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Abstract

In the (very) long run, a sustainable economy must rely on renewable resources. Until that time, an economy can be based on either renewable resources alone or a mix of renewable and non-renewable resources, but the particular mix may constrain the types of economic structures that are possible. A particularly important consideration is the quantity of resources required to extract the resources on which the economy is based, whether it is seeds retained for planting or petroleum used to extract oil. In the case of energy this is called "energy return on energy investment", or EROI. More generally, it can be considered "resource return on resource investment", or RROI. EROI has drawn attention lately both because the EROI of fossil fuels is falling and because the EROI of some renewable alternatives – especially for liquid fuels – is low compared to fossil fuels. In conventional economic analysis it is not clear what the relation between EROI, energy price, and macroeconomic outcomes might be. However, it raises immediate concerns within an Ecological Economic framework, in which resources – which may contribute only a small amount to GDP – are viewed as essential to the functioning of the economy. Resources are pictured as sitting at the base of an inverted pyramid, with the rest of the economy balanced on top of them. In this paper we show that when prices are set by markup, a standard Post-Keynesian assumption, then the "inverted pyramid" picture of the economy emerges naturally. We use this result to develop a computational framework for a "markup economy", and apply it to the question of the macroeconomic impact of changes in resource prices and resource return on investment. We use the resulting model to explore several macroeconomic questions, demonstrating that the model is quite useful for exploring the role of natural resources in the macroeconomy. We then show our main result, that RROI has a surprisingly limited effect on real wages until it reaches quite low values.

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Introduction

The concept of energy return on energy investment (EROI) was introduced by Cleveland et al. (1984) as one indicator of the long-term sustainability of an economy. At the time, the EROI of coal, oil imports, oil discovery, and oil production in the United States were all falling, consistent with the observation that the most accessible coal and oil fields had already been heavily exploited. More recently, Cleveland (2005) estimated the EROI of oil and gas extraction in the US. Correcting for energy quality, he found that the EROI was roughly stable from 1954 to 1972; dropped sharply from 1972 to around 1982 (a peak year for drilling intensity: Guilford et al. 2011); rose slightly; and was relatively stable between 1987 and 1997 at a level 42 per cent below its peak. While these results were for the US, Gagnon et al. (2009) have estimated EROI for global oil and gas production, and found it also to be declining, from a peak of 33 in 1999 to 18 in 2006.

These trends should not be surprising. Oil and gas are non-renewable resources, and it is reasonable that the effort to extract further oil and gas should increase as reserves are depleted. The problem of falling EROI may also not be the most important consideration for oil and gas production: the urgent need to avert dangerous climate change (Schellnhuber et al. 2013) requires sharp decreases in fossil fuel use before fossil sources become too costly to extract, as any net carbon emissions must be either avoided or sequestered (e.g., Praetorius and Schumacher 2009). However, those promoting EROI as a sustainability indicator are concerned about more than the increasing effort required to extract fossil fuels. Rather, they portray the unprecedented economic growth since the industrial revolution as having been literally fueled by abundant modern energy sources, and caution that if high-quality fuels result in low EROI then we cannot maintain our current standard of living, and may not be able to support civilization (Hall et al. 2009). More generally, they expect that EROI should have significant macroeconomic impacts, although the precise mechanisms are not always clear (Murphy and Hall 2011; Cleveland et al. 2000). Against this argument is the observation that only about four per cent of total economic output is spent on energy (US EIA 2012). In neoclassical theory, this is a small contribution that, at the margin, ought to have a correspondingly small impact on the economy. However, as Hamilton (2008) has pointed out, the evidence does not support this marginalist expectation; changes in energy prices have disproportionate macroeconomic impacts.

In this paper we propose a macroeconomic model in which EROI (or, more generally, "resource return on investment" RROI) appears naturally and explicitly. The approach is broadly Post Keynesian and Post Sraffian. As a contribution to Ecological Economics it is therefore one of several papers that have pointed out the relevance of Post Keynesian ideas to Ecological Economics (e.g., Gowdy 1991; Mathieu 1993; Kronenberg 2010), and follows Judson (1989) in seeing a kinship between net energy analysis and Sraffian (neo-Ricardian) ideas. The resulting formalism is quite flexible, and can be added to a wide range of existing macroeconomic models, such as those reviewed by Taylor (2004). The essential result is that GDP can be expressed as a sum of economy-wide markups on the cost of external inputs into the economy, such as labor and raw materials. The economy-wide markups are determined by firm-level (or sector-level) markups and the length of production chains, and can be much larger than firm or sector-level markups.

Within an input-output framework we show that the image of the economy as an "inverted pyramid" (Daly 1995) balanced on a small amount of resources emerges naturally from the model. We then take the insights from the input-output model to construct an aggregate macroeconomic model. We show that the model can make sense of empirical data, including a long-standing puzzle: the strength of the macroeconomic response to an oil price shock. Elaborating on this basic model, we show that RROI enters as a natural parameter when resource prices are treated endogenously. In the resulting model, wages and resource prices are jointly determined, and we show that in this case the real wage is surprisingly insensitive to RROI except at quite low values. We then consider the characteristic of renewable resources that their annual flow is limited, and investigate its implications for long-term growth.

Goods, production, and competition

The theory presented in this paper is concerned with the production of commodities by means of commodities (Sraffa 1960). Firms set their prices as a markup on costs (Lavoie 2001), and the markup propagates through production chains. This is quite different from the dominant macroeconomic modeling approach today, computable general equilibrium (CGE). In fact, CGE modeling emerged from the type of input-output analysis that we carry out below, but today CGE is justified by reference to neo-Walrasian general equilibrium theory (Mitra-Kahn 2008). CGE models are closed by appealing to two neoclassical theories: that of the consumer and of the competitive firm.

The neoclassical basis for CGE is known to have internal theoretical problems, separate from any empirical critique of the assumptions. The theory of the individual consumer can be expressed in an elegant mathematical framework; working within that framework, economic theorists found that even when individual-level consumption decisions are well-behaved, aggregate consumption can take almost any form (Kirman 1989; Ackerman 2001). The theory of the competitive firm is flawed because it is impossible that firms' collective production influences price while at the same time individual production does not, and the discrepancy cannot be resolved through an appeal to the limit behavior of a very large number of identical firms (Keen 2003). The theory also has empirical problems. Theoretical assumptions about consumers' cognitive capacity is at odds with psychological research (Simon 1984; Loasby 2001), and in controlled laboratory experiments subjects were unable to consistently rank bundles of goods (Sippel 1997). This failure is not surprising given human cognitive limitations, but another possible reason is that if people rank goods based on a set of desirable characteristics, rather than the goods themselves (Lancaster 1966), then it is easy to generate situations in which it is impossible for consumers to consistently rank bundles of goods (Kapeller et al. 2012). Considering the pricing decisions of firms, a classic study carried out in 1939 asked entrepreneurs how they set prices, and nearly all said that they usually set prices as a markup on costs (Hall and Hitch 1939). More recent empirical work has confirmed that firms do indeed set prices as a markup on costs, with typical markups of about 20 per cent (Hall 1988; Wu 2009; Loecker and Warzynski 2009). While the study of Hall and Hitch relied on anecdotal evidence, a more recent study found that executives respond to relatively high or low demand in a variety of ways, only one of which – and not the most important – is a change in price (Blinder 1994; Blinder 1998).

In this paper we propose a replacement for the theory of the firm, but do not consider alternatives to consumer theory. In practice, demand functions in CGE models are of a nested form that assumes separable preferences so that, for example, butter and margarine are considered as closer substitutes than, say, butter and diamonds, and that splits consumers into groups with similar preferences. Although nested demand functions were to a large extent an *ad hoc* device, introduced to deal with the vexing empirical problem that countries both import and export the same kinds of goods (Armington 1969), empirical and theoretical work in consumer economics and behavioral psychology offers support for shared and separable consumption functions (Lavoie 2004). Also, when Strotz (1957) first introduced a separable consumption function, he explicitly related it to individual decision-making processes, and argued that consumers are likely to share a roughly equivalent structure, so that the structure of aggregate demand ought to look similar to that of individual demand. The demand functions used in practical applications of general equilibrium may therefore be reasonable for many analyses.

A QUALITATIVE THEORY

Most of this paper is devoted to a quantitative theory, but that theory is not complete; it is sufficiently well developed that it can produce insights and interesting results, but it is also sufficiently complicated that adding important but not central components, such as long-term dynamics, money and finance, and an explicit treatment of fixed capital, would obscure the insights. Before descending into quantitative detail, this section presents a qualitative theory as an organizing framework.

The qualitative theory distinguishes three different kinds of goods: raw materials, such as iron ore, crude oil, and harvested crops; bulk commodities, such as refined iron, steel, petroleum, and graded agricultural products; and branded goods and services. The three types of goods and services have distinct characteristics. Raw materials are both essential to the economy and produced from outside of it. In the case of iron ore and crude oil, the materials were produced over geological time scales (or cosmological, if the formation of iron and carbon atoms is taken into account). In the case of agricultural goods they are produced by photosynthesis. They enter the economy when they are extracted or harvested, and (in the case of crops), in the process of domestication, breeding, and preparing land. Raw materials are rarely useful in their natural form, so they are processed and converted into bulk commodities.

Bulk commodities are, by design, uniform. While bulk commodity producers have brands that they protect by their reputation for reliability, the commodities themselves are indistinguishible. One example is ethylene, a bulk chemical commodity produced from petroleum products that is a versatile building block for a large number of commercial chemical products (Smiley and Jackson 2002). Another is the graded agricultural commodity “No. 2 Red Winter Wheat” used as an example by Debreu (1959). Because they are indistinguishable, bulk commodities are expected to have a uniform price within a particular market.

Branded goods and services are produced using bulk commodities and other branded goods and services. The products of different firms in this category may be closely substitutable, but are not uniform. Firms seek to distinguish their brand from other brands. For example, a firm that produces bread may try to distinguish its product from that of other firms by the quality and healthiness of ingredients, the artisanal nature of production, or its popularity with children. Such non-price distinctions allow different bakeries to sell bread at very different prices and in different markets. Some buyers develop brand or store loyalty, and anchor their price expectations to those brands (Chintagunta 1993; Han et al. 2001; Bonfrer and Chintagunta 2004). Firms also compete on price, so that prices of similar goods are not completely independent of one another.

