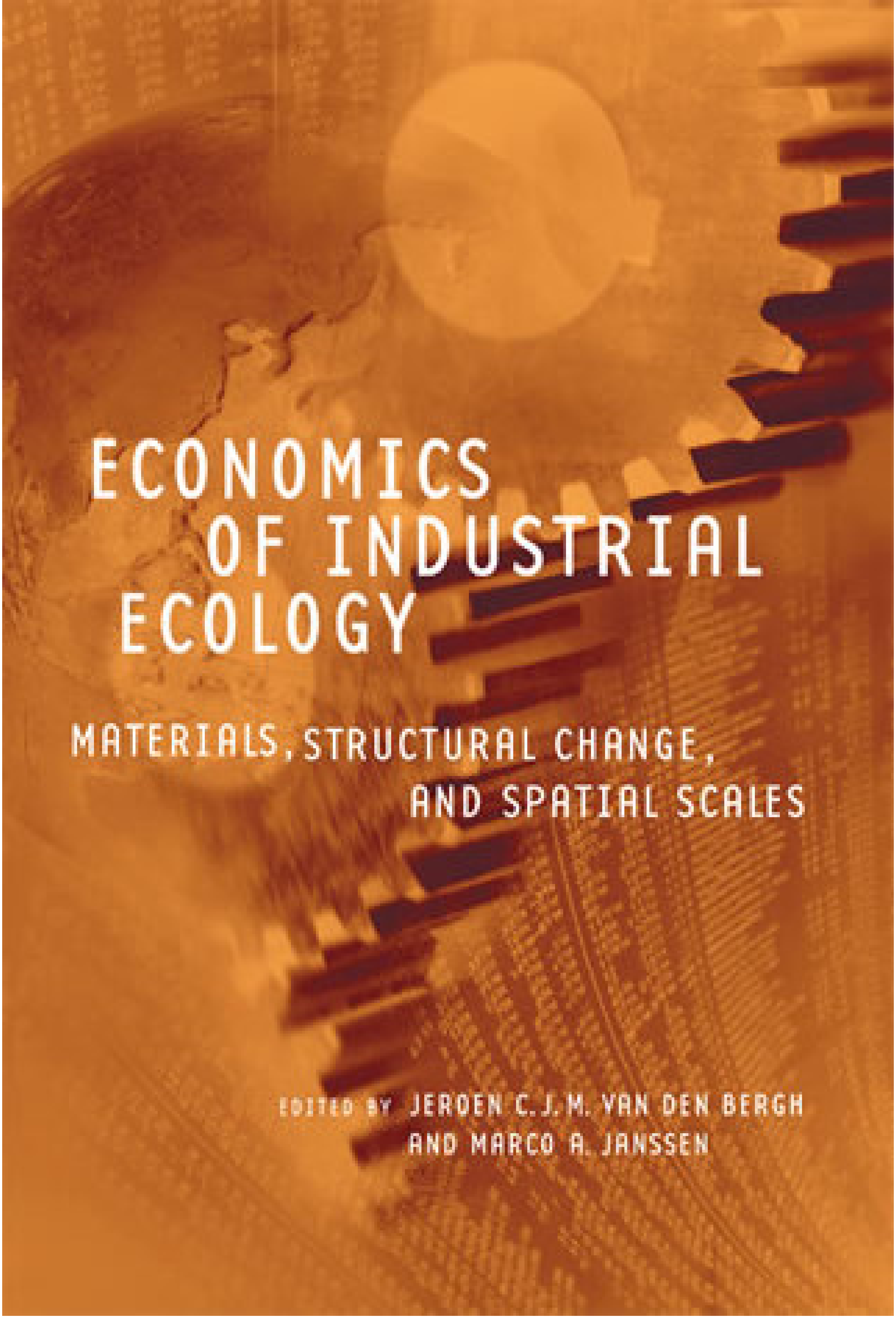

ECONOMICS OF INDUSTRIAL ECOLOGY

MATERIALS, STRUCTURAL CHANGE, AND SPATIAL SCALES

EDITED BY JEROEN C.J.M. VAN DEN BERGH
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6 Modeling Physical Realities at the Whole Economy Scale

Barney Foran and Franzi Poldy

6.1 Introduction

6.1.1 The Physical Economy

Although this chapter is primarily a description of physical economy modeling in Australia, it also acts as a bridge between the more focused ideals of industrial ecology and broader concepts such as the dynamics and resilience of socioeconomic and ecological systems. Without such a bridge, broad implementation of industrial ecology could languish between scales of space and time. Regional applications of industrial ecology need to pervade and then saturate a whole national economy before material and energy flows moderate and then begin to decline. Models of the physical economy can test the physical feasibility of industrial ecology concepts and whether they have sufficient strength and importance to stimulate structural change in the economic system and the material transactions that underpin it. The main issue is that the key elements of a nation's stocks of infrastructure have to change before the flows driven by those stocks change substantially. National stocks, such as houses, vehicles, and electricity generators, are typified by their size, age, and location. Implementing industrial ecology nationally requires that the stocks of infrastructure and the linkages among them are turned over in unison, in sympathy with some grand plan over time scales that span human generations. Physical economy models can help design and test the grand plan, but implementation is another matter.

The complexity of socioeconomic systems makes it unlikely that technological progress alone will force an economy-wide implementation of industrial ecology. To understand this complexity, Holling (2001) suggests that an analytical framework be as simple as possible (but no simpler), be dynamic and prescriptive (rather than static and descriptive), and embrace uncertainty and unpredictability. He further suggests that human systems are distinguished from natural systems by having foresight and intentionality, communicating and storing experience and using technology to amplify the effect of management actions. If the development of resilience in socioeconomic systems is seen as a necessary attribute and one of the driving rationales to implement industrial ecology, for example, then Carpenter et al. (2001) stress the importance of time scales and of separating and understanding slow- and fast-moving variables. In their context, the slow-moving variables define the underlying structure of the system (e.g., stocks of infrastructure in a modern economy), whereas the fast-moving variables, such as production values or pollutant flows, depend in turn on the dynamics of the underlying structure. These broader philosophies of complexity science and resilience science help define some characteristics of physical economy models that are useful in designing the implementation of industrial ecology. Such models should be reasonably simple, dynamic, and prescriptive, track information flows, and focus on slow-moving variables that act as controlling variables of the whole socioeconomic system.

In implementing these concepts at a more practical level, Ayres (1998a) makes the case for more measurement and modeling of the physical economy for two reasons. The first is that national decisions are generally guided by computable generalized equilibrium (CGE) models, which seldom recognize the material and energy flows on which the function of the socioeconomic system is based. The second is that national accounting procedures generally ignore hidden flows such as the removal of mine overburden, since little economic value is derived from them. The volume of visible and hidden material flows is increasing in line with economic growth and development. Prior to the Industrial Revolution, the volume of material flow was inconsequential relative to the assimilation capacity of natural ecosystems. However, von Weizsäcker (1998) notes that material flows induced by humans now compare with large-scale global processes and that it is unlikely that they can continue to grow exponentially forever. This realization has led to the concept of "ecological rucksacks" intended to increase awareness of hidden material flows behind products, and to the concept of a Factor Four and a Factor Ten economy, in which economy-wide reductions in material and energy flows are implemented. The ability to foresee the requirements for dematerialization at an economy-wide level, as well as the design and implementation of pathways for individual processes, creates the niche where models of the physical economy become useful to the concepts of industrial ecology.

This chapter describes the design and implementation of two physical economy models in Australia.

6.1.2 Physical Economy Models in Australia

The development of physical economy modeling in Australia was stimulated by the national population debate within the context of long-term sustainability issues. The concepts of population targets and carrying capacity have a long history in Australia, starting in the 1920s, when a Sydney university geographer, Thomas Griffith Taylor, set Australia's estimated carrying capacity at sixty-five million people and later reduced this estimate to twenty million people (Cocks 1996). During the 1980s and 1990s there were several national inquiries on population, the most recent of which was the Jones Inquiry (Long-Term Strategies Committee 1994), which stopped short of recommending a national population policy (Cocks 1996). By default, Australia's population seems to be moving toward a more or less stable population of twenty-three to twenty-five million people in one to two human generations' time. During the 1990s, the national population debate evolved to include a wide range of linked issues, such as resilience of ecological systems, material consumption levels, and changes to the structure and function of the economic system.

