Dematerialization, Decoupling, and Productivity Change

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Abstract: The prospects for long-term sustainability depend on whether, and how much, we can absolutely decouple economic output from total energy and material throughput. While relative decoupling has occurred – that is, resource use has grown less quickly than the economy – absolute decoupling has not, raising the question whether it is possible. This paper proposes a two-part explanation for why decoupling has not happened historically. First, drawing on theories of cost-share induced productivity change, it assumes that innovation which save on inputs to the production of goods and services is biased toward inputs with a higher cost share. Second, following post-Keynesian pricing theory, it posits that resources, but not goods or labor, are priced in competitive markets. These assumptions set up two halves of a dynamic, which we explore from a post-Keynesian perspective. In this dynamic, resource costs as a share of GDP move towards a stable level, at which the growth rate of resource productivity is typically less than the growth rate of GDP. The paper then discusses conditions under which absolute decoupling might occur in the context of current climate mitigation policy debates.

Keywords: decoupling; dematerialization; cost-share induced technological change

JEL classifications: E12, O31, O33, Q32

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1 Introduction

When the UN General Assembly (2015) adopted the 2030 Agenda for Sustainable Development, it brought a renewed focus to a long-standing question: the potential for material and energy throughput to decouple absolutely from economic growth. Goal 12 is to "Ensure sustainable consumption and production patterns," including "the sustainable management and efficient use of natural resources" by 2030, while Goal 13 is to "Take urgent action to combat climate change and its impacts." As climate mitigation requires that most remaining fossil resources remain in the ground (McGlade and Ekins 2015), taking urgent action implies an immediate decoupling of fossil energy consumption from economic output. Recently, carbon emissions from fossil fuel use and industry have stagnated, indicating some success toward this goal, although not at a rate fast enough to meet globally-agreed climate targets (UNEP 2016). However, total energy and material use has not absolutely decoupled from GDP. Rather, we have seen relative decoupling, in which material and energy intensity declines at a slower rate than GDP grows, while absolute resource and energy consumption continue to rise (Bernardini and Galli 1993; Ayres and Warr 2009).

The substantial literature on dematerialization and decoupling has not reached consensus on mechanisms. Two persistent and partially competing concepts are Jevons' paradox (Jevons 1865; Khazzoom 1980; Alcott 2005; Sorrell 2009) and the Environmental Kuznets Curve (EKC) hypothesis (Auty 1985; Dinda 2004). Jevons' paradox states that an increase in resource efficiency leads indirectly to an absolute increase in the use of that resource, as a falling price brings formerly unprofitable resource-consuming processes into production and rising incomes drive consumption. The EKC hypothesis is motivated by a narrative of economic development. Early in the process, resource-intensive industrial production dominates, and raising incomes is more important than protecting the environment. As labor productivity and wages grow, industry declines relative to services, while environmental quality becomes more important than rapid growth. Jevons' paradox suggests that decoupling will never happen, while the EKC hypothesis suggests that decoupling can occur after a sufficiently long period. Both are contested. For Jevons' paradox, in particular, a number of papers argue both for and against the hypothesis as it applies to mature economies (e.g., Sorrell 2009; Cullenward and Koomey 2016). The evolving empirical literature on the EKC appears to disprove its existence (Stern 2004; Wagner 2008), but the concept is attractive enough for discussion to continue (Dinda 2004; Kijima, Nishide, and Ohyama 2010). We do not address the controversies in this paper, but note that proponents of Jevons' paradox and of the EKC propose distinct causal relationships between energy and material use on long-run GDP growth. Jevons' paradox assumes that resources constrain growth, so releasing those constraints stimulates expansion, while the EKC hypothesis assumes that economic growth drives resource use, with a relationship that depends on the developmental stage of the economy.

In this paper we provide a parsimonious explanation, different than existing explanations, for the failure of resource throughput to decouple absolutely from economic output, which we explore from a post-Keynesian perspective. We start from two assumptions: 1) innovation that saves on inputs to the production of goods and services is biased toward higher-cost inputs, as measured by the cost share; and 2) resources are priced in competitive markets, with prices rising in the short run when demand increases relative to capacity, while manufacturing prices are administered (Lee 1999). These two assumptions set up two halves of a process, which can be thought of as a supply-demand dynamic that plays out over time. Firms buy resources on spot markets, or (more commonly) claims to resources on futures markets, at prevailing and publicly-announced prices. Those prices clear their markets in a short period during which firms' production schedules determine an inelastic level of demand. Demand for resources responds to price changes indirectly, and after a delay, as firms reduce costs at prevailing prices through technological innovation, and then adjust their administered prices to reflect their revised cost structure. Industrial firms pay very little attention to demand when setting prices (Coutts and Norman 2013), so their prices are not market-clearing; in this post-Keynesian model, it is productivity growth rates and cost shares, rather than prices, that adjust to move the system toward an equilibrium.