The qualitative differences between these kinds of products helps to explain an apparent oddity. In general, price and quality are not closely related (Curry and Riesz 1988; Gerstner 1985), but they are closely related for energy (Cleveland et al. 2000). This is understandable, because energy sources are bulk commodities, and the quality of bulk commodities is the only criterion that one can usefully apply when deciding between them. More specifically, ratios of energy prices of different fuels generally track the ratios of their marginal productivities (Kaufmann 1994). We address this more specific result when we develop the quantitative model.

The theory presented in this paper makes the following assumptions, which are recognizably Post Keynesian (Holt and Pressman 2001; Lavoie 2001), with some evolutionary elements in the tradition of Schumpeter (Fagerberg 2003). There are also some overlaps with the qualitative model expounded by Joffe (2011) and, with Joffe and Galbraith (2007), we consider firms to be the essential actors in capitalist economies, viewing them as complex and purposive institutions.

- The prices of raw materials are driven by (perhaps temporary) scarcity, and adjust to imbalances in supply and demand, while firms that produce bulk commodities and branded goods and services set their prices as a markup on normal costs. When costs change, firms do not change their prices immediately, and may resort to a variety of non-price adjustments before passing through an increase in prices. As costs may differ from one firm to another, while prices are similar between comparable goods, the markup will vary between firms.

- Most of the time, firms producing bulk commodities and branded goods and services detect imbalances in supply and demand through an increase or decrease in their levels of stock, and adjust to the imbalance by increasing or decreasing production. Firms may also anticipate rising or falling demand (for example, around a holiday). To allow for changing levels of demand, in normal times firms maintain idle productive capacity, so that they face falling unit costs with modest increases in production, and rising unit costs when they decrease production, contrary to the assumption in the standard theory of the competitive firm.

- Firms that produce bulk commodities and branded goods and services typically respond to prolonged high demand by running equipment more efficiently or by expanding production. They typically respond to prolonged low demand by idling equipment and laying off employees or, in more extreme situations, closing down production lines or going out of business.

- Competition between firms producing bulk commodities and branded goods and services drives the markup toward a common value – in competitive markets, firms that are not profitable given their costs go out of business, while firms receiving high profits are emulated by others. New entrants (or an incumbent defending its position) can compete on price, driving prices down generally and shrinking profits.

- Firms also seek to lower costs, allowing them to capture greater profits in the short term, and leading to lower prices in the longer term. When they achieve cost reductions by reducing inputs, as a side benefit, they increase the real purchasing power of consumers. (According to Joffe (2011), this self-interesed and spontaneous behavior is the root cause of economic growth.)

- Entry of firms is costly, because firms must take on fixed costs. In most cases firms borrow from investors in order to establish themselves, launch a new product line, change processes, or expand their operations. Because entry is costly, and firms have proprietary processes, equipment, and intellectual property, markets are normally oligopolistic (that is, dominated by a few firms), with some temporary or regulated monopolies and some highly competitive sectors. In addition to differences in costs between firms, this is a further reason for the markup to differ between firms and sectors.

These assumptions address some outstanding questions that computable general equilibrium appears to answer. Lack of satisfactory answers to these questions from heterodox theory has been an important reason that heterodox critique has not led to the replacement of computable general equilibrium as an analytical tool. These questions are:

1. Why are prices normally close to (if not exactly at) the values that ensure that supply equals demand?

2. How do individual firms receive signals about demand?

The assumptions also address a question that CGE does not answer:

3. How can the economy even temporarily be in equilibrium if there are unrealized economies of scale?

The answer to the first question is that firms that cannot meet their costs at a reasonable profit must normally go out of business or close down the unprofitable product line, while firms that are making higher than normal profits may (but will not always) face other firms who compete with them on the basis of price. Also, firms may adjust to changing costs (such as the cost of raw materials) by passing the costs on to consumers. Under these assumptions, the adjustment process for prices of goods in most of the real economy is slow, in contrast to the rate of adjustment in stock markets and markets for raw materials.

The second question was posed clearly by Arrow (1974) in his Nobel Prize address. After acknowledging that price is not the only mechanism for adjusting to imbalances in supply and demand, he asked, "Nevertheless, while the criticisms are, in my judgment, not without some validity, they have not given rise to a genuine alternative model of detailed resource allocation. The fundamental question remains, how does an overall total quantity, say demand, as in the Keynesian model, get transformed into a set of signals and incentives for individual sellers?" The answer given here is that firms normally learn about imbalances of supply and demand by performing inventories of their stock, and tracking stock levels over time, while price signals come to firms through the cost side. Also, increasing or decreasing levels of stock are normally corrected by adjusting production levels – that is, through quantity adjustment – rather than through prices. After prolonged low demand, firms may lower their prices, and they continually seek to reduce costs, which eventually translate into lowered prices.

Part of the answer to the third question is that any equilibrium (or quasi-equilibrium) is temporary, and the economy is always changing. Another part is that firms do, indeed, grow very large, and considering global brands, there is no obvious maximum scale. However, the most important part of the answer is that to grow, any firm must borrow; to borrow, it must convince lenders that it can make a profit; and to make a profit there must be sufficient demand. This last consideration means that the expansion of firms is limited by effective demand and the availability of finance.

As already noted, these ideas are not new, and are essentially post Keynesian and evolutionary. The innovation in this paper is that it explicitly treats the assumption that in markets for raw materials demand-supply imbalances are corrected through prices, as in neoclassical theory. As shown later, this leads to an analogue to standard general equilibrium that has some interesting properties.

Natural resources in an input-output framework

The model presented in this section abstracts from the assumptions given in the previous section in order to focus clearly on a few issues. It takes sectors, rather than firms, as the unit of analysis, and assumes that a common markup applies to all sectors across the economy. It also assumes immediate pass-through of both rising and falling costs. The model applies to relatively stable conditions, so that aggregate demand can be represented by a well-behaved demand function, and over a sufficiently short time horizon that the structure of the economy can be assumed fixed. These abstractions permit the economy to be represented by an input-output model. In the following section, some of these assumptions are relaxed.

The starting point is a basic physical input-output model that includes productive sectors and final demands. In the model economy there are m sectors producing bulk commodities or branded goods and services. At a particular point in time, the economy is characterized by an $m \times m$ physical technical matrix A, where an entry A_{ij} in the matrix represents the amount of good i required to produce a unit of good j. There is also an $m \times 1$ column vector of final demands F, and a production vector Y of the same dimensions. The physical balance is expressed as

$$Y = A \cdot Y + F. \tag{1}$$

Following the conventional input-output calculations, the production vector Y is determined by

$$\begin{aligned} Y &= \left(\mathbf{1} - A\right)^{-1} \cdot F \\ &\equiv \Lambda \cdot F, \end{aligned} \tag{2}$$

where Λ is the Leontief inverse, and **1** is the identify matrix.

The output of each sector is assigned a representative price, so that across all m sectors there is a vector of prices p. Also, firms in all sectors apply a uniform markup μ. In terms of value, the balance for the economy is therefore

$$p^T = \mu p^T \cdot A, \tag{3}$$

where a superscript T indicates a transpose.

It has been shown that if A is irreducible (that is, the technical matrix does not contain an independent sub-economy) and productive (that is, it is possible, although maybe not demanded, to simultaneously supply a nonzero final demand for every good produced in the economy), then, aside from scaling by a *numéraire*, there exists a unique nonnegative vector of prices and a unique markup that satisfies Equation (3) (Blatt 1983).

This calculation shows that in a closed economy, where production is completely interconnected, there is no flexibility in setting prices. This is – or should be – a surprising conclusion, since it is inconsistent with the prevailing marginalist belief that prices are determined by the intersection of supply and demand curves. As will be shown later in this paper, the marginalist condition reemerges in an open economy, when raw materials are added to the model, but not for all goods. The constraint on prices expressed in Equation (3) is still present, and leads to different results than those suggested by the standard theory of general equilibrium.

NATURAL RESOURCES

In addition to the model presented above, in which m sectors produce bulk commodities or branded goods and services, we now assume that the economy makes use of n different raw materials. There are many more firms than there are raw materials, $m \gg n$, and none of the raw materials appear in final demand. The input-output model is the same as in the previous subsection, so that

$$Y = \Lambda \cdot F, \tag{4}$$

where Λ is the Leontief inverse.

Unlike the physical input-output equations, the equations for price are different from the basic model presented earlier. In the extended model, in addition to intermediate goods, all firms must pay for labor, and firms providing bulk commodities must pay for the raw materials from which the bulk commodities are produced. Demand for labor, *L*, is given by multiplying the transpose of a vector for labor per unit of good produced, λ^T, by the production vector *Y*,

$$L = \lambda^T \cdot Y. \tag{5}$$

In this expression, λ is an $m\times 1$ column vector. Demand for raw materials is given by an $n\times 1$ column vector *R*, computed using the transpose of an $m\times n$ matrix ρ,

$$R = \rho^T \cdot Y. \tag{6}$$

We assume that labor is paid a uniform wage, *w*. Following convention, heterogeneity within the workforce can be captured by expressing labor in productivity-adjusted "worker-equivalents". Prices of raw materials are given by an $n\times 1$ column vector p_R.

With these additions, the price equation is now

$$p^T = \mu\left(p^T \cdot A + w\lambda^T + p_R \cdot \rho^T\right). \tag{7}$$

This is equation is solved by

$$\begin{aligned} p^T &= \left(w\lambda^T + p_R \cdot \rho^T\right)\cdot\left(\mathbf{1} - \mu A\right)^{-1}\mu \\ &\equiv \left(w\lambda^T + p_R \cdot \rho^T\right)\cdot \Lambda_\mu, \end{aligned} \tag{8}$$

where

$$\Lambda_\mu \equiv \left(\mathbf{1} - \mu A\right)^{-1}\mu. \tag{9}$$

This last expression is very similar to that for the Leontief inverse, but it contains the markup; we refer to it as the "markup" Leontief inverse. It reduces to the ordinary Leontief inverse when there is no markup – that is, when μ is equal to one.

