Green Macroeconomics:
Growth and Distribution in a Finite World

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A GDAE Teaching Module on Social and Environmental Issues in Economics

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NOTE – terms denoted in **bold face** are defined in the **KEY TERMS AND CONCEPTS** section at the end of the module.

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1. INTRODUCTION

Macroeconomics—the study of economic aggregates at the level of the whole economy—has a long history, going back at least to the 18th century. Since that time, different schools of macroeconomic analysis have emerged. In this module we will refer to three of them: **neoclassical**, **post-Keynesian**, and **classical** (see Box 1). Neoclassical theory currently dominates in most economics journals, but all three traditions (and others) are under active development. While we strive to present each school of thought on its own terms, allowing students to make their own judgments, we will use classical theory for studying the long-run implications of economy-environment interactions. Classical theory makes comparatively simple behavioral assumptions, and while these have been challenged by other schools in terms of their implications for short and medium-run policy, we will focus here on long-run issues involving macroeconomics, resources, and the environment.

BOX 1: HISTORICAL TRENDS IN ECONOMIC THEORY

Classical economic theory, developed in the eighteenth and nineteenth centuries, focused on "big" questions about what governs economies, economic growth, and distribution. The eighteenth century physiocrats, forerunners of classical theory, saw the economy as strongly grounded in physical reality, in particular agricultural production. Classical economists saw the economy as developing its own logic and equilibrium, based on the operations of markets and the material needs of the workforce. Neoclassical theory, developed in the late nineteenth century and widely accepted in the twentieth, refocused on **microeconomic** analysis of individual and business decision-making and the workings of markets, and moved away from the "big" macro questions, assuming that equilibrium in multiple markets would provide economic stability. This approach was questioned by John Maynard Keynes and others during the Great Depression. Keynes argued for the importance of a macro perspective, an activist role for government, and a focus on the importance of distribution. These concerns were diluted in the "neoclassical synthesis", which attempted to combine a generally neoclassical perspective with some Keynesian macroeconomic analysis, but have been reasserted by the "post-Keynesian" school, who argue that the neoclassical synthesis has removed key Keynesian insights into economic instability and inequity, and attempt to return to some of the more radical implications of a Keynesian analysis.

"Green" macroeconomics is both very new, appearing as a term only in the last few decades, and very old, as it revisits themes of the 18th century physiocrats and the 19th century classical economists. Just what it includes is still open for debate.[1] It broadly covers the macroeconomic aspects of sustainable development, including analysis of "green growth" strategies, low-carbon

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[1] There is no universal guide to what is and is not a branch of economics. Many papers in green macroeconomics are published in the journal *Ecological Economics*, but the field does not have a dedicated journal, which is often taken as a test, and there are no graduate programs. The name is also in flux, with "ecological", "sustainability", or even "doughnut" sometimes used in place of "green". Finally, in the widely-used list of economic subjects curated by the American Economic Association's *Journal of Economic Literature* (the "JEL codes"), no single code covers the work of economists who might identify themselves as working on green macroeconomics.

development, and the natural resource base of the economy. As a working definition for this module, we will say that **green macroeconomics** is the study of economic aggregates at the level of the whole economy, where the economy is seen as embedded in society, which in turn is embedded in the environment.

1.1. Why Macroeconomics?

Some economists question whether macroeconomics should be its own area of study. After all, aggregates are made up of individuals. If theory can give us some understanding of individual actions, then why not simply add them up to get the aggregate result? This argument motivates both the search for "microfoundations" of aggregate behavior and the expanding field of agent-based economic modeling. Yet, while all aggregate behavior must be consistent with individual behavior, the influences go both ways. Individual behavior is affected by features of society and the economy, including formal institutions and informal norms and expectations. Not only currency and the legal institutions governing how business is conducted, but also labor arrangements, the relationship between businesses and their customers, and the role of government in economic life vary considerably between countries, and can change within a country over time.

Institutions and norms provide the context for one-on-one interactions. They also help to resolve economic constraints at the aggregate level that are not obvious at the individual level. For example, in a closed economy with no government sector, total saving must equal total investment – we will derive this result later in the module – but saving and investment are separate decisions, often made by entirely different actors. They must balance at the end, but it is not immediately obvious how that will happen. Similarly, the total amount of what is bought has to be available for sale, but not the other way around – what if the amount that people want to buy is less than what businesses have produced?

In a healthy economy, businesses and households develop relatively stable expectations such that the economy operates as a going concern, with businesses confidently producing goods for sale, and households equally confident that those goods will be on the shelves when they visit the store.[2] Economic conditions fluctuate constantly, and the actors in the economy – firms, households, and banks, the government, and so on – compensate by making small adjustments in their behavior in accordance with explicit procedures, personal habits, and shared norms. Under ordinary circumstances, those small adjustments tend to keep the economy hovering around a "normal" level.[3]

The existence of social norms and shared expectations allows us to carry out macroeconomic analysis in terms of **social groups** (see Box 2). While individuals differ widely in their habits, life conditions, and preferences, those differences are not always relevant at the aggregate level. By contrast, common behaviors amongst similar individuals can lead to meaningful differences between social groups. For example, many employees are paid an hourly wage, with the possibility of overtime pay, rather than a fixed salary. Managers and technical professionals typically receive a salary, while upper management may be offered a share in the ownership of the company. Some

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[2] This view of the economy is associated with the 20th Century American economist Gardiner Means.

[3] It is important to keep in mind that "small" macroeconomic fluctuations can have dramatic microeconomic impacts as people are laid off or hired, lose or start a business, and see jobs shift to another part of the country. Macroeconomic analysis helps to see the big picture, but it obscures impacts on individuals.

very wealthy people may not need to work at all (although they may choose to), as they derive a substantial part of their income from returns on their investments. Thus, sources of income and conditions of work characterize broad social groups. People within economically-defined social groups tend to associate with one another. Average consumption and saving outcomes differ systematically between groups because individuals within a particular group face similar incentives and constraints and evolve norms through their repeated interactions.

BOX 2: SOCIAL GROUPS

Neoclassical theorists downplay the idea of social groups and emphasize individual preferences. In practice, however, neoclassical models use one or more "representative agents". If the agent is representative of anything, it must be of an aggregate group of individuals – that is, a social group. It is difficult to escape this conclusion if the model has more than one representative agent distinguished by preferences and income.

Agent-based modelers seek to avoid the limitations of neoclassical models by running computer simulations with large numbers of (simulated) individual agents. They then look for "emergent" structure that arises as a result of individual-level interactions. However, to the extent that structure is reflected in a partitioning of agents into identifiable groups, agent-based models can be seen as providing a justification for aggregate analysis: social groups are an emergent property arising from individual behavior.

Admittedly, theorizing in terms of social groups can be problematic. In the past, some social scientists, including some economists, made the extreme assumption that everything important about an individual follows from their membership in a group. That is a problem even if you accept the idea of social groups. While social groups are part of an individual's reality, and so can influence their actions, they do not dictate individual choices. Furthermore, people always belong to multiple groups. If an individual is to align themselves with a group, then which one should they choose? To take one important example, conflicts over employment and wages often fracture along gender, ethnic, or racial lines.

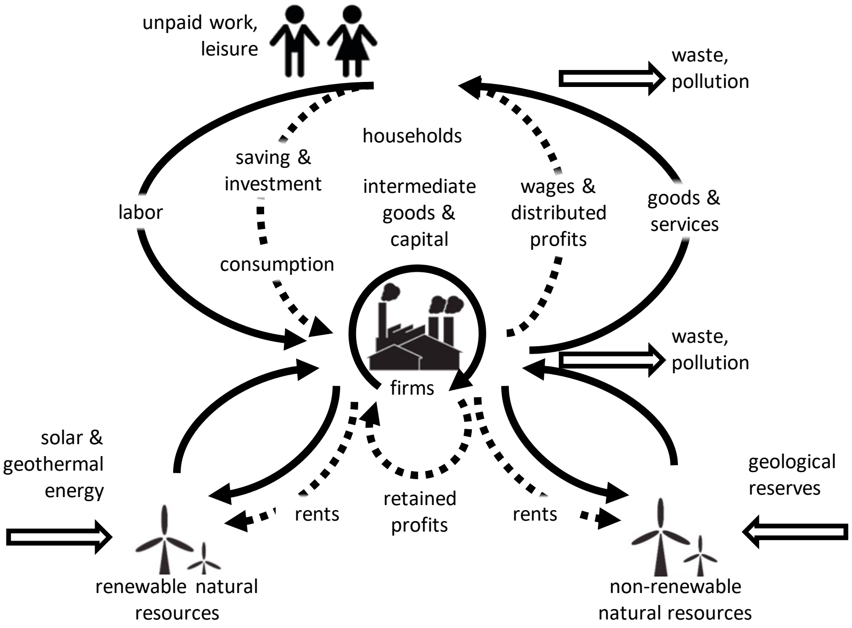
In this module we take a pragmatic approach to social groups that is consistent both with classical and post-Keynesian theory (and central to another school of thought, structuralism). We ask, "Do the variables we assign to social groups have some causal relationship to aggregate outcomes?" In particular, we will argue that households and firms who receive profit income have different aggregate consumption and saving behavior than households whose main source of income is wages and salaries. So, a shift in aggregate income from wages to profits or *vice versa* will affect levels of consumption and saving.

1.2. Flows in the Economy

We now turn from social processes to physical ones. The individuals who make up society are alive and they expend energy and resources in maintaining their society. From a physical point of view, these facts imply that society is not in thermodynamic equilibrium. Such an out-of-equilibrium situation can be maintained only by a regular throughput of energy and matter. Within societies, people must eat; replace worn-out clothing; repair their houses; heat their food and living spaces; travel; clean themselves; replace the water in their bodies; dispose of their wastes; and so on. The economy, as a part of society, is one way in which those flows are organized. While the economy also allows people's "higher" needs to be met in more or less material and energy-intensive ways – such as the need to belong, the need to create, or the need to have a degree of control over one's environment[4] – all economic activity requires some use or exchange of matter and energy.

Matter and energy are conserved, but some matter and energy is degraded or lost to the system whenever they are put to use. As shown in Figure 1, this means that economies feature one-way flows of energy and materials: from **renewable** and **non-renewable** resources, through production, to final use. These internal physical flows are shown as solid lines in the figure. Because of losses and degradation, the economy must replenish them from external flows of natural resource inputs, while producing pollution and waste outputs. The external flows are shown as open arrows in the figure.

Figure 1. The one-way flow of energy and materials through the circulating monetary economy



External flows can be minimized through the "three R's" of conservation: reduce, reuse, and recycle. However, there are limits to these strategies. As noted earlier, some minimal flows of energy and materials are needed to sustain society. Energy cannot be recycled, and it takes energy to return materials to a usable condition. For some materials – for example, the trace metals in modern electronic components – the energy cost is so high that they are essentially unrecoverable.

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[4] Several human needs frameworks have been proposed. This list includes one each from the frameworks of Abraham Maslow, Manfred Max-Neef, and Martha Nussbaum.

Figure 1 shows processed inputs from both renewable and non-renewable natural resources flowing to the rest of the productive economy, labeled "firms" in the figure. For simplicity, government and trade are not shown. Firms exchange goods and services among themselves as intermediate inputs to production. Final goods and services are sold to households (and to the government, and for export). They are also sold to firms as fixed capital stocks, such as buildings and machinery. Unlike intermediate inputs, which are used up in the course of production, fixed capital stocks are used repeatedly. Households provide labor to firms, while also providing unpaid labor within the household itself.

Production, consumption, and investment form a circular loop of monetary payments that overlays the one-way flow of goods and materials. Key monetary flows are shown as dotted lines in Figure 1. Firms receive payment for goods and services from households (and the government, and buyers of the country's exports). They then use that income to pay for intermediate goods, as well as wages, profits, interest, and taxes. They retain some profit for themselves, and distribute the rest to households. Households spend some of their untaxed income and save the rest. Through banks, bonds, and initial purchases of stock, those savings are provided to firms, which combine them with their own retained profits for new capital investment.

In Figure 1, a special set of firms is treated separately from the rest: the natural resource producers that convert natural resources (such as crude oil or wind) into processed goods and energy carriers (such as petroleum, chemicals, or electricity). These firms are different from the rest because their main input comes from outside the economic system; they are the first step in the one-way flow of materials and energy. This special feature affects how their prices are determined.

In common with all firms, natural resource producers have costs that they must cover. Resource extraction and processing are typically capital-intensive, and firms must pay back their creditors and investors for their previous capital investment. They must also pay the wages and salaries of their staff. Natural resource firms may also pay the government or a private individual a royalty for the right to extract or grow resources, or for the right to use a plot of land to place a wind turbine.

Unlike other firms, prices for the commodities produced by natural resource firms, such as crude oil, electricity, or wheat, are set in commodity markets. Aside from episodes of substantial over-production, the price will exceed costs, and the excess is the "**rent**".[5] The rent varies with the level of demand and the conditions of supply. When supplies are abundant relative to demand, prices tend to be close to the cost of production and rents are low. When supplies fall, or demand expands, the price can rise substantially relative to the cost, generating large rents and windfall profits. This concept of rent, which emerged from studies of natural resources, has since been extended to other contexts in which excess profits are possible because the seller controls access to a limited resource.

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[5] The economic concept of "rent" has a great deal of historical and theoretical baggage attached to it. This definition is the one used by the World Bank to calculate the resource rents that they report in the World Development Indicators global database. They take the prevailing price on international markets for the commodity and subtract average unit costs of production.

1.3. The Functional Income Distribution

Firms sell an enormous variety of final consumption goods and services, which households can buy in a store or online. They also sell final investment goods, or capital goods, such as buildings and machinery, for purchase by other firms. In addition, they sell intermediate goods and services, which other firms use in their production. Some intermediate goods are often available to final consumers as well, such as bolts, spark plugs, and fuels, but are usually provided to firms in quantities suitable for industrial use. Other intermediate goods, such as specialized parts or chemicals, are only sold to businesses.

After a firm receives income from sales, it distributes that income to different recipients. Most of the distributions are pre-determined through contractual arrangements, including payments to other firms for intermediate inputs. Employee compensation is a combination of contractual payments – wages and salaries – and non-contractual payments, such as bonuses. The firm pays taxes out of its income, net of any government subsidies it receives. The remainder after payments for intermediate outputs, employee compensation, and taxes net of subsidies is gross profit (called the "gross operating surplus" in the national accounts). As discussed earlier, the profits of natural resource firms include an imputed resource rent.

Some spending out of gross profit is contractually obligated, such as payment for previously ordered investment goods and interest on loans. Another portion may be paid out to investors as dividends, often according to an announced schedule, much of which is immediately reinvested. The rest – often a substantial portion – is retained by the firm. Part of retained profits cover depreciation of capital (after which it becomes net profit). The remainder may be used for new investment, to add to cash reserves, to buy the firm's own stock to make it scarcer and therefore boost its price (a stock buyback), or any other purpose the firm's management deems appropriate.

The net result of selling and buying intermediate goods between firms is zero at the level of the whole economy, although not at the level of individual sectors. **Gross domestic product (GDP)** is the total value of final goods and services, net of intermediate sales. (It is called "gross" domestic product rather than "net" because it does not account for depreciation of capital.) The distribution of GDP between wages, profits, and rents is called the **functional income distribution**, which plays an important role in macroeconomic analysis. Different economic traditions have divergent views on how the functional income distribution is determined:

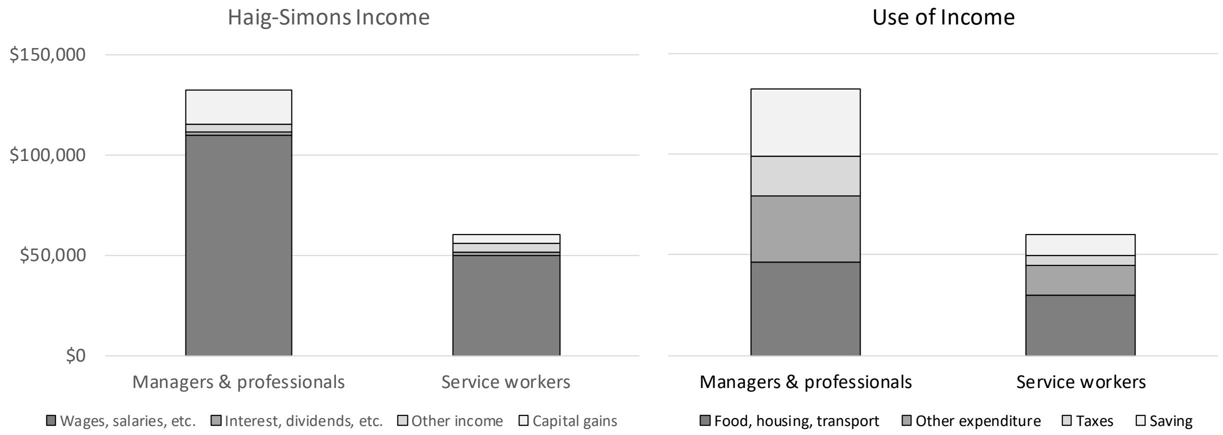
- Neoclassical theorists argue that each factor of production, such as labor or capital, is paid the value of its marginal contribution to output by profit-maximizing and competitive firms. Firms choose their combination of labor and capital from a set of possible techniques, as defined by a production function.
- Post-Keynesian theorists argue that the functional distribution is determined by firms' markups on their costs in imperfectly competitive markets dominated by a few large firms (oligopoly). Market-leading firms have considerable flexibility when setting their markups, but do not set them so high that they invite competition from rival firms.
- Classical theorists usually assume that competition in the search for investment funds drives firms toward a uniform rate of profit. The realized rate of profit depends on the relative bargaining power of the owners of the firms, on one hand, and workers, on the other.

In both post-Keynesian and classical theory, wages are believed to be strongly influenced by social processes beyond competition in the labor market.

The functional income distribution should be distinguished from the personal income distribution – that is, the distribution of income between households or individuals. Both are important for understanding social trends. Most countries around the world have experienced growing disparities in their personal income (and wealth) distribution. A highly unequal distribution of personal income can create social conflict, so the global trend toward higher inequality has drawn considerable attention.

Despite the importance of the personal income distribution, the functional distribution is a particularly useful guide to understanding macroeconomic dynamics. The large bulk of wage and salary earners spend most of their income on food, housing, transport, and other consumption. Figure 2 shows income inclusive of capital gains (known as "Haig-Simons" income) and use of income for expenditure, taxes and savings (as a residual) for two occupational categories: managers & professionals and service workers. As with firms, much household expenditure is contractual, in particular rent and debt payments (including mortgage payments). Another portion is devoted to physical necessities, such as food, water, heat, clothing, and health care. The remainder, if any, might be spent in a variety of ways, for example on appliances, movies and other entertainment, exercise equipment or education. If expenditure is less than income, households save. Conversely, if expenditure exceeds income, then household savings are reduced, or the household's debt is increased.

Figure 2. *Haig-Simons Income and Use of Income, 2016*



Note: Saving is calculated as a residual so that total use of income = total income.
Source: 2016 US Bureau of Labor Statistics' Consumer Expenditure Survey

These individual behaviors by households and firms translate into regular patterns at the level of the whole economy. In particular, a substantial portion of profits is saved, while most wages are spent, directly or indirectly, on consumption. Thus, shifts in the functional income distribution translate into different aggregate levels of saving.

1.4. The ABC Approach to Macroeconomics

We have defined macroeconomics as "the study of economic aggregates at the level of the whole economy." A macroeconomic *analysis* (Greek for "breaking down" or "releasing") separates this intimidating problem into more manageable steps.

The first step is to construct a set of accounting relationships between the assets and expenditure of different social groups. Economic accounts were invented at least five thousand years ago, as evidenced by tablets and tokens left by the Sumerians. The modern practice of double-entry bookkeeping, in which every asset must have a corresponding liability, was invented more recently, less than one thousand years ago, in Europe. The modern system of national accounts was constructed in the 20th century.