It was against this background that the Commonwealth Scientific & Industrial Research Organization (CSIRO), a national science agency, initiated a strategic project to underpin the population debate, and its linkages to resource use and environmental quality, with scientific analysis. The project's initial aim was to focus on the environmental aspects of population impact with particular emphasis on the quality and quantity aspects of water, soils, biodiversity, atmosphere, and natural amenity. Initially, the work proceeded along a traditional scientific route, in which plans were made to examine the effect of population on water resources, land resources, and so on. However, because of the complex linkages among all sectors of society and the economy, the traditional approach of defining tight boundaries around a well-defined problem prior to analysis was judged difficult to implement. In addition, the project faced the challenge of tackling a future-oriented and long-term topic that required integrated advice and a range of possible solutions. At this point in the project, the project members became aware of two important methodological approaches. The first involved Godet's (1991) work on *strategic prospectives* and thence the use of foresighting and scenario development by multinational companies such as Royal Dutch Shell. The second was the implementation of population-development-environment simulators (particularly the work by the International Institute for Applied Systems Analysis [IIASA] in Mauritius) (Lutz 1994), the physical analysis paradigm using the design approach (Gault et al. 1987), and the embodied energy approach of Slesser (1992; Slesser, King, and Crane 1997) and colleagues.

The project design then evolved to the development of new designs for the socioeconomic system, in order to lessen the effect of humans on resource depletion and environmental quality. The first theme of work was the development of a number of robust and well-documented national scenarios to lead and inform debate on national development and sustainability issues. Three scenarios, *economic growth, conservative development*, and *postmaterialism*, were published as part of a book that arose out of the project (Cocks 1999). The second theme of work developed to underpin the scenario work with physical economy analyses. Within this theme, two system simulators were developed based on different paradigms of physical analysis. One of these, OzEcco (Foran and Crane 1998), used the embodied energy approach of Slesser (1992; Slesser, King, and Crane 1997) to construct a top-down and aggregated simulator of Australia's physical economy. This analytical approach assumed that the delivery of goods and services to a domestic economy is a function of the extraction, delivery, and efficiency of use of energy resources, most of which are derived from fossil sources.

The second simulator, the Australian Stocks and Flows Framework (ASFF), was a disaggregated set of linked models that access a database describing the last fifty years of Australia's physical function or physical metabolism. The *design* approach used by the ASFF is philosophically attractive for two reasons. First, it treats the complete range of physical function as separate entities (crops, animals, people, cars, steel production, chemical production) and allows a detailed treatment of vintaging or age for most big-ticket items of physical infrastructure. Secondly, the physical functioning is retained within the modeling code and termed "machine space." The management and policy decisions that guide this physical functioning are retained as part of a scenario under development and testing by the user or policy analyst and are termed "control space." Gault et al. (1987) describe the design approach as follows:

> The design approach is a philosophy for building computer-based simulation frameworks, which represent socio-economic systems, and for using the simulation framework to design alternative futures through repeated simulation. It is the exploration of alternative futures by the user, who forms part of the system, which

> distinguishes this approach from that of macro-economics with its emphasis on prediction. The exploration and the involvement of the user result from the absence of optimisation or equilibrating mechanisms in the physical representation of the socio-economic system. This ensures that the user, working alone or with the aid of a model of decision processes, controls the system. The policy decisions necessary to exercising this control are required to be explicitly stated, and they form a record of how the future, resulting from the simulation, was arrived at. (23–24)

In section 6.2, the physical economy simulators will be described in more detail. Section 6.3 will give some current examples of model use within policy and science processes. Section 6.4 will describe some challenges for analytical approaches in achieving their goal of influencing national policy. The chapter will conclude with some insights in section 6.5 into the many conundrums that face integrative modeling of the physical economy in implementing concepts such as industrial ecology.

6.2 Model Descriptions

6.2.1 The OzEcco Embodied Energy Model

The OzEcco model is designed to integrate the driving forces of population, lifestyle, organization, and technology and to explore their possible impacts on environmental loadings. It is a systems dynamics representation of Australia's metabolism, based on the philosophy of embodied energy analysis. This analysis evolved from the integration of financial input-output tables (Leontief 1970; Rose and Miernyk 1989), with national physical accounts, such as those for energy (Herendeen 1998). Slow-moving variables such as capital stocks are expressed as a physical measure in petajoules of embodied energy rather than in monetary terms. Fast-moving variables have been expressed as energy flows, again in petajoules per year rather than dollars per year. In this way economic activity has been transformed into physical activity, which is consistent with the first and second law of thermodynamics. All economic transactions are thus represented by the physical transformations that underpin them. This simplification is consistent with the slow-moving variables that determine the rates of growth and development of any modern economy.

Conceptually the OzEcco model has five broad components: natural resource stocks, the energy transformation sectors, consumption activities, pollution generation, and whole system indicators. The core modeling concept is that access to and transformation of energy (typically

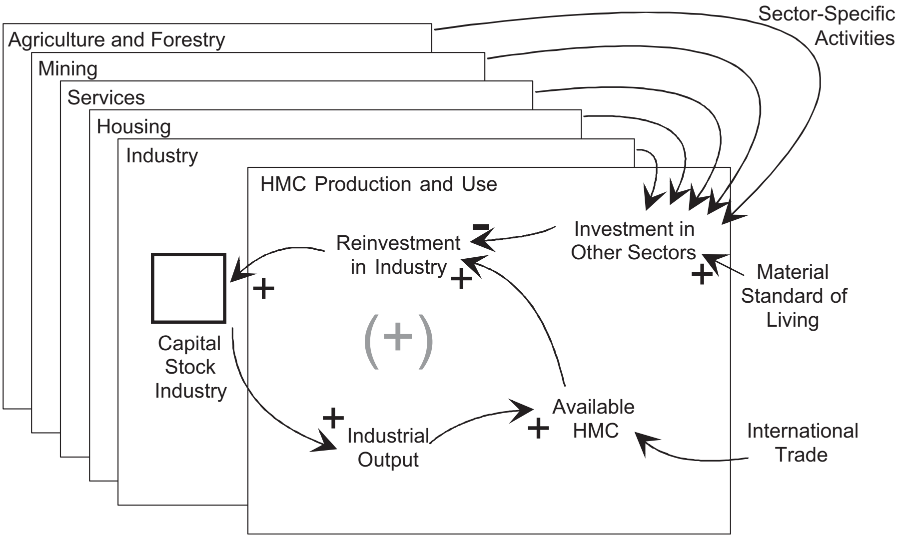

Figure 6.1
A diagram of the central growth-determining loop in the OzEcco model, with the aggregated industrial sector depicted here as the core resource on which growth depends. The processes of fixed and human-made capital (HMC in the diagram) are depicted as an influence diagram, illustrating the main causative features represented in the model. The total human-made capital available is the sum of imports and domestic production.

stocks of fossil fuel) are the determinants of physical growth in a modern industrial economy. Thus all goods and services are expressed in terms of the chain of energy processes that eventually become included (embodied) in a final good (a motor car) or a service (banking or education). Some sectors, such as domestic housing, act as long-term accumulators of fixed energy capital (embodied energy), whereas personal consumption dissipates embodied energy relatively quickly. The concept is shown in figure 6.1. The capital stock of industry (stock of embodied energy) is the primary focus through which human-made capital is created. Industry contributes to other sectors such as agriculture (fertilizer, machines) and domestic housing (bricks, carpets, stoves).