Total output from this economy is given by the value of consumption, because receipts for all intermediate production are matched by an equal payment from another firm. Therefore, GDP, *G*, can be calculated as

$$\begin{aligned} G &= p^T \cdot F \\ &= \left(w\lambda^T + p_R \cdot \rho^T\right)\cdot \Lambda_\mu \cdot F. \end{aligned} \tag{10}$$

To better understand this expression, assume that firms do not apply a markup on costs, so that $\mu = 1$. In this case, Λ_μ becomes simply the Leontief inverse Λ, and

$$\begin{aligned} G &= \left(w\lambda^T + p_R \cdot \rho^T\right) \cdot \Lambda \cdot F \\ &= \left(w\lambda^T + p_R \cdot \rho^T\right) \cdot Y \\ &= wL + p_R \cdot R. \end{aligned} \tag{11}$$

That is, in the absence of a markup, GDP is simply the sum of labor costs and the costs of raw materials, which we can write in words as

$$\text{GDP (no markup)} = \text{Wages} + \text{Raw Materials.} \tag{12}$$

In the absence of a markup, wages and raw materials costs are passed from the companies who purchase them directly through the economy without adding any costs, so that the cost of final consumption is equal to the expenditure on the raw materials and labor themselves.

For the general case, consider the expression

$$\Lambda_\mu \cdot F = \left(\mathbf{1} - \mu A\right)^{-1} \cdot \left(\mu F\right). \tag{13}$$

This can be seen as a Leontief-type calculation for an economy in which both final demand for each good and the amount of each intermediate good per unit of output are increased by the markup μ. Denoting the output of this "markup economy" as

$$Y_\mu \equiv \Lambda_\mu \cdot F, \tag{14}$$

with corresponding labor and raw material requirements $L_\mu \equiv \lambda^T \cdot Y_\mu$ and $R_\mu \equiv \rho^T \cdot Y_\mu$, total economic output is seen to be

$$G = wL_\mu + p_R \cdot R_\mu. \tag{15}$$

That is, GDP is the total labor, resource, and capital requirements of this (fictitious) markup economy.[2] The difference between this expression and the total of wages, rents, and interest is profit, so we can write in words

$$\begin{aligned} \text{GDP} &= \text{Wages} + \text{Raw Materials} + \text{Profits} \\ &= \text{Wages}_\mu + \text{Raw Materials}_\mu. \end{aligned} \tag{16}$$

This is an explicit representation of the idea of the economy as an inverted pyramid resting on inputs (Daly 1995). The direct cost of those inputs may be small, but they are enlarged by applying markups across production chains. The more elaborate the economy – and therefore the more opportunities for markup – the larger will be profits, and therefore *G*, compared to the sum of the wage and raw materials bills.

We return to this result in a later section.

SUPPLY AND DEMAND

In the model presented above no mention was made of how demands are determined. We assume that consumers settle on a preferred bundle of goods, perhaps after a search (Loasby 2001). As a

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[2] This is formally the same procedure that Sraffa (1960) followed in his construction of production in terms of "dated labor", without the interpretation of intermediate steps as representing time.

result of that search, when the economy is not changing much, the aggregate response of consumption to changes in price approximates that of an idealized utility-maximizing consumer (Hoderlein 2011). Since this is the condition that is assumed to prevail for the input-output model developed above, we make the conventional assumption that final demand for depends on the vector of prices for all goods,

$$F \to F(p). \tag{17}$$

From Equation (8), the price vector p can be written

$$p = \Lambda_\mu^T \cdot \left(w\lambda + \rho \cdot p_R\right), \tag{18}$$

where we have taken the transpose of Equation (8) and used the fact that p_R is a diagonal matrix, so that it is equal to its transpose. Comparing Equation (17) to Equation (18), it can be seen that when the technology and markup are held fixed, demand for all goods is effectively a function of the wage w and prices of raw materials p_R. For the rest of this section we assume a sticky wage and fixed markup and technical matrix, so that final demand is effectively a function only of the prices of raw materials. We therefore introduce the shorthand notation

$$F(p_R) \equiv F\left[\Lambda_\mu^T \cdot \left(w\lambda + \rho \cdot p_R\right)\right]. \tag{19}$$

Next, we recall the definition of the $n\times 1$-dimensional demand vector R for raw materials, and note that it depends on the prices of raw materials. From Equation (6) we therefore have

$$R(p_R) = \rho^T \cdot Y. \tag{20}$$

From the standard input-output result, given by Equation (2), this can also be written

$$R(p_R) = \rho^T \cdot \Lambda \cdot F(p_R). \tag{21}$$

As discussed in the introduction, we assume that the producers of raw materials face rising costs with rising production. We also assume that their industries are competitive, so that they raise prices to a similar degree when they increase their output. As a consequence, we expect a reasonably well-defined supply schedule for each raw material, $S(p_R)$, expressed by an $n\times 1$ column vector.

It is not necessarily the case that the market in raw materials ever clears – there may be unsold produce, grain, or ore, and there may be some who would willingly pay at the announced price, if any materials were still available – but the equilibrium price is an interesting quantity. When raw materials reach their equilibrium price p_R^*, by definition, supply equals demand,

$$S(p_R^*) = R(p_R^*). \tag{22}$$

Suppose that the price is at its equilibrium level p_R^* when the supply schedule is $S_1(p_R)$, and a supply shock shifts it to a new schedule $S_2(p_R)$. The gap between the current and new equilibrium price vector, Δp_R, can be calculated from the condition

$$S_2(p_R^*) - R(p_R^*) = -\Delta p_R \cdot \left(J_S(p_R^*) - J_R(p_R^*)\right), \tag{23}$$

where $J_S(p_R^*)$ is the Jacobian of $S_2(p_R)$ evaluated at p_R^*, and similar for $J_R(p_R^*)$, with entries

$$J_{Sij}(p_R^*) = \frac{\partial S_{2i}}{\partial p_{Rj}}(p_R^*), \tag{24}$$

$$J_{Rij}(p_R^*) = \frac{\partial R_i}{\partial p_{Rj}}(p_R^*). \tag{25}$$

Equation (23) is an analogue to the usual price adjustment equation in general equilibrium. The important difference is that in Equation (23) only the prices of raw materials enter the equation explicitly. All other prices are calculated from the prices of raw materials (and the wage, assumed fixed), using Equation (18).

Natural resources in a macroeconomic model

The model developed in the previous section assumes a detailed knowledge of the economy, in the form of input-output relationships. Such an analysis is often, but not always, necessary. It becomes problematic when exploring long-term changes in the economy, such as a low-carbon or sustainability transition, that dramatically reconfigure production and consumption. More useful would be a theoretical apparatus that can link to existing approaches to macroeconomics, such as those surveyed by Taylor (2004). For this purpose an aggregate model is preferable to a disaggregated input-output model. We develop such a model in this section.

AMPLIFICATION OF THE MARKUP

As the markup is applied at each intermediate stage in the conversion of raw materials into final goods, the initial cost can be amplified substantially. Equation (14) gives an explicit way to calculate the amplification of the markup, but the presence of the technical matrix obscures general features of the amplifying factor. In this subsection we construct a simplified model of the markup in order to draw general conclusions. We consider a particular external input – labor, or raw material – as it passes through production chains. Conceptually, we divide the input into a large number of “bins” of equal size, such as individual workers (or productivity-adjusted worker-equivalents), litres of oil, or bushels of wheat (or person-minutes, microlitres of oil, and grains of wheat, for an even finer sub-division). We then track the value of one bin as it passes from sector to sector through the economy. At each intermediate step the initial cost of a bin is amplified by the markup μ. After ℓ steps the value is amplified by μ^ℓ. Of interest is the average amplification factor $\alpha(\mu)$, which depends on the probability P_ℓ of encountering production paths of length ℓ in passing from the labor or raw material input to the finished good. It is calculated as

$$\alpha(\mu) = \sum_{\ell=1}^{\ell_{\max}} \mu^\ell P_\ell, \tag{26}$$

where $\ell_{\max}$ is the maximum possible chain length. The maximum length is, in theory, infinite, because it is possible for a single input to be passed back and forth between intermediate sectors an indefinite number of times before reaching the consumer. This infinite sequence is formally captured in the expression for the Leontief inverse given in Equation (2). As argued by Sraffa (1960) in his exposition of dated labor, in practice it is both possible and reasonable to truncate the series when the contributions become suitably small.

The probability distribution P_ℓ depends on the input-output matrix of the economy, but as noted above, that means that it depends on the detailed structure of the economy. To draw general conclusions we motivate a form for the probability distribution that makes the calculation of $\alpha(\mu)$ tractable. The essential assumption is that the probability of extending or shrinking the length of a supply chain does not depend on the current length of the chain. Production chains can be extended when an entrepreneur sees an opportunity for combining materials in a new way, to offer as a service an activity that currently is carried out internally by firms, or to provide a new input that replaces an existing one, and that has a longer production chain than the input it is replacing. Production chains can contract when firms fail, or merge, or bring a service in-house that they were previously out-sourcing, or switch to an input that itself has a shorter production chain than the one they were using previously. The supposition is that in these activities the entrepreneurs and firms do not consider the current length of the production chain. In this case, if p_+ is the probability of extending the chain, and p_- is the probability of shrinking it, then the expected value in the change in the number of chains of length ℓ, denoted n_ℓ, is

$$E(\Delta n_\ell) = p_+ n_{\ell-1} + p_- n_{\ell+1} - (p_+ + p_-) n_\ell. \tag{27}$$

In a steady-state, this expected value will be equal to zero. The steady-state distribution n_ℓ^* then satisfies

$$0 = p_+ n_{\ell-1}^* + p_- n_{\ell+1}^* - (p_+ + p_-) n_\ell^*. \tag{28}$$

We propose the following expression for the steady-state distribution:

$$n_\ell^* \propto a^\ell. \tag{29}$$

Then the condition in Equation (28) becomes, after substution, dividing through by $a^{\ell-1}$, and rearranging,

$$p_- a^2 - (p_+ + p_-) a + p_+ = 0. \tag{30}$$

This is a quadratic equation with two solutions, $a = 1$ and $a = p_+ / p_-$. The first solution can be shown to be unstable to small perturbations, while the second is stable as long as $p_- > p_+$. That is, it is stable as long as the probability that a given chain will shrink is greater than the probability that it will grow.