The accounts can be useful by themselves. They must be in balance, which places constraints on aggregate economic quantities. In the introduction we used as an example the fact that saving must equal investment in each reporting period. Nevertheless, accounts are limited. They give the "what" of an economy. The second step is to say *why* the transactions happen, and in what quantities. That is, a macroeconomic analysis makes assumptions about how social groups behave in the aggregate.

The third step is to reconcile the accounts once economic actors have acted, a process often called "closure". This is necessary because there is no reason to assume that individual actions will automatically result in consistent accounts, while by definition the accounts must be in balance.

We can call this combination of **a**ccounts, **b**ehaviors, and **c**losures the "ABC" approach to macroeconomics. The ABC approach is a very flexible way of thinking about macroeconomic analysis that can be applied to every economic tradition.[6] While accounts are specified by international standards, economic traditions and theories differ in their behavioral assumptions and closures:

- Neoclassical theorists propose as behaviors that firms maximize profits, while consumers maximize utility, given their budgets and the prices for goods and services. Neoclassical models are closed by adjusting prices to achieve a "general equilibrium" in which all markets clear. Temporary departures from equilibrium are captured through "sticky" prices and wages.
- Post-Keynesian theorists in the Kaldorian tradition[7] assume that prices adjust to close the accounts, but unlike in neoclassical theory, the adjustment takes place through firm markups on labor costs, so the effect is to change the distribution of income between wages and profits.
- Post-Keynesian theorists in the Kaleckian tradition[8] argue that the level of economic activity adjusts to close the accounts, thus explaining booms and recessions.
- Classical theorists focus on the long run, arguing that in that case it is possible to assume full use of capital when saving equals investment. Saving is determined by the functional income distribution and saving propensities out of wages and profits. Firms are assumed to compete for investment funds, which results in a uniform rate of profit.

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[6] While he did not call it the "ABC approach", this is the method used by the economist Lance Taylor in his book *Reconstructing Macroeconomics: Structuralist Proposals and Critiques of the Mainstream*.

[7] After Lord Nicholas Kaldor, British economist and pioneer of macroeconomic modeling.

[8] After Michał Kalecki (KA-lets-ki), Polish economist and contemporary of Keynes.

2. A CLASSICAL MODEL OF GROWTH AND DISTRIBUTION

To illustrate and apply macroeconomic concepts, we develop a model along classical lines, although we relax the assumption of a uniform rate of profit. In fact, rates of profit vary from one sector to another depending on the degree of market concentration. We choose a classical model for a practical reason: classical theorists tend to make simpler behavioral assumptions than either neoclassical or post-Keynesian theorists. It is therefore easier to follow the analysis and understand how the assumptions lead to the results. A further, theoretical reason to choose classical theory is that green macroeconomics is often applied to analysis of long-run sustainability, for which a classical analysis is well suited. However, *caveat lector*: let the reader beware. Both neoclassical and post-Keynesian theorists can point to potential pitfalls of classical theory, and for some purposes (for example, exploring "green" policy responses to recession or the impact of "green" taxes) other approaches may be preferable.

Neoclassical theorists object to classical theorists' emphasis on institutions and norms as determinants of the functional income distribution, arguing that classical theorists downplay the role of markets. Neoclassical theory assumes that profits, wages, and goods prices are determined in competitive markets for investment funds, labor, and goods, where profit-maximizing firms choose their production technique from a set of possibilities described by an aggregate production function and households choose between leisure, on one hand, and labor and consumption, on the other, in order to maximize "utility".[9]

Post-Keynesian theorists argue that by focusing on the long run, classical theorists miss the possibility that the responses to short-term disequilibrium can lead to a different outcome, resulting in path-dependent growth. They also point out that history has numerous examples in which capital was underutilized for long periods of time – for example, the Great Depression, Russia after the dissolution of the Soviet Union in 1991, and to a lesser degree the recent Great Recession that followed the 2007-2008 financial crisis.

From these comments, it is clear that different theoretical traditions have quite different visions of how economies work. The reader may find that frustrating. Certainly many economists have felt that way, and prefer to develop their work based on one school of thought. Since at least the mid-1970s, neoclassical economics has dominated the economic mainstream. It has accommodated imperfect markets and added other realistic features while maintaining the core assumption that macroeconomic outcomes are the aggregate result of individual optimizing behavior. However, neoclassical dominance has not stopped ongoing research in post-Keynesian and classical theory, as well as Sraffian (or neo-Ricardian)[10], Marxian, evolutionary, structuralist, Austrian, and other traditions. Meanwhile, even within neoclassical economics there are signs of dissent, with challenges from behavioral economics and New Growth Theory, the rise and fall of monetarism (see Box 3), widespread disillusionment following the 2007-8 financial crisis, and an ongoing split between New Classical and New Keynesian theorists.

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[9] Utility, the quantity that households are supposed to maximize, is not observable but in theory can be inferred from behavior. In practice, utility is usually assumed to be an increasing function of both consumption and leisure that exhibits diminishing returns. That is, a dollar increase in consumption provides less utility for someone whose consumption level is already high than it does for someone whose consumption is low.

[10] Piero Sraffa, an Italian economist, sought to redefine economic analysis using concepts first developed by classical economist David Ricardo, seeing the origins of economic value as arising from the structures of production and distribution rather than the workings of markets.

BOX 3: IS-LM, MONETARISM, AND THE NEW CONSENUS MODEL

For roughly a quarter-century, starting in the 1950s, macroeconomic policy analysis was dominated by the "neoclassical synthesis", a compromise between Keynes and the "classical" (actually neoclassical) economists that he criticized. The core of the synthesis is a set of intersecting supply and demand curves proposed by the British economist Sir John Hicks. The axes on Hicks' graph are GDP and the interest rate. The interest rate is both the cost of borrowing (to firms) and the returns to lending (by banks or households). An upward-sloping supply curve (the LM curve) represents "liquidity" or the quantity of money circulating in the economy: the higher the interest rate, the greater the supply of liquidity. A downward-sloping demand curve (the IS curve) represents investment and consumption: high interest rates discourage borrowing, so a falling interest rate stimulates investment demand and growth. The intersection of the two curves gives an equilibrium for the size of the economy and the interest rate.

From the 1970s, the experience of combined stagnation and inflation, called "stagflation" led to dissatisfaction with the neoclassical synthesis and, more generally, the "Keynesian" models of the time. (Post-Keynesians object to calling them Keynesian.) Milton Friedman, who was awarded the Nobel Memorial Prize in Economic Sciences in 1976, provided an alternative "monetarist" theory of inflation. He relied on an equation that expresses GDP in nominal terms (that is, not corrected for inflation) in two ways. On one hand, it is the general price level, P, multiplied by the real GDP, Y. On the other hand, it is the quantity of money, M, multiplied by the velocity of money, V,

$$PY = MV.$$

Friedman turned this identity into a theory by proposing that the velocity, V, is, for all practical purposes, a constant. Because real output is determined by the productive capacity of the economy, the price level P, and therefore the inflation rate, is determined by the quantity of money, M. Friedman famously wrote, "Inflation is always and everywhere a monetary phenomenon in the sense that it is and can be produced only by a more rapid increase in the quantity of money than in output."

Monetarism rose rapidly in prominence and then gradually faded. Today there is a general if not universal understanding that the central bank (in the US, the Federal Reserve) sets an interest rate rather than a quantity of money. This is captured in the "New Consensus Model", which is a variant of IS-LM. The New Consensus Model includes three behavioral relationships. First, real output is a declining function of the central bank interest rate. Second, the inflation rate increases with the size of the economy relative to an equilibrium level (the Phillips curve). Third, a central bank rule balances two goals: high growth and low inflation.

While these topics are important, they are not our main interest. Moreover, these are not the only theories of money and interest. In this module we focus on biophysical constraints to growth and distribution and do not discuss inflation or monetary policy. The interested reader can consult the references at the end of the module.

In this module we take a "pluralist" approach, arguing that this kind of fragmentation is normal within social science. The study of societies is notoriously difficult, not least because their members can read what researchers say about them and change their behavior as a result. Members of a society reproduce the structure of their society in each generation, but they also modify it. So, while social structure exhibits a great deal of persistence, it also changes over time. Given the nature of societies, it is unreasonable to expect that any one social theory – including any single economic theory – will be suitable for all purposes at all times. We recommend that the student read economic history and learn about a variety of schools of thought. With that understanding, he or she will be in a much better position to choose an appropriate theoretical framework for the problem at hand. A list of readings is offered at the end of this module.

2.1. Constructing a Simple Model of the Economy

We consider a very simplified case: a one-sector closed economy with no government in which the single sector produces goods and services for both consumption and investment. The economy has two inputs to production, capital and labor. As we discuss below, we assume that the labor supply is flexible enough that it does not constrain economic growth, and focus our attention on the accumulation of capital.

We start by writing gross domestic product (GDP), or the total final output of the economy, in three different ways. First, we express GDP (which we denote by the symbol Y) as the total value of goods and services produced. That is, it is the sum of the value of consumption goods and services, C, and investment goods, I,

$$Y = C + I. \tag{1}$$

We neglect rents at this point, so firms distribute the income they receive from selling their output as wages, W, and profits, Π (the capital Greek letter "pi"). Thus, GDP can also be written

$$Y = W + \Pi. \tag{2}$$

The functional income distribution indicates how GDP is shared out between wages and profits. We use the Greek letter omega (ω) to represent wages as a share of GDP, and lower-case pi (π) to represent profits as a share of GDP. Dividing equation (2) by Y, we then have

$$1 = \omega + \pi. \tag{3}$$

Part of wages and profits is used for consumption, C, while the rest is saved, in an amount S, which gives us a third and final expression for GDP,

$$Y = C + S. \tag{4}$$

Note that the value of consumption expenditure is equal to the value of consumption goods sold, so although the "C" in equation (1) is conceptually different than that in equation (4), they have the same value and are represented by the same letter. Combining the two equations, C cancels on each side, and we find, as a matter of accounting, that saving must equal investment[11]:

$$S = I. \tag{5}$$

This is the accounting relationship that we used as an example in the introduction.

2.2. Investment and the Accumulation of Capital

When firms purchase investment goods, they add them to their existing capital stock. They also discount their existing stock due to depreciation. Therefore, capital stock in the next period, K_{+1}, is equal to the current value of the capital stock, K, plus current investment, I, less depreciation, which we write as the depreciation rate, δ, multiplied by the value of the current stock,

$$K_{+1} = K + I - \delta K. \tag{6}$$

The growth rate of the capital stock, g, net of depreciation, is the difference between the next-period and current-period stock divided by the current stock,

$$g = \frac{K_{+1} - K}{K} = \frac{I}{K} - \delta. \tag{7}$$

The process of capital accumulation leads to exponential growth of the capital stock at the rate g. We showed in equation (5) that saving must equal investment. We use that equation to close the model, and propose a behavioral relationship for saving, in which a fraction s_w is saved out of wages going to households, with s_π saved out of total profits, including both the profits retained by firms and profits distributed to investors. While these fractions may change over time, we treat them as **exogenous** parameters – that is, they are determined outside the model. (The variables that are determined within the model are **endogenous**.) Total saving, S, is then given by

$$S = s_w W + s_\pi \Pi. \tag{8}$$

Put in terms of the functional income distribution, we can write W as ωY, and Π as πY, so

$$S = \left(s_w \omega + s_\pi \pi\right) Y. \tag{9}$$

The shares ω and π of the functional income distribution sum to one, as shown in equation (3) – an accounting relationship. We can use that relationship to eliminate π and express saving entirely in terms of the wage share,

$$S = \left[s_\pi - \left(s_\pi - s_w\right)\omega\right] Y. \tag{10}$$

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[11] More generally, "leakages" of money from the domestic spending cycle must equal "injections" of expenditure. Allowing for trade and a government sector, leakages include private saving, S, imports, M, and taxes, T. Injections include investment, I, exports, X, and government expenditure, G. Equating leakages and injections gives the expanded accounting relationship $S + M + T = I + X + G$.

From the discussion of behavioral norms in the introduction, we expect saving out of profits to exceed saving out of wages. So, $s_\pi - s_w$ should be positive, implying that total saving decreases when the wage share increases.

To find the growth rate in equation (7), we need an expression for I divided by K, but because we are closing the model by requiring saving to equal investment, we can replace I/K by S/K. Combining equations (7) and (9), the growth rate can be shown to equal

$$g = \left[s_\pi - \left(s_\pi - s_w\right)\omega\right]\frac{Y}{K} - \delta. \tag{11}$$

This expresses the growth rate of the capital stock in terms of the functional income distribution (ω); saving behavior for wage and profit earners (s_w and s_π); the rate of capital depreciation (δ); and the ratio of GDP to the capital stock (Y/K). The last of these factors, the ratio of GDP to the capital stock, is called **capital productivity**, and we turn to it next.

2.3. Capital and Labor Productivity

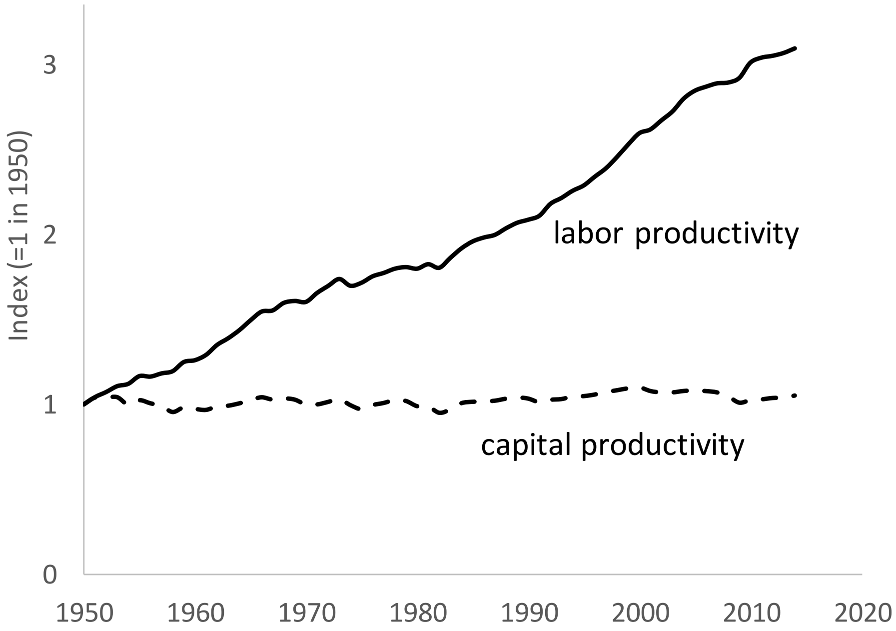
For any input to production, the productivity of that input is calculated as GDP divided by the value of the input. So, for example, US GDP in 2017 was about 20 trillion dollars per year. In the same year, average seasonally-adjusted nonfarm employment, as reported on payrolls by businesses, was about 150 million people, or just under half the population. Average labor productivity is given by GDP divided by employment, which comes to about 130 thousand dollars per person per year. The value of the capital stock was around 60 trillion dollars, so dividing GDP by the capital stock gives a capital productivity of around 0.3 per year.

A strong regularity across time and between economies is that labor productivity tends to grow, while capital productivity remains relatively stable; this is illustrated for the US in Figure 3. One explanation for this tendency starts with the observation that investors tend to compare the profit rates on offer; that is, the ratio of profits to capital. The profit rate can also be written as the profit share, π, multiplied by the capital productivity,

$$r \equiv \frac{\Pi}{K} = \frac{\Pi}{Y}\frac{Y}{K} = \pi v. \tag{12}$$

Suppose that capital productivity were to fall. Then to maintain their profit rate, firms would raise the profit share at the expense of wages. When the cost of an input rises relative to other costs, firms have an incentive to reduce the use of that input. This is the thought behind the concept of **cost-share induced technological change**. Under this mechanism, a rising profit share would encourage greater savings of capital, encouraging firms to raise capital productivity, offsetting the initial decline. That creates a negative feedback that tends to keep capital productivity from falling.

***Figure 3**. Trends in labor and capital productivity in the US from 1950 to 2014*



Source: Penn World Tables 9.0

A complementary negative feedback tends to keep capital productivity from rising. If it were to rise, generating a higher profit rate, then it would attract competitors, while wage-earners would push for a share of the increased revenue. To discourage competitors and encourage workers, firms would raise the wage share at the expense of profits. That would depress the profit rate. Firms would favor labor productivity growth at the expense of capital productivity, which would tend to fall back to its original position. This pair of negative feedbacks tends to keep capital productivity relatively stable.[12]

While not a hard-and-fast rule (and also noting that comparatively small variations in capital productivity can make a significant difference in people's lives) constant capital productivity combined with growing labor productivity is a reasonable starting assumption. The post-Keynesian economist Nicholas Kaldor referred to these as "stylized facts" about economies.

For this exercise, we assume that Kaldor's stylized fact of constant capital productivity holds. That means that economic output, Y, cannot exceed the level determined by capital productivity, v, multiplied by the capital stock K, which we assume to be valued at replacement cost (see Box 4 on pricing capital stocks and the use of production functions). Output also cannot exceed the level determined by the labor productivity, which we denote by the Greek letter lambda (λ), and the labor force, L. We therefore have

$$Y \leq \min(vK, \lambda L). \tag{13}$$

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[12] This argument draws on the author's recent research.

BOX 4: PRICING CAPITAL STOCKS AND THE USE OF PRODUCTION FUNCTIONS

We simplify our model by suppressing prices. Implicitly, this means that we assume that both consumption C and investment I are given in terms of a homogeneous good with a uniform price. While this is somewhat unrealistic, maintaining separate prices for different goods would add complexity without providing much insight. We expect the price to change over time through inflation, but because inflation affects all values equally, it does not matter for most of the variables in the model.

Where inflation can matter in our model is in the value of capital stocks, because capital used today was bought in the past. That means that the price at which it was bought was different from the current price. The difference, which is quite relevant to businesses, is reflected in two ways of recording capital stock on company books: at *historical cost* or *replacement cost*. In this analysis, we assume replacement cost. That is, the value of the existing capital stock K is the cost of replacing it at the price that holds for current investment goods I. That assumption allows us to ignore the price when comparing consumption and investment goods, and also when comparing current investment with existing capital.

We use “price of capital stocks” to mean the price of the physical investment goods, such as buildings and machinery. That is how the value of capital stocks enters into business ledgers, and is the way we treat it in this analysis. However, the profit rate that investors expect to receive in return for their investment is also sometimes referred to as the “price of capital”. That brings us to a controversial subject.

Most texts would refer to the right-hand side of (13) as a Leontief or fixed-coefficient production function. We do not do that, because the production function is a neoclassical concept (generally a smooth function, such as the Cobb-Douglas or constant elasticity of substitution, or CES) and both Sraffian and post-Keynesian economists object to the use of production functions.
Capital is extremely heterogeneous, a point that has been emphasized by the MIT economist Franklin Fisher. It includes chemical reactors, buildings, generators, roads, weaving machines, printing presses, and so on. A “quantity of capital” can only be defined if all of those are priced and added up to give a money value. But in neoclassical theory, the price of capital is derived from its marginal contribution to output as captured by a production function. That is circular reasoning, as shown by Piero Sraffa: the price determines the quantity of capital, but the quantity of capital determines the price.

Neoclassical theorists sometimes respond that they use production functions because they “work”, in that statistical tests of production functions give excellent results for goodness-of-fit. But an extraordinarily good fit when none should be expected can be a warning sign in statistics. The tests might be confirming an underlying identity, not testing a model. This was first argued by Phelps Brown in 1957 for the production function and has been confirmed multiple times since then. The arguments against the use of production functions are laid out in detail in the book *The aggregate production function and the measurement of technical change: “Not even wrong”* by Jesus Felipe and John McCombie.