The assumption that resource productivity growth is driven by resource costs is an extension to natural resources of theories of cost-share induced technological change, in which the relative pace of labor-saving or capital-saving innovation increases with the shares of labor and capital costs in production (Hicks 1932, 124 ff.; Duménil and Lévy 1995; Foley 2003, 42 ff.; Kemp-Benedict 2017). This can be contrasted with neoclassical theories of induced technological change, in which profit-maximizing firms choose technologies within a space of possibilities that is bounded by an expanding production possibilities frontier (Kumar and Managi 2009; Acemoglu et al. 2012). The approach to cost-share induced technological change followed in this paper, and described in detail in Kemp-Benedict (2017), does not require a production possibilities frontier. Instead, consistent with evolutionary theories of technological change (Nelson and Winter 1982; Duménil and Lévy 1995), firms seek marginal improvements on existing technology, and adopt discoveries that increase profits at prevailing prices.

Regarding the assumption that resources are priced in competitive markets, in post-Keynesian theory most firms operate in an oligopolistic environment and have considerable flexibility in setting prices, including wages. Prices are cost-based, largely insensitive to demand, and maintained across pricing periods that can be several quarters long (Coutts and Norman 2013). The price system is determined by the costs of inputs, inter-industry relationships, and profit margins, which are set high enough to maintain the enterprise as a going concern but not so high as to encourage entry by rivals. Natural resource producers, in contrast, typically operate in competitive markets with possible short-term supply constraints, and adjust their prices in response to changes in demand relative to capacity. This argument, derived from Kalecki (1969, 11), appears to be generally accepted in post-Keynesian pricing theory (e.g., see Kriesler 1988; Coutts and Norman 2013, 8)

In a partial equilibrium setting, we show, using a two-sector model consisting of an extractive and a productive sector, that resource costs as a share of GDP (the "resource share") and resource productivity growth rates move towards stable levels, at which the growth rate of resource productivity is nearly always less than the growth rate of GDP. In a model with multiple productive sectors a similar result obtains, but with the possibility that average resource productivity growth exceeds GDP growth during a structural shift toward sectors with low resource intensity. That is, we find relative but not absolute decoupling arising from the behavioral assumptions of the model. The explanation applies both when resource availability constrains growth and when it does not. We then extend the result to a general equilibrium setting, where, as noted earlier, equilibrium is defined in terms of cost shares and productivity growth rates rather than prices.

The theory presented in this paper can be compared to those of Ayres and van den Bergh (2005), Warr and Ayres (2012), and Cogoy (2004), who introduce decoupling through value-creation in the service sector. In these theories, rising demand for services relative to physical goods is reinforced by increasing service sector labor productivity through human capital accumulation. While these trends can indeed lead to decoupling, it is unclear what economic forces or policy initiatives would bring the decoupling mechanism into play.

In this paper we seek to identify general economic behaviors that can underlie both relative and absolute decoupling in different environments. Using a model of cost-share induced technological change, we show that when resources are comparatively abundant, relative decoupling should occur, while absolute decoupling should not, although transitory deviations are possible during technological or structural transitions. That is, the model explains the dominant pattern of resource use observed in high-income countries. We then discuss what conditions might lead to absolute decoupling, and connect those insights to current debates on climate mitigation policy.

2 A two-sector model

In this section we present the basic argument using a two-sector model with an extractive and a productive sector. In the next section we expand the number of productive sectors. We assume a single aggregate resource, with a price p_r per unit (for example, per MJ or kg), and denote natural resource productivity – the ratio of real output to natural resource input – by ν. The resource price will typically be a short-term future price over a relevant planning period (e.g., 1-4 quarters). Denoting the average price level of GDP over the planning period by P, the share of resource costs in GDP, ρ, is the ratio of the real resource price to resource productivity,

$$\rho = \frac{p_r}{\nu P}. \tag{1}$$

The growth rate of the resource share is then equal to

$$\hat{\rho} = \hat{p}_r - \hat{P} - \hat{\nu}. \tag{2}$$

We assume that resource producers adjust their prices in response to changing demand, R, relative to capacity, C. For a storable resource with variable yield, such as an agricultural commodity, capacity might equal the previous-period yield (or anticipated yield, on a futures market) plus stocks. When yields are more predictable, as for crude oil, or storage is particularly costly, as for electricity, the capacity might be closer to installed production capacity or realized yield. Denoting real GDP by Y, demand for resources in the economy is equal to

$$R = \frac{Y}{\nu}. \tag{3}$$

We further assume that the real resource price, using the GDP deflator, increases with total demand relative to capacity, such that locally we can relate resource demand to the price through a function F. Using a prime to denote the derivative of F with respect to R/C,

$$p_r = PF\left(\frac{R}{C}, t\right), \quad F' > 0. \tag{4}$$

This is a mathematical formulation of the second assumption in the introduction – resources are priced in competitive markets, and prices rise when demand increases relative to capacity.