The probability of encountering a production chain of length ℓ is proportional to the number of paths of that length, so the probability P_ℓ has the same form as n_ℓ^*, given in Equation (29). With this form for the probability distribution, and taking the limit in which the maximum chain length approaches its theoretical value of infinity, $\ell_{\max} \to \infty$, it is possible to show, using standard summation formulas, that

$$a = 1 - \frac{1}{\overline{\ell}}, \tag{31}$$

where $\overline{\ell}$ is the mean chain length. The normalized probability function is, with these assumptions,

$$P_\ell = \overline{\ell}^{-1} \left(1 - \overline{\ell}^{-1}\right)^\ell. \tag{32}$$

Substituting into Equation (26) to find the mean amplification factor $\alpha(\bar{\ell},\mu)$ gives

$$\alpha(\bar{\ell},\mu)=\bar{\ell}^{-1}\sum_{\ell=1}^{\ell_{\max}}\left[\left(1-\bar{\ell}^{-1}\right)\mu\right]^{\ell}. \tag{33}$$

Because $a<1$, we have $\left(1-\bar{\ell}^{-1}\right)\mu<1$, so the sum converges in the limit $\bar{\ell}\to\infty$. Again using standard summation formulas, we find that

$$\alpha(\bar{\ell},\mu)\simeq\frac{1}{\mu-\bar{\ell}(\mu-1)}. \tag{34}$$

Considering some examples, for a markup μ = 1.2, the amplification factor diverges when the mean path length is $\bar{\ell}=6$. At that point the assumption that $\left(1-\bar{\ell}^{-1}\right)\mu<1$ no longer holds. For a mean path length $\bar{\ell}=5$,

$$\alpha(5,1.2)=5, \tag{35}$$

while for a mean path length $\bar{\ell}=2$,

$$\alpha(2,1.2)=1.25. \tag{36}$$

Thus, for very short paths the amplification factor is not much larger than the markup, and it rises sharply with increasing mean path length.

Interpretation of the amplification factor

Examining the expression for GDP given by Equation (15), it can be seen that both labor costs wL and raw materials costs $p_R\cdot R$ are amplified across production chains. We consider the case of a single raw material input, and emphasize the difference from the vector R of raw material inputs by denoting it with a lower-case r. We define economy-wide markups μ_w and μ_r on wages and raw materials as

$$\begin{aligned}\mu_w&\equiv\frac{L_\mu}{L},\\ \mu_r&\equiv\frac{r_\mu}{r}.\end{aligned} \tag{37}$$

These economy-wide markups depend on the structure of the economy. They depend on how goods are passed between firms in the process of converting labor and raw material inputs into consumption goods. Applying the model developed above, we can write these as

$$\begin{aligned}\mu_w&=\alpha(\bar{\ell}_w,\mu),\\ \mu_r&=\alpha(\bar{\ell}_r,\mu).\end{aligned} \tag{38}$$

In this formulation we assume, as before, that a uniform markup is applied by all firms to all costs, so that μ is the same in both expressions. However, we allow the mean production chain length $\bar{\ell}$ to differ for labor and raw materials inputs. We generally expect $\bar{\ell}_r$ to exceed $\bar{\ell}_w$, and therefore for μ_r to exceed μ_w. This is because labor inputs occur at every step, from extraction to production to distribution to retail, while raw material inputs occur only at the initial start of production chains, when they are converted into bulk commodities.

Equation (38) shows that the economy-wide markup depends on both the firm (or sector) level markup μ and also on the mean production chain length $\bar{\ell}$. As it is an increasing function of both variables, if production chains generally lengthen – for example, because of innovations in transport (Dicken 2011) – then the economy-wide markup will increase. This will also increase the share of output going to profits, but these will not be captured by a single firm, since all firms apply a uniform markup. Instead, it will be spread among a variety of firms, some of which may be quite small, along the supply chain.

Energy prices and marginal products

We now return to the result of Kaufmann (1994), who found that relative energy prices tend to track relative marginal productivity. He estimated an empirical economy-wide production function, and took the partial derivative of the production function with respect to consumption of different fuels. He then showed that ratios of prices generally moved in tandem with relative marginal products, although for several energy sources the ratios were not equal.

To show the relationship between Kaufmann's results and the theory developed in this paper, recall from Equations (10) and (15) that GDP is given by

$$G = p^T \cdot F = \left(w\lambda^T + p_R \cdot \rho^T\right) \cdot \Lambda_\mu \cdot F = wL_\mu + p_R \cdot R_\mu. \tag{39}$$

In the last term, the vector R_μ is the "markup" version of the raw materials vector. Each raw material i has an economy-wide markup μ_i defined by

$$\mu_i \equiv \frac{R_{\mu i}}{R_i}, \tag{40}$$

so GDP can be written

$$G = wL_\mu + \sum_{i=1}^{n} p_{Ri}\mu_i R_i. \tag{41}$$

The marginal product of raw material i is then

$$\frac{\partial G}{\partial R_i} = \mu_i p_{Ri}, \tag{42}$$

and ratios of prices are given by

$$\frac{p_{Ri}}{p_{Rj}} = \frac{\mu_j}{\mu_i}\frac{\partial G}{\partial R_i}\left(\frac{\partial G}{\partial R_j}\right)^{-1}. \tag{43}$$

If the economy-wide markups are steady compared to changes in marginal product, then this equation says that relative prices should track relative marginal product, but will not be equal to the ratios of marginal product. Instead, they will differ by the ratios of the markups on the different energy sources.

Kaufmann (1994) considered four energy sources: number 2 heating oil, coal for electricity, natural gas for industrial uses, and electricity for industry. In general, we expect electricity to have a smaller economy-wide markup than coal, because coal is used to produce electricity, and therefore occurs earlier in the production chain. Examining Equation (43), this implies that the ratio of the price of electricity to that of coal should be higher than the ratio of their marginal productivities. Trends for other combinations of fuels are more difficult to predict, because the relative markups are not obvious. The theory in this paper therefore has three concrete predictions: the ratios of prices do not have to equal the ratios of marginal products; if the structural use of fuels is not changing significantly, then relative prices will track marginal productivity; and the ratio of the price of electricity to the price of coal should be higher than the ratio of their marginal productivities. All three of these can be observed in Kaufmann's data. Ratios of prices were often different for ratios of marginal productivities, but tended to track them; in particular, the ratio of electricity to coal price was close to twice the ratio of marginal productivities.

We conclude that Kaufmann's (1994) observations are consistent with the theory presented in this paper, and they follow directly from the linear structure of the energy-output relationship. Because economy-wide markups for different fuels can change over time, the theory in this paper does not require that relative prices always track relative marginal productivities, so it can accommodate the behavior that Kaufmann observed for oil relative to natural gas, in which prices broadly followed an opposite trend from marginal productivities. The observed trends can be explained if the markup on natural gas was about 4.5 times the markup on number 2 oil in 1955, but the markups converged so that the markup on natural gas was about 2.0 times the markup on number 2 oil by 1992.

The interpretation arising from the model in this paper is quite different from that of Kaufmann, who argued that rational consumers and producers pushed prices towards their marginal productivities, making use of the moderate market freedom allowed them by the government, which otherwise strongly influenced energy prices (Kaufmann 1994, p.156). In contrast, this paper argues that at least part of GDP is given by a structural economy-wide markup on energy costs. If relative economy-wide markups are stable, then relative productivities are determined by relative prices, with no assumption of rational (or irrational) behavior.

RESOURCE PRICES AND WAGES

In this subsection we construct a simple model of an economy that takes labor and raw materials as inputs to production, in which profits are determined by markups on inputs. At this point we shift from an input-output framework to an aggregate macroeconomic framework. The aggregate framework is more flexible, and can be used to address general questions, as we show in this and following sections.

Total economic output for this model economy – that is, GDP – is given by

$$PX = \mu_w w \lambda X + \mu_r p_r \rho X, \tag{44}$$

where P is the general price level, X is real output, λ and ρ are aggregate labor and resource inputs, and μ_w, μ_r are the economy-wide average markups on labor and raw materials. Because real output can be eliminated from both sides of this equation, the equation determines the price level P, but not the level of real output. Additional relationships, such as a price-output curve or production function, are required to specify X.

Dividing both sides of Equation (44) through by *PX* gives an equation in terms of the real wage and raw material price. From this point forward we denote real values with a tilde, so that, for example, where w is the nominal wage, $\tilde{w}$ is the real wage. The result is,

$$1 = \mu_w \tilde{w}\lambda + \mu_r \tilde{p}_r \rho. \tag{45}$$

Note that $\tilde{w}\lambda$ is the share of wages in total output, which we denote s_w, while $\tilde{p}_r\rho$ is the share of expenditure on resources, s_r. With this notation,

$$1 = \mu_w s_w + \mu_r s_r. \tag{46}$$

It is possible to estimate μ_w and μ_r from this equation. We demonstrate two ways to do this. First, suppose that the real resource price changes by a small percentage u, and in response the real wage changes by a percentage v. Then to first order,

$$\begin{aligned} s_r &\to s_r(1+u), \\ s_w &\to s_w(1+v). \end{aligned} \tag{47}$$

Substituting into Equation (46) and rearranging gives the elasticity of the real wage with respect to a change in the real resource price, ε,

$$\varepsilon \equiv \frac{v}{u} = -\frac{\mu_r s_r}{\mu_w s_w}. \tag{48}$$

Combining this expression with Equation (46) determines the markups in terms of s_r, s_w, and ε,

$$\begin{aligned} \mu_w &= \frac{1}{s_w} \cdot \frac{1}{1+|\varepsilon|}, \\ \mu_r &= \frac{1}{s_r} \cdot \frac{|\varepsilon|}{1+|\varepsilon|}, \end{aligned} \tag{49}$$

where we have used the fact that ε is negative to express the two equations in terms of its absolute value $|\varepsilon|$.