We make two assumptions that are commonly applied to classical models: first, additional labor is always available, so it does not constrain output; second, the economy runs at full capacity. Other assumptions are appropriate during recessions or booms.[13] With these assumptions,

$$Y = vK. \tag{14}$$

Combining this equation with the expression for the growth rate in equation (11), we find

$$g = \left[s_\pi - \left(s_\pi - s_w\right)\omega\right]v - \delta. \tag{15}$$

This is an estimate for the growth rate of the capital stock. Because we assume a constant capital productivity, it is also the growth rate of GDP.

At this point it is helpful to anchor the analysis to the real world by putting in some numbers. In recent years in the US[14], the personal saving rate has been about $s_w = 7\%$, while employee compensation as a share of GDP (that is, the wage share) has been close to 53%, corresponding to a profit share of $\pi = 47\%$. Gross private saving as a share of gross national income is near 22%. That is the quantity in square brackets in equation (15), so we can calculate the rate of saving out of profits to be $s_\pi = 39\%$.

Capital productivity has been about 0.32 per year, while the depreciation rate has been close to 4.7% per year. Inserting these figures into equation (15) gives an estimate for g of 2.3% per year. That estimate is close to, but slightly higher than, the average GDP growth rate of 2.1% per year in the post-Great Recession recovery period from 2011 through 2017.

2.4. The Cambridge Equation

Saving out of wages is relatively small, and a common approximation in classical and post-Keynesian theory is to set it to zero. Setting $s_w = 0$ in equation (15) gives a version of the so-called "Cambridge equation". The equation is normally written in terms of the profit rate, which is defined in equation (12). With this definition and setting $s_w = 0$ gives the relationship

$$s_\pi r = g + \delta. \tag{16}$$

The right-hand side of this equation is the gross rate of increase in the capital stock.

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[13] Neither assumption is true in an economy like that of the US, but we are taking a long-term view that smooths over business cycles. In the short run, labor supply becomes constraining during an expansion as unemployment falls. Workers gain bargaining power relative to employers (a classical or post-Keynesian view) or firms must offer incentives to unemployed workers to give up leisure time (a neoclassical view), so the wage rate tends to rise, which pushes up prices (inflation) as firms pass on the costs to consumers. The Federal Reserve may then raise interest rates (and therefore firms' borrowing costs) in an attempt to slow the expansion (see Box 3). In recessions and depressions, output falls below capacity. The Federal Reserve may then lower interest rates to stimulate investment, while the federal government may increase expenditure to drive up demand (a "stimulus").

[14] Personal and gross private saving rates: 2011-2017 averages from the Federal Reserve Economic Data (FRED) database; Employee compensation: 2011-2017 average from the US Bureau of Economic Analysis (BEA) Table 1.11, "Percentage Shares of Gross Domestic Income"; Capital productivity and depreciation rate: 2011-2014 averages from the Penn World Tables 9.0.

Equation (16) is a balance in which the left-hand side is saving and the right-hand side is investment. As a balance, this equation says nothing about causality – that is, about behavior. A "supply-led" theory would assume that saving leads investment, so causality goes from left to right. This is a form of "Say's Law"[15], which states that supply creates its own demand. Post-Keynesians argue that while Say's Law was relevant to the agricultural economies of his time, modern industrialized economies are "demand-led", with investment leading saving. In that case, the causality in equation (16) goes from right to left.

We will follow the post-Keynesian path and say that investment determines saving. Profit-earners can choose their rate of saving, s_π, so the profit rate, r, is determined by the growth rate. Growth of the economy is ultimately bounded by the rate of increase in labor productivity and the expansion of the labor supply, as shown in equation (13). This is called the "natural rate" of growth g_n. We therefore set $g = g_n$ and rearrange equation (16) to derive the Cambridge equation[16],

$$r = \frac{g_n + \delta}{s_\pi}. \tag{17}$$

This equation suggests that, given the growth rate of the labor force and labor productivity growth, the profit rate is determined by the saving propensity of profit-earners. The lower the saving rate, the higher the profit rate. From a saving-led growth perspective this might seem surprising. Higher saving ought to lead to higher investment and thus higher profits. However, in equation (17) we have assumed that the economy is growing at its maximum rate as determined by technological potential (labor productivity growth) and growth of the labor force. Implicitly, we assume that firms are investing at the level that maintains growth at the maximum rate. Any saving beyond that level cannot be absorbed, so to bring saving and investment in line, some variable must adjust. In Kaleckian post-Keynesian models, output falls when savings cannot be absorbed – this counter-intuitive result is called the "paradox of thrift". In contrast, equation (17) is consistent with Kaldorian post-Keynesian theory, in which the functional income distribution – e.g., the wage share – adjusts to make saving equal to investment.

We might ask what happens as the saving rate approaches zero. Can profit earners really decide their share of profits based only on their saving behavior? Yes and no. The interpretation of the Cambridge equation is that *given* a potential growth rate of the economy g_n, and a saving rate s_π, the only profit rate consistent with full utilization of the available capital stocks is given by equation (17). It is a long-run equilibrium outcome that ignores the details of how the equilibrium is reached. If the saving rate falls and the profit rate rises, then at some point the profit share will become extremely high and the wage share extremely low. Presumably the extreme inequality would create social stress, but the Cambridge equation tells us nothing about how that stress might be resolved.

The Cambridge equation is a convenient expression for drawing broad conclusions about long-run possibilities, but it is not universal: it only holds when wage-earners do not save and in a long run

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[15] After the 19th Century French economist Jean-Baptiste Say.

[16] There is more than one "Cambridge equation". This one was introduced by the Sraffian economist Luigi Pasinetti and much discussed by post-Keynesian economists in Cambridge, UK. In most presentations, g_n is gross of depreciation rather than net as we show here, so the usual formulation is $r = g_n/s_\pi$.

in which the economy operates at full capacity and grows at the natural rate. Later, we will derive a "green" version of the Cambridge equation.

3. EMBEDDING THE ECONOMY IN THE ENVIRONMENT

The model we just developed features exponential growth at a rate g indefinitely into the future. Green macroeconomists object to this, because if exponential growth in GDP means exponential growth in resource use and other demands for provisioning and regulating **ecosystem services**[17], then the model cannot possibly hold forever on a finite planet. In this section we introduce some links between the macroeconomy and the environment, and in the next section we use them to extend the classical model to take into account the issue of physical limitations on growth. But first we take a detour into the past.

The ancient Mesopotamian civilization of Sumer, where the oldest known economic accounts appeared, was an agricultural economy, rather than an industrial economy as we have been supposing. But we can learn something from their experience. Sumerian temple complexes would distribute seed for consumption, while retaining some for the next season's planting. The ratio of seed harvested to seed sown could exceed 30, providing a considerable surplus to support the many non-agricultural activities found in Sumerian society. By contrast, grain ratios near classical Rome were around 5 seeds harvested per seed sown. The city relied on Egypt, with its 10-27-fold yields, for about a third of its grain supply and supported its many activities through an extensive empire, slave labor, and trade. Given the thermodynamic constraint that useful energy output must be less than the energy input, the existence of any surplus at all in agriculture is because the major energy input into the system – sunlight – is considered to be freely provided by nature, and is not accounted for. By contrast, some of the useful resource (the seed) must be diverted to produce more of the resource, and must be accounted for.

Agricultural economies like ancient Sumer provide some general lessons about physical limits on economic activity: 1) a surplus over and above essential material needs exists because of captured sunlight and 2) extracting resources requires some expenditure of resources. These principles hold true, with some modifications, for all economies. Rome met its material needs by expanding its footprint through greater use of resources. Modern economies follow the same strategy, while relying on other resources: the decay of radioactive atoms in the earth's crust for geothermal and nuclear energy and fossil deposits of energetically rich carbon-based compounds created through a combination of ancient captured sunlight and geological processes.

Those fossil deposits provide us with **fossil fuels**. The sunlight was captured hundreds of millions of years ago, through early photosynthetic plants. Before bacteria evolved that could consume the plants, they were buried relatively intact, providing a rich reservoir of captured carbon. Radioactive elements in the earth kept the interior hot (and still do), driving the formation of mountains, which were then weathered by wind and rain (themselves driven by sunlight), to bury the carbon stores ever more deeply. Under great pressure from the layers of rock above them, and under intense heat, the carbon and other elements in the plants underwent chemical changes that

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[17] Ecologists identify four broad types of services that ecosystems provide to people: provisioning, regulating, habitat/supporting, and cultural. Provisioning services include raw materials and food; regulating services include carbon sequestration and waste-water treatment; habitat/supporting services include genetic diversity; and cultural services include recreation and aesthetic appreciation.

produced energetically dense compounds. We extract those compounds as coal, crude oil, and natural gas, from which we produce fossil fuels.

3.1. Energy Return on Energy Invested (EROI) and Net External Power Ratio (NEPR)

When crude oil was first extracted, the reserves were relatively close to the surface and were under great pressure. It took energy to build the oil rigs and to drill down to the deposits, but once high-pressure deposits were reached, the oil rose of its own accord, sometimes creating spectacular (and dangerous) “gushers” that sprayed oil high into the air. Despite the accessibility of early oil deposits, equipment was inefficient and oil was wasted. Since the first oil production in the 1860s, the energy produced per unit of energy expended (**energy return on energy invested**, or EROI[18]) has been driven upward by improvements in technology and downward as easily-accessed resources were exhausted. The net effect has been a rise and then fall in EROI, with a peak close to the middle of the 20th century.

The same patterns can be seen for other fossil fuels, although the EROI for coal may not have reached its peak. While estimates vary, one long-run historical study[19] put the EROI of all fossil fuels at between 10 and 20 in 1800, peaking around 35-40 near 1970, and gradually declining since then, to roughly 30 today. This is close to the Sumerian ratio of seed harvested to seed sown. Fossil fuels are much better energy carriers than grain, and engines convert fossil energy into productive work much more efficiently than animals or humans convert food, but in terms of the ratio of resources produced per unit of resource applied, we are not far from the early Mesopotamian civilizations.

While EROI – the energy return on energy invested – seems to be conceptually clear, in fact there are different ways to define it. It always includes the energy used to extract energy, which should account for energy used in building the extractive equipment, but might also include energy used in processing and transportation to the point of use (point-of-use EROI, or EROI_{pou}). It can also include the energy used to build the infrastructure for transport, such as roads and pipelines (external EROI, or EROI_{ext}).

These energy lifecycle concepts are important to a full understanding of the role of energy in the economy, but are too complex for the kind of analysis we carry out in this module. Instead, we will use the **net external power ratio** (NEPR), defined as

$$\text{NEPR} = \frac{\text{Annual Energy Production} - \text{Energy Industry Own-Use}}{\text{Energy Industry Own-Use}}. \tag{18}$$

This is called a “power” ratio rather than an “energy” ratio because it refers to the energy produced or used within a year, and power is energy use per unit of time. For example, electricity generating stations are characterized by the power they can produce, in millions of watts (megawatts, MW), while energy usage in the home is measured in thousands of watt-hours (kilowatt-hours, kWh);

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[18] EROI was introduced by the biophysical and ecological economists Cutler Cleveland, Robert Costanza, Charles Hall, and Robert Kaufmann.

[19] Court et al., 2017.

see Table 1 for a list of common energy units. The NEPR for all types of fossil energy in the US gradually fell from 9.6 in 1960 to 8.7 in 2010.[20]

Table 1. Common energy units

Name	Symbol	Equivalent	
Joule	J	1	kg m^2/s^2
Megajoule	MJ[a]	10^6	J
kilowatt-hour	kWh	3.6	MJ
British thermal unit	Btu	1055.06	J
Millions of Btus	MBtu	10^6	Btu
Barrel of oil equivalent	boe[b]	5.80	MBtu
Tonne of oil equivalent	Toe	39.68	MBtu
Tonne of coal equivalent	Tce	27.8	MBtu

[a] Also Gigajoules (GJ = 10^9 J), Terajoules (TJ = 10^{12} J), Petajoules (PJ = 10^{15} J), and Exajoules (EJ = 10^{18} J).
[b] The "barrel" is a measure of volume. The plural, "barrels" is often written "bbl".

For renewable energy sources the EROI concept is usually more appropriate than NEPR. Many renewables, including wind, solar, and hydropower, are passive – they need negligible amounts of energy to operate. Most energy inputs are upstream, during construction, so the EROI concept is more suitable. Biofuels are also best treated using EROI. The first-generation biofuels are agricultural crops like soybean, corn (maize) or sugarcane. Energy is used in processing the crops to produce biodiesel and ethanol; that is the energy that would go into a NEPR assessment. But modern agriculture has high upstream fossil fuel inputs as well for fertilizer and machinery, so again a lifecycle approach is more appropriate. Second-generation biofuels, which use cellulose as an input, can potentially be treated using NEPR, depending on how the crops are produced. They require more energy to convert to ethanol, but by making use of the stalks and woody parts of plants, second-generation biofuels require less upstream energy.

While EROI is more relevant than NEPR for most renewables, we nevertheless use NEPR to simplify the analysis. NEPR only counts energy consumed to produce energy at the time it is produced, but for a long-run analysis we can think of it as EROI spread over the lifetime of the energy-producing equipment.

A 2009 survey of EROI estimates for wind found an average of 19.8 for turbines in operation.[21] Moreover, the same study found an EROI of 25.2 when conceptual designs were included, illustrating the potential for efficiency gains to raise output and therefore EROI over time. For solar photovoltaics (PV), EROI estimates vary widely. One survey reported estimates between 8.7 and 34.2, with the differences due mainly to upstream energy inputs.[22] These are reasonably high values. In contrast, estimates of EROI for corn ethanol in the US are very low. One survey found estimates from ranging from 0.8 to 1.7.[23] Other bioethanol sources perform better. Sugarcane has a relatively high EROI, with one estimate placing it at 10.2.[24] Second-generation biofuels tend to

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[20] King et al., 2015.
[21] Kubiszewski et al., 2010.
[22] Bhandari et al., 2015.
[23] Hammerschlag, 2016.
[24] Goldemberg, 2007.

perform better than US-based corn ethanol. However, estimates vary widely depending on the feedstock. The technologies are still in development, so efficiencies can be expected to improve over time.

For fossil resources we expect the ratio – EROI or NEPR – to fall over time. As fossil reserves are depleted, more energy is required to extract a given quantity of the resources. Improvements in extraction technology can raise EROI or NEPR, but the long-run trend is downward. For renewable energy sources we assume that NEPR takes a moderate value (e.g., close to 10) and does not either rise or fall very far over time. As with fossil fuels, the best sources of renewable materials are likely to be exploited first, so the incremental energy gains will fall as total renewable energy supply expands, but we will treat this as a constraint on the amount of energy available each year rather than a trend towards lower NEPR.

3.2. Climate Change

One of the most crucial regulating services that the world's ecosystems provide is absorption of carbon from the atmosphere. When carbon-rich fossil fuels are extracted and combusted they provide useful energy and, as a by-product, carbon dioxide (CO_2). Carbon dioxide has the property that it is transparent to visible light but opaque to infrared radiation. When visible light from the sun passes through the atmosphere, some of it lands on the earth and warms it up. The warm surface of the earth emits infrared radiation, some of which is intercepted by carbon dioxide and other "greenhouse gases". Greenhouse gases then re-radiate some of the infrared radiation back towards the earth, making it even warmer.

Without the greenhouse effect, the earth would be much colder (average global temperature would be lower by about 60°F or 32°C), so we certainly benefit from it. However, as we raise the concentration of CO_2 and other greenhouse gases in the atmosphere through our activities, we warm the earth. Warmer sea and land surfaces put more energy into the climate system, creating more intense storms. As temperatures rise, more water vapor enters the atmosphere, forest fires become more frequent, plant growth is affected, and sea levels rise as water in the oceans expands. Higher temperatures near the poles lead to melting ice sheets (which raises sea level even further) and melting permafrost (which releases methane, a potent greenhouse gas). Warm temperatures mean less sea ice at the North Pole. That affects arctic ecosystems, but it also means that more sunlight is absorbed, which leads to further warming.

We rely on the oceans to absorb much of the CO_2 that we emit – a regulating ecosystem service. But our use of that service is placing pressure on oceans. The carbon dioxide that the oceans absorb from the atmosphere combines with water (H_2O) to make carbonic acid (H_2CO_3), thereby raising the acidity of the oceans ("ocean acidification"). Combined with higher ocean temperatures, ocean acidification has harmful effects on marine life. What is more, as the acidity of the oceans increases, they become less able to absorb carbon dioxide, so our use of the oceans today as a reservoir for CO_2 means that they will be a less effective reservoir for future generations.

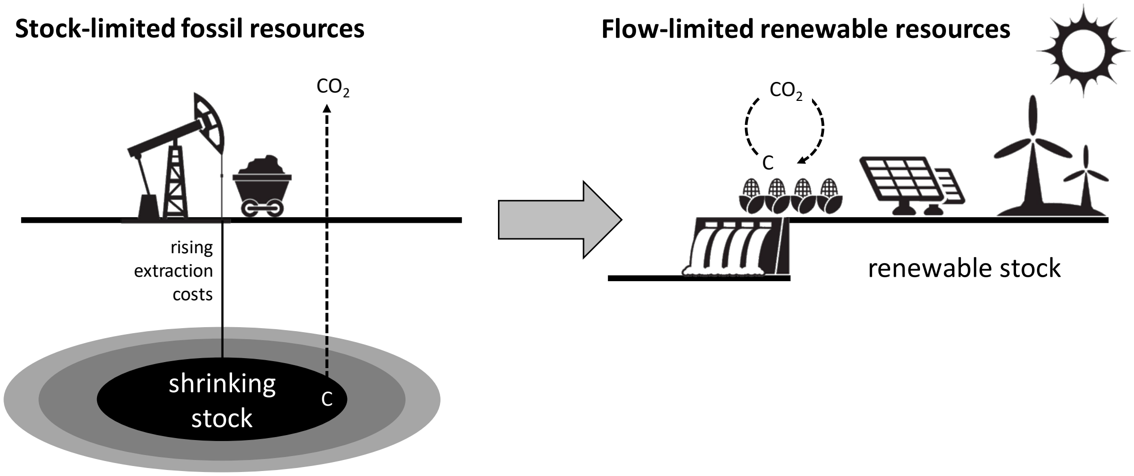
If we are to mitigate these and other impacts from fossil fuel combustion, we must rapidly and dramatically curtail our use of carbon-rich fossil fuels and replace them with carbon-neutral or zero-carbon energy sources. These certainly include renewable energy and, more controversially, could also include nuclear power and carbon capture and sequestration (CCS) combined with carbon-intensive energy sources. We must also transform industrial processes that produce carbon dioxide, such as steel and cement production.

This process of "decarbonization" will likely require substantial changes to the ways that we produce and consume and is an area of active research in green macroeconomics. One major change is that it would almost certainly accelerate the transition to renewable sources of energy and materials. That raises the question of the potential supply from renewable resources.

3.3. Renewable Resources

Unlike fossil resources, the supply of renewable resources can be maintained indefinitely, but there is a limit to how much can be produced each year. These crucial differences are illustrated in Figure 4.