The rate at which the aggregated industrial sector can grow in any one year is limited by its contribution to other sectors of the physical economy and the consumption activities of the population at large. Both of these activities (industrial growth and personal consumption) act as negative feedbacks to restrict the rate at which the physical economy may grow. The effects of international trade and financial flows can be either positive or negative. Exports are classified as a negative drain on the amount of embodied energy available nationally. Physical imports and monetary inflows are positive additions, because they increase the capability to provide physical transactions and services. All of these factors are linked in a systems dynamics framework (Richardson and Pugh 1981). The simulated economy has an endogenous growth mechanism constrained by the availability of renewable and nonrenewable energy and by the need to maintain national infrastructure with personal consumption activities. Global financial issues, such as the balance of payments and international debt, are regarded as flows and stocks of virtual embodied energy that, in the short term, help overcome resource and infrastructure issues limiting the expansion of the physical economy.

To date, acceptance of the OzEcco approach by both the science and the policy community is restricted. The use of integrating concepts such as "embodied energy" is limited by the background of policy analysts, although embodied energy is similar to money as a numeriare for economic analysis. However, two recent developments in energy and greenhouse policy have increased the potential acceptability of this approach. Using input-output tables to compute energy embodiment for different economic sectors and to highlight energy use and greenhouse gas emissions (Lenzen 1998) is gaining general acceptance. There is also interest in simulations of a methanol economy based on biomass (Foran and Mardon 1999).

6.2.2 The Australian Stocks and Flows Framework

6.2.2.1 General Description ASFF is a highly disaggregated simulation framework that keeps track of all physically significant stocks and flows in the Australian socioeconomic system. In this context, stocks include people, livestock, trees, buildings, vehicles, capital machinery, infrastructure, land, air, water, energy, and mineral resources—disaggregated, as appropriate, according to their physical characteristics and, importantly, age or vintage. Flows, resulting from physical processes of many kinds, represent the rates of change of stocks and constitute the development of the system in more or less desirable directions. In the context of this chapter, ASFF is a nationally scaled framework that provides both a database and a simulation model in which industrial ecology concepts can be tested.

The simulation model consists of thirty-two hierarchically connected modules or calculators, which account for the physical processes of demography, consumption, buildings, transport, construction, manufacturing, energy supply, agriculture, forestry, fishing, mining, land, water and air resources, and international trade. Each calculator deals with the stocks and flows relevant to a sector and with the physical processes through which they interact.

Calculator assumptions are based on the technical and scientific understanding of the processes involved and are intended to provide a plausible representation in physical terms of the workings of the sector concerned. Indeed, it is a criterion of validity for the calculator that a professionally informed person should be able to follow the structure of the representation and conclude that it and the values of the parameters are plausible and appropriate to the level of aggregation of the treatment.

An overview of the whole framework is given in figure 6.2, in which the arrows link calculators arranged in functionally similar and hierarchically related groups (note that the arrows do not represent sector linkages or information flows; these are shown in figure 6.3).

6.2.2.2 The Model Calculators In figure 6.2, the unshaded boxes with heavy borders represent hierarchical groupings and the shaded boxes represent calculators. At the highest level, the Australian socioeconomic system is conceived of in terms of people (Demography) and the physical needs of their way of life (Materials and Energy). Population is an important driver in the framework, and other things being equal, more people require more materials and energy. However, other things are not necessarily equal, and one of the goals of the ASFF approach is to explore the interplay and trade-offs among issues such as population, affluence, institutional organization, and technological innovation.

The five Demography calculators account for various population issues, including overseas and internal migration. These calculators also transfer information to other calculators that depend directly on population and its distribution over age, sex, and location, such as education, morbidity and health requirements, internal travel, household formation, labor force participation, demand for personal services, and inbound tourism. Population and inbound-tourist numbers are independent drivers in the framework. The parameters that determine their level and growth are specified exogenously outside the model in the control space. Information from these demography calculators is passed to later calculators and used to determine the requirements for infrastructure, goods, and services of all types.

The Consumables calculator determines the need for food and other consumable items directly from population (including overseas visitors)

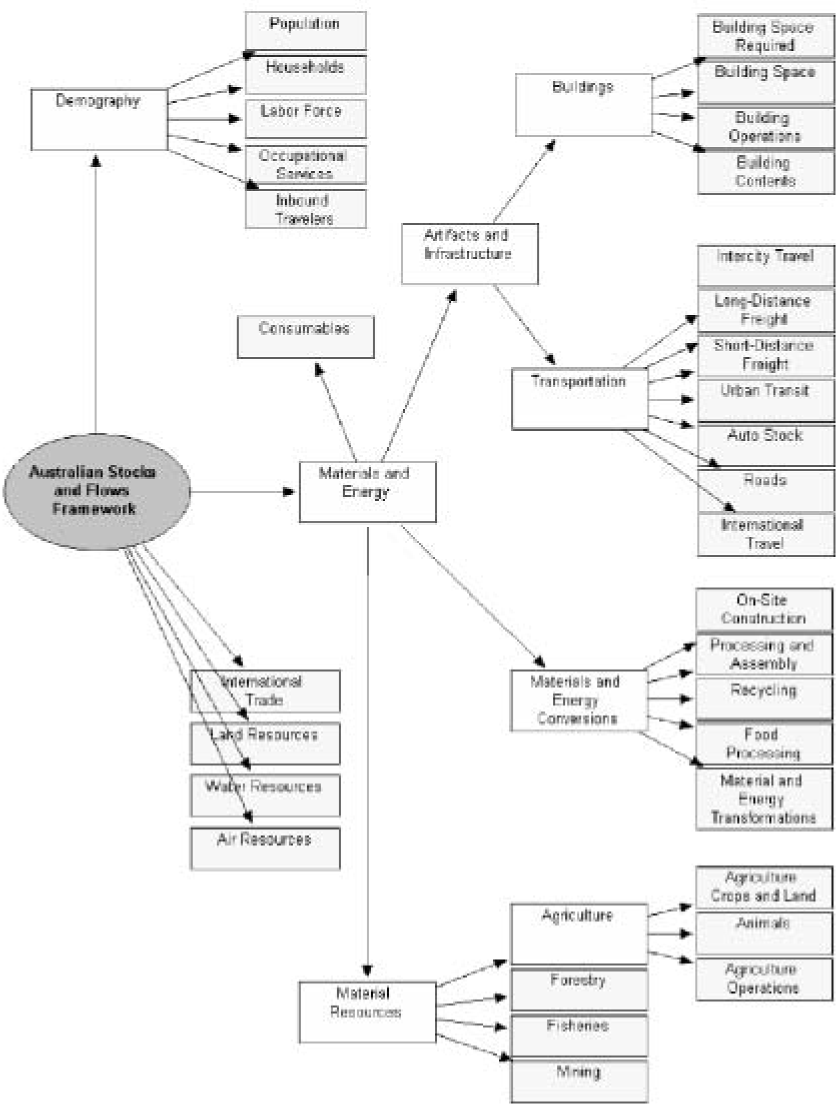

Figure 6.2
Hierarchy of calculators in the Australian Stocks and Flows Framework. (See figure 6.3 for information flow among calculators.)