Estimates are available for the parameters in Equation (49), if oil is considered to be the only resource. The elasticity of the wage with respect to oil price in the United States was estimated by Keane and Prasad (1996) to be about -10 per cent (using data between 1966 and 1981). Prior to the 1973 oil price shock, the cost share of energy in the United States was 4.5 per cent (Bohi 1991). In 1973, the share of gross domestic income (in theory equal to GDP) disbursed to employees was 51.6 per cent (Federal Reserve Bank of St. Louis 2013). Assuming $s_r = 4.5\%$, $s_w = 52\%$, and $|\varepsilon| = 10\%$, Equation (49) yields estimates

$$\begin{aligned} \mu_r &= 2.0, \\ \mu_w &= 1.7. \end{aligned} \tag{50}$$

In the second approach, we use time-series data to estimate μ_w and μ_r, and show that recently the energy markup appears to be higher than in the 1970s. The data are shown in Figure 1. Between 1995 and 2010, except for two excursions during the oil price rises of 2000-2001 and 2007-2008, the wage and expenditure shares have remained very close to the line defined by Equation (46), with $\mu_r = 3.8$ and $\mu_w = 1.9$ ($r^2 = 0.98$). As lower energy markups move points rightward of the line in Figure 1, holding the markup on labor costs fixed, it can be seen from the figure that from

1987 to 1994, the energy markup generally rose, perhaps continuing a process of shifting from direct energy expenditures to energy embodied in goods that had already been observed in 1984 (Cleveland et al. 1984). As Cleveland et al. noted, "...a dollar's worth of fuel purchased by households represented 145,000 kilocalories in 1972, whereas a dollar's worth of *nonfuel* good or service purchased by households represented only 5,600 to 11,800 kilocalories" [emphasis in original]. In the model presented in this paper, the difference is explained using Equation (44) by the need to pay for embodied labor and the markup on the cost of the fuel embodied in the final good. Cleveland et al. went on to say that eighty-eight per cent of the reduction in the energy intensity of the economy between 1973 and 1980 could be attributed to the phenomenon of shifting from final energy consumption to consumption of energy embodied in goods. In the model presented in this paper, this translates into an increase in the markup on energy, which flows to profits rather than wages, resulting in an overall reduction in the wage share, as seen in the trajectory between 1987 and 1994 in Figure 1.

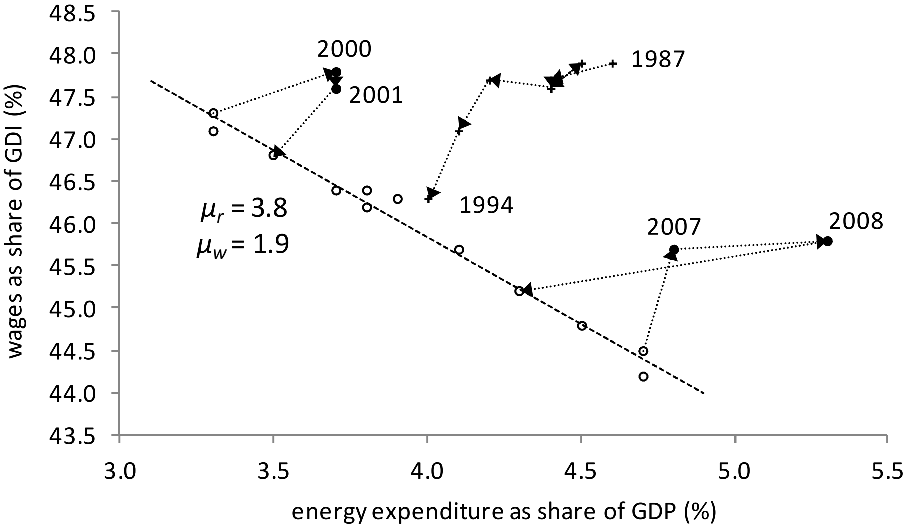

Figure 1: Wage share vs. energy expenditure share, 1987-2010
Sources: Energy expenditure share (US EIA 2012); wage compensation as a share of GDI (Federal Reserve Bank of St. Louis 2013). (Note: In theory, GDI = GDP, but differ in practice due to statistical discrepancies.)

Applying the model for amplification along production chains developed in the previous subsection, and assuming a 20 per cent markup ($\mu = 1.2$), the estimates for μ_r and μ_w circa 1973, given in Equation (50), correspond to average production chain lengths of $\bar{\ell}_r = 3.5$ and $\bar{\ell}_w = 3.1$, while the more recent estimates shown in Figure 1 correspond to average production chain lengths of $\bar{\ell}_r = 4.7$ and $\bar{\ell}_w = 3.3$. In this interpretation, the increased markup represents an extension of production chains, a notable feature of the global economy over this period (Dicken 2011). For energy used in production, the initial energy purchase is pushed further back in the chain, raising the markup. Note that the increase in production chains can be understood from the amplification model developed above. From Equation (31), and noting that $a = p_+ / p_-$, it is possible to show that

$$\bar{\ell} = \frac{p_-}{p_- - p_+}. \tag{51}$$

This is a decreasing function of p_-, the probability that a particular production chain will shorten by one link. The kinds of innovations that Dicken (2011) calls "circulation" technologies, such as containerization and digital communications, make the failure of extended supply chains less likely, thereby reducing p_-; a lower value for p_- can also give confidence to entrepreneurs and investors, thereby driving up the probability p_+ that a chain will be extended; the combination of falling p_- and rising p_+ increases $\bar{\ell}$, the average length of production chains.

Figure 1 shows that a relatively stable relationship of the form given in Equation (46) can persist for over a decade, but also that it is not an iron rule. If the energy price abruptly changes, firms may initially respond by holding prices steady and reducing markups (and thereby moving rightward of the line). Also, the relationship depends on the structure of the economy. If energy inputs are buried deeply in production chains, then the markup on energy costs will be higher than if they are closer to final demand.

In this interpretation, the pathway from 1987 to 1994 in Figure 1 is of a very different character from those during the 2007-2008 and 2000-2001 oil price shocks. The difference is captured by the two variables, $\bar{\ell}$ and μ, that determine the amplification factors in Equation (38). Between 1987 and 1994 production chains were generally lengthening, thereby raising the economy-wide markup – a structural change. In contrast, the interpretation of the oil price shocks is that the length of production chains did not change, but initially firms absorbed at least part of the oil price rise. This had the effect of lowering the firm-specific markup μ, which therefore also lowered the economy-wide markup on wages. Within the model the net effect of these changes is to slightly raise the wage share immediately after the shock, followed by a fall in the wage share once the markup returns to its normal value. These features can be seen in Figure 1 for the 2000-2001 oil price rise. The 2007-2008 oil price rise has a somewhat different structure, suggesting that other factors were influencing the wage share at that time. As this was a period of financial crisis, this is not surprising. What is perhaps surprising is that after 2008 the relationship between the energy and wage shares should return to the pattern it had followed since 1995.

These observations have implications for alternative energy scenarios that distinguish between local and global production systems. For example, if rising transport costs make today's extended production chains unprofitable, then production chains may generally shrink (Curtis 2009).

Extending production chains and wages

The results above suggest that since the 1970s the markup on resources μ_r has increased, while the markup on wages has remained roughly the same, around $\mu_w = 1.8$. Meanwhile, the energy expenditure share first fell and then rose, varying around a value close to four per cent. From Equation (46), this implies that the wage share must change, with

$$\Delta s_w \simeq -\frac{s_r}{\mu_w}\Delta\mu_r. \tag{52}$$

With a change in the markup on resources of $\Delta\mu_r = 1.8$ (that is, increasing from 2.0 to 3.8), this suggests that the wage share must have fallen by about $\Delta s_w = 4$ percentage points. In fact, it has fallen by somewhat more than that, by $\Delta s_w = 5.2$ percentage points between 1973 and 1995 (US EIA 2012). The wage share has fallen further since 1995, a commonly-observed phenomenon that as the economy has expanded, wages have remained stagnant (e.g., as reported by Greenhouse 2013).

While the causes of stagnant wages are many, Equation (52) suggests a new mechanism that may explain part of the change. It links a falling wage share with a rising markup on resources because the increasing markup results in a higher profit share. The rise in the markup occurs by extending production chains: the initial energy input is pushed farther down the chain, while a markup is applied at each link. Note that the rising profits under this mechanism do not necessarily go to one or a few companies. Instead, they could be shared by many small firms, each of which takes a cut along a production chain – although each markup is amplified as it is passed up the chain.

This mechanism cannot explain the continued fall in the wage share after 1995, since at that time the relationship shown in Figure 1 appears to have stabilized. Instead, this model suggests that since 1995 the wage share has eroded because the energy share increased, particularly during the general rise in real energy prices since 2001. The model in this paper therefore suggests a two-part explanation for a falling wage share: until 1995, lengthening supply chains increased aggregate profits; after 2001, rising energy costs with fixed markups on wages and energy reduced the wage share.

The macroeconomic effect of an oil price shock

In 1977, Rasche and Tatom (1977) showed that the oil price rise of 1973 had led to a strong and persistent decline in the economic output of the United States. Subsequently, it was found that nearly all recessions had been preceded by a rise in oil price, which became a puzzle for neoclassical economic models. The problem is that in a standard neoclassical model, the elasticity of GDP with respect to a change in oil price should be equal to (minus) the share of oil expenditures in the economy. That is, it should be equal to s_r, in the notation used above (Hamilton 2008). As already noted, around 1973 s_r was close to four percent, 0.04; however, observations suggest that the response should be at least ten times higher than this theoretical value (Hamilton 2008). The theory presented in this paper can explain the magnitude of the empircal observations, although it is not sufficiently detailed to study, for examples, changes in labor allocation and the profile of GDP over time (Jones et al. 2004). The mechanism is a conventional Post Keynesian one: an oil price rise drives down the real wage, as shown above; the fall in the real wage means a drop in effective demand, which, through a Keynesian multiplier, is much larger than the initial fall in the real wage.