Figure 4. Differences between fossil and renewable resources



Ultimately, renewable energy is driven by sunlight. Sunlight is captured directly by solar PV and by ecosystems' "primary producers" during photosynthesis. It is captured indirectly by wind and hydropower due to sunlight driving the climate. The energy flux from the sun per unit of area when it reaches the earth's upper atmosphere is called the solar constant. It is equal to 1366 watts per square meter (W/m^2). The watt is a measure of power, or energy per unit time, and is equal to one Joule per second. (For common energy units see Table 1 on page 23.) There are 365 days × 24 hours/day × 3600 seconds/hour = 31,536,000 seconds per year. Multiplying that by the solar constant gives the total annual energy reaching the top of the atmosphere as 43 billion joules per square meter (J/m^2). The earth's radius is about 6,370,000 meters. The earth is a sphere, but from the point of view of the light reaching it from the sun it appears as a disk blocking the way with area $\pi \times (6{,}370{,}000)^2$ m^2. Multiplying that by energy per unit area, we find the total energy incident on the earth each year to be 5.5×10^{24} J. That is a very large number, so we put it in a more convenient unit, the exajoule (EJ), equal to 10^{18} J. We estimate the energy reaching the top of the atmosphere each year as 5,500,000 EJ.

We now ask how that number compares to world total energy supply. Total supply is what we extract for all purposes, both for producing energy and for our own consumption. In 2015 that was just over 550 EJ, so the energy reaching the top of the atmosphere is 10,000 times what we are currently consuming. It seems like we have plenty of available solar energy. But do we?

To extract the energy that reaches the top of the atmosphere we would have to put a massive solar collector array in space that would form a sort of umbrella over the earth. Not all of the energy would be converted to electricity – solar PV efficiencies vary widely, from around 10% to 50%. However, even at 10% efficiency we would have 1000 times what we are currently using.

But an umbrella over the earth would be devastating. No sunlight would reach the planet's surface, so there would be no driver for the climate and no photosynthesis. It would be a cold, dead world. For us to have a world to live in, sunlight must reach the surface of the earth. As it passes through the atmosphere, some will be reflected or absorbed and reradiated back to space. Of the sunlight that reaches the earth, most will fall on the oceans because they cover most of the earth's surface where some will be absorbed by plankton, the major primary producers of ocean ecosystems. Some of the light reaching the land surface will also be taken up by primary producers, such as green plants and algae. Over both ocean and land, much of the energy will drive the climate, providing wind, snow and rain.

We can extract only a portion of that energy. There are massive amounts of energy in ocean currents and waves, but it is difficult to extract it even near coasts. For wind energy, even the largest turbines must be comparatively close to the earth's surface. Solar arrays are promising because they can cover rooftops, areas near freeways, and other features of the built environment. They can also be placed in deserts. Nevertheless, as we discuss below, we cannot extract the full potential.

The use of photosynthesis by plants and other photosynthesizers to capture solar energy, other than what they need for their own respiration, is called Net Primary Production (NPP). Using bioenergy requires us to appropriate part of NPP, and we are already placing great pressure on ecosystems through other forms of NPP appropriation such as agriculture and forestry. One estimate gives a mean value of human appropriation of terrestrial (not ocean) net primary production (HTNPP) as 32% of the total.[25] The uncertainties in this analysis are very large, and the estimates ranged from 10% to 55%, but this is in any case a very large proportion for a single species. If we are to protect ecosystems while still producing enough food for a growing global population, then the amount of energy we can extract from plants and animals will be limited.

A further challenge arises when transporting the energy from where it is produced to where it will be used. Renewable energy sources are typically dispersed and intermittent. That is, the energy must be collected from over a large area or from a large distance, and it is not always available. For example, solar arrays can be placed in deserts to produce extremely large quantities of electricity, but the transmission and distribution network is costly and transmission losses increase with distance.

There are considerable uncertainties over the size of the sustainable renewable energy resource. Technological advances can push the boundary outward, but ultimately, thermodynamic limits on

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[25] Rojstaczer et al., 2001.

collection and transmission of renewable energy will place a cap on the total available each year. The International Renewable Energy Agency (IRENA) emphasizes the need for reductions in energy demand to accompany the expansion of renewable sources.[26] One estimate for wind power found a potential of just under 300 EJ per year when land constraints are taken into account.[27] Solar energy potential is large, but technically challenging. For example, if 10% of the Saharan desert were covered with solar panels at 25% efficiency (higher than average, but not out of reach), then it would produce nearly 2000 EJ of electricity. But that would be a massive deployment into a harsh environment, and the electricity would have to be transmitted to where it would be used, with inevitable losses.

The implication is that the renewable energy potential is large, but finite. The ultimate limits for what is both technically feasible and ecologically sustainable appear to be in the range of a few thousand EJ per year – that is, a few times what we consume today.

4. THE CLASSICAL MODEL WITH CLIMATE CHANGE

In this section we extend the classical model to include greenhouse gas emissions and climate mitigation. This is one half of the task of bringing climate change into macroeconomic models. The other half, which we will discuss but not model, is adaptation; that is, responding to and paying the costs of climate impacts.

4.1. Climate Change Mitigation

We split the discussion of mitigation into two parts. In a later section we consider a shift towards renewable energy. In this section we consider greenhouse gas emissions from operating fixed capital. By focusing on the production side of the economy and associating greenhouse gas emissions with capital stocks, we simplify the analysis. It is a reasonable starting assumption, because operating capital – running machines, heating and cooling buildings, driving trucks, and so on – is highly energy and carbon intensive. But it leaves some important factors out. We mention a few of them below.

Writing greenhouse gas emissions per unit time as G and the average **emissions intensity** per unit of capital as γ (the Greek letter "gamma"), we can add an equation to our model,

$$G = \gamma K. \tag{19}$$

Average emissions intensity per unit of capital has generally been falling over time. As shown in Figure 5, γ has declined in the US since at least 1950, aside from a pause from around 1960 to the 1973 oil crisis. The 1960s, like the decade before it, was one of expansion in the US. Since the oil crisis period ended, around 1980, γ has been falling at about 1.9% per year. This trend suggests that the emissions intensity of new capital – that is, the emissions intensity at the **extensive margin** – is less than the average emissions intensity of current capital. An additional marginal change happens when older capital is retired through depreciation. When the capital being retired was first

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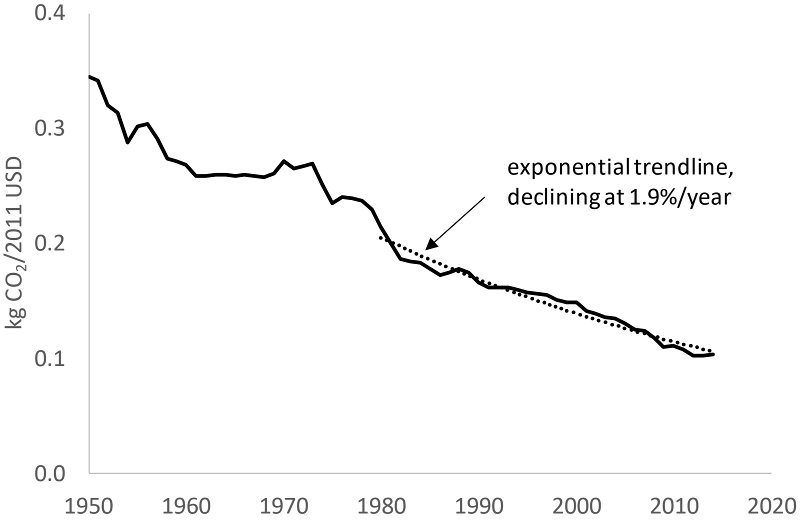
[26] IRENA, 2018.
[27] Moriarty and Honnery, 2012.

installed, marginal emissions per unit of capital were higher, so removing that capital from the stock means removing a relatively high-emissions source, thereby reducing emissions even further.

Figure 5. *Carbon intensity of capital stock in the US, 1950-2014*



Source: Capital stock from the Penn World Table (PWT) 9.0; carbon dioxide emissions from the Carbon Dioxide Information Analysis Center (CDIAC)

We write the marginal emissions intensity of new capital as γ_m. The emissions intensity of capital being retired is higher than the average. We write it as γ_r.[28] With these two parameters we find an equation for the change in emissions associated with the capital stock,

$$\underset{\substack{\text{next-}\\\text{period}\\\text{emissions}}}{G_{+1}} = \underset{\substack{\text{current}\\\text{emissions}}}{G} + \underset{\substack{\text{emissions}\\\text{associated}\\\text{with new}\\\text{capital}}}{\gamma_m I} - \underset{\substack{\text{emissions}\\\text{associated}\\\text{with retired}\\\text{capital}}}{\gamma_r \delta K}\,. \tag{20}$$

We can combine this equation and equation (19) with equation (6), which gives the evolution of the capital stock, to find an equation for the change in average emissions intensity over time. First, combining equations (19) and (20),

$$\gamma_{+1}K_{+1} = \gamma K + \gamma_m I - \gamma_r \delta K. \tag{21}$$

Next, using equation (6) and substituting $K_{+1} - I + \delta K$ for K in the first term on the right-hand side, we find

$$\gamma_{+1}K_{+1} = \gamma K_{+1} + \left(\gamma_m - \gamma\right) I - \left(\gamma_r - \gamma\right)\delta K. \tag{22}$$

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[28] In fact, capital has a useful life, so the age profile of retiring capital is not the age profile of all capital in operation. In practice, this is dealt with by using a vintage model, which keeps track of capital stocks of different ages. Implementing a vintage model would make the model more realistic, but would add a great deal of complexity.

Rearranging and dividing by K_{+1} gives

$$\gamma_{+1} = \gamma + \left(\gamma_m - \gamma\right)\frac{I}{K_{+1}} - \left(\gamma_r - \gamma\right)\delta\frac{K}{K_{+1}}. \tag{23}$$

This is almost in terms of familiar variables. For the final step, we make an approximation. Using equation (6) again, and remembering that $g = I/K - \delta$, we find that

$$\frac{I}{K_{+1}} = \frac{g+\delta}{1+g}. \tag{24}$$

Earlier, we estimated g to be 2.1% per year recently in the US, while the depreciation rate was around 4.7% per year. Using those figures, the difference between $g + \delta$ and $(g + \delta)/(1 + g)$ is 0.1% per year. A tenth of a percent is not in fact a very small difference when calculating economic growth rates, but it is small for our present purposes. We have already set aside more important factors, so we ignore that relatively small term. We get a similar small correction in the final term and replace $\delta K/K_{+1}$ with δ. That gives us

$$\gamma_{+1} \cong \gamma + \left(\gamma_m - \gamma\right)\left(g + \delta\right) - \left(\gamma_r - \gamma\right)\delta. \tag{25}$$

It is convenient to express the marginal emissions intensity reduction relative to the average emissions intensity as a factor φ_m (the Greek letter “phi”, with a subscript “m” for “marginal”) and the emissions intensity of retired capital as a factor $1 + \varphi_r$ greater than the average emissions intensity. That is,

$$\gamma_m = \left(1 - \varphi_m\right)\gamma, \quad \gamma_r = \left(1 + \varphi_r\right)\gamma. \tag{26}$$

With this definition, equation (25) becomes

$$\frac{\gamma_{+1}}{\gamma} \cong 1 - \varphi_m\left(g + \delta\right) - \varphi_r\delta. \tag{27}$$

We can assign some numbers to estimate the value of φ_m needed to reach an emissions reduction target. But first we must estimate φ_r. We assume that historically there was a steady rate of marginal improvement φ_m^{hist}. Our task is to estimate that value. Assuming the recent depreciation rate in the US of $\delta = 4.7\%$ per year, the typical lifetime of capital is $1/\delta = 21.3$ years. Capital introduced that many years ago would have an emissions intensity larger than that being introduced today by an amount $(1 - \varphi_m^{\text{hist}})^{-1/\delta}$. We can then estimate

$$\gamma_r = \left(1 - \varphi_m^{\text{hist}}\right)^{-1/\delta}\gamma_m = \left(1 - \varphi_m^{\text{hist}}\right)^{1-1/\delta}\gamma. \tag{28}$$

Substituting into equation (27),

$$\frac{\gamma_{+1}}{\gamma} \cong 1 - \varphi_m^{\text{hist}}\left(g + \delta\right) - \left[\left(1 - \varphi_m^{\text{hist}}\right)^{1-1/\delta} - 1\right]\delta. \tag{29}$$

Using the historical rate of decrease of γ of 1.9% per year, of g at 2.1% per year, and δ of 4.7% per year, this gives us an implicit equation for φ_m^{hist},

$$0.019 = 0.068\varphi_m^{\text{hist}} + 0.047\left[\left(1-\varphi_m^{\text{hist}}\right)^{-20.3} - 1\right]. \tag{30}$$

This is a highly nonlinear equation and we cannot solve it using algebra. Using the solver in Excel, we estimate $\varphi_m^{\text{hist}} = 1.6\%$ per year, with which we can calculate a value for φ_r of 38% per year.

To estimate the value of φ_m needed to reach a target level of emissions, we first look at historical emissions. In 1995, emissions from the US were about 6,700 million metric tonnes of carbon dioxide-equivalent (MtCO$_2$e) per year.[29] Emissions rose until the Global Financial Crisis of 2007-8 and then began to fall. By 2015, the year of the Paris climate agreement, emissions were about the same as in 1995. The Obama administration's pledges under the Paris agreement would have reduced emissions to about 5,000 MtCO2e per year by 2030, or about 75% of 2015 emissions. In terms of our variables,

$$\frac{G_{+15}}{G} = \frac{\gamma_{+15}K_{+15}}{\gamma K} = \left[1-\varphi_m\left(g+\delta\right)-\varphi_r\delta\right]^{15}\left(1+g\right)^{15} = 75\%. \tag{31}$$

Rearranging this equation, we find an expression for φ_m

$$\varphi_m = \frac{1}{g+\delta}\left(1-\varphi_r\delta-\frac{\sqrt[15]{0.75}}{1+g}\right). \tag{32}$$

Assuming $g = 2.1\%$ per year, $\delta = 4.7\%$ per year, and $\varphi_r = 38\%$ per year, if all emissions reductions came from turnover of existing capital (a big "if", as we discuss below), this would mean that φ_m has to equal 31% per year. That is, every year, emissions from each dollar of new capital investment must be nearly one-third less than the emissions from each dollar's worth of existing capital at replacement cost.

Why such a high rate of reduction? Because the emissions reductions from new capital have to make up for emissions coming from the capital already in place. To some extent that is already happening. According to the International Energy Agency's (IEA) World Energy Outlook for 2018, in 2017 wind and solar PV accounted for nearly half of new electrical generation capacity. Nevertheless, it is challenging. One option is to retire capital more quickly, pushing δ up by an amount δ_{retire}. This was the strategy behind the Obama administration's Car Allowance Rebate System (CARS) or "cash for clunkers" program, in which the government bought people's old cars with the requirement that they replace them with more fuel-efficient ones. Suppose that an additional two percent of the capital stock were retired each year, so that $\delta_{\text{retire}} = 2.0\%$ and the effective depreciation rate is 6.7% per year. Then φ_m would be much lower, 15% per year. That is still a substantial reduction, but it illustrates how innovation can be combined with early retirement to more rapidly push emissions down.

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[29] Carbon dioxide-equivalent values combine the effect of different greenhouse gases, weighting them by their global warming potential (GWP). The figures reported here are from the online Climate Action Tracker.

In addition, emissions can be reduced at the **intensive margin** without replacing long-lived capital, a possibility that we did not include in our model. Intensive measures include changing operating procedures using existing capital (e.g., running engines at their most fuel-efficient speed), switching from diesel to biodiesel, replacing very short-lived capital, and retrofitting. The capital intensity of the economy can also change. We have assumed a constant capital productivity, in line with Kaldor's stylized fact. But a stylized fact is not a law of nature and in principle it is possible to **dematerialize** – that is, to reduce emissions by shifting to more service-oriented and less capital-intensive activities.

Despite these caveats, the calculation makes an important point: much of an economy's emissions is tied up in its capital stock, and replacing capital takes time. A further point to consider is that it is expensive to buy cutting-edge technologies and some mitigation expenditure will address emissions reductions at the expense of output. It is reasonable to suppose that at present low-emitting capital will cost more for the same increase in the productive capacity of the economy. At some point it is likely to be less costly, and the transition will proceed on its own, but until then it will require some additional expenditure. We could represent this with a lower capital productivity, but for our present purposes we will treat at least some mitigation expenditure as "nonproductive" capital expenditure.

One of the most prominent climate-economy models in use, William Nordhaus' DICE model, assumes all mitigation expenditure is nonproductive. The alternative CRED model developed by Frank Ackerman and his colleagues assumes that half of mitigation expenditure is nonproductive. We assume that at least some mitigation expenditure is nonproductive, in an amount c_m per unit capital stock. Combining early retirement and mitigation costs, gross investment is

$$I = \left(g + \delta + \delta_{\text{retire}} + c_m\right)K. \tag{33}$$

Mitigation costs c_m and accelerated depreciation δ_{retire} increase the amount of investment needed to maintain growth of productive capacity at the rate g.

4.2. Macroeconomic Implications of Climate Mitigation

From the basic economic balance $Y = C + I$ in equation (1), the additional investment costs in equation (33) will reduce the amount of income available for consumption. While early retirement δ_{retire} is discretionary, nonproductive mitigation costs c_m are not. This illustrates the use of economic balances to draw conclusions. Our balances are missing some terms, particularly government expenditure and trade, and we have not included the financial sector. Furthermore, as we noted earlier, the steps that took us to equation (33) ignore possibilities to reduce emissions at the intensive margin, without new capital investment. But those are technical issues. We can improve the balances by adding more terms, but the fundamental requirement still remains: if we want to grow the economy and reduce emissions at the same time, then more of GDP must go towards investment, with a correspondingly lower fraction going towards consumption.

In the ABC approach to macroeconomic modelling, once the balances are in place, the next step is to consider behavior. From the Cambridge equation , if wage-earners do not save at all (or save very little) and profit-earners do not change their saving rate, then higher gross investment will raise the profit rate at the expense of wages. But that is not the only possibility. During the Second

World War, soldiers abroad bought very few goods from home. For those who remained at home, goods were rationed and households were encouraged to buy War Bonds. In that way, wage-earners increased their saving substantially during the war. Another possibility is for the government to both save and invest by taxing profit and wage income in order to fund the transformation of the economy. This illustrates the important point that while balances are a matter of accounting, and cannot be negotiated away, behavior involves choice.[30]

Regardless of how the investment funds are raised, the absolute level of consumption will depend on the size of the economy. Recall that the growth rate of the economy is ultimately limited by the natural rate g_n, which is the sum of the growth rates of the labor force and labor productivity. That rate can increase if either the labor force growth rate or labor productivity growth rate (or both) increases.

It is reasonable to expect labor force growth to accelerate. A major decarbonization effort would most likely require more labor than is currently employed. As demand for labor rises and unemployment falls, wages will tend to rise. People of working age who are currently out of the workforce can be expected to enter it in response to opportunities and higher pay. Their spending would create secondary demand, which would stimulate the economy more broadly.

Labor productivity is another matter. The claim is sometimes made that the green economy will be job creating because it requires more labor for the same level of economic output. If that is true, and if economic output does not change, then more people will be employed. However, this claim also implies that the same number of workers will produce less output. We expect them to produce more overall benefit to society (a positive **externality** not captured in market exchanges). That is the motivation for the decarbonization program. But from the point of view of the economic accounts, output per worker, or labor productivity, will initially decline. As firms gain experience with the new technologies, we can expect them to make labor-saving innovations that will drive labor productivity up, so the overall trajectory may be an initial slowing of labor productivity growth followed by an acceleration.

The two effects go in different directions, but a plausible outcome would be a substantial expansion of the labor force combined with a modest reduction in labor productivity. That would imply an increase in the natural rate of growth. The actual rate of growth will normally be different than the natural rate, and may well be lower (see Box 5). But suppose that the natural growth rate were achieved and that it is higher than historical rates by one percentage point. That would be a significant jump if it were sustained for several years – from 2.1% per year to 3.1% per year. Then, using equation (32), φ_m would have to be 39% per year if there were no early retirement of capital.