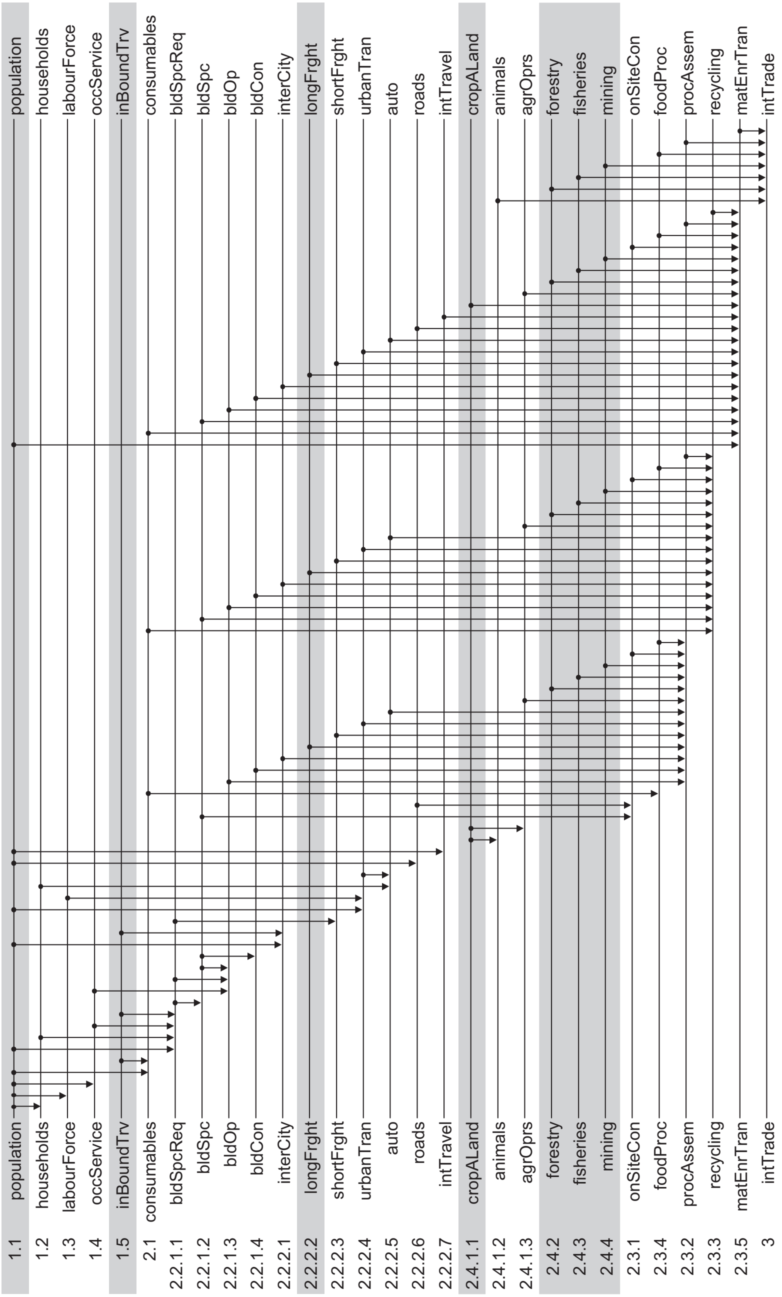

Figure 6.3
One-way information flow (vertical arrows) among calculators (horizontal lines) of the Australian Stocks and Flows Framework. Shaded calculators receive only exogenous input (no arrowheads on shaded lines).

on a per capita basis. The four Buildings calculators use information from demography to determine the needs of the population for residential, commercial, educational, health care, and institutional buildings.

Seven calculators deal with various aspects of Transportation. Broadly, these cover domestic passenger and freight transport in urban and rural areas. Separate calculators deal with the car fleet, roads and their maintenance, and fuel for international travel. In most cases, a transport task is determined in relation to demographic parameters, and with the help of load factors and average yearly distance traveled, the task is translated into a need for vehicles. The Material Resources calculators describe production processes in the country's primary industries: agriculture, forestry, fisheries, and mining. Like population, tourism, and long-distance freight, these industries are independent drivers in the framework and receive no information from earlier calculators. Their planned levels of production are specified exogenously, because much of the produce from Australian primary industries is destined for export.

Agriculture is covered by three calculators, which deal with crops and land, livestock, and agricultural operations in each statistical division. Cropping deals with the areas of land devoted to each of ten different crops (or land may remain fallow or idle), the impact of cropping activity on four indicators of soil quality (acidity, dryland salinity, irrigation salinity, and soil structure), and the effect on yield of genetic improvements to crop varieties, of the application of fertilizer and irrigation, and of declining soil quality due to the cumulative effects of previous cropping. The Animals calculator deals, in each statistical division, with the stocks of animals of different types, the quantities of animal products they yield, and their feed requirements in terms of crops and area of grazing land.

The Forestry calculator deals with fifteen different types of forest, managed under regimes that vary from full protection to clear cutting and managed plantations. Fire frequency and tree growth and survival rates are taken into account. Inventories are kept of land areas and of tree numbers and wood volumes by age. The Fisheries calculator deals with both wild fishing and fish farming. Wild fish stocks vary in response to their own natural rates of reproduction and mortality—and to the level of fishing. Each fishery can sustain some moderate level of fishing, but if overfished, the stock collapses to levels at which catch per unit effort no longer warrants fishing. Fishing effort is allocated among fisheries in an attempt to meet planned production levels with minimum effort.

The Mining calculator covers exploration for mineral and energy resources, evaluation and classification of resources as reserves, and extraction of minerals and energy materials to meet planned production. "Resources ever found" are the current estimate of the nation's total endowment of a material. Unless augmented by new discoveries, cumulative production will never exceed this quantity. The Materials and Energy Conversions group of calculators covers construction, manufacturing, and energy supply. These calculators deal with the need for materials, energy, goods, and infrastructure identified in earlier calculators. The Processing and Assembly calculator consolidates the requirements for vehicles, machinery, building contents, and operating goods of all types from previous calculators and, allowing for imports and exports, determines the level of domestic production of these goods. The Recycling calculator consolidates all discarded goods, vehicles, and machinery and determines the proportions to be recycled or disposed of to landfill. The material content of the recycled fraction is determined from a knowledge of the material composition and vintage of the goods and vehicles. The Material and Energy Transformations calculator ensures that the needs of the whole economy for materials and energy are met.

The International Trade Balance calculator consolidates domestic production and domestic requirements for primary materials, secondary materials, vehicles and machinery, and intermediate and final demand goods and determines import and export quantities. These are combined with a set of import and export prices and an interest rate to determine the value of the trade flows, the current merchandise trade balance in nominal dollar terms, and its contribution to the international debt (or surplus), again in nominal dollar terms. Finally, the Land Resources, Water Resources, and Air Resources calculators consolidate information from the whole framework into accounts which provide an overview of the state of these important resources.

The framework is grounded in a database for a fifty-year historical period which is complete (all data gaps are filled) and in which variables are consistent with one another and with the assumptions in the calculators. These assumptions are based on technical and scientific understanding of all the processes required to describe the physical stocks and flows underlying the Australian socioeconomic system. At the basic level, this ensures that fundamental requirements, such as the conservation of matter and energy and the laws of thermodynamics, are observed. For particular calculators, the assumptions must be consistent with a relevant specialist's understanding of the processes involved.

The process of model validation is a variant of normal model calibration procedures. Essentially, validation is based on reconciling stocks (people, houses, cars) with the flows (births and deaths, electricity use, petrol use) that are derived from those stocks. It can be seen as the application of accounting principles across many dimensions in which a number of more robust national data series over fifty-year time frames (total population, total primary energy use) set constraints and reality checks for the operation of all thirty-two submodels. Any important irregularities in sets of nested output variables (people, per capita car ownership, car numbers, per car gasoline use, total gasoline use) is traced back and adjusted until the fifty-year historical foundation of the model has real data and modeled data in close agreement. For future scenarios, the control variables from history are used as reasonable guides for assumptions about future trajectories out to 2050 or 2100.

6.2.2.3 Calculator Linkage, Feedback, and Tensions The calculation linkages are shown in figure 6.3, in which arrows flow downward only, indicating that feedbacks caused by demand and supply imbalances are controlled by the user, who separates control space from design space. In order to calculate the quantities demanded within the physical economy, the population calculator (1.1 in figure 6.3) passes down

- the requirements for households (1.2) through an age- and sex-determined household formation rate);
- the availability of a labor force (1.3) through an age- and sex-determined participation rate;
- the demand for employment in nonphysical sectors of the economy, such as services (1.4), as a proportion of the total population;
- consumables, such as food, plastics, paper, pharmaceuticals and chemicals (2.1), on a per capita per year basis;
- the demands for building space (2.2.1.1), intercity travel (2.2.2.1), urban transit (2.2.2.4), roads (2.2.2.6), international travel (2.2.2.7), and material transformations (2.3.5).