As mentioned above, Equation (44), which expresses GDP in terms of production, cannot be used to determine real output, X. To do that, we express X in terms of consumption,

$$PX = \theta_w w\lambda X + \theta_p\left[(\mu_w - 1)w\lambda X + (\mu_r - 1)p_r\rho X\right] + I, \tag{53}$$

where θ_w is the marginal propensity to consume from wages, θ_p is the marginal propensity to consume from profits, and I is investment. Dividing through by P gives an expression in terms of real quantities,

$$X = \theta_w \tilde{w}\lambda X + \theta_p\left[(\mu_w - 1)\tilde{w}\lambda X + (\mu_r - 1)\tilde{p}_r\rho X\right] + \tilde{I}. \tag{54}$$

Collecting terms on the right-hand side then gives

$$X = \left(\mu_w\theta_p + \theta_w - \theta_p\right)\tilde{w}\lambda X + \theta_p(\mu_r - 1)\tilde{p}_r\rho X + \tilde{I}. \tag{55}$$

We assume that shortly after the oil price shock, real investment $\tilde{I}$ does not change. What does change is the real oil price $\tilde{p}_r$, the real wage $\tilde{w}$, and real output X. Expressing small changes in these variables with a delta symbol Δ, the first-order response of real output to a change in the oil price can be expressed as

$$\Delta X = \left(\mu_w\theta_p + \theta_w - \theta_p\right)\lambda\left(\Delta\tilde{w}X + \tilde{w}\Delta X\right) + \theta_p(\mu_r - 1)\rho\left(\Delta\tilde{p}_r X + \tilde{p}_r\Delta X\right). \tag{56}$$

It is convenient to put everything in terms of proportional changes. Noting that $s_w = \lambda \tilde{w} X$ and $s_r = \rho \tilde{p}_r X$, Equation (56) can be rearranged to yield

$$\frac{\Delta X}{X} = \left(\mu_w \theta_p + \theta_w - \theta_p\right)\left(\frac{\Delta \tilde{w}}{\tilde{w}} + \frac{\Delta X}{X}\right) s_w + \theta_p (\mu_r - 1)\left(\frac{\Delta \tilde{p}_r}{\tilde{p}_r} + \frac{\Delta X}{X}\right) s_r . \tag{57}$$

Next, collecting all of the terms multiplying ΔX/X on the left-hand side of the equation gives

$$\left[1 - \left(\mu_w \theta_p + \theta_w - \theta_p\right) s_w + \theta_p (\mu_r - 1) s_r\right] \frac{\Delta X}{X} = \left(\mu_w \theta_p + \theta_w - \theta_p\right) \frac{\Delta \tilde{w}}{\tilde{w}} s_w + \theta_p (\mu_r - 1) \frac{\Delta \tilde{p}_r}{\tilde{p}_r} s_r . \tag{58}$$

This is somewhat complicated, but it can be simplified by noting, by reference to Equation (55), that the quantity in brackets on the left-hand side is equal to $\tilde{I} / X$ – that is, it is the national average investment rate *i* (also the national marginal propensity to save). The right-hand side can be simplified by noting, from Equation (48), that

$$\frac{\Delta \tilde{w}}{\tilde{w}} = -\frac{\mu_r s_r}{\mu_w s_w} \frac{\Delta \tilde{p}_r}{\tilde{p}_r} . \tag{59}$$

Substituting this into Equation (58), and expressing the quantity in brackets on the left hand side as the investment rate *i*, the equation becomes, after some simplification and rearrangement,

$$\frac{\Delta X}{X} = -\left[\theta_p + \left(\theta_w - \theta_p\right) \frac{\mu_r}{\mu_w}\right] \frac{\Delta \tilde{p}_r}{\tilde{p}_r} \frac{s_r}{i} . \tag{60}$$

We expect that the marginal propensity to consume from wages, θ_w, is larger than the marginal propensity to consume from profits, θ_p, so the elasticity of GDP with respect to the oil price is always negative. To estimate the elasticity, we assume that all wages are consumed, and all profits are saved, so that $\theta_w = 1$ and $\theta_p = 0$. In this case, the elasticity of GDP with respect to oil price is

$$\frac{\tilde{p}_r}{\Delta \tilde{p}_r} \frac{\Delta X}{X} = -\frac{\mu_r}{\mu_w} \frac{s_r}{i} . \tag{61}$$

The private savings rate in September 1973, just before the October oil price rise, was 10.2 per cent. Setting *i* (the multiplier) to this value, s_r to four per cent, and μ_r and μ_w to their values in Equation (50), this yields an estimate of -0.46 for the elasticity. This is of the correct sign and of the same order of magnitude as the observed response.

The Keynesian multiplier, *i*, plays an essential role in this explanation of the macroeconomic response to an oil price shock. In a neoclassical model the change in the real wge should have almost no impact. While we have not made any assumptions about the nominal wage, it is reasonable to suppose that it is fixed in the short run. In neoclassical theory, firms are constrained from expanding production by the scarcity of inputs, mainly labor. The small change in their direct energy costs would make almost no difference in their production decisions. Conversely, if the nominal wage were to track the real wage, then firms would face falling input costs and should therefore increase output, the opposite of the prediction given above. As already noted, these neoclassical expectations are at odds with the empirical results.

Consumption and profits

In this section we follow Minksy (2008), who was himself following Kalecki (1939; 1969) and ask how the markup translates into profits in a closed economy. We expand on the previous model by separating the economy into two sectors, one producing consumption goods and the other producing investment goods. Prices in the two sectors are determined by an equation like Equation (44)

$$P_C X_C = \mu_{Cw} w \lambda_C X_C + \mu_{Cr} p_r \rho_C X_C, \tag{62}$$

$$P_I X_I = \mu_{Iw} w \lambda_I X_I + \mu_{Ir} p_r \rho_I X_I. \tag{63}$$

Profits are given by the markup, less inputs. That is, total profits π for the economy are given by

$$\pi = \left(\mu_{Cw} - 1\right) w \lambda_C X_C + \left(\mu_{Cr} - 1\right) p_r \rho_C X_C + \left(\mu_{Iw} - 1\right) w \lambda_I X_I + \left(\mu_{Ir} - 1\right) p_r \rho_I X_I. \tag{64}$$

As in the previous subsection, we assume some consumption from both wage and profit income. In this closed economy, the total must equal the production of consumption goods, $P_C X_C$. That is,

$$P_C X_C = \theta_w w \left(\lambda_C X_C + \lambda_I X_I\right) + \theta_p \pi. \tag{65}$$

Setting this equation equal to Equation (62) gives

$$\mu_{Cw} w \lambda_C X_C + \mu_{Cr} p_r \rho_C X_C = \theta_w w \left(\lambda_C X_C + \lambda_I X_I\right) + \theta_p \pi. \tag{66}$$

From Equation (64), it can be seen that the left-hand side is equal to

$$\mu_{Cw} w \lambda_C X_C + \mu_{Cr} p_r \rho_C X_C = \pi + w \lambda_C X_C + p_r \rho_C X_C - \left(\mu_{Iw} - 1\right) w \lambda_I X_I - \left(\mu_{Ir} - 1\right) p_r \rho_I X_I. \tag{67}$$

Substituting this equation into Equation (66) then gives

$$\pi + w \lambda_C X_C + p_r \rho_C X_C - \left(\mu_{Iw} - 1\right) w \lambda_I X_I - \left(\mu_{Ir} - 1\right) p_r \rho_I X_I = \theta_w w \left(\lambda_C X_C + \lambda_I X_I\right) + \theta_p \pi. \tag{68}$$

This equation can then be rearranged to find a relationship similar to that found by Minsky and Kalecki,

$$\left(1 - \theta_p\right) \pi = w \left[\mu_{Iw} \lambda_I X_I - \left(1 - \theta_w\right)\left(\lambda_C X_C + \lambda_I X_I\right)\right] + p_r \left[\left(\mu_{Ir} - 1\right) \rho_I X_I - \rho_C X_C\right]. \tag{69}$$

This is already a useful expression, but before discussing it we rewrite it in another useful way. Referring to the equation for $P_I X_I$ in Equation (63), it can be seen that this equation reduces to

$$\left(1 - \theta_p\right) \pi = P_I X_I - \left(1 - \theta_w\right) w L - p_r R, \tag{70}$$

where $L = \lambda_C X_C + \lambda_I X_I$ is total labor in both sectors and $R = \rho_C X_C + \rho_I X_I$ is total resource use.

Suppose for a moment that workers spend all that they receive (so $\theta_w = 1$) while profits go only toward investment (so $\theta_p = 0$). Also suppose that the cost of resources can be neglected. In this case,

$$\pi = P_I X_I. \tag{71}$$

Profits thus equal investment, which, in turn, will be used to generate further profits. This is the source of the short paraphrase of Kalecki's conclusion that the worker spends what he gets, while the capitalist gets what he spends. In the general case, as consumption out of profits increases, it pushes profits higher. The same holds for consumption out of wages – savings out of wages decrease profits. This result is an expression of the paradox of thrift. In Equation (70) the inclusion of raw materials means that some money that does not flow to wages also does not flow to profits – it is used to pay for raw materials – and so profits are reduced by the value of natural resources.

Equation (70) does not tell the whole story, because buried in the expression for $P_I X_I$ is a markup on resource costs. The expression is expanded in Equation (69), where it can be seen that changes in the material intensity of the consumption and investment goods sectors, as measured by ρ_C and ρ_I, have different implications for profits. Specifically, dematerialization in the consumption goods sector (lower ρ_C) increases aggregate profits, while dematerialization in the investment goods sector (lower ρ_I) decreases aggregate profits. Note that this non-intuitive result does not hold at the level of a firm, where resources are a cost to production – holding the price temporarily fixed, reducing material use will lower costs and raise the firm-specific markup. Over time the price will tend to fall, eroding the temporary advantage of the cost-saving firm. To the extent that it is easier to dematerialize consumption goods compared to investment goods, dematerialization will tend to increase aggregate profits.

Resource return on resource investment

In this section we extend the macroeconomic model developed in the previous section by endogenizing resource production. This is necessary for an understanding of energy return on energy investment (EROI), or, more generally, resource return on resource investment (RROI). The essential idea is that extracting resources takes resources and labor, and this affects prices, wages, and total output.

Those researchers who study EROI argue, correctly, that energy plays a unique role, and is not like other resources. Economic production takes work, and work takes energy, and the entire economic process can be viewed as the conversion of low-entropy energy to high-entropy energy (Georgescu-Roegen 1975; Cleveland et al. 1984). The role of energy is particularly stark today, as we are rapidly depleting stores of high-quality, low-entropy energy (fossil fuels) to support production and consumption. However, for most of humanity's existence, energy was provided on an ongoing basis by sunlight.[3] The energy input is still essential, but it is useful to think of the derived material separate from the sunlight that produced them, and not always in terms of energy. For example, in the ancient world, when land was not scarce and seed yields were low, farmers thought in terms of seed harvested to seed sown (Evans 1980); that is, as resource return on resource invested.