That is an even faster rate of decline in emissions intensity than if the growth rate stayed the same. Why? Because, while low-carbon investment is bringing emission down, faster growth is pushing emissions up. A greater reduction in carbon emissions per unit of capital stock is needed to meet the same total emissions reduction target in a booming economy.

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[30] When the subject under discussion is about the direction of the overall economy, then choice implies politics, which is why classical economics was called "political economy". A decarbonization program requires support from the public and their representatives. This can be seen in the US, where policies of the Obama administration – which were still modest compared to the needed reductions – were reversed by the Trump administration.

BOX 5: THE GROWTH IMPACTS OF CLIMATE MITIGATION

The natural growth rate is the level made possible by the increase in the labor force and improvements in labor productivity. We argued that the labor force may well expand fast enough in a major decarbonization effort that it would exceed any fall in labor productivity. The high levels of investment will require labor, thereby putting people to work. The investment must be matched by high levels of saving, which would be achieved through a combination of taxes (for public investment) and incentives (for private investment). The rate of expansion would be limited by the rate at which people can be brought into the workforce and the rate of increase in their productivity – that is, the natural rate of growth.

There is no guarantee that the natural growth rate will be achieved, even if it rises above historical rates. The actual growth rate will depend on the degree of public investment and the confidence of private investors in future returns. Private investors may feel considerable uncertainty over the benefits of specific green technologies and the reliability of public support. If that is the case, then the pace of investment may fall below what the economy could actually deliver. Political economy considerations suggest other problems. Some investors are likely to find their existing investments threatened by a decarbonization program and decide to actively lobby against it, and proponents of particular technologies may argue that the government is trying to “pick winners” with its investments. If these political and technological challenges are not managed well, then economic growth could slow rather than accelerate.

These arguments follow from a post-Keynesian, demand-led view of the economy. In those models, investment determines saving. Most climate-economy models foresee slower growth with decarbonization, but not for these reasons. They are neoclassical models in which saving determines investment – a supply-led view. In Nordhaus’ DICE model, saving is given as a proportion of GDP net of the costs of climate damage and nonproductive adaptation costs. In keeping with neoclassical theory, households both own and provide labor for firms. They choose an optimal saving rate that maximizes their discounted utility, which is an increasing function of per capita consumption. Because households discount the consumption of future generations, they are reluctant to lower their own consumption by an appreciable amount. Thus, nonproductive adaptation costs tend to depress saving, and therefore investment, in the DICE model.

These divergent results from different theoretical traditions illustrate the importance of behavioral assumptions in macroeconomic models. Would a decarbonization effort be stimulating or depressing? In both our classical model and the standard neoclassical climate-economy models, consumption must fall relative to saving to meet the needed level of investment expenditure – that follows from the accounts. But they specify different behaviors. If households are ready to save more and consume less in order to meet the climate challenge, as in the mobilization for World War II, then economic growth might well accelerate. If mitigation expenditure, climate damage, and the wish to consume lead to low levels of productive investment, then the economy will likely slow.

4.3. Combining Mitigation and Adaptation

In this module we only attempt to model mitigation. But macroeconomic models for climate policy must include climate impacts as well as emissions. There are many channels through which climate change can affect economies. These include: damage to buildings, roads and other infrastructure from floods, fires and storms; damage or delays to transportation networks; damage to communications infrastructure; disease; heat-related stress; migration; and changes in ecosystem function.

We will try to give a flavor of the sorts of calculations that go into integrated assessment models (IAMs), which are built to study emissions and impacts together. Integrated assessment modeling is a very active area of research and it is not possible to do it full justice here. The interested student can find a large number of reports and papers (and in some cases downloadable code) for IAMs actually in use, such as the DICE model referred to earlier.

As greenhouse gas concentrations in the atmosphere rise, global average temperature will rise as well through the greenhouse effect. To connect emissions to temperature, IAMs must calculate global emissions, not just emissions from a single country as we did in the previous section. Many IAMs calculate emissions for several greenhouse gases, such methane and nitrous oxide, in addition to carbon dioxide.

For carbon dioxide, IAMs track exchanges between the atmosphere and ecosystems using carbon cycle models. Tracking carbon in the atmosphere, oceans and land is essential for applied work because of delays and feedbacks between emissions and uptake, including saturation effects. Delays in natural carbon uptake mean that even after we succeed in halting emissions, global temperatures will continue to rise before they fall. Feedbacks include, among others, release of carbon stocks through warming (such as the methane in arctic tundra) and lower absorption by the oceans as they become more acidic.

IAMs estimate the change in global temperature by calculating the “radiative forcing” provided by each gas as a function of its concentration. Total radiative forcing determines changes in temperature, which is then used as a parameter in one or more “damage functions” to estimate damages. The economist Richard Tol distinguishes two ways to estimate damage functions. The first, which he calls the “enumerative” method, is to look at papers in diverse fields of study to construct physically-based estimates of damage as a function of global temperature. The second, which he calls the “statistical” method, relies on observed correlations between climate variables and economic impacts.

Neither method is ideal, as noted by Tol. Physically-based studies done in one region of the world may not apply to other regions, while assumptions about adaptive responses are hidden within a damage function that depends only on temperature. Statistical studies are limited by the available data, and may incorrectly attribute differences between outcomes in different locations to climate, when in fact other factors are more important. Because our knowledge is and always will be limited, questions over the proper form for damage functions will persist.

Regardless of the method, damage functions are not well-suited to representing thresholds or “tipping points”, which are usually excluded from the analysis. Tipping points arise in complex systems as a result of slow changes in some parameter (e.g., temperature, sea level rise or greenhouse gas concentrations in the case of climate change). As the tipping point is passed, the system changes its behavior in a way that cannot be reversed. Even if the parameter is brought back down, the system has permanently changed. Examples of climate tipping points include accelerating loss of ice sheets and release of methane from thawing tundra.

4.4. Optimal Policy and Discounting the Future

Because IAMs calculate both mitigation and adaptation costs, as well as monetary losses arising from climate impacts, they can and are used to calculate "optimal" emissions trajectories that maximize the net benefits from mitigation. This is a controversial subject. At the heart of the debate is how to balance the ethical claims of future generations against those of the current generation. The dominant models are neoclassical, and the terms of the debate are the weighting of future costs and benefits relative to the present. There are two major areas of contention. The first is the proper value of the "social discount rate". The second is whether cost-benefit analysis can or should be carried out at all.

In business and public procurement, discounting is common and unproblematic. A dollar of income or expenditure next year is worth less than a dollar of income or expenditure this year. The present value of next year's dollar is the amount that should be invested today to have a dollar in the investment account a year from now. If interest rates are 5.5% per year and inflation is 1.5% per year, then the present value of a dollar next year is 96 cents.

The social discount rate is a different matter. In a neoclassical optimizing model (a "Ramsey model", after the early 20th Century British philosopher, mathematician and economist Frank P. Ramsey), the discount rate r should be

$$r = \rho + \eta g_{\mathrm{pc}}, \tag{34}$$

where ρ is the "pure rate of time preference", η connects a change in consumption to a change in utility, and g_{pc} is the growth rate of per capita consumption.

Among neoclassical economists, and even among some non-neoclassical economists, there is little controversy over the inclusion of the second term in equation (34). If the economy is expanding, then people in the future will be able to consume more and therefore be better off (have greater utility) than we are today. An additional dollar will be worth less to them than it is to us, so we count their dollars at a discount. Whatever controversy exists for the second term is over the possibility that g_{pc} might be large and negative because of catastrophic climate change. (Many non-neoclassical economists entirely reject the utility-maximizing framework, particularly the practice of identifying well-being with consumption.)

The main controversy is over the first term, which discounts future well-being absolutely. Ramsey himself thought that it should be zero. Some economists, in particular William Nordhaus, who won the Nobel Memorial Prize in Economic Sciences in 2018, look to discount rates used in practice, which leads them to assume a positive pure rate of time preference. They argue that this is the most ethical position to take because actual discount rates reveal social preferences. This has been called the "descriptivist" approach. Others, most prominently Lord Nicholas Stern, argue that the value of future well-being is not ours to decide and the pure rate of time preference should be zero (or very close to zero, to take account of the possibility that humans become extinct). This is the "prescriptivist" approach.

The practical difference between these positions is profound. In one, climate change is a serious challenge, but a challenge that can be met with gradual changes to our economies. In the other, climate change looks like a crisis that must be met through substantial and rapid changes to our economies. The difference arises from competing ethical claims: for those alive today and those yet to be born. If our collective past choices indeed reveal our ethical choices, as Nordhaus argues, then it appears that we strongly prefer our own generation's well-being over that of future generations. The generation now entering adulthood is likely to be significantly impacted by climate change during their lifetimes. It remains to be seen whether that will change the ethical calculus.

The other controversy is whether a discounted cost-benefit analysis can be applied to climate change at all. Some economists, such as Frank Ackerman, argue that cost-benefit analysis of climate strategies is fundamentally flawed because of the way social costs are calculated and because there are irreducible and large uncertainties about both the climate and its impacts. Instead, economists should focus their energies on finding the least-cost strategy for reaching zero or negative net emissions.

Martin Weitzman, while not rejecting cost-benefit analysis in general, argues that it should not be applied to climate change. He notes that cost-benefit calculations assume normal "thin-tailed" probability distributions of future events, while the appropriate distributions for climate change are "fat-tailed" (implying a larger possibility of catastrophic events) and it is mathematically meaningless to do a cost-benefit calculation with fat-tailed distributions. He points out that even if, in reality, the probability distribution of future events is thin-tailed, as long as we are uncertain about the variance in that distribution – how far any given outcome might differ from the average – then for all practical purposes we have to assume a fat-tailed distribution.

In this module, we did not do a cost-benefit analysis. We treated the future exactly like the present, so no discount rate entered into equation (31). This choice is consistent with the descriptive (but not "descriptivist") approach we have followed throughout the module. We are most interested in behavior, and for that we want to model what people in the future might experience and react to in their own context.

If we knew that people today were using a discount rate of, say, 5% per year, then we might put that in our behavioral model. That would be superficially similar to what descriptivists say they are doing. But we would not use a discount rate to calculate an "optimal" policy. Instead, we would simulate long-run outcomes and reflect on the implications for the longer-run future of discount rates in use today.

5. THE CLASSICAL MODEL WITH NATURAL RESOURCES

In this section we will extend the classical model to include natural resources. Because energy inputs are fundamental to the maintenance of any complex system, such as a society and the economy embedded within it, we focus on energy and set aside other natural resource inputs, including agricultural commodities, metals, and non-metallic minerals.

We continue to use Y to denote the value of all final goods and services produced in the economy, including consumption and investment goods. (From here onward, to simplify the text, we will refer to this as "final goods" production rather than "final goods and services".) We introduce energy as a new intermediate input, and write the physical production of total energy as E. Because we now have two outputs in the economy – final goods and energy – we must pay attention to relative prices. We denote the price of energy in terms of final goods by p_E. (This choice means that we are using final goods as the ***numéraire***, or reference of value, for the economy.) The energy price has units of inflation-corrected money per unit of physical energy production, such as 2011 US dollars/MJ (see Table 1 on page 23 for a list of common energy units).

We assume that any directly extracted energy source must be processed before it can be used – for example, by converting crude oil into petroleum or home heating oil – so the extractive sector does not produce any goods for final use.[31] The final goods sector needs energy inputs for production, and as we saw in the previous section, the energy sector needs energy inputs as well.[32] We express the demands using technical coefficients a and b that multiply the value of output in each sector,

$$E = aY + bE. \tag{35}$$

That is, a is the energy needed to produce a dollar of GDP, and b is the energy needed per unit of energy produced. The coefficient a, which has units of energy per inflation-corrected money unit (e.g., MJ/2011 US dollar) is called the **energy intensity** of final goods production.

We can solve equation (35) for E, isolating it on the left-hand side, to find

$$E = \frac{a}{1-b}Y. \tag{36}$$

This is in terms of physical energy, so to find the monetary value of energy flows we must multiply E and a by p_E.

To calculate gross domestic product, we add the output from both sectors (Y and $p_E E$) and subtract the value of intermediate inputs ($p_E aY$ and $p_E bE$),

$$\text{GDP} = Y + p_E E - p_E aY - p_E bE. \tag{37}$$

From equation (35), we see that the value of intermediate inputs is exactly equal to the value of output in the energy sector. That is because we assume all outputs from the energy sector are intermediate goods and we ignore other intermediates based on natural resources (such as flour used for commercial baking). Because the last three terms cancel, we find that GDP is equal to the value of output from the final goods sector,

$$\text{GDP} = Y. \tag{38}$$

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[31] Households directly extract energy as a final good when they collect firewood or generate off-grid wind, hydroelectric, or solar electricity. In high-income economies today, these are comparatively minor activities.

[32] The energy sector also needs outputs from the final goods sector. That intermediate demand is relevant for some analyses, but for our purposes it adds unnecessary complication, so we ignore it.

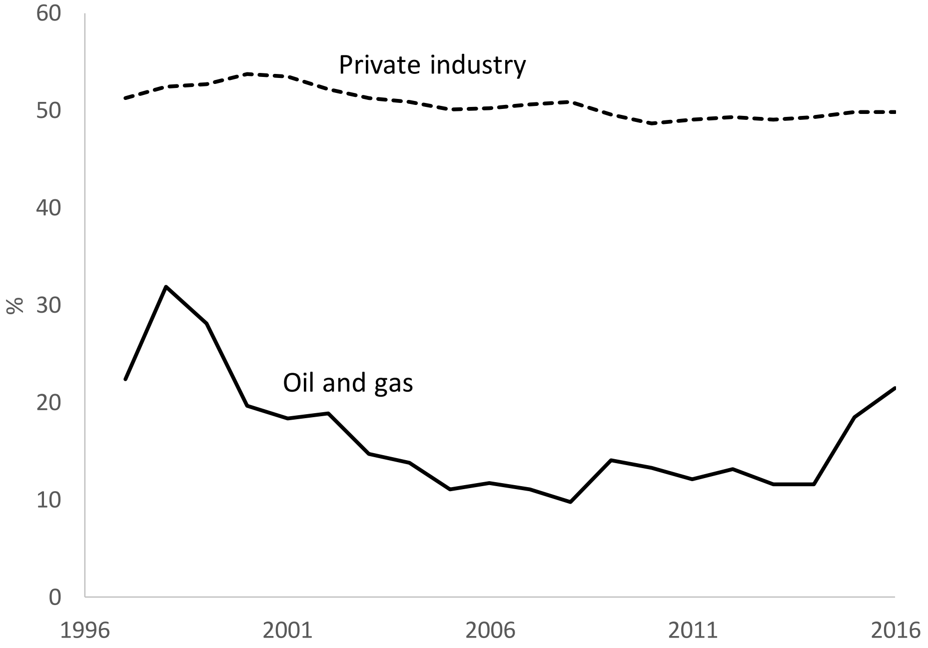
This is an example of the general accounting rule that we discussed earlier in this module. GDP is net of intermediate transactions between firms, so it is equal to the value of final goods.

5.1. The Functional Income Distribution

Both the energy and final goods sectors generate profits, and as we saw earlier, the profits of the energy sector are referred to as "rents", according to the World Bank definition. Both also pay wages, but we now argue that we can ignore wages in the energy sector.

The energy sector is highly capital-intensive, and must devote a great deal of its income to paying for previous investment. As a result, wages make up a relatively small fraction of the value added by the sector. This is shown for oil and gas in the US in Figure 6. Moreover, value added by the energy sector is relatively small compared to the rest of the economy, so wages in the energy sector are an even smaller proportion of total wages in the economy than they are of value added in the energy sector. Based on this observation, we simplify the analysis by ignoring wages in the energy sector.

Figure 6. *Employee Compensation as a Share of Value Added*



Source: BEA/Kemp-Benedict 2018

With the simplifying assumption that we can ignore wages in the energy sector, the income of the final goods sector, Y, pays for all wages in the economy, W, and intermediate expenditure on energy, with the remainder being profits, Π,

$$Y = W + \Pi + p_E aY. \tag{39}$$

In the energy sector, income $p_E E$ is spent on own-use, with the remainder being rents, R,

$$p_E E = R + p_E bE. \tag{40}$$

Inserting these expressions into equation (37) for GDP, and recalling that GDP is equal to Y, it is possible to show that

$$Y = W + \Pi + R. \tag{41}$$

Dividing through by Y, we get the shares in the functional income distribution,

$$1 = \omega + \pi + \rho. \tag{42}$$

The notation for the wage and profit shares is the same as before, with the Greek letters omega and pi. Rents as a share of GDP are given by the lower-case Greek letter rho (ρ).

The left-hand side of equation (39) is equal to the left-hand side of equation (41) – they are both equal to Y. Setting their right-hand sides equal to each other and cancelling common terms, we find that rents are what the final goods sector pays to the energy sector,

$$R = p_E aY. \tag{43}$$

Dividing both sides by Y, we find that $p_E a$ is equal to the rental share in the functional income distribution, ρ,

$$\rho = \frac{R}{Y} = p_E a. \tag{44}$$

Recall that a represents the energy needed to produce a dollar of GDP, or the energy intensity of the economy, so the higher a is, the greater the rent paid to the energy sector by the final goods sector.

5.2. Cost-Share Induced Technological Change and Energy Rents[33]

We can apply the concept of cost-share induced technological change to resource rents. Recall that the price of energy, p_E, is determined by conditions of supply as well as demand. The conditions of supply are partly determined by economic factors: extractive firms will develop new resources if they think future purchases will cover the costs. However, they are also partly determined outside of the economy by biogeophysical conditions – the resource can only be extracted if it exists – and political actions. Examples of the latter include the 1970s oil embargo, when the Organization of Petroleum Exporting Countries (OPEC) deliberately restricted supply, and the creation of the US Strategic Petroleum Reserve (SPR) in response.

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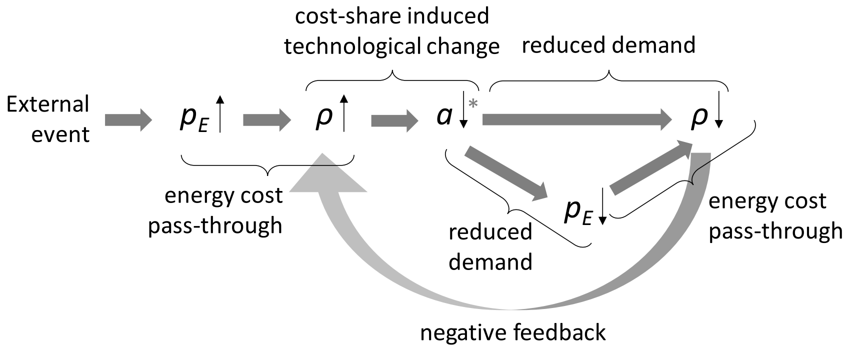
[33] This section draws on the author's recent research.

Suppose that the price p_E were to rise, whether by rising demand or shrinking supply, or a combination, as illustrated in Figure 7. The result is a rising resource rent share, ρ. Under cost-share induced technological change, firms respond by reducing the intensity of their energy use, represented in our model by a. Demand falls, which lowers the rent share, but it also tends to reduce the price if other conditions remain the same. That drops the resource rent share further. As shown in Figure 7, the net result of cost-share induced technological change is a negative feedback. A rising price drives the rent share upward, which leads firms to invest in cost-saving technology, which drives the rent share back down after a delay for developing and implementing the new technology.

Figure 7. Stabilizing dynamics for resource rents with cost-share induced technological change



* The ability to lower *a* depends on technological potential

When a system has a negative feedback with a delay, it tends to fluctuate around a stable point. We therefore expect a roughly constant energy cost share, with fluctuations driven by external events. The ability to maintain a constant energy cost share and the speed at which equilibrium is restored depend on technological potential – specifically, the ability to lower the energy intensity a of the final goods sector.