This process is continued down the hierarchy of calculation procedures, which provides a complete set of quantities demanded by the population driver and the subsequent flow on effects. In order to supply the quantities demanded, production or control variables are set in the primary material sectors (agriculture, forestry, fishing, mining) or the international trade sector, so that the quantities demanded by the

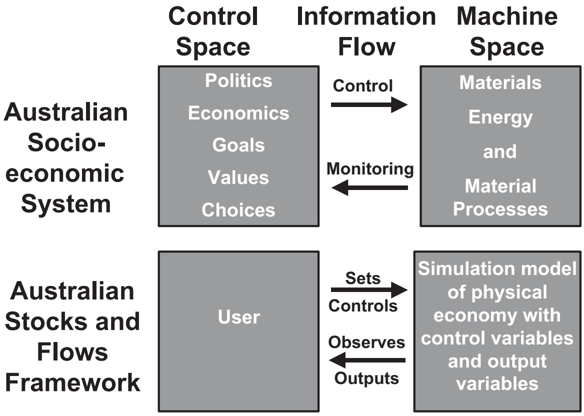

Figure 6.4
Content and information flow between control space and machine space in the reality of the Australian socioeconomic system and in the control and machine space of the Australian Stocks and Flows Framework.

population may equal the quantities supplied over the period of the simulation.

The *design* approach that lies behind the implementation of the ASFF model distinguishes control space from machine space (figure 6.4). Control space is occupied by the user or analyst, who makes assumptions on the basis of current knowledge and future expectations and then alters control variables in the ASFF model. Machine space is occupied by the modeling code and the equations that describe the processes that drive the physical economy. This is the domain of the materials, energy, and physical processes, which are central to the implementation of industrial ecology. What happens in machine space depends on physical laws, but it also depends on choices made in control space according to people's values. However, people's control of the physical world is imperfect, both because the physical world is very complex and because their goals and values conflict with other people's. From control space, the analyst can monitor what happens in machine space during model simulation and evaluate the outcomes according to goals and values set by a policy analyst or a research group. In practice, the iterative nature of design and testing can be slow and spasmodic, because simulation outcomes are delivered to clients as documents with scenario graphs and written interpretations. In theory, a policy client and a simulation analyst could sit together at the computer screen and facilitate the process of learning and design.

In the design approach used in ASFF, generally the physical processes in machine space are modeled. The analyst occupies control space, observes the situation in machine space, and makes decisions about the settings of the control variables. The analyst is therefore an integral part of the feedback loop, using a wide variety of information sources from society and its political and economic agents. As such, the analyst is in a position to learn a great deal about the system-wide effects of new industrial ecology designs being tested.

Resolving tensions (imbalances between quantities demanded and quantities supplied) may be obligatory or optional. If a tension indicates a physical or accounting inconsistency, it must be resolved. If insufficient primary energy is supplied to meet electricity and transport requirements, then its supply and delivery must be increased. Another form of tension might indicate the failure to meet some nonphysical goal or desirable criterion. In this case, its resolution is judged to be optional, as illustrated by an imbalance between the labor demanded and the labor supplied. If there is more labor supplied than is demanded, then this is called unemployment, and the scenario is still physically feasible. If there is more labor demanded than supplied, then the production goals might be regarded as infeasible. Production goals might have to be decreased, or the labor force increased.

Currently, the model operation focuses on the larger material flows and the slow-moving dynamics of important stock variables. To deal with small important flows, such as the liberation to the environment of heavy metals or toxic organic materials, the material and energy input-output table at the heart of the model is being redeveloped to account for small, potentially harmful flows as well as the major volumetric flows. Where short-run dynamics are important, particular model calculators are redeveloped with shorter time steps. This was particularly important in the fisheries calculator, in which five-year time steps were able to deal effectively with long-lived species such as bluefin tuna. However, for short-lived species, such as squid and prawns, a yearly time step was needed. There is a constant challenge in model redevelopment to constrain the types of issues that are analyzed and to stay with the underlying theory that the stock vintages driving slow-run dynamics are important and must remain the prime focus of the modeling activity. There are many other modeling frameworks and research groups that focus only on the quick short-term variables. In terms of resilience theory, healthy, well-balanced stocks of resources and built infrastructure will probably confer more resilience than stocks that are characterized by a limited range of ages and sizes.

6.3 Applications and Results

6.3.1 The OzEcco Design for a Methanol Economy

For a policy client interested in alternative land use scenarios that might help restore landscapes suffering from dryland salinity, scenarios were implemented within OzEcco to produce alcohol fuels from woody biomass (Foran and Mardon 1999). A number of assumptions underpinned this methanol production scenario: (1) The scenario would aim to supply 90 percent of Australia's total oil requirements specifically to meet 100 percent of the requirements for transportation fuels. (2) The feedstock share would be 100 percent woody material from plantation biomass resources managed as forests with a twenty-year rotation and an average mean annual increment of twenty cubic meters per year. (3) Approximately 60 percent of the woody biomass would be derived as logs and the remainder as branches and waste wood. (4) The rate of plantation biomass establishment would be four hundred thousand hectares per annum. (5) The capital cost in constant dollar terms of the methanol plant was fifty million dollars per petajoule of production capacity, and the lifetime of plant was twenty years.

The high-level indicators simulated by the OzEcco model with these scenario assumptions are shown in figure 6.5. The simulated growth rate in GDP for the methanol scenario dips below the base case scenario for the first twenty years of the transition and then tracks with it. The first dip in the base case curve due to domestic oil depletion is avoided, and the second drop due to the depletion of natural gas stocks is not as large. The per capita affluence measure (gigajoules per capita of energy embodied in personal consumption) tracks slightly below the base case for most of the simulation. The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by a factor of four (from 8 MJ per dollar to 2 MJ per dollar) by 2050. The emissions of carbon dioxide from the energy sector diverge from the base case after 2005 and rise gradually to 800 million tonnes per annum by 2050, a reduction of 400 million tonnes per year compared with the base case.

Successful simulations of the modeled economy do reveal a number of perverse outcomes, as revealed in figure 6.5. One of these is the intersectoral rebound effect, in which CO_2 emissions rebound after the investment period has made the transition to a methanol economy. This results from the release of capital, both from older, now-defunct sectors (domestic oil mining and refining) and new, more efficient sectors (as gas turbines replace coal-fired electricity generators). The capital release stimulates

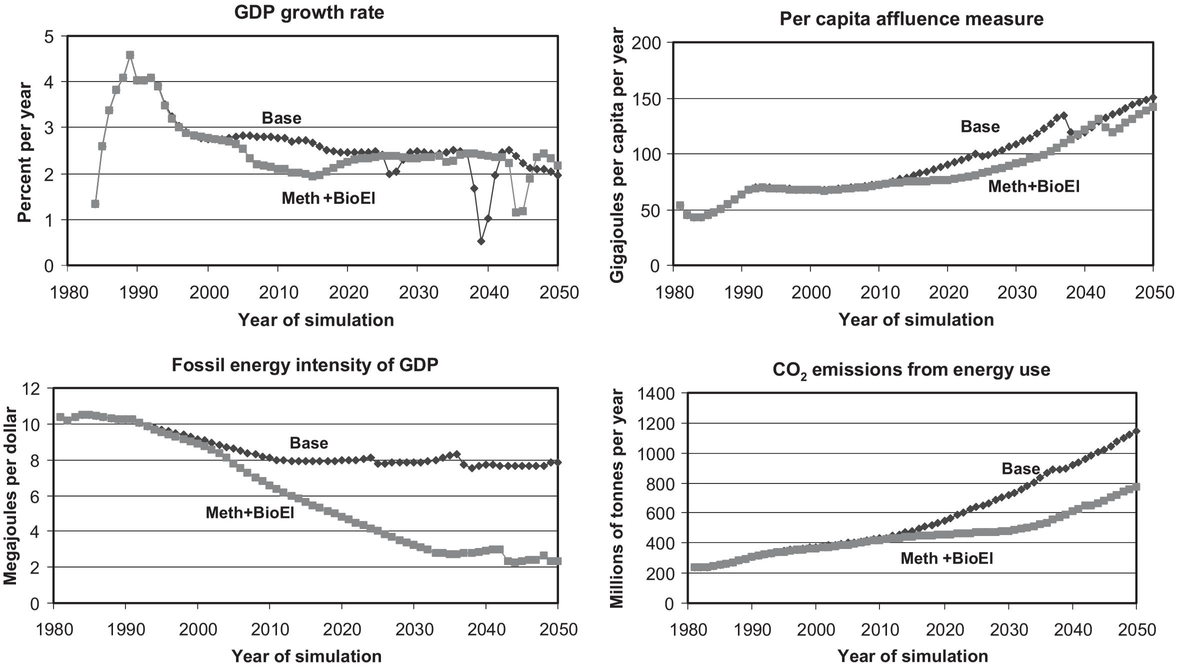

Figure 6.5
Report card for the methanol scenario (Meth+BioEl) compared to the base case (Base). Figure shows growth rate in GDP (top left), per capita embodied energy in personal consumption index (top right), energy intensity of GDP (bottom left), and carbon dioxide emissions from energy use (bottom right).

