27, 28, 30, 51, 55, 78, 84, 90, 161, 166
- Energy return on investment, 13, 32, 38, 84
- Energy theory of value, 112, 131, 132, 150
- EROI. *See* Energy return on investment
- Evolution, 32, 124, 125
- Exergy, 29, 56, 77, 78, 129
- F**
- Financial depreciation, 16, 97
- First Law of Thermodynamics, 50, 78, 80, 82, 85, 92–94, 97, 100, 103
- Fossil fuel, 27, 30, 56, 129, 140
- Free cash flow, 15, 16
- G**
- Gas
natural, 4, 11, 15, 35, 52, 67, 72, 79, 82
- Georgescu-Roegen, 31, 51, 131
- Government sector, 93, 139
- Gravitational energy, 78
- Great Recession, 3, 7, 24, 73
- Gross domestic product (GDP), 1, 11, 112, 118, 159, 165
- Gross energy ratio (GER), 84
- H**
- Herendeen, Robert, 132, 140–142, 152–154
- Household sector, 25
- Hydro energy, 15, 130
- I**
- IEESA, 114, 170
- Implicit theory of value, 153
- India, 1
- Input-output (I-O)
energy. *See* Energy input-output (EI-O)
matrix, 137, 138, 153
method, 32, 71, 73, 129
physical, 73
ratio, 133, 134, 138, 182
tables, 73, 122
- Integrated Environmental-Economic System of Accounts. *See* IEESA
- K**
- Kinetic energy, 78
- Kleiber's Law, 36, 37
- L**
- Lake Erie, 5
- Leontief, Wassily, 127
- LINEX, 29
- London, 25
- M**
- Machine metaphor. *See* Metaphor: machine
- Materials
quality of, 56
- Matrix
input-output. *See* Input-output (I-O): matrix transaction. *See* Transaction matrix
- Metabolism metaphor. *See* Metaphor: metabolism
- Metaphor
clockwork, 25–27, 31, 32, 128
machine, 24, 28–30, 129
metabolism, 32, 34, 36–40
- Metamorphosis, 32
- Metabolism metaphor, 32, 34, 36–40
- Minerals, 32, 118
- Model

- traditional, 25–27, 31, 32, 128
engine, 28–31, 129
- N**
NAICS. *See* North American Industry Classification System
Natural resources, 6, 24, 26, 27, 30, 47, 58, 59, 64, 70, 112, 113, 118, 159, 163–165
NEA. *See* Net energy analysis
Net energy analysis, 32, 129
Newtonian physics, 25, 27
Nigeria, 6
North American Industry Classification System, 57, 87, 143
Nuclear energy, 14, 78
- O**
Ocean thermal energy, 130
OECD, 1, 11, 38, 57, 113
Organisation for Economic Co-operation and Development. *See* OECD
- P**
Photovoltaic, 14, 130
Physical depreciation, 16, 50, 97, 138, 178
Physical Input-Output (PI-O), 73
Price elasticity of supply, 10
Production function
 LINEX. *See* LINEX
 Cobb-Douglas. *See* Cobb-Douglas
 constant elasticity of substitution. *See* CES
Puberty, 32
- R**
Renewable energy, 39, 130
Resources, 5–7, 12–15, 17, 19, 20, 25, 27, 28, 32, 33, 35, 50–59, 61, 62, 66, 67, 71–73, 84, 90, 96–98, 112, 113, 118, 122, 133–135, 155, 160–162, 164–166
 natural. *See* Natural resources
Resource quality, 84, 98, 130
Russia, 6
- S**
Saudi Arabia, 6
Second Law of Thermodynamics, 30
SEEA, 39, 113, 114
Solar Energy, 84, 90, 112, 118, 129, 130
Solar thermal energy, 130
Steam, 3, 78
Strategic Petroleum Reserve, 82
South Africa, 6
Subjective theory of value, 111–114, 117, 118, 125
SNA, 5, 29, 39, 113
System of Environmental-Economic Accounts.
 See SEEA
System of National Accounts. *See* SNA
Theory of value
 energy. *See* Energy theory of value
 implicit. *See* Implicit theory of value
 subjective. *See* Subjective theory of value
- T**
Thermal energy, 50, 78, 80
Thermodynamics, 40, 162
 First Law of. *See* First Law of Thermodynamics
 Second Law of. *See* Second Law of Thermodynamics
Total energy, 11, 55, 87, 91–104, 132–135, 138, 139
Transaction matrix, 138
- V**
Value
 theory of. *See* Theory of value
Venezuela, 6
- W**
Waste, 5, 14, 31, 34, 35, 49, 52, 54, 55, 70, 80, 92, 96, 101, 118, 139, 155–158, 161, 165, 170
World Energy Outlook, 29
- Y**
Yank tanks, 35, 36

Author Query

Chapter 1

AQ1 Author: Please check whether the edits made in the sentence “This predilection results...pursuit of income.” retain your intended sense.

Chapter 2

AQ1 Please provide the publishers' main locations for the following references: “Ref. [1, 6, 9, 11, 31, 34, 35, 40, 44]”.

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Chapter 3

AQ1 Please provide the significance of “?” in the sentence “is there a flow of resources . . . ”.

AQ2 Please provide the publishers' main locations for the following references: Ref. “[7, 10, 11]”.

Chapter 6

AQ1 Please try rephrasing the text “assess the biophysical reality...” for clarity.

AQ2 Please provide the publishers' main locations for the following references: “[3] and [4]”.

Chapter 7

AQ1 Please provide the publishers' main locations for the following references: “[10]”, “[19]”, and “[22]”.

Chapter 8

AQ1 We have changed the word “ambodied” to “embodied” in the abstract. please check and confirm.

- AQ2 We have inserted the full form of the abbreviation “BEA”. Please check and confirm.
- AQ3 Please provide access dates for the following references: “[1]”, “[14]”, “[17]” and “[19]”.
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