How well does this work in practice? Figure 8 shows oil rents and oil prices for the US from the 1970s through the mid-2010s.[34] The impact of the OPEC oil embargo is clear, as both prices and oil rents jump dramatically. A second spike occurs after the 1979 Iranian revolution. By the late 1980s, prices and rents had fallen close to the levels that prevailed before 1973. The recent (and more gradual) price rises since the end of the 1990s have been accompanied by nearly constant oil rents.

The overall trajectory in Figure 8 is broadly consistent with the mechanism in Figure 7. In the 1970s, the oil price spikes drove fuel substitution, as oil and natural gas use fell while use of coal and nuclear power rose. This lowered the oil intensity of economic activity to some degree.

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[34] Oil rents are from the World Bank World Development Indicators (WDI). The oil price index is constructed using data from the US Energy Information Agency (EIA). The core time series are the US average wellhead price or first purchase price of crude oil. To correct for price controls during the oil crises of the 1970s and 1980s, the series was adjusted by the ratio of refiners' acquisition price of domestic and imported crude oil, as suggested by WTRG Economics (http://www.wtrg.com/prices.htm).

Lowering it further required energy efficient technologies, but these were not well developed in the early 1970s. After the oil price shocks, publicly and privately funded research drove advances in energy efficient technologies. The economy also became less energy-intensive through a structural shift away from manufacturing and towards services. The net result is a greater ability to lower energy intensity, *a*, in the US economy today than in the 1970s.

Figure 8. *Oil rents and oil price in the US*

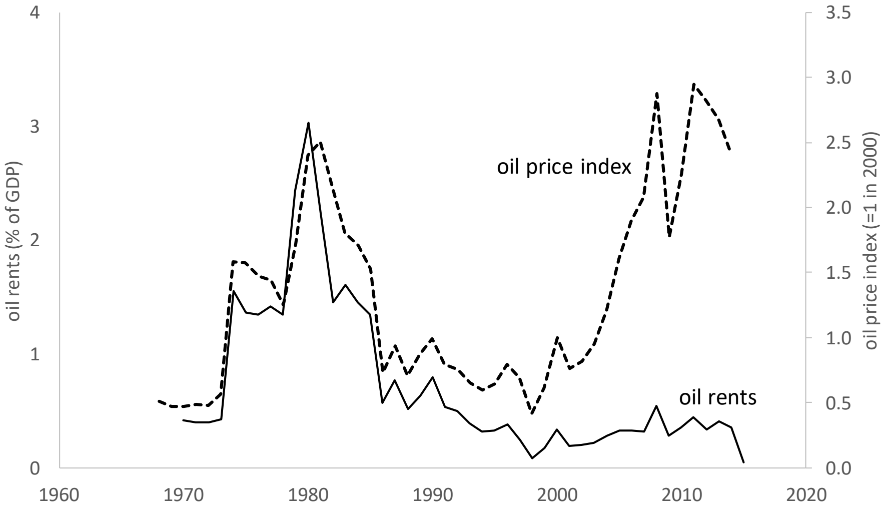

Figure 8 presents a vivid picture of what the "short run" can look like in a long-run analysis. We will assume below that the energy cost share ρ hovers around a level determined by technological potential. That assumption is, as noted above, broadly consistent with the history of energy rents in the US in the past 40 years. However, the experience of oil price shocks was traumatic at the time. Gasoline was rationed, as illustrated in Figure 9, and it took over a decade before the economy became resilient to oil price changes.

Figure 9. *Gasoline rationing in Oregon in 1974*

Source: (photo from the U.S. National Archives, ID 412-DA-13067)

From equation (44), for small changes in the energy price or energy intensity, the rate of change in the energy cost share is approximately equal to

$$\frac{\Delta\rho}{\rho} \cong \frac{\Delta p_E}{p_E} + \frac{\Delta a}{a}. \tag{45}$$

If the cost share is constant, then the intensity has to decline as fast as the price is rising,

$$\frac{\Delta a}{a} = -\frac{\Delta p_E}{p_E} \quad \text{when} \quad \Delta\rho = 0. \tag{46}$$

Later we will discuss what might happen if the intensity cannot decline, or declines very slowly, due to physical limits on reducing energy throughput.

5.3. The Net External Power Ratio

From the expression for the value of total output from the energy sector in equation (35), we see that own-use by the energy sector is equal to bE. We can then calculate the NEPR, n, as

$$n = \frac{E - bE}{bE} = \frac{1-b}{b}. \tag{47}$$

Rearranging this equation, we find that

$$b = \frac{1}{1+n} \quad \text{and} \quad 1-b = \frac{n}{1+n}. \tag{48}$$

Substituting into the expression for E in terms of Y in equation (36), we find

$$E = \frac{1+n}{n} aY. \tag{49}$$

When energy is easy to extract, such that NEPR is very high, own-use by the energy sector is negligible and total energy production is very close to energy use by the goods sector. When NEPR is low, own-use can make a significant difference. At the current NEPR for energy production in the US, total energy production is about 11% higher than energy consumed by the goods sector.

5.4. Savings, Investment, and Accumulation of Capital

The economy grows through new capital investment. We assume that capital productivity is constant in each sector separately, with a capital productivity of v_g in the final goods sector and v_e in the energy sector. They have separate levels of capital stocks K_g and K_e, so

$$Y \le v_g K_g, \tag{50}$$

and

$$E \le v_e K_e. \tag{51}$$

Note that capital stocks are in inflation-corrected money units (e.g., 2011 US dollars), while GDP is in units of money per unit of time (e.g., 2011 US dollars per year), so the units for v_g are 1/year. By contrast, E is in physical units (e.g., MJ/year), so v_e is in units of, for example, MJ/2011 US dollar/year.

We write (50) and (51) as inequalities because there may be other constraints on economic growth, as in equation (13). In addition to labor productivity and the size of the labor force, the economy may be constrained by physical limits on the annual supply of energy, E_{phys}. In that case, we have

$$E \le \min(E_{\text{phys}}, v_e K_e), \tag{52}$$

and, from equation (49),

$$Y \le \min\left(v_g K_g, \lambda_g L_g, \frac{n}{1+n}\frac{E}{a} \right). \tag{53}$$

For now, we will suppose that we have abundant energy and labor and that the economy is operating at full capacity. In that case, the inequalities in (50) and (51) become equalities. Substituting into equation (49), we find a relationship between the capital stocks in each sector,

$$K_e = \frac{v_g}{v_e}\frac{1+n}{n} a K_g. \tag{54}$$

For convenience in later expressions, we will denote the proportionality factor between K_e and K_g by c,

$$\frac{K_e}{K_g} = \frac{v_g}{v_e}\frac{1+n}{n} a \equiv c. \tag{55}$$

Each sector has its own level of investment. In practice, the different sectors will have different depreciation rates, but to simplify the analysis we will assume they are the same, and write

$$\Delta K_g = I_g - \delta K_g, \tag{56}$$

and

$$\Delta K_e = I_e - \delta K_e. \tag{57}$$

These grow at rates g_g and g_e, where

$$g_g = \frac{\Delta K_g}{K_g} = \frac{I_g}{K_g} - \delta, \tag{58}$$

and

$$g_e = \frac{\Delta K_e}{K_e} = \frac{I_e}{K_e} - \delta. \tag{59}$$

Total investment must equal total saving. We allow for different saving rates out of wages, profits, and rents, and write total saving, S, as

$$S = s_w W + s_\pi \Pi + s_\rho R. \tag{60}$$

Closing the model by requiring that saving equals investment at full utilization, we have

$$S = I_g + I_e. \tag{61}$$

Dividing equation (60) through by Y, we find the saving rate in terms of the functional income distribution,

$$\frac{S}{Y} = s_w \omega + s_\pi \pi + s_\rho \rho. \tag{62}$$

We know from equation (42) that cost shares sum to one – that is one of our accounting relationships. We further assume, following arguments introduced earlier, that rents as a share of GDP, ρ, are determined by technological potential – a behavioral relationship.

We now add a further behavioral assumption, that firms set their prices as a markup on costs, and show that the markup determines the profit share. This behavioral assumption is consistent with a view of the economy in which most markets are oligopolistic. The largest firms have considerable but not unlimited freedom to set their markups, as they are constrained by the need to discourage competition by rival firms and from the demands of wage-earners for a share of income.

We add an equation to the model in which firms in the final goods sector set their price as a markup on their labor and energy costs. We denote the average markup by m. GDP is one plus the markup multiplied by costs, so we have

$$Y = (1+m)(W + p_E R). \tag{63}$$

Profits are, by definition, GDP less costs, so we can replace the costs in parentheses by $Y - \Pi$,

$$Y = (1+m)(Y - \Pi). \tag{64}$$

Solving for $\pi = \Pi/Y$, we find

$$\pi = \frac{\Pi}{Y} = \frac{m}{1+m}. \tag{65}$$

From this equation we see that the profit share is determined entirely by the average markup of the firms in the final goods sector.

Rents are the profits of the extractive sector, by the World Bank definition we adopted earlier. It is reasonable to assume that the saving behavior of rent earners is similar to that of profit earners. They may not be identical, but it is convenient to combine them into an average saving rate $s_{\pi\rho}$,

$$s_{\pi\rho} = \frac{s_\pi \pi + s_\rho \rho}{\pi + \rho}. \tag{66}$$

Using this definition and equation (42), we can write the saving rate in terms of the wage share as

$$\frac{S}{Y} = s_{\pi\rho} - \left(s_{\pi\rho} - s_w\right)\omega. \tag{67}$$

This expression looks very similar to equation (10) for the saving rate without natural resources. For that equation, we argued on behavioral grounds that s_π is greater than s_w. It is reasonable to assume that saving out of rents, which are a form of profits, will also be greater than saving out of wages, so we expect the average $s_{\pi\rho}$ to be greater than s_w. Just as in the economy without natural resources, the average saving rate is a decreasing function of the wage share.

5.5. Balanced Growth

From equations (54) and (55), we see that the capital stock in the energy sector is proportional to the capital stock in the final goods sector. If the proportionality factor c is not changing, then for **balanced growth**, the capital stocks in each sector must grow at the same rate.

Can we assume a constant proportionality factor? From equation (55), c depends on several parameters. First, it depends on the ratio of the capital productivities v_g and v_e. We assume they do not change, in keeping with Kaldor's stylized fact. The parameter c also depends on the product $a(1+n)/n$. This product is, from equation (49), the average energy intensity of the whole economy. According to World Bank figures, total energy intensity fell in the US relatively steadily at 2.0% per year between 1990 and 2015. This means that we *cannot* assume a constant proportionality factor in equation (54) between capital stocks in the energy and final goods sectors. Instead, we write[35]

$$g_e = g_g - \alpha, \tag{68}$$

where α is the rate of decline of total energy intensity; using the figures above, α has been about 2.0% per year for the US in recent decades.

Substituting equations (58) and (59) for g_g and g_e into equation (68), we find that the ratios of investment to the capital stock – that is, the gross investment rates – are related by

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[35] For this equation we use a common approximation. The growth rate of a product of two variables is approximately the sum of the growth rates of each of the variables. The error is equal to αg_g. If each is close to 2% per year, then the error over a year is 0.04% per year, which is small enough to ignore.

$$\frac{I_e}{K_e} = \frac{I_g}{K_g} - \alpha. \tag{69}$$

5.6. Saving, Distribution, and Growth

From the balance of investment and saving in equation (61), we know that total saving S is the sum of investment in each sector. We can therefore set I_e equal to $S - I_g$, and write equation (69) as

$$\frac{S - I_g}{K_e} = \frac{I_g}{K_g} - \alpha. \tag{70}$$

From this, we can get an expression for I_g/K_g. After some rearrangement, we find

$$\frac{I_g}{K_g} = \frac{S + \alpha K_e}{K_g + K_e}. \tag{71}$$

Substituting this into equation (58) gives an expression for the growth rate of the final goods sector in terms of total saving,

$$g_g = \frac{S + \alpha K_e}{K_g + K_e} - \delta. \tag{72}$$

At this point it is useful to express this equation in terms of the ratio K_e/K_g, which equals the proportionality factor c in equation (55). Dividing the numerator and denominator of the first term on the right-hand side by K_g, we find

$$g_g = \frac{1}{1+c}\left(\frac{S}{K_g} + \alpha c\right) - \delta. \tag{73}$$

Saving is determined by wage, profit, and rent-specific saving rates. Dividing S by Y gives the saving rate, while Y/K_g is capital productivity in the goods sector, v_g, so we can write the ratio S/K_g as

$$\frac{S}{K_g} = \frac{S}{Y}\frac{Y}{K_g} = \left[s_{\pi\rho} - \left(s_{\pi\rho} - s_w\right)\omega\right]v_g. \tag{74}$$

Substituting into equation (73), we find an expression for the growth rate of the final goods sector,

$$g_g = \left[s_{\pi\rho} - \left(s_{\pi\rho} - s_w\right)\omega\right]\frac{v_g}{1+c} + \frac{\alpha c}{1+c} - \delta. \tag{75}$$

Comparing this to equation (15), which gives the growth rate for the economy without natural resources, we see the following differences: 1) the saving rate now includes saving out of rents;

2) capital productivity in the goods sector is divided by $1 + c$, to correct for capital needed in the energy sector; and 3) there is an additional term correcting for declining energy intensity.

Note that if α is nonzero, then c is changing, so the balanced growth path is continually shifting. It is "balanced" in the sense that the capital stocks in the energy and final goods sectors grow in such a way that they are always in the correct proportions given the energy productivity of the final goods sector.

We can get some feel for the magnitudes in equation (75) by assuming that saving propensities, capital productivity, the wage share, and depreciation are the same as they are today. We further assume that saving out of rents is the same as out of profits. Using the figures introduced before, this means that $s_w = 7\%$, $s_{\pi\rho} = 39\%$, $v_g = 0.32$ per year, $\omega = 53\%$, and $\delta = 4.7\%$ per year. From equation (55), c is defined as the ratio of the capital stock in the energy sector to the capital stock in the final goods sector. We estimate[36] that to be 0.04, while we earlier we estimated α to be 2.0% per year. The growth rate in the goods sector is then 2.1% per year. This is less than the growth rate calculated using equation (15), and is essentially identical to the observed average GDP growth rate of 2.1% per year from 2011 through 2017.

5.7. A "Green" Cambridge Equation

We can use equation (75) to derive a "green" version of the Cambridge equation that focuses on the saving behavior of profit earners in the final goods sector. As with the original Cambridge equation, we set $s_w = 0$ in equation (75) to find

$$g_g = s_{\pi\rho}\left(1-\omega\right)\frac{v_g}{1+c} + \frac{\alpha c}{1+c} - \delta. \tag{76}$$

Using the fact that cost shares sum to one and applying the definition of $s_{\pi\rho}$ from equation (66), we have

$$g_g = \left(s_\pi \pi + s_\rho \rho\right)\frac{v_g}{1+c} + \frac{\alpha c}{1+c} - \delta = \left(s_\pi + s_\rho \frac{\rho}{\pi}\right)\frac{r_g}{1+c} + \frac{\alpha c}{1+c} - \delta. \tag{77}$$

In the final expression, $r_g = \pi v_g$ is the profit rate of the final goods sector. Setting g_g to equal the natural rate of growth g_n and solving for r_g, we find

$$r_g = \frac{\left(1+c\right)s_\pi \pi}{s_\pi \pi + s_\rho \rho}\left(\frac{g_n + \delta}{s_\pi} - \frac{c}{1+c}\frac{\alpha}{s_\pi}\right). \tag{78}$$

This is the "green" Cambridge equation. It has two correction factors compared to the standard equation (17) . Assuming an identical saving rate from profits and rents, there is an overall factor

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[36] This is an average over 2011-2017 as estimated from Bureau of Economic Analysis (BEA) data. We took the ratio of the net value of private fixed assets at current cost (that is, using replacement cost) for the oil and gas sector to that for the rest of the economy.

of $(1 + c)/(1 + \rho/\pi)$. Earlier we estimated c to be 0.04, while we estimate[37] the ratio ρ/π to be 0.02. That gives a roughly +2% correction to the original formula. The second correction is the final term in parentheses. With the figures given before, we find a value of -0.2% per year.

These are small corrections and they offset one another. With $g_n = 2.1\%$/year, we estimate r_g to be 0.18/year with or without the green correction terms. In fact, when we set $s_w = 0$ to derive the Cambridge equation we made a much more significant change, because when saving out of wages is included, it reduces the profit rate to 0.15/year. Even if half of all energy produced were used to extract energy, so that $n = 1$, the correction on the first term would be about +6%, if ρ/π stays the same, while the second term would become -0.4% per year. Because the changes offset each other, the profit rate is still close to 0.18/year.

The implication of this analysis is that, at least in the US, the macroeconomic consequences of increasing energy demands for energy extraction may be comparatively modest, as long as it is still possible to extract the resources and drive down the energy intensity of the economy. The big changes happen when these assumptions fail. We take up this possibility in the next section.

6. LONG-TERM GROWTH PROSPECTS AND THE STEADY STATE

We now ask, what can the growth rate of the final goods sector, g_g, be in the very long run? This is an essential sustainability question. Green macroeconomists point out that an economy based entirely on non-renewable, fossil, resources must eventually come to a halt, because those resources are finite. Moreover, the earth has a finite capacity to absorb wastes. An economy based on renewable resources can continue indefinitely, but there are limits to the rate at which we can extract those resources; we illustrated this earlier in Figure 4. At some point the provision of ecosystem services becomes constraining. Indeed, we may have already exceeded biogeophysical "**planetary boundaries**", including for climate change, land use change, phosphorous and nitrogen flows, and extinction rates.[38]

We have already discussed the most pressing ecological limit on economies today – the absorption of greenhouse gases from the atmosphere, a regulating service. In this section we represent biophysical constraints through a provisioning service – energy. We consider a long-run future in which stock-limited resources like oil have been replaced by flow-limited renewable resources. The total annual energy consumption, E, is absolutely constrained in this future by the physical limit E_{phys} in equations (52) and (53). From the discussion of renewable potential in Section 3.3, this might be several times our current energy consumption, but it is not unlimited. The absorptive capacity of the environment – that is, regulating ecosystem services like carbon dioxide removal – might ultimately prove to be a tighter constraint on economic growth than energy supply, but both are finite.

Between now and the long-run future, we assume that the world switches from non-renewable to renewable sources of energy up to a maximum level that represents biophysical potential. The global population is larger than it is today, but following recent trend towards gradually slowing

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[37] This is an average over 2011-2017 as estimated from Bureau of Economic Analysis (BEA) data. We calculated the ratio of the gross operating surplus (that is, the profit) for the oil and gas sector to that for the rest of the economy.

[38] See: https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html

growth rates, we assume that population has stabilized and is no longer growing. The maximum energy supply is determined by energy flows in the environment (such as wind, sun, water, and biomass) and technologies for capturing and diverting energy flows in ways that preserve ecosystem function. Through technological improvements, increasing amounts of useful energy are extracted from natural flows, but at some point thermodynamic constraints prevent any further advancement. With this assumption, GDP is given by

$$Y \le \frac{1}{a}\frac{n}{1+n}E_{\text{phys}}. \tag{79}$$

For a given physically feasible level of annual energy supply, E_{phys}, output is constrained by the need to expend energy in order to extract energy, given by the NEPR n, and the energy intensity of the economy, given by a. With fossil energy sources, n tends to fall over time as the most accessible reserves are exhausted, although it can be driven up in the short run by new discoveries and improvements in extractive technology. For renewable resources we expect n to stabilize near limits set by thermodynamics and the need to preserve ecosystem function. Under these conditions, economic growth is limited by the potential to reduce energy intensity, so Y grows at most at the rate α.

The question then becomes for how long we can bring the energy intensity of the goods sector, a, down. There are absolute energetic needs for human survival. Societies also have minimal energy requirements for transport, space conditioning (heating and cooling), hygiene, manufacturing processes, and so on. Beyond that it is possible to provide value through low-energy activities, such as personal or business services.