MACROECONOMIC BALANCES IN A TWO-SECTOR MODEL

In this extended model, GDP is given by the sum of outputs from the extractive (resource) sector and the rest of the economy (the "business" sector), which has the same structure as the model developed in the previous section. The value of output from the business sector is allocated to wages, payment for resources, and profits as determined by markups on wages and resources,

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[3] In fact, all of our energy except for geothermal, tidal, and nuclear energy is derived from sunlight, as fossil fuels and peat were once plants that captured sunlight through photosynthesis, while wind, hydropower, and wave power are driven by heat provided by the sun. In the long run economies must rely on contemporary sunlight, as humans had mostly done until the wide-spread use of coal.

$$P_b X_b = \mu_w w \lambda_b X_b + \mu_r p_r \rho_b X_b. \tag{72}$$

Value added V_b from the sector is equal to $P_b X_b$ less the value of non-labor inputs,

$$V_b = P_b X_b - p_r \rho_r X_b. \tag{73}$$

We assume that the extractive sector is self-contained and therefore applies only one level of markup. Also, the ratio of fixed costs to total costs in the extractive sector is high, so we explicitly introduce fixed costs in the extractive sector, F_r. Resources from the extractive sector are used for the extractive process, as expressed by RROI. In general, resources can either be used directly, termed “own-use”, or bought on the market. Although buying resources on the market means that the extractive sector must pay a markup that it, itself, has applied, it may still result in lower overall costs through specialization. However, in this model, we assume that own-use is the dominant strategy, so that

$$\begin{aligned} p_r(1-\rho_r)X_r &= \mu\left(w\lambda_r X_r + F_r\right), \\ p_r X_r &= \frac{\mu}{1-\rho_r}\left(w\lambda_r X_r + F_r\right). \end{aligned} \tag{74}$$

Because this model bundles resource rents into fixed costs F_r, and only takes into account the effort to extract and process the resource, the value added from the sector is simply $p_r X_r$, so GDP, equal to a general price level P, multiplied by total real output, X, is given by

$$PX = \left(P_b X_b - p_r \rho_b X_b\right) + p_r X_r. \tag{75}$$

Total requirement for labor, L, is the sum of labor inputs to both sectors,

$$L = \lambda_b X_b + \lambda_r X_r, \tag{76}$$

and the total resource requirement is equal to the sum of the requirements from the business and extractive sectors. Moreover, it is equal to the total output from the resource sector (assuming no net change in stocks), so that

$$X_r = \rho_b X_b + \rho_r X_r. \tag{77}$$

Rearranging this equation gives an expression that will be useful later,

$$\rho_b X_b = (1-\rho_r)X_r. \tag{78}$$

Note that ρ_r is the amount of resource inputs required to produce a unit of resource outputs, so it is the inverse of RROI,

$$\mathrm{RROI} = \frac{1}{\rho_r}. \tag{79}$$

THE REAL WAGE AS A FUNCTION OF RROI

We now recombine the equations above into a more useful form through a series of substitutions and rearrangements. First, we substitute the expression for $P_b X_b$ given by Equation (72) into the expression for GDP given by Equation (75). The result is

$$PX = \mu_w w\lambda_b X_b + (\mu_r - 1)p_r\rho_b X_b + p_r X_r. \tag{80}$$

Next, we substitute for $\rho_b X_b$ in this equation using Equation (78), and collect terms in $p_r X_r$. The result is

$$PX = \mu_w w\lambda_b X_b + p_r X_r\left[1 + (\mu_r - 1)(1 - \rho_r)\right]. \tag{81}$$

We then substitute in this equation for $p_r X_r$ using Equation (74), to give

$$PX = \mu_w w\lambda_b X_b + \left[1 + (\mu_r - 1)(1 - \rho_r)\right]\frac{\mu}{1 - \rho_r}\left(w\lambda_r X_r + F_r\right). \tag{82}$$

For convenience, we now define an effective markup on resources

$$\begin{aligned} \mu_r' &\equiv \left[1 + (\mu_r - 1)(1 - \rho_r)\right]\frac{\mu}{1 - \rho_r} \\ &= \mu\left(\mu_r + \frac{\rho_r}{1 - \rho_r}\right). \end{aligned} \tag{83}$$

From this expression it can be seen that own-use in the extractive sector (or, more generally, resource consumption by the extractive sector) drives the effective markup on resources above the markup in the non-extractive sector. As RROI falls (and ρ_r rises), the effective markup increases, and it diverges as RROI approaches one.

Applying Equation (83) to Equation (82) gives

$$\begin{aligned} PX &= \mu_w w\lambda_b X_b + \mu_r'\left(w\lambda_r X_r + F_r\right) \\ &= w\left(\mu_w\lambda_b X_b + \mu_r'\lambda_r X_r\right) + \mu_r' F_r. \end{aligned} \tag{84}$$

In this expression, $\lambda_r X_r$ is the labor used in the extractive sector, and $\lambda_b X_b$ is the labor used in the business sector – see Equation (76). Writing the share of labor devoted to resource extraction as ω_r, sectoral labor requirements can be written

$$\begin{aligned} \lambda_r X_r &= \omega_r L, \\ \lambda_b X_b &= (1 - \omega_r)L. \end{aligned} \tag{85}$$

Substituting these expressions into Equation (84) gives

$$PX = wL\left[\mu_w(1 - \omega_r) + \mu_r'\omega_r\right] + \mu_r' F_r, \tag{86}$$

and dividing through by PX gives an expression in terms of real quantities,

$$1 = \tilde{w}\bar{\lambda}\left[\mu_w(1 - \omega_r) + \mu_r'\omega_r\right] + \mu_r'\frac{F_r}{PX}. \tag{87}$$

In the last equation, $\bar{\lambda} \equiv L/X$ is the inverse of the real economy-wide labor productivity. The final term includes the effective resource markup multiplied by fixed costs in the extractive sector as a share of total output. Denoting this factor by $\varphi \equiv F_r/PX$, and rearranging, the real wage can be written

$$\tilde{w} = \frac{1}{\bar{\lambda}} \frac{1 - \mu_r' \varphi}{\mu_w (1 - \omega_r) + \mu_r' \omega_r}. \tag{88}$$

In the case where there is no resource input, and output is allocated only to labor and profit, this equation reduces to

$$\tilde{w}_{\text{no resource}} = \frac{1}{\mu_w \bar{\lambda}}. \tag{89}$$

That is, the real wage is simply the labor productivity reduced by the markup. In the general case, Equation (88) captures the effect of resource inputs to the economy, RROI, labor inputs in the extractive sector, and fixed costs in the extractive sector. This occurs because the effective resource markup μ_r' depends on these additional factors through its definition in Equation (83).

THE SURPRISING INSENSITIVITY OF THE WAGE SHARE TO RROI

The wage share of output (equal to the real wage divided by real labor productivity), is given by Equation (88). Given the labor share ω_r in the extractive sector and the ratio φ of fixed costs in the extractive sector to GDP, the ratio of the real wage to real labor productivity can be calculated as a function of RROI. For the US, the share of national labor costs going to extractive industries (NAICS codes 211, 212, and 213) can be calculated directly from US Bureau of Labor Statics (BLS) figures (US BLS 2013) as four per cent in 2011. The fixed cost share is not readily available, but energy extraction is a high fixed-cost business: assuming that fixed costs are 50 per cent of value added, and noting from BLS statistics that value added from extractive industries was three per cent of GDP in 2011, we estimate φ to be 1.5 per cent. The result is plotted in Figure 2, with values on the right-hand axis.

It is also useful to look at an indicator of the resource price. The resource price depends on RROI, the real wage, and other factors, according to Equation (74). We assume that the nominal wage remains fixed, while the general price level depends on the resource price, the wage, and relative output from the business and extractive sectors. Closing this set of equations requires additional assumptions. We make the simplifying assumption that differences in the general price level, which depend on the resource price itself, make a second-order contribution to the change in the resource price level due to changes in RROI. Leaving all factors other than RROI (or, equivalently, ρ_r) fixed, we therefore define a "first-order" price index Π_1, where

$$\Pi_1 \equiv \frac{1}{1 - \rho_r}. \tag{90}$$

This index is plotted on the left-hand axis in Figure 2.

Also shown in Figure 2 are estimates of energy return on energy investment (EROI) for several fuels. The important point to take away from the figure is that the wage share curve is nearly flat until the RROI is quite small – less than two. Among the fuels, only US corn ethanol, a notoriously inefficient energy source (Kreith 2012), is in the range where the price and wage curves diverge strongly from their asymptotic levels. This is a surprising and interesting finding, since it suggests that the "net energy cliff" (Murphy and Hall 2010) is rather far away. Considering EROI alone, only if we were to base the global economy on corn ethanol (or perhaps tar sands) would it become difficult to maintain increases in real wages in step with increases in labor productivity. As noted by Kreith (2012), there are many renewable fuels with much higher EROI than corn ethanol.

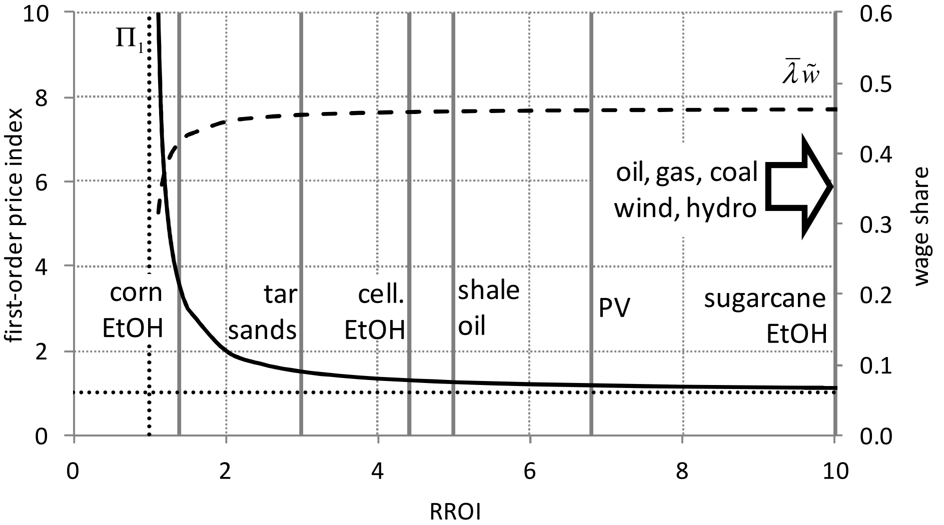

Figure 2: First-order price-index (left axis) and real wage share (right axis) vs. RROI
Sources for EROI examples: photovoltaics (PV), shale oil, tar sands, and sources with EROI greater than 10 from Murphy and Hall (2010); US corn ethanol (corn EtOH) and cellulosic ethanol (cell. EtOH) are mid-range values from Hammerschlag (2006); Brazilian sugarcane ethanol (sugarcane EtOH) from Goldemberg (2007).