personal consumption in a general sense. This consumption in turn restimulates the requirement for oil, gas, and coal, some of which is imported if domestic supplies become constrained. Perverse outcomes are difficult to manage in a modeling sense, as well as in a real market-based economy operating in a globalized world. In order to constrain carbon emissions, it may in the end be necessary to restrict the physical amount of carbon used as inputs to the physical economy. A twenty-year process is now underway in Australia's Murray Darling Basin to restrict, in an absolute sense, the use of water for irrigation. That such a restriction will ever be imposed on fossil energy inputs seems unlikely under current political ideologies.

Analyses such as these are not predictions in a traditional sense. Rather, they test the likely behavior of the simulated physical economy in response to the implementation of large-scale industrial ecology. A measure of scenario success is the degree to which indicators for a scenario under test diverge from, or remain with, the base case scenario. Although the OzEcco model is driven by physical processes, it is possible to derive a number of economic indicators, such as nominal GDP, because of the strong relationship, in the current structure of the economy, between flows of dollars and the flows of fossil energy that underpin them.

The evaluation of what constitutes a successful scenario is a difficult one in a policy or industry context. Compared with the indicator sets commonly used in state-of-environment reporting, the advantage of the physical modeling approach (compared with series of reporting indicators obtained from a wide variety of partially linked national statistics) is that modeling indicators are structurally linked to one another within the operations of the physical economy. Provided that the modeling has a sound philosophical and biophysical basis, a simulated output provides a thorough basis for interpretation and understanding, as well as a cogent and robust look-ahead capability.

6.3.2 The Australian Stocks and Flows Framework

The intended use of the ASFF analytical approach is now shown through two complementary analyses. They are extracted from a population study undertaken for a government policy client who sought to compare high, medium, and low rates of population growth, driven in turn by three different rates of net immigration. Material flow analysis and greenhouse gas emissions from the energy sector are selected as higher-level issues that integrate industrial ecology concepts at a whole-of-economy level.

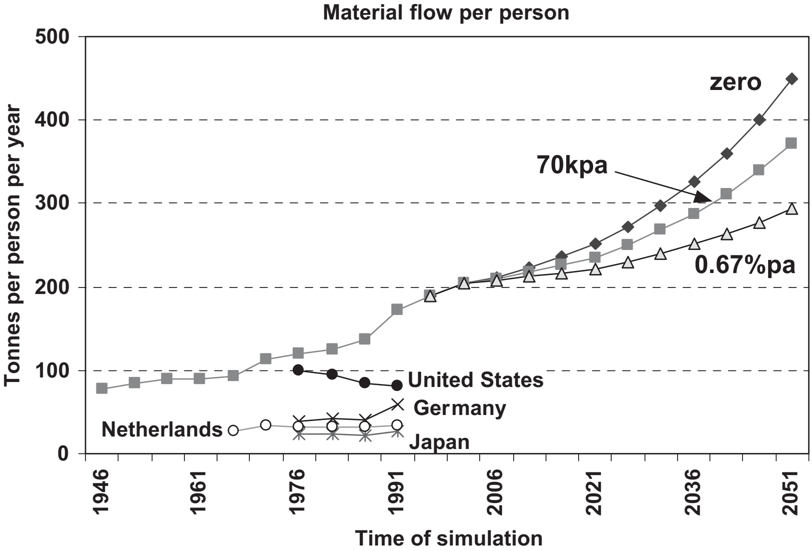

Figure 6.6
Total material flow in tonnes per person per year for three population scenarios: the medium growth rate driven by 70,000 net immigration per year (70 kpa), the lower growth rate driven by zero net immigration per year (zero), and the higher growth rate driven by 0.67 percent of current population as net immigration per year (0.67% pa). Data for four industrialized countries are also displayed (Adriaanse et al. 1997).

6.3.2.1 Material Flow Analysis Australia has maintained a materially intensive economic system for many reasons, and the standard assumption of this study is a continued expansion for many primary exports. This results in a material flow account that continues to expand beyond a contemporary level of 200 tonnes per capita per year to 300 tonnes for the high population growth rate, 370 tonnes for the medium growth rate, and 450 tonnes for the low growth rate (figure 6.6). The higher population scenarios give lower indices of per capita material flow because of a dilution effect of higher population numbers within a material flow driven primarily by export trade decisions. For comparison purposes, the analyses of Adriaanse et al. (1997) are presented in the figure for the material requirements of the United States, Germany, the Netherlands, and Japan. For the period 1970 to 1990, the structural and trade arrangements of those countries allowed much lower material flows on a per capita basis, although higher populations in Germany, the United States, and Japan would give comparable or larger material flows on an aggregated whole nation basis.

There are many ways in which these data may be examined. For the medium population growth rate, the direct and hidden flows for domestic requirements are maintained at below 100 tonnes per capita for the duration of the simulation, as the result of a stabilizing population. Most of the effect is due to hidden flows of material tied to the nation's exports and specifically refers to items such as overburden for open cut mines, material removed in ore concentration activities, and effects of crop and animal agriculture. In general, the mining industry for both metals and energy materials accounts for most of the increase from current levels of the per capita material flows.

In comparison with other developed economies, a variety of material flow indicators for the Australian economy will be higher and will also trend upward. This is because of a mixture of historical antecedents, contemporary policy directions, and future strategic directions already well underway within a variety of major commodity groups with production bases in Australia. None of these are preordained, and global trade and political forces may cause major changes to the base case scenario and the analyses derived therefrom. A carbon tax on coal usage in countries such as Japan and South Korea and those of the European Union would cause a significant reduction in per capita material flow but have large implications for the level of export income. What energy source might replace coal in those countries also presents a large imponderable for both industry and policy. The transition to a Factor Four or Factor Ten economy in countries such as Japan, South Korea and China and those of the European Union, which currently take the majority of Australia's minerals exports, would also have large repercussions. However, many Factor Four transitions rely on advanced composite materials for lightness and strength, and many of these materials rely on large hidden material flows themselves.

In terms of national policy issues, there are three important areas that determine the implications of Australia's future material flow account. The first and most immediate link is to energy use and greenhouse gas emissions. The more material that is moved, the more energy that is required. In physical law terms, these are the realities of thermodynamics and mass balance that lie behind all modern economic systems. Thus, if more material is moved, even allowing for changes in a wide range of efficiencies, then total energy use may increase. Depending on the source of the energy, greenhouse gas emissions do not necessarily increase, but for all practical purposes they must.

The second important issue for material flows would arise if there were to be negotiations between countries on how to account for, and apportion, the responsibility for such flows. In the analysis presented here, the material flows are apportioned directly to the nation and each person classified as a citizen. The rationale for this is that all citizens reap the reward of the material transactions, whether it be a direct effect (employment, food, and housing) or an indirect effect (export income to purchase a video recorder or an overseas holiday). However, there are equally valid arguments that the material flows should be apportioned to the countries that use the material that Australia exports to them. Thus, in both material and energy terms, Australia's major trading partners would take on the direct and hidden flows of the material exported to them.