To investigate the implications of thermodynamic limits, we will apply the green Cambridge equation from equation (78) with $g_n = \alpha$ to capture the physical constraints on economic growth in equation (79). We also assume for simplicity that the saving rates out of rents and profits is the same, and set $s_\rho = s_\pi$. We then have

$$r_g = \frac{1+c}{1+\rho/\pi}\frac{1}{s_\pi}\left(\frac{\alpha}{1+c}+\delta\right). \tag{80}$$

Next, we substitute for the profit rate, setting $r_g = \pi v_g$ and divide by π to find

$$v_g = \frac{1+c}{\pi+\rho}\frac{1}{s_\pi}\left(\frac{\alpha}{1+c}+\delta\right). \tag{81}$$

Capital productivity is output divided by the capital stock, $v_g = Y/K_g$, so we find (one over) the energy intensity to be

$$\frac{1}{a} = \frac{1+n}{n}\frac{Y}{E_{\text{phys}}} = \frac{1+n}{n}\frac{1+c}{\pi+\rho}\frac{1}{s_\pi}\left(\frac{\alpha}{1+c}+\delta\right)\frac{K_g}{E_{\text{phys}}}. \tag{82}$$

While any of these factors can change, most are bounded. We have already argued that n will approach a limiting value in the long run in a renewables-based economy. The profit and rent shares can change, but can be assumed not to fall below some minimal level determined by technology and energy supply and demand (for ρ) and the relative bargaining strength of profit earners vs. wage earners (for π). Greater consumption out of profits (and therefore a lower saving rate s_π) can also drive the intensity downward, but it must be sufficient to at least replace depreciated capital. It is possible in principle for c to vary within wide limits, depending on the relative capital intensity of energy extraction and transformation vs. the rest of the economy. Nevertheless, some physical capital is required to deliver final goods and services, so it is likely to remain bounded. The remaining factor is the energy intensity of the capital stock in the final goods sector.

Capital stock is required in the final goods sector for reasons listed above: transportation, hygiene, space conditioning, and manufacturing. Aside from space conditioning, these are irreducible requirements that have been a feature of all societies, including the ancient ones. In agricultural economies, animal and human labor was necessary to prepare the ground, plant seeds, collect and store the harvest, and later mill and distribute it. Water was transported using a combination of natural water resources, water distribution networks, and human and animal labor. Early agricultural societies manufactured tools, pottery, baskets, clothing, shelters, and other goods, and many such societies traded amongst each other, sometimes over very long distances. This suggests a lower (thermodynamic) limit to the energy consumption associated with operating capital stock in the final goods sector.

The implication from the above is that ultimately there are limits to how low energy intensity can go. That might seem surprising. After all, if services require minimal energy inputs, why not continually add more valuable services, thereby increasing value added without using more energy? The answer, which is built into the Cambridge equation, is that what is bought will be sold at prices that depend on wages. Added value goes either to profits or to wages, which are then used to buy investment goods, a few material-intensive final goods, and an expanding amount of services. The costs of the services are, in turn, determined mainly by wages and the markup. In this economy, the net effect of a rise in service sector value added is a negligible change in purchasing power: wages and profits go up but, as a direct consequence, so do prices.

The only way to grow a service economy is to increase labor productivity in services (through expansion of the capital stock and increased energy consumption) or rising inequality, in which a few people with high incomes buy services from people with low incomes. The first option is captured in equation (82) through the factor K_g/E_{phys}, while the second is captured in the rate of saving out of profits, in that a low saving rate corresponds to a high rate of consumption out of profits, which can then be spent on services. As we discussed above, each of these strategies is ultimately limited.

The implication is that in the long run we must eventually approach a **steady-state economy**.[39] This is an important concept associated with the pioneering ecological economist Herman Daly. In the steady state (and assuming constant capital productivity), $\alpha = 0$. Existing capital can be replaced, but the stock of capital cannot grow. We make the optimistic (but not unreasonable)

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[39] In terms of energy supply, this statement might have to be modified if there is a breakthrough in nuclear fusion. Unlike nuclear fission, which relies on finite geological deposits of radioactive isotopes, nuclear fission combines hydrogen atoms to produce helium. However, this would remove only one constraint. The supply of materials through ecosystem provisioning services and the management of wastes through ecosystem regulating services would still be finite and would place limits on the material and energy throughput of the economy.

assumption that energy intensity a reaches a very low value through **dematerialization** of the final goods sector. This means that c also reaches a very low level, and we set it to zero in equation (80) to find the approximate expression

$$r_g \cong \frac{1}{1+\rho/\pi}\frac{\delta}{s_\pi}. \tag{83}$$

Given a capital productivity v_g, we can write the profit share as

$$\pi = \frac{r_g}{v_g}. \tag{84}$$

From this and the resource share we can calculate the wage share as

$$\omega = 1-\pi-\rho = 1-\left(1+\frac{\rho}{\pi}\right)\frac{r_g}{v_g}. \tag{85}$$

Substituting for r_g from equation (83) then gives an expression for the wage share in the steady-state economy,

$$\omega = 1-\frac{\delta}{s_\pi v_g}. \tag{86}$$

The characteristics of the steady-state economy are captured in equations (83) and (86). While in today's economy the rent share is much smaller than the profit share, it can be expected to increase when there are limited resources and little technological potential to reduce energy intensity. Furthermore, because the capital stock is also at a steady state, the gross investment rate is the depreciation rate δ, which is less than potential growth from labor productivity, $g_n + \delta$. From equation (83), this means that profit earners must save less in this economy relative to the current economy if they are to protect their rate of return. From equation (86), this will lower the wage share, unless capital productivity were to grow sufficiently high that it offsets the fall in s_π.

Ultimately, life in the transition to and operation of a steady-state economy depends on behavior and institutions. If the institutions of the future are like those of today, then when an individual firm sees an opportunity to raise its profits it can be expected to do so. In that case, the economy will accelerate, driving up demand for energy and other raw materials. Because the supply of natural resources is constrained, resource prices will rise, raising rents while eating into profits and wages. That will reduce aggregate demand, causing the economy to shrink again. Ultimately, the physical constraint limits growth, but only after a boom and bust, with different firms or sectors trying to gain a temporary advantage within an absolutely constrained system.

Institutions evolve in response to changing conditions, so while we do not know what the institutions of the future will not be like, we can be certain that they will be different from the ones we have today. Regardless of the precise form, they must be consistent with human behavior, both as individuals and as members of societies. It is interesting to speculate on how they might be different – this is taken up in one of the "deep dive" questions at the end of the module – but a more immediate concern is whether the institutions we have today are capable of moving us towards more sustainable and decarbonized economies. That is a very open and challenging topic in green macroeconomics.

7. FINAL COMMENTS

This module introduces some key concepts in the growing field of green macroeconomics, with a particular focus on the long-run prospects for sustainability. The themes and arguments presented may not be shared by everyone who might identify as a “green” macroeconomist. Despite the effort to present different theoretical traditions in their own terms, the module inevitably reflects the author's interests and theoretical commitments. But that would be true of any presentation of a young and diverse field. The goal throughout has been to spark students’ interest and to invite them on a potentially long trek into largely unexplored territory.

We summarize a few key take-away messages:

- There is more than one school of thought in macroeconomics, and a green macroeconomist should keep an open mind;
- The accounts-behaviors-closures (ABC) approach to macroeconomic analysis is very flexible and applies to any macroeconomic tradition;
- The circular flow of money sits on top of a one-way flow of materials and energy through the economy;
- Economic activity is possible because of external energy inputs through sunlight (whether current or fossil) and the radioactive decay of elements in the earth’s crust;
- Resource extraction requires the expenditure of resources;
- Fossil resources are finite, so we must ultimately rely on renewable resources, which can be maintained indefinitely but can only produce a finite flow in any given period of time;
- We can expect immediate feedback to the economy from constraints on provisioning ecosystem services, such as the renewable supply of energy and materials;
- But the most pressing ecological problem today is with a regulating service – the capacity to absorb greenhouse gases from the atmosphere – that has very slow and indirect feedbacks.

The module sometimes presents material in English prose and sometimes using mathematics. Both are necessary. Social science requires descriptions of different aspects of the social world and of causal processes that connect them. Sometimes the descriptions and causal relationships can be put in quantitative terms and mathematical relationships; other times they cannot.

When we have used models, we tried to illustrate good practice in model building. First, all variables should be defined and have real-world analogues. Even better, their values should be estimable using reported data. (Admittedly, we did not follow best practice in data analysis, since that would have taken us too far afield. Instead, we estimated parameters from recent data and resorted to visual inspection of graphs.) Second, the number of free parameters in the model should be reduced by using accounting relationships (where possible) or behavioral relationships (when accounting relationships are not enough). The proposed behaviors should be motivated by sensible real-world reasoning and supported by empirical observation of actual behavior. Third, results should be checked for plausibility by substituting estimates for the parameters.

A further guideline is that the model builder should step back at the end and ask whether it offers any general implications. For the models developed in this module, we have two kinds of findings. First, using accounting relationships, we have found some "adding-up" constraints. These are comparatively robust. For example, for the classical model with climate change, one implication is that a decarbonization program is likely to require a larger fraction of GDP be devoted to investment rather than consumption. Another, which is intuitive but good to see in numbers, is that if the decarbonization effort stimulates faster growth, then the emissions intensity must drop more quickly to compensate. In the case of the classical model with natural resources, a mature renewables-based economy can be expected to approach a long-run steady state in which GDP is constrained by the annual supply of resources as the thermodynamic potential for increasing efficiency is exhausted.

The other kind of findings are those that follow from the quantitative analysis. These will always be more tentative, because they depend on the simplifying assumptions and specific behavioral and closure assumptions of the model. It is better to work with more detailed models whose parameters have been estimated or calibrated using real-world data. While we have followed the spirit of that approach by estimating the parameters of the models using US data where possible, we can only draw broad conclusions with the simplified models in this module. One substantive conclusion is that the carbon emissions from operating new capital stocks must be much lower than the average today if we are to make meaningful progress on reducing greenhouse gas emissions. Another is that rising demand for energy to extract energy – that is, falling NEPR or EROI – is unlikely to significantly disrupt economic growth as long as it can still be extracted. The real challenge arises when the flow of energy – for example, the annual supply – is absolutely constrained.

Otherwise, we are left with more questions, such as: Who is likely to gain or lose in a decarbonization effort? Are our current economic institutions suitable? What are the employment implications? Does lower material throughput necessarily mean lower GDP? What are the likely macroeconomic implications of a carbon tax? Can we create a sustainable economy built mainly on services? And so on.

Those questions, and many others, make up the research program of green macroeconomics. Some lend themselves to mathematical analysis, while others do not. None of them have easy answers, and offer considerable scope for research and policy analysis.

8. KEY TERMS AND CONCEPTS

Balanced growth: capital stocks in the energy and final goods sectors grow in such a way that they are always in the correct proportions given the energy productivity of the final goods sector.

Capital and labor productivity: the real economic output per unit (e.g., dollar) of fixed capital and per unit (e.g., hour) of labor, respectively.

Classical economic theory: developed in the eighteenth and nineteenth centuries, focused on "big" questions about what governs economies, economic growth, and distribution. Classical economists saw the economy as developing its own logic and equilibrium, based on the operations of markets and the material needs of the workforce.

Cost-share induced technological change: the hypothesis that technological change is driven by firms' efforts to increase the productivity of their inputs in order to reduce costs.

Dematerialization: an absolute or relative reduction in the use of materials and generation of wastes per unit of economic output.

Ecosystem services: beneficial services provided freely by nature, such as flood protection, water purification, and soil formation.

Emissions intensity per unit of capital: the quantity of emissions per unit of fixed capital, such as the tons of carbon emissions per dollar of capital.

Energy intensity: the quantity of energy produced per unit of real economic production (e.g., per dollar of real GDP).

Energy return on energy invested (EROI): the ratio of net energy output to energy input in energy production, including the energy used to build extraction and conversion facilities. Different EROI calculations apply different system boundaries and definitions.

Endogenous: variables that are determined within the model.

Exogenous: variables determined outside the model.

Extensive margin: a change in the quantity of an input, such as the quantity of capital used in production.

Externality: side effects in which market mechanisms fail to inform economic actors about some consequences of their actions—consequences which, however, are felt by unrelated persons or entities (such as the environment)

Fossil fuels: a natural fuel such as coal or gas, formed in the geological past from the remains of living organisms

Functional income distribution: the distribution of GDP between wages, profits, and rents.

Green macroeconomics: the study of economic aggregates at the level of the whole economy, where the economy is seen as embedded in society, which in turn is embedded in the environment.

Gross domestic product (GDP): the total value of final goods and services, net of intermediate sales.

Intensive margin: a change in the intensity of existing resource use, such as producing a greater quantity or lower emissions through efficiency gains.

Macroeconomics: the study of economic aggregates at the level of the whole economy.

Microeconomics: the study of individual and business decision-making and the workings of markets.

Neoclassical theory: developed in the late nineteenth century and widely accepted in the twentieth, bases macroeconomic analysis on the microeconomic analysis of individual and business decision-making and the workings of markets.

Net external power ratio (NEPR): the ratio of energy output per unit time, net of energy industry own use, relative to own use. Unlike EROI, NEPR excludes the energy used to build extraction and conversion facilities.

Non-renewable resources: resources that cannot be reproduced on a human time-scale, so that their stock diminishes with use, such as oil, coal, and mineral ores.

Numéraire: reference of value

Planetary boundaries: the biogeophysical point where the provision of ecosystem services becomes constraining including for climate change, land use change, phosphorous and nitrogen flows, and extinction rates.

Post-Keynesian theory: developed from original work by Keynes and Kalecki, bases macroeconomic analysis on the concept of effective demand. Following Keynes, it argues for the importance of a macro perspective, an activist role for government, and a focus on the importance of distribution.

Renewable resources: resources that are regenerated over time through natural and biological processes, such as forests, fisheries, and freshwater.

Rent: payments for the use of any capital asset. As used in this module, resource rents are the income received by the extractive sector net of costs.

Social groups: an aggregate group of individuals who share an identity. For this module, the definition is restricted to identities (such as wage workers vs. salaried professionals) that are relevant to a macroeconomic analysis.

Steady-state economy: a system that permits qualitative development but not aggregate quantitative growth.

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10. QUESTIONS

We provide questions for each section. We have split them into three categories: **exercises**, which are mostly applications of the models with some reflection; **short research**, which require some outside reading; and **deep dive**, which are open-ended discussion questions.

10.1. Section 1: Introduction

Exercises

1) Examine Table 2, which reports consumer unit characteristics, expenditure, and income, for surveyed households in the Midwest and Northeast US for the 2015-2016 round of the Bureau of Labor Statistics Consumer Expenditure Survey.
   a) What stands out to you in this table? Mention any notable or surprising features.
   b) Based on these tables, would you agree or disagree that households earning between $5,000 and $9,999 per year have different income sources and expenditure patterns than households earning $70,000 per year or more? What are the major differences, if any?
   c) Based on these tables, would it be misleading to combine households from the Midwest with those of the Northeast in the $5,000-$9,999 income bracket into one group? What about the ≥ $70,000 income bracket?

Table 2. *Consumer expenditure in the Midwest and Northeast of the US, 2015-2016*

		Midwest			Northeast	
	Total	$5,000-$9,999	≥ $70,000	Total	$5,000-$9,999	≥ $70,000
Consumer unit characteristics						
Income before taxes	$68,594	$8,083	$130,097	$79,079	$8,021	$149,196
Income after taxes	60,008	8,698	108,343	67,086	8,433	120,965
Age of ref. person	51.0	50.7	47.8	52.1	46.7	49.8
People/household	2.4	1.7	3.0	2.4	1.5	2.9
At least one vehicle	90%	61%	99%	79%	45%	94%
Average expenditure	$54,989	$21,014	$86,852	$59,876	$24,620	$95,104
Food	13%	18%	12%	12%	15%	11%
Housing	31%	39%	29%	35%	45%	32%
Transportation	17%	12%	16%	14%	12%	14%
Healthcare	9%	9%	8%	8%	4%	7%
Entertainment	5%	6%	6%	5%	3%	5%
Education	2%	4%	3%	3%	6%	4%
Pensions & Soc. Sec.	11%	1%	15%	11%	2%	15%
Other	12%	12%	12%	12%	12%	13%
Sources of income and personal taxes:						
Pre-tax income	$68,594	$8,083	$130,097	$79,079	$8,021	$149,196
Wages and salaries	79%	29%	85%	78%	31%	84%
Self-employment	6%	2%	7%	6%	3%	7%
Soc. Sec., retirement	12%	33%	5%	11%	27%	6%
Property income	2%	3%	3%	2%	1%	3%
Public assistance	1%	23%	0%	1%	24%	0%
Unemployment, etc.	1%	2%	0%	1%	4%	0%
Other income	0%	8%	0%	1%	10%	0%

Source: BLS Consumer Expenditure Survey

2) In 2015, the member states of the United Nations adopted Agenda 2030, which includes the Sustainable Development Goals. Sustainable Development Goal 8 is to, "Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all." Discuss what features would have to be included in a macroeconomic model to analyze

strategies for SDG 8. In particular, what would need to be included to evaluate strategies for the following targets:
  a) Target 8.1: "Sustain per capita economic growth in accordance with national circumstances and, in particular, at least 7 per cent gross domestic product growth per annum in the least developed countries"
  b) Target 8.4: "Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead"

Short research

1) Examine one or more of the standard textbooks in the reading list at the end of the module. What topics do they cover that are not covered in this module? What does this module cover that they do not cover? What themes are emphasized in the introduction to the textbook you have chosen?

2) Because neoclassical economics is currently dominant, any alternative school of thought, no matter how well-established, must position itself relative to neoclassical theory. Choose one the alternatives to the standard textbooks from the reading list at the end of the module. Then,
   a) Summarize why the author believes that an alternative to neoclassical economics is called for;
   b) Briefly state the main features of the author's preferred alternative;
   c) Evaluate the critique and the alternative. Did they convince you? Why or why not?

Deep dive

Which of the three economic schools of thought discussed in this module – neoclassical, post-Keynesian, and classical – seems most compelling to you as a way to understand macroeconomic phenomena? Why that one, and not the others? With that in mind, reflect on the idea of pluralism in economics. What are the potential benefits of studying different schools of thought? What are some potential drawbacks?

10.2. Section 2: A Classical Model of Growth and Distribution

Exercises

1) Assuming $s_w = 7\%$, $s_\pi = 39\%$, $\omega = 53\%$, and $\delta = 4.7\%$ per year, calculate g according to equation (15) for $v = 0.25$, 0.30, and 0.35.
   a) What is the value of the profit share, π?
   b) How sensitive would you say the growth rate is to capital productivity?

2) The profit rate, r, is equal to the product of the profit share, π, and the capital productivity, v. Assume the same figures as in the previous question, aside from the wage share. Then suppose that firms adjust their profit share to reach a target profit rate of 0.15 per year.
   a) For $r = 0.15$ per year, what is the profit share if $v = 0.25$, 0.30, and 0.35?
   b) What is the wage share for those values of v?
   c) What is the growth rate, according to equation (15)?
   d) Is the growth rate more or less sensitive to changes in capital productivity under a target rate of return compared to the fixed wage (or profit) share of the previous question?

3) In a closed economy with a government sector, $S = I + G$, where G is *net* government spending (that is, it is government spending minus taxes). Suppose that the government is engaged in deficit spending, so that $G > 0$. Writing net government spending divided by the capital stock as the Greek letter gamma ($\gamma = G/K$), modify equation (11) to include government spending. We emphasize that the goal of the exercise is to get experience manipulating the equations, not to derive a model of an economy with a government sector.