Next, we relate the growth rate of resource productivity to the growth rate of the price. We denote exogenous growth in *F* by β and the elasticity of *F* with respect to its first argument by ε,

$$\beta \equiv \frac{1}{F}\frac{\partial F}{\partial t}, \quad \varepsilon \equiv \frac{R}{C}\frac{F'}{F}. \tag{5}$$

The growth rate of the price is then given by

$$\hat{p}_r = \hat{P} + \beta + \varepsilon\left(\hat{R} - \hat{C}\right). \tag{6}$$

The term β is an exogenous vertical shift in the supply price schedule, which could arise from a change in technology or market structure, a resource tax, or a change in operating costs. The final term is the local elasticity of the price with respect to resource capacity utilization, ε, multiplied by the growth rate of R/C; ε is a positive quantity. Both ε and β depend on the ratio of resource extraction to capacity, R/C, and, if β is nonzero, on the time *t*. From equation (2) we have

$$\hat{\rho} = \beta + \varepsilon\left(\hat{R} - \hat{C}\right) - \hat{v}. \tag{7}$$

Substituting for *R* using equation (3) then gives

$$\hat{\rho} = \beta + \varepsilon\left(\hat{Y} - \hat{C}\right) - (1+\varepsilon)\hat{v}. \tag{8}$$

This expresses the change in the resource share as a function of GDP and resource productivity growth. It also allows for a possible exogenous shift in the resource supply schedule through β. Through its final term, this relationship provides one half of a supply-demand dynamic.

The other half of the dynamic is given by cost-share induced technological change, in which the rate of resource productivity improvement increases with the resource cost share (Kemp-Benedict 2017),

$$\frac{\Delta\hat{v}}{\Delta\rho} > 0. \tag{9}$$

Suppose that the right-hand side of equation (8) is initially positive (a similar argument holds if it is negative). Then the resource share is increasing, which implies, from equation (9), that the pace of resource productivity improvement is also increasing. This induces a negative feedback in equation (8) that slows the growth in ρ. Due to the negative feedback, the resource share rises until it reaches a stable value at which the right-hand side of equation (8) is zero.

This system is not closed, because a changing resource cost share must be balanced by a change in the profit or wage share, which will then induce further productivity changes. We introduce a fully closed model later in the paper. For now, we proceed with a partial equilibrium framework. In this system, an equilibrium is characterized by a constant resource cost share. Setting the left-hand side of equation (8) to zero and solving for the resource productivity growth rate gives its equilibrium value,

$$\hat{v}_{\text{eqm}} = \frac{\beta}{1+\varepsilon} + \frac{\varepsilon}{1+\varepsilon}\left(\hat{Y} - \hat{C}\right). \tag{10}$$

Suppose that capacity C is either expanding or stable, while the supply schedule is fixed, so $\beta = 0$. Under these conditions at equilibrium we find the growth rate of resource productivity is less than the growth rate of real GDP,

$$\hat{v}_{\text{eqm}} = \frac{\varepsilon}{1+\varepsilon}\left(\hat{Y} - \hat{C}\right) < \hat{Y}, \quad \beta = 0. \tag{11}$$

This is the essential result: under normal circumstances, we expect relative but not absolute decoupling.

If β is positive, then resource productivity can rise faster than GDP. Under a temporary increase in the resource price, from equation (5), β will be positive for a time and then return to zero. From equation (8), this implies that ρ will also grow. From equation (9), this will stimulate faster resource efficiency improvements, until a new equilibrium is established, at which equation (10) holds. While β is positive, resource productivity can, for a time, rise faster than GDP. However, after the exogenous price rise, β returns to zero and the equilibrium rate of increase in resource productivity falls below the growth rate of GDP. The net effect is a temporary jump in productivity growth, as was seen after the oil crises of the 1970s. It was a transient phenomenon that extended through the mid-1980s (e.g., see Ayres and Warr 2009, fig. 3.5f and 3.6).