However, the chain of attribution would not stop there if a full life cycle analysis were implemented and full system boundary applied. Logically, the next step would be to attribute the hidden material flows embodied in the array of goods that each nation imports. Thus, the copper, aluminium, steel, and magnesium in each imported car would be finally attributed to the country in which the consumption finally takes place. Most OECD countries would be disadvantaged in this system of accounting, which would see the accounting responsibility for 80 percent of the world's material and energy flows attributed to 20 percent of the world's citizens in the richer countries currently. However, it is possible that the balance might change over the next fifty years as populous less-developed countries become more developed. Wernick and Ausubel (1999) make the policy assertion that without the data collection and the development of GDP-like metrics that describe material flows, an economy and its political system are navigating blind on the course that leads inexorably upward to higher and higher levels of material consumption.

The third important issue in the material flow dilemma concerns the type of economy (materially heavy or materially light) that the nation's citizens wish to maintain. In commenting on the structure and performance of the U.S. economy, Greenspan (1998) questioned "whether over the past five to seven years, what has been without question, one of the best economic performances in our history, is a harbinger of a new economy, or just a hyped-up version of the old, will be answered only in the inexorable passage of time" (85). In examining the progress of transition to the knowledge-based economy for Canada, Gera and Mang (1998) concluded that "Canadian industrial structure is becoming increasingly knowledge-based and technology-intensive, with competitive advantage being rooted in innovation and ideas, the foundations of the new economy" (177). However, despite the undeniable growth in employment and economic activity in the services portion of the U.S. economy over the last three decades, Salzman (1999) notes that manufacturing in America has not declined. In a comprehensive analysis of the U.S. economy, Ayres, Ayres, and Warr (2003; chapter 3 of this volume) note that total consumption mass and per capita measures of mass and exergy have continued to increase over the one-hundred-year time frame in spite of considerable technological innovation and awareness of environmental and resource issues. The dilemma is that the service economy exists to service the old economy and to make it more efficient in terms of finance, labor, quality, and delivery schedule. What has been saved materially through efficiencies in production processes has been consumed in increasing the diversity of products and opportunities, few of which have zero material and energy contents. The dilemma of material flows could be that in order to halve material flows, the total material consumption of each citizen would also have to be halved, while properly accounting for direct and indirect flows as well as the exported and imported components of globalized trade (see chapter 3).

6.3.2.2 Greenhouse Gas Emissions from the Energy Sector The continuing emissions of carbon dioxide and other greenhouse gases from the energy sector are viewed by many political and scientific groups as an issue of global concern. The possible effects within the span of two to eight human generations include the increased frequency and intensity of weather events, the displacement of agricultural systems, the loss of amenity and infrastructure close to regions of possible sea level rise, and the loss of process diversity in natural systems as key elements of function are lost as a result of the interaction of many factors. Although Australia is a small emitter of greenhouse gas in total terms, an affluent lifestyle and a lower population base in relation to the sum total of its physical transactions makes it a high per capita emitter, among the top five in the world. As a relatively advanced country in technological terms, Australia might be expected to have the capacity to reduce greenhouse emissions through a mixture of technological innovations and changes in the volume and composition of personal consumption. Alternatively, in the future, new institutional arrangements at an international level might implement greenhouse accounting measures that allocate the responsibility for greenhouse emissions to the consumer of the final product or service in the country where the consumption happens. Again, Australia would

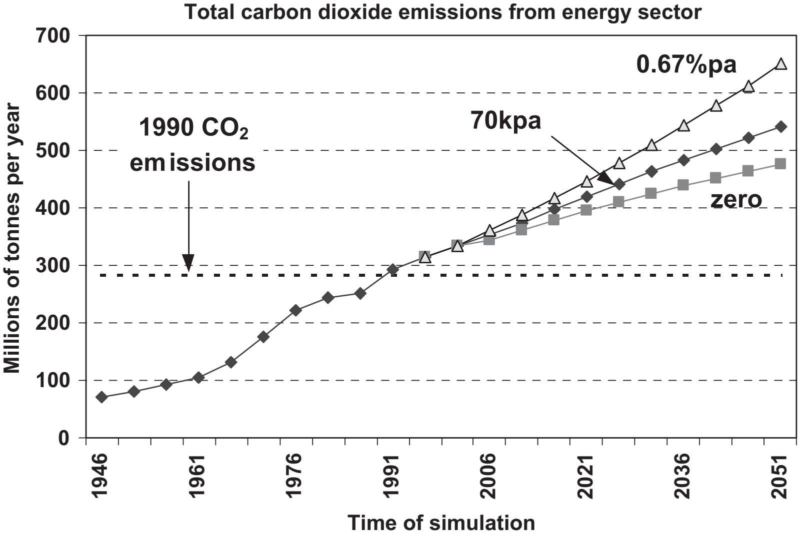

Figure 6.7
Carbon dioxide emissions in million tonnes per year from the energy sector to 2050, for three population scenarios: the medium growth rate driven by 70,000 net immigration per year (70 kpa), the low growth rate driven by zero net immigration per year (zero), and the high growth rate driven by 0.67 percent of current population as net immigration per year (0.67% pa).

not necessarily be advantaged in these new arrangements, as its imports contain more embodied energy, and therefore carbon emissions, than its exports.

The standard assumptions used as a starting position underlying all population scenarios suggest that carbon dioxide emissions will continue to expand up to 2050 for all population scenarios (figure 6.7). In spite of a wide range of technologically optimistic assumptions, throughout most sectors of the physical economy, the carbon dioxide emissions continue to rise. Even under the lower assumed rate of population growth, they continue to grow strongly because of four factors. The first is the inbuilt demographic driver, which, over the next 50 years, meets the requirement for additional houses and cars for younger people who continually enter the consumption economy. Three other important factors are the growth in per capita affluence, large increases in international inbound tourism, and steady expansion of a wide range of export commodities and goods that have energy-intensive production systems.

When a series of technological innovations are combined, then the emission trajectories do change markedly. The band of population-driven emissions shown in figure 6.7 could be reduced by 200 million tonnes per year by 2050 if best practice technologies were implemented throughout all physical sectors. Alternatively, the emissions band could occupy a zone 200 million tonnes higher if current technological options are retained and if lifestyles become more energy intensive overall. Implementing individual technologies, such as better car engines, in the main produces only marginal effects on the overall emissions trajectories. This emphasizes that for industrial concepts to have a major influence on national aggregate indicators, they must be fully implemented throughout all corners of the physical economy.

6.4 Strategy for National Policy Influence

The strategic plan for the physical economy project in which the OzEcco and ASFF models are used has three linked goals. The first goal is to pin the debate about transforming the physical economy to more sustainable modes of operation, such as the dematerialized Factor Four or Factor Ten economy, as detailed by von Weizsäcker, Lovins, and Lovins (1997), Ayres (1998b), and others. The second goal is to have accepted, at national policy levels, the concepts of physical analysis of the national economic function. The third goal is to contribute to changing national policy on a number of key aspects that relate to the physical economy.

The route to achieving these goals is a complex and difficult one, with two important considerations. The first is the dominance of economic theory and debate in assessments of national population development issues, combined with the belief that market mechanisms will deal with environmental problems if they are sufficiently important to require a solution. Allied with these economic arguments is the view that technological innovation is a driver of progress in its own right that will implement industrial ecology if the market sees an economic advantage. The second consideration is that the integration and modeling within these physical economy models is a challenging one in which scientific proof in a traditional sense is difficult. In addition, a modeling framework is always open to improvement. In a project management sense, this can result in an imbalance among investment in modeling, the outputs from scenario simulations, and subsequent contributions to the long-term analysis of national policy issues.

Given these constraints, the route chosen to the project's strategic goals is a partial and iterative one, with an overall integration phase in the final two years of the process. Although the insights into strategic policy require an analysis of the whole physical economy, the way forward requires that twenty important sectors, such as agriculture, building, manufacturing, and energy, each be investigated in a partial sense for an identified client who will underwrite the task. This allows deeper scrutiny and appropriate model development for each main sector for a client with which we might investigate and learn about an important physical sector. The base case scenario must also be further developed in an iterative manner, with additional insights from the client and the particular analysis undertaken. Using this client-focused partial approach, it is possible that important insights that might help accelerate an industrial ecology transition might be lost in a welter of detail or simply not recognized.