Short research

1) Look at Figure 3. Does the labor productivity curve appear to rise at a more or less steady rate, or have there been times when it has been faster or slower? Identify such a period, and put it in context using a short history of the period.

2) Download the Penn World Table database (https://www.rug.nl/ggdc/productivity/pwt/). For at least five different countries, select all of the available data (with the year) for the variables *emp* (employment), *rgdpna* (real GDP from national accounts data), and *rkna* (real capital stocks from national accounts data). Then create a graph for each country like that in Figure 3.
   a) Are Kaldor's stylized facts seemingly violated in any country?
   b) How do the different values compare between countries?
   c) Using ordinary least squares (OLS) on the logarithm of labor productivity vs. time, estimate the annual growth rate of labor productivity in each country. How similar are they between countries?
   d) Select two countries with very different capital and/or labor productivity in recent years (e.g., from 2010 onward) or that have experienced very different rates of labor productivity growth. Can you explain the differences?

Deep dive

In the text we used classical theory to motivate model development. But first we listed some possible objections from neoclassical and post-Keynesian perspectives. Critique the models from those perspectives. Do they undermine the results, or do they suggest refinements and extensions? In light of your critique, how might the models be modified to make them more realistic?

10.3. Section 3: Embedding the Economy in the Environment

Exercises

1) If NEPR = 9, what is energy industry own-use as a fraction of total annual energy production?
2) What is NEPR equal to when half of all energy consumption is for own-use?

Short research

1) Nearly all ecosystem services can enter the economy in one way or another. Find one or more examples of how habitat/supporting services and cultural services are commodified in practice, in that some individual, firm or government receives money payments for those services.

2) Choose either steel or cement making and explain why they produce carbon dioxide. What low or zero-carbon alternatives exist?
3) Carbon capture and sequestration (CCS) is a controversial technology. Find one or more sources that explain arguments *pro* and *con*. With that background, argue for or against including CCS in a mitigation policy study. (Note that an alternative name for the technology

is “carbon dioxide removal”, or CDR. Also “Carbon capture and storage” is still sometimes used.)

4) Proponents of nuclear energy as a zero-carbon alternative to fossil fuels are often very critical of renewable energy sources. Find one or more sources that explain the arguments *pro* and *con* for nuclear energy rather than renewable energy as a mitigation option. With that background, argue for or against including nuclear energy in a mitigation policy study.

5) The EROI of coal may still be rising. Find a brief history of the technologies used in coal mining. How has the energy required for coal extraction been brought down? Do they have other environmental impacts? If yes, what kinds of ecosystem services do they either require or degrade?

6) One energy source that was not covered in the text is nuclear fusion. Unlike nuclear fission, which requires nonrenewable fossil sources of radioactive material, nuclear fusion relies on a supply of hydrogen. The problem is that economically viable production of electricity from fusion has never been achieved, and it is not clear when or if it will be. Find at least one recent news article that discusses research and development of fusion energy. How likely do they say an eventual breakthrough might be? When might that breakthrough happen? And how long might the delay be between the breakthrough and commercial production? On the basis of that assessment, can we rely on fusion as an answer to climate change? And even if we cannot, should it feature in a very long-run scenario?

Deep dive

Ecosystem service monetization – saying how much those services should be worth to us in money terms – can be contrasted with commodification – actually selling the services for money. Critics of the ecosystem services approach argue that monetization leads to commodification, which threatens the viability of the ecosystems. Defenders disagree and say that without monetization we will continue to undervalue and damage ecosystems. Drawing on additional materials and your own experiences, defend one side of this debate against the other.

10.4. Section 4: The Classical Model with Climate Change

Exercises

1) Consider equation (32). Suppose that emissions in 2030 should be 50% of 2015 emissions. What should φ_m be in that case?

2) Using equation (32), create a table with the value of φ_m for all four combinations of $g = 1\%$ and 2%/year and $\delta = 5\%$ and 6%/year. How sensitive is φ_m to a one percentage point change in each of the two variables?

3) Follow these steps to derive an equation for consumption as a share of GDP under a decarbonization program:
   a) Divide both sides of the accounting relationship $Y = C + I$ by Y. Derive an equation for consumption as a share of GDP, c, in terms of investment as a share of GDP, i.
   b) Divide both sides of equation (33) by Y. Using the answer to part (a), express the result in terms of g, δ, δ_{retire}, c_m, capital productivity v, and investment as a share of GDP, i.

c) Suppose that mitigation costs increase with the degree of mitigation effort, such that $c_m = 0.05\ \varphi_m$. Further assume that there is no early retirement, so that $\delta_{\text{retire}} = 0$. For each of the entries in the table from the previous question, calculate consumption as a share of GDP. The student should specify the capital productivity.

4) Extend the analysis to include emissions reductions at the intensive margin. First, revise equation (20) to read

$$G_{+1} = \left(1-\varphi_i\right)G + \left(1-\varphi_m\right)\gamma I - \left(1+\varphi_r\right)\gamma\delta K.$$

(The subscript *i* is for "intensive".) Then,

a) Follow the derivation in the module to find a revised version of equation (27). (Hint: After revising equation (21) it is easiest to separate the factor $\varphi_i K$ first and then substitute as in equation (22)).
b) How quickly does the average emissions intensity respond to a change at the intensive margin rather than at the extensive margin? (Note: There is not necessarily one "correct" answer this question.)
c) Extend the analysis in equations (31) and (32) to find an expression with φ_m on the left-hand side and φ_i on the right-hand side. How sensitive is the needed reduction at the extensive margin to an increase in the reduction at the intensive margin?

Short research

1) Some activists, politicians and economists have proposed a "Green New Deal" (GND), in which a decarbonization effort is used to create jobs and stimulate the economy.
   a) Find one or more policy statements proposing a GND. (Hint: There's more than one.) What are the key elements?
   b) Evaluate the concept based on the material in this module. Do the goals seem plausible? Do the proposed elements connect in meaningful ways to the goals?
   c) What problems could a GND solve? What problems could arise?
   d) Throughout the module we have pointed out important issues that we excluded from the model to reduce complexity or keep the focus on long-run outcomes. What have we excluded that you would need to consider for a proper evaluation of a GND proposal?

2) Go to the main page for the registry of Nationally Determined Contributions (NDCs) of the United Nations Framework Convention on Climate Change (UNFCCC) (https://unfccc.int/process/the-paris-agreement/nationally-determined-contributions/ndc-registry) and follow the link to the (interim) registry. Select one country's NDC.
   a) Name the country. What is the size of the country's proposed contribution to climate mitigation?
   b) How does the country propose to meet its goals?
   c) What adaptation measures does the country foresee having to implement?
   d) What legal or ethical arguments does the country put forward to justify its proposed actions?

Deep dive

Consider these two statements. The first, which defends the prescriptivist approach to choosing a discount rate, is from the Stern Review:

> Standard treatments of discounting are valuable for analyzing marginal projects but are inappropriate for non-marginal comparisons of paths: the approach to discounting must meet the challenge of assessing and comparing paths that have very different trajectories and involve very long-term and large inter-generational impacts. We must go back to the first principles from which the standard marginal results are derived.

The second, which advocates for a descriptivist approach, is a critique of the Stern Review by William Nordhaus that was published in the *Journal of Economic Literature*:

> The *Review* takes the lofty vantage point of the world social planner, perhaps stoking the dying embers of the British Empire, in determining the way the world should combat the dangers of global warming. The world, according to Government House utilitarianism [utilitarianism imposed undemocratically by an elite], should use the combination of time discounting and consumption elasticity that the *Review*'s authors find persuasive from their ethical vantage point.
>
> I have always found the Government House approach misleading in the context of global warming and particularly as it informs the negotiations of policies among sovereign states. Instead, I would interpret the base line trajectory, from a conceptual point of view, as one that represents the outcome of market and policy factors as they currently exist.

Both authors make ethical claims. On whose behalf do they make those claims? Do you find one more convincing than the other? Explain.

10.5. Section 5: The Classical Model with Natural Resources

Exercises

1) The energy intensity of the US in 2015 was close to 5.5 MJ/$ (in 2011 dollars).
   a) Using Table 1, how many barrels of oil is that equivalent to, per dollar? (You will have to make two transformations, from MJ to MBtu and then from MBtu to boe.)
   b) The US GDP was close to 20 trillion dollars in 2017. Using the intensity from (a), how many barrels of oil equivalent (boe) of energy did the US consume?

2) Countries report profits and wages in their national statistics. Resource rents are not reported by countries. Instead, the World Bank estimates rents indirectly. To ensure that cost shares sum to one, the World Bank's estimate of rents as a share of GDP should be subtracted from either the wage share or the profit share calculated from national statistics. Which should it be subtracted from, and why?

3) Consider equation (55), which is the definition of c. We estimated c to be about 0.04 today, while n is about 9. Suppose that n were to drop from today's value to $n = 1$, so that half of all energy extracted would go toward extracting energy.
   a) If the energy intensity of the final goods sector, a, and capital productivities in the energy and final goods sectors remain the same, what would the value of c be?
   b) What would g_g become with this new value of c, using equation (75) and the parameter values in the following paragraphs?
   c) If changing the functional income distribution (as represented by the wage share) is the only way to get the growth rate back to its original level of 2.1% per year, what would the wage share have to equal for that to happen at the new value of c?

4) One policy option for curbing greenhouse gas emissions is to put a price on carbon. Suppose it is applied as a revenue-neutral tax that is charged to firms and distributed to households. That would raise the price that firms pay for fossil fuels (and thereby encourage them to invest in energy-saving equipment), but would not be paid as rents to the energy sector. Instead, it would be paid (via the tax system) to households. In our model, which has no government sector, the exchange is entirely between firms and households. Firms would mark up the cost of the tax, raising prices and eroding purchasing power. However, the cost of the tax itself would be rebated to households. Setting aside technological change and focusing on distribution, the imposition of a revenue-neutral carbon tax would result in a transfer x from wages to profits, so that $\omega \rightarrow \omega - x$.
   a) Using the values found in the text, and assuming $x = 0.05$, calculate the growth rate using equation (75). Does it increase or decrease, and by how much?
   b) Compare the change in the growth rate to the fluctuations in the annual rate of GDP growth in the US between 2011 and 2017 (the standard deviation is 0.48%/year). Is it much larger, smaller, or about the same?
   c) Noting that the compensation share in the US fell by about 5 percentage points between 1980 and 2005 and was viewed as a substantial change in the wage share, reflect on your answer to the previous question: Using this model, would you say that the impact of the tax on the wage share is large or small? What about the impact on the GDP growth rate?

Short research

1) Between 1948 and 1972, all but one recession in the US was preceded by a rise in oil prices and for at least some recessions the link between the two events was statistically significant. That pattern was broken by the late 1980s and early 1990s.
   a) Is this result broadly consistent with the data shown in Figure 8? Explain why or why not.
   b) Oil prices and rents did spike before the recessions of 1991, 2001, and 2007. Are those spikes relatively large, or are they typical of the variation in the time series?
   c) Find one or more sources that discuss the recessions of 1991, 2001, and 2007. What explanations did they give for the onset of the recessions?

2) In this section we assumed that energy and labor did not constrain GDP, so we replaced the inequality in (53) with an equality that only depends on the capital stock in the final goods sector. When an input to production like energy or labor is constraining, its price tends to rise, which pushes up the price level of GDP. With that in mind, and referring to Figure 8, generate hypotheses: What might have been the primary cause of the two periods of high inflation in the US: the early 1940s (1941-2) and the 1970s (1973-5 and 1978-81)? Find one or more sources that describe the economic conditions and trends in those two periods and check your hypothesis against the explanation offered by the source. Do they support or challenge your hypotheses, and why?

Deep dive

We took a microeconomic procedure – firm markups – and applied it to a macroeconomic analysis. In this deep dive you will critically assess that procedure.

Markups at the level of an economic sector vary considerably, but a typical value is $m = 0.25$. Using equation (65), calculate the profit share, π.

   a) How does that compare to the observed profit share of around 47%?
   b) What markup is implied by a profit share of 47%, using equation (65)?

If it did not perform well, note that firms apply a markup to all costs, including intermediate inputs. Those amount to about half of all costs in the US on average. To take that (roughly) into account, divide your estimated profit share from (a) by 0.5 (which is one minus one-half). How does that result compare to the observed profit share?

Reflect on the extrapolation of microeconomic behavior to macroeconomic analyses. What benefits does it offer? What problems can it raise?

10.6. Section 6: Long-Term Growth Prospects and the Steady State

Exercises

1) Consider equation (83), which is the expression for the profit rate in the steady-state economy. Using the parameter estimates from the section for today's values for s_π, δ, and ρ/π,
    a) Calculate what the profit rate would be in a zero-growth economy with other parameters remaining the same.
    b) Compare your result to the profit rate calculated using the standard Cambridge equation, which is equation (17) in the module. (Do the calculation for a zero-growth economy, with $g_n = 0$.) Which is higher?
    c) Calculate the wage share using equation (86). Is it higher or lower than today's?
    d) What would the rate of saving out of profits have to equal in order to bring the steady-state profit rate equal to today's profit rate? Does it increase or decrease? Explain why.
    e) Using equation (86), calculate the wage share with the revised saving rate. Does it increase or decrease compared to your calculation for (b)? Why?

2) Some proponents of "degrowth" – that is, shrinking our economies to reduce our environmental footprints – suggest more reuse and repair to extend the lifetimes of equipment, buildings and machinery.
    a) What parameter in equation (83) best captures that change, s_π, δ, or ρ/π? And would it be reflected in an increase or decrease?
    b) Propose a change in the parameter you identified and in the correct direction (for example, increase or decrease by 50%). Then, recalculate the profit rate using parameter from part (a) of the previous question. Does it increase, decrease, or stay the same, and by how much?

Short research

1) Consult the list of planetary boundaries (https://www.stockholmresilience.org/research/planetary-boundaries/planetary-boundaries/about-the-research/the-nine-planetary-boundaries.html) and the list of ecosystem services (http://www.teebweb.org/resources/ecosystem-services/).
    a) Classify the planetary boundaries by type of ecosystem services.
    b) Choose one planetary boundary. Could you put it in a macroeconomic model? If not, why not? If you can, what variables would you need to include in order to analyze its interaction with the economy?

2) The size of the human population is a major driver of environmental impact. There is a broad consensus that population is likely to stabilize at some point, but the ultimate level is strongly debated. Find one or more sources that discuss future projections of global population.
    a) What are the main drivers of population growth?

   b) Why did it accelerate rapidly in the 20th Century?
   c) Why did it slow in the late 20th Century?
   d) What would have to happen to the drivers of population growth for population to grow without limit? Is that plausible?
   e) What would lead the global population to stabilize or decline? How much larger might the global population be, compared to what it is today?

3) There is an ongoing debate between proponents of "weak" and "strong" sustainability.
   a) Find one or more sources that define weak and strong sustainability in ways their proponents would likely recognize.
   b) Critique the model for the steady-state economy presented in this module from both weak and strong sustainability perspectives. What does the model miss? What does it capture?

Deep dive

Toward the end of this section, we described a possible cycle in a steady-state economy of rising profits, accelerating growth, rising prices, and then a fall in prices and wages. That hypothetical cycle illustrates the operation of a market. The argument for markets is that that they effectively coordinate decentralized actions even when everyone is acting in their own self-interest. Centralized decision-making, by contrast, is (theoretically) inefficient. Some also argue that it is unfair or even immoral (because it removes some freedom of choice). Another perspective was offered by Elinor Ostrom, who was awarded the Nobel Memorial Prize in Economic Sciences in 2009. She argued that markets are not the only decentralized decision-making framework. In her research, she documented the ways in which social norms and institutions in diverse societies have helped to manage the "commons" in mutually beneficial ways. While acknowledging the difficulty of extrapolating those systems to global commons, such as the climate, she argues that they at least provide starting points for thinking of solutions. These two positions – markets vs. commons – draw on a common set of values – individual freedom and social cohesion – but balance them in different ways. Which do you think is most likely to be effective in a steady-state economy, and why?

11. FURTHER READING

Standard textbooks

The standard textbooks in intermediate macroeconomics cover neoclassical theory. The following is an incomplete list:

Abel, Andrew B., Ben Bernanke, and Dean Croushore. 2016. *Macroeconomics*. 9th edition. Boston: Pearson.

Barro, Robert J., Angus Chu, and Guido Cozzi. 2017. *Intermediate Macroeconomics*. Cengage Learning EMEA.

DeLong, Bradford. 2001. *Intermediate Macroeconomics*. Boston, Mass.: McGraw-Hill Education.

Fisher, Douglas. 2001. *Intermediate Macroeconomics: A Statistical Approach*. World Scientific Publishing Company.

Hoover, Kevin D. 2011. *Applied Intermediate Macroeconomics*. Cambridge University Press.

Mankiw, N. Gregory. 2015. *Macroeconomics*. Ninth edition. New York: Worth Publishers.

Alternatives to the standard textbooks

Some textbooks and curriculum materials push the boundaries of the standard approach. These include:

Fontana, G., and M. Setterfield. 2016. *Macroeconomic Theory and Macroeconomic Pedagogy*. New York: Palgrave Macmillan.

Goodwin, Neva, Jonathan M. Harris, Julie A. Nelson, Brian Roach, and Mariano Torras. 2019. *Macroeconomics in Context*. Third Edition. New York; London: Routledge, Taylor and Francis Group.

Online curriculum materials for the CORE Project: https://www.core-econ.org/.

Others are specifically about classical, post-Keynesian, or structuralist approaches:

Foley, Duncan K., Thomas R. Michl, and Daniele Tavani. 2019. *Growth and Distribution*. 2nd Edition Cambridge, Mass: Harvard University Press.

Godley, Wynne, and M Lavoie. 2007. *Monetary Economics: An Integrated Approach to Credit, Money, Income, Production and Wealth*. Basingstoke, UK; New York: Palgrave Macmillan.

Lavoie, Marc. 2014. *Post-Keynesian Economics: New Foundations*. Cheltenham UK: Edward Elgar Publishing Limited.

Lavoie, Marc. 2015. *Introduction to Post-Keynesian Economics*. Basingstoke: Palgrave Macmillan.

Lavoie, Marc, and Gennaro Zezza, eds. 2011. *The Stock-Flow Consistent Approach*. Palgrave Macmillan.

Mitchell, William, L. Randall Wray, and Martin Watts. 2016. *Modern Monetary Theory and Practice: An Introductory Text*. Callaghan, NSW: Centre of Full Employment and Equity (CofFEE).

Taylor, Lance. 2004. *Reconstructing Macroeconomics: Structuralist Proposals and Critiques of the Mainstream*. Cambridge, MA: Harvard University Press.

Taylor, Lance. 2011. *Maynard's Revenge*. Cambridge, MA: Harvard University Press.

High-level perspective on green economics are provided in:

Daly, Herman E., and Joshua Farley. 2004. *Ecological Economics: Principles and Applications*. Washington, D.C.: Island Press.

Nadal, Alejandro. 2011. *Rethinking Macroeconomics for Sustainability*. London: Zed Books.

Raworth, Kate. 2017. *Doughnut Economics*. White River Junction, VT: Chelsea Green Publishing.

Biophysical economics is presented in both of the following textbooks:

Ayres, Robert U., and Benjamin Warr. 2010. *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Cheltenham, UK: Edward Elgar Publishing.

Hall, Charles A. S., and Kent A. Klitgaard. 2012. *Energy and the Wealth of Nations*. New York, NY: Springer New York.

History of economic thought

There are numerous books on the history of economic thought. These are comparatively accessible:

Heilbroner, Robert L. 1999. *The Worldly Philosophers: The Lives, Times and Ideas of The Great Economic Thinkers*. 7th Revised edition. New York: Touchstone.

Kurz, Heinz D. 2016. *Economic Thought: A Brief History*. Translated by Jeremiah Riemer. New York: Columbia University Press.