The analysis in this section must be qualified by two important caveats. First, we have only considered the resources required to extract resources. It is also necessary to ship the resources to where they will be used, and then to have enough available to support "civilization". Hall et al. (2009) estimated that for these purposes an EROI of at least three is essential. To capture this, we must shift the curves in Figure 2 rightward, but it should otherwise leave the shape roughly the same. This would make corn ethanol an even less likely candidate than it already is, and also raise considerable doubts about tar sands. It may also make cellulosic ethanol look less desirable, but the other fuels still look viable, including Brazilian sugarcane ethanol.

The analysis above also did not take into account the fact that renewable resources, while able to produce indefinitely into the future, provide a limited annual flow. This is a familiar feature for water and food production, and we are currently placing strong pressures on our water resources and food production systems (Rockström and Karlberg 2010). This is not yet a feature of our energy system, but short of a major breakthrough in fusion research,[4] or a substantial shift to nuclear fission, it is likely to become one. We consider this issue in the next subsection.

FLOW-LIMITED RESOURCES

As illustrated in Figure 2, the EROI of several renewable energy sources is quite large: photovoltaics, Brazilian ethanol from sugarcane, wind, and hydropower. Even cellulosic ethanol may be large enough to be a reasonable option. Moreover, as long as the environment that generates these resources is maintained, they can produce indefinitely into the future, unlike fossil energy sources. However, they are less desirable than fossil fuels for at least three reasons: their annual production is limited, they are intermittent, and they have low energy densities. Intermittency can be addressed through storage and by spreading variability across large connected grids, while low energy density can be addressed to some degree through conversion to higher-density energy carriers (at the expense of lower EROI, since energy must be expended in the process). However, there will always be a limit to annual production. In this section we consider the implications if the annual production of a resource, X_r, is constrained.

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[4] As the ITER research facility expects to achieve (http://www.iter.org/).

Total output is provided by both the extractive and "business" sectors, as seen in Equation (75). The extractive sector provides employment, but the measure of affluence is the size of the business sector. Output from this sector can be expressed in terms of X_r through Equation (78):

$$X_b = \frac{1-\rho_r}{\rho_b} X_r . \tag{91}$$

If X_r is limited, then X_b can be increased by reducing ρ_r, ρ_b, or both. That is, it can be increased by increasing RROI (and thereby shrinking ρ_r), or dematerialization (shrinking ρ_b). This surprisingly mechanical result helps explain why, over the long run, energy and output have generally kept pace with each other (Cleveland et al. 2000), and also how dematerialization and changing EROI can lead resource use to grow more slowly than GDP (Ayres and van den Bergh 2005). It is possible for RROI (or EROI) to increase, but at best this can happen slowly. Thus from Equation (91), sustainable economic growth when resources are flow-limited must be achieved mainly through dematerialization, meaning that people must add value (that is, doing things for which other people want to pay them) without adding material resources. This may, indeed, be possible, as explored by Fagnart and Germain (2011) and Ayres and van den Bergh (2005). However, there seems to be little evidence of it so far. Apparent "decoupling" of GDP and material throughput appears to be a consequence of efficiency improvements in material-intensive production, rather than a fundamental shift from material to non-material consumption (Cleveland and Ruth 1998). If continual and substantial dematerialization is not possible, then relying on flow-limited resources may lead to an "end to (rapid) growth", as envisioned by Murphy and Hall (2011), Daly (2013), Gordon (1999) and others.

Discussion

This paper introduced several ideas, and produced several results. Importantly, it provides an analytic mechanism for addressing outstanding problems in Ecological Economics. Within an input-output framework, Post Keynesian and Post Sraffian ideas lead to a natural representation of the "inverted pyramid" view of the economy. The resulting expression can then be applied at an aggregate level, and interpreted in terms of growing and shrinking production chains. The main difference from conventional macroeconomic models is that profits emerge from a markup; the relevant variables are the markup and the average length of production chains, rather than the profit share itself. The model differs from conventional economic models because it is grounded in heterodox (Post Keynsian) theory, although in modified form, because the economy-wide markup can be quite a bit larger than, and partly independent of, the firm-level markup. The dependence of the economy-wide markup on the length of production chains partially de-links aggregate profits from the private profits that drive investment. The model further differs from other Post Keynesian macroeconomic models because, like other biophysical theories (Cleveland 2010), it explicitly includes inputs of natural resources into the economy.

The model's usefulness was demonstrated with six examples. First, it was shown to explain a relationship between the labor and energy expenditure shares. Between 1995 and 2010 these were mostly linearly related, a prediction of the model in this paper when the economy-wide markups on labor and resources are stable. Departures from the linear relationship could also be explained by the deepening of production chains that was observed to be taking place and by the delayed price response following an energy price shock. Second, it was used to interpret an empirical result reported by Kaufmann (1994), that relative prices of fuels generally track relative productivities of those fuels. Third, it was used to argue that dematerialization in the consumption goods sector will tend to increase profits, while dematerialization in the investment goods sector decreases profits. Fourth, an outstanding puzzle, the disproportionately large macroeconomic response to an oil price shock, was found to have a natural explanation by combining the model with a standard Keynesian multiplier analysis. Fifth, the model could explain the historical fall in the wage share, through two processes: lengthening production chains – an effect of globalization – shifted the distribution of income towards profits, and away from wages; subsequently, rising energy costs further displaced wages. Sixth, we extended the model by endogenizing the resource price. As a natural consequence, this brings the resource return on investment, RROI, into the model as an explicit parameter. We then showed that RROI has a surprisingly limited effect on the wage share (and therefore on the real wage) until it reaches quite low values. This has some important implications, which we explore below.

The quantitative models are abstracted from a qualitative theory that is quite a bit more rich. The qualitative theory views the economy essentially as an adaptive complex network (Boccaletti et al. 2006; Sayama et al. 2013). There is by now a well-established literature that views economies as complex, interconnected systems (e.g., Foster 2005; Schenk 2006; Earl and Wakeley 2010; Li et al. 2010), so this idea is not new. More specifically, it pictures firms as being pushed towards a critical state. Systems with dynamics that move towards a critical state typically exhibit self-organized criticality (Bak et al. 1988), a behavior that has been studied in the context of inventory dynamics (Bak et al. 1993; Scheinkman and Woodford 1994). An interesting feature of such systems is that they are vulnerable to "cascades", and the size of the cascades follows a probability distribution with a long tail (a power law). This would suggest that, for example, firm bankruptcies might follow a power law, which has in fact been observed empirically (Hong et al. 2007). A full model would require some way to simulate innovation; evolutionary economists have developed a variety of techniques that could support such an analysis (Safarzyńska and van den Bergh 2010).

The result that real wages are insensitive to a falling RROI (or, in the important case of energy, EROI) is significant, if it is correct. It may trouble those who have warned of the impending impacts of "peak oil" (Murphy and Hall 2011) that the impacts may be far off, but in fact it makes the problem only more alarming. The reason for this is that it makes the "net energy cliff" portrayed by Murphy and Hall (2010) very abrupt. If we estimate our distance from that cliff based on changes in our living standards, then we may reach the cliff – and fall off of it – almost before we realize. For someone concerned with climate change, as this author is, the result is also troubling, although less surprising. It has been clear for some time that declining finite fossil resources are almost certainly not going to lead us to the kinds of deep carbon reductions that will be needed to avoid dangerous climate change, and the model in this paper offers an explanation for why this is so: even the dramatic declines in EROI of fossil fuels that have occurred so far are not expected to significantly impact upon living standards.

In general, our analysis suggests moving away from EROI as a macroeconomic indicator, although it is certainly important from an engineering perspective (Kreith 2012). Instead, attention should focus on the limitations of renewable fuels: intermittency, low energy density, and annual limits on flow. These are not insurmountable problems. More generally, it is important to avoid thinking of the future as being like the past. While converting biomass into liquid fuels may not be a good long-run option (Kemp-Benedict et al. 2012), converting renewable energy sources into electricity is. Deep carbon reduction scenarios emphasize the importance of electricity in the final energy mix (e.g., Heaps et al. 2009).

As discussed in the body of the paper, reliance on flow-limited resources can, if the potential for dematerialization is limited, lead to very low growth. It is important to recognize that an end to rapid growth does not mean that the quality of life has to be low, as real GDP per capita can stabilize at a comparatively high, and slowly rising, level. Also, it does not mean an end to economic activity. Instead, firms can continue to increase their margins by decreasing their inputs. Also, firms can introduce new products, thereby (temporarily) driving up the price of scarce resources; either the venture fails, or other firms with small margins go out of business, or both. Each of these spontaneous activities – reducing inputs and introducing new products – has the net effect of dematerializing the economy, and therefore contributing to real growth.

Conclusion

This paper presents a theory and a model that can be used to address questions in Ecological Economics. The theory is essentially Post Keyensian and evolutionary. The main innovation is that the role of natural resources in the macroeconomy was explicitly derived from a disaggregated model: using an input-output framework in which prices are set by markup, the image of the economy as an "inverted pyramid" was seen to emerge naturally. The paper makes use of this representation to explain several observations: the erosion of real wages in the last quarter of the 20th century, a relationship between the prices of energy carriers and their marginal contributions to GDP, and the macroeconomic impact of an oil price shock. Also, a relationship between energy and wage shares of GDP was predicted using the model, and the predicted behavior was shown to hold empirically. Finally, the model was shown to predict (but without empirical confirmation) that dematerialization of consumption goods increases aggregate profits, while dematerialization of investment goods reduces profits.

After demonstrating the utility of the basic model, in which resources are external to the economy, the paper then endogenized the resource price, which led directly to the introduction of resource return on investment (RROI). An important finding is that the wage share in the economy is insensitive to changes in RROI until very low levels. This finding is relevant for ongoing debates about the impact of "peak oil" and the potential for the world's economies to be based on renewable energy sources. The results suggest that energy return on investment (EROI) is not an effective macroeconomic indicator of scarcity, although it is a good engineering indicator, and very useful for thinking about long-term sustainability. This paper joins others in decisively rejecting corn ethanol (at least as produced in the US) as a sustainable biofuel option. More generally, the results suggest that a minimum EROI should be specified, but above that minimum, changes in EROI have little impact on macroeconomic outcomes. Rather than EROI, the results in this paper suggest that the maximum annual flow of renewable resources, the potential for dematerialization, and the length of production chains are important macroeconomic factors in a transition to a sustainable economy.

While this paper focused on resource return on resource investment, the model is quite flexible, and can be used to bring natural resources into Post Keynesian macroeconomic models. The paper offers several examples.

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