6.5 Discussion

6.5.1 The Approach

This chapter has described a framework of analysis around future design issues for Australia's physical economy. The approach aims to create new whole economy designs, as well as revealing physical flaws in national policies. It relies on three key criteria to influence national policy directions. The first is that policy designers, with model analysts, should become active learners within the iterative simulation process. Central to the analytical approaches is that the analyst or user is seen as the human dimension within the modeling procedure, rather than being a value-free controller outside the simulation process. The second criterion focuses on the relationship between the physical economy and the monetary economy. The physical economy should conform to the physical laws of thermodynamics and mass balance. Because of its behavioral basis, the monetary economy is open to a wider array of innovations and beliefs than the physical economy. Creating harmony between the two analytical disciplines will remain a challenge.

The third criterion concerns the nature of predictive analysis versus the nature of scenario analysis. The concept of scenario analysis used in this approach relies on a wide array of expert opinion and data analysis. These help set the control variables that drive simulation outcomes in a transparent and explicit manner. A simulation of a scenario may seek to test the physical feasibility of a particular national policy. Alternatively, it may seek to design the pathways along which a policy must progress, if it is to reach an explicit goal by a future point in time. Whether the policy analyst thinks of himself or herself as an observer or as an architect in national affairs could be seen as an important distinction. An observer might anticipate incremental policy changes at the margin. An architect might seek to redesign and foster the entirely new structures that could force the transition toward concepts of economy-wide industrial ecology.

It is true that many of the issues on which ASFF and OzEcco focus are dealt with in part by many specialist modeling groups in both academia and consulting in Australia. Thus, national statistical agencies undertake national population projections, national resource agencies model the development of petroleum, minerals, agriculture, and water use, and so on. National econometric models also analyze the effect of policy innovation and shocks on a wide range of whole economy variables, usually, but not always, described by financial-reporting variables. Many of the econometric models are focused on equilibrium concepts and contain only rudimentary dynamics. Assumptions about technological change and learning are seldom constrained by natural resource realities (land, water, oil, and gas availability) or process realities in mass balance and thermodynamic terms. The issues that are missed by these other approaches are well described in chapter 5's analysis of the capacity for change in the steel, paper, and ethylene industries in the United States. Their analysis of the dynamics of key infrastructure stocks in these industries, and the degree to which stock inertia confers resistance to change in the face of aggressive financial penalties for carbon emissions, provides a salutary lesson for policy designers who ignore the importance of stock dynamics in setting real limits to the pace of change and innovation.

6.5.2 Advantages and Disadvantages of the Physical Modeling Approach

A design and testing approach that combines the process of understanding how a physical economy functions with a complete and consistent database that underpins the process model is seen as the main advantage for physical economy models. Such an approach relies on complex calibration and validation procedures that construct a foundation for the physical economy in the historical period before the future scenario is simulated. These "grounding" procedures enable a proof of concept to be displayed and an acceptance gained that the underlying modeling procedures compute appropriately in historical time. The treatment of slow-moving variables such as stocks of people, cars, houses, and agricultural fields is central to the concepts of momentum and inertia, central to complexity and resilience in the physical economy. The description and vintaging of stocks is seldom implemented fully in economic models, yet it is a key limiting variable to the sustainability transition. The associated concept of physical realism that drives most production processes is also vital and also not included in many economic models.

The modular and stepwise nature of model design and computation procedure allows partial simulations to be undertaken relatively easily and further model development to be undertaken on a component without disturbing the integrity of the whole. The level of detail is reasonably flexible and in the ASFF model ranges from fifty-eight regions for agricultural productivity to sixteen regions for human population dynamics to eight city air sheds for vehicle emissions and one national account for balance of trade computation. One advantage in national and international terms is that a limited amount of simulation modeling of physical economies has been undertaken in a policy context, when compared with the dominant force of econometric modeling. This may provide an advantage in the policy marketplace for concepts and analyses describing physical sustainability. However, there is little policy experience in the promotion and refutation of design theories dealing with the physical economy and its underlying dynamics.

The size and complexity of the analytical undertaking present an immediate disadvantage to scientific management, funding agencies, national policy analysts, and scientific colleagues. The gulf between the constrained boundaries and reputable sureness of traditional reductionist research approaches, on the one hand, and a nationally scaled modeling approach that uses scenarios, on the other hand, has never been greater. Lutz (1994) noted that the challenge of physical economy modeling lies in its being able to combine a "hard-wired model which only includes unambiguous relationships on which scientific consensus can be expected" with a "soft model which can quantify all kinds of feedbacks and interactions that the user wants to define" (362).

This approach mentioned by Lutz in design and implementation appears to be meeting the project goals. But the absence of price mechanisms in both the OzEcco and the ASFF models poses a significant barrier to acceptance by national policy analysts. Some suggest that the physical and the economic approaches should be hybridized and blended. Others are satisfied to keep them as distinct and separate analytical approaches, each of which contributes insights to the policy process. The philosophical approach behind the development of the physical economy simulators argues that prices and market mechanisms are critical to balancing the economic concepts of supply and demand in the short term. However, the strategic intent of the long-term physical modeling approach is to provide information flows from longer-term horizons to current market, policy, and business agendas. For these long-term horizons, price and market mechanisms become diffuse and indeterminate, while the workings of the physical economy still depend on people and the flows of energy and materials.

6.5.3 Economic and Physical Limits

The complexity of model building and validation sometimes hides obvious tensions between viewpoints that are mostly economic or mostly physical. For the Australian economy at least, each extra dollar of GDP requires an extra ten megajoules of primary energy, thirty-seven liters of water, and three square meters of permanently disturbed land. Under conditions of limited technological progress and economic growth rates of 3 percent per annum, this will mean that physical requirements approximately double every twenty-five years or so. The modeling approaches implemented for Australia and the long-run analyses of the U.S. economy by Ayres, Ayres, and Warr (2003; also chapter 3) provide a compelling picture of these physical realities at the macroeconomy level. That technological progress is constrained by the lock-in of important capital stocks and industrial processes over long periods is well described in chapter 5 and their conclusion that "even more credence in the modeling arena must be given to models that are able to capture the impact of policies on the turnover of the capital stock and its associated impact on energy use and carbon emissions" (225–226).

Whereas physical approaches are driven in a longer-term sense by technological parameters and the dynamics of turnover in capital stocks, economic approaches are driven by price and policy changes within shorter-term horizons. Even with a reasonably upbeat interpretation, the hybrid economic-physical models STREAM (chapter 7) and DIMITRI (chapter 8) give little suggestion that the physical approaches are substantially in error. The conclusions of the STREAM modeling are that there is no absolute decline of material use in OECD countries and that tax measures to reduce the use of materials are largely ineffective. The DIMITRI modeling emphasizes that policies constraining energy and material use have to be applied to all trading partners of a nation-state, because of the complex interdependencies of international trade and the degree to which the market realities of loopholes in national policies make it easy to shift production to lower-cost locations where energy and material use are often not constrained.

This leads to the vexing questions of physical limits within an economic world that is seemingly limitless. There is no doubt that the processes of material and process substitution will continue, allowing some measure of affluence growth for the next century. However, the emphasis in "limits" identification has shifted from the sources of material progress to the sinks, where the by-products of energy use and material transformation are eventually deposited. Whether it is the atmospheric commons of the global change debate or the local problems of water quality and toxified agricultural soils, only the most myopic of policymakers are unable to recognize that real physical limits are now more than just a blip on this century's optimistic horizons. However, what most citizens and policymakes do not appreciate is the huge challenge posed by the inability of advanced measures of technological progress to penetrate the capital stocks of most modern economies and thus to moderate or reduce material use. The challenge is even greater when an economy is maintaining high rates of growth fueled by the expanding personal consumption that underpins it.

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