3 A multi-sector model

In this section we continue to assume a single resource, with price p_r, but expand to N productive sectors $i = 1,\ldots,N$. Each sector is characterized by its value added, Y_i, price level p_i, and resource productivity v_i. Resource use within each sector, R_i, is given by

$$R_i = \frac{Y_i}{v_i}. \tag{12}$$

Total resource use, R, is the sum of resource use by sector. Defining the share of resource use in sector i by r_i, the growth rate of resource use is equal to the weighted sum of resource use by sector,

$$\hat{R} = \sum_{i=1}^{N} r_i \hat{R}_i = \sum_{i=1}^{N} r_i\left(\hat{Y}_i - \hat{v}_i\right). \tag{13}$$

The resource cost share in sector i is given by the same expression as in the two-sector model, equation (1), but applied to each sector,

$$\rho_i = \frac{p_r}{p_i v_i} \quad \Rightarrow \quad \hat{\rho}_i = \hat{p}_r - \hat{p}_i - \hat{v}_i. \tag{14}$$

Assuming the resource price behaves as in the two-sector model equation (6), we find the multi-sector equivalent of equation (8),

$$\hat{\rho}_i = \beta + \varepsilon\left[\sum_{i=1}^{N} r_i\left(\hat{Y}_i - \hat{v}_i\right) - \hat{C}\right] - \left(\hat{p}_i - \hat{P}\right) - \hat{v}_i. \tag{15}$$

As with the two-sector equation, we assume that resource productivity growth responds positively to the resource costs share, applying it separately in each sector,

$$\frac{\Delta\hat{v}_i}{\Delta\rho_i} > 0. \tag{16}$$

Combining (15) and (16), we again find a stable dynamic. Leaving other factors the same, a rise in the cost share in sector *i* drives up the pace of productivity change, from (16), which then, from (15), slows the rate of increase in the cost share. The equilibrium is defined by a stable cost share in each sector. Setting the left-hand side of equation (14) equal to zero, we find an equilibrium at which the rate of change in resource productivity is given by

$$\hat{v}_i = \hat{p}_r - \hat{p}_i. \tag{17}$$

That is, resource productivity growth is determined entirely by the relative change between the resource price and the price index for the sector.

The difference between the multi-sector and two-sector models is that stable sector cost shares need not translate into a steady average cost share across the economy. The average resource cost share is given by

$$\rho = \frac{p_r R}{PY} \quad \Rightarrow \quad \hat{\rho} = \hat{p}_r - \hat{P} + \hat{R} - \hat{Y}, \tag{18}$$

where *Y* is real GDP and *P* is the GDP price level. Nominal GDP is the sum of nominal value added,

$$PY = \sum_{i=1}^{N} p_i Y_i. \tag{19}$$

Defining inflation using a Laspeyre's index, we can express the inflation rate and real GDP growth rate as averages weighted by the value added shares s_i,

$$\hat{P} = \sum_{i=1}^{N} s_i \hat{p}_i, \quad \hat{Y} = \sum_{i=1}^{N} s_i \hat{Y}_i, \quad \text{where } s_i = \frac{p_i Y_i}{PY}. \tag{20}$$

The weighted average rate of change in the resource cost share, using value added shares as the weights, is then seen to equal

$$\sum_{i=1}^{N} s_i \hat{\rho}_i = \sum_{i=1}^{N} s_i \left(\hat{p}_r - \hat{p}_i - \hat{v}_i\right) = \hat{p}_r - \hat{P} - \sum_{i=1}^{N} s_i \hat{v}_i. \tag{21}$$

Substituting into the growth rate expression from equation (18) and using equation (13) for the growth rate of total resource use, we find

$$\hat{\rho} = \sum_{i=1}^{N} s_i \hat{\rho}_i + \sum_{i=1}^{N} \left(r_i - s_i\right)\left(\hat{Y}_i - \hat{v}_i\right). \tag{22}$$

At equilibrium, the first term is zero. Substituting from equation (17), we also have

$$\sum_{i=1}^{N}(r_i - s_i)\hat{v}_i = \hat{p}_r\sum_{i=1}^{N}(r_i - s_i) - \sum_{i=1}^{N}(r_i - s_i)\,\hat{p}_i = -\sum_{i=1}^{N}(r_i - s_i)\,\hat{p}_i. \tag{23}$$

At equilibrium, the rate of change in the average cost share is then determined by relative growth rates in nominal value added between sectors,

$$\hat{\rho} = \sum_{i=1}^{N}(r_i - s_i)\left(\hat{Y}_i + \hat{p}_i\right). \tag{24}$$

In relatively resource-intensive sectors, $r_i > s_i$. If those sectors are declining in nominal terms relative to less resource-intensive sectors, then the average resource cost share can fall, even as it remains constant within each sector. This can happen because a single resource price is shared across sectors, and it responds to total demand, not the demand within any particular sector.

A falling average resource cost share leads to a higher average rate of resource productivity change than is experienced in each sector. From the definition of the average resource productivity, v, as Y/R, from equation (18) we have

$$\hat{v} = \left(\hat{p}_r - \hat{P}\right) - \hat{\rho}. \tag{25}$$

This can be positive if resource price inflation exceeds the general level of price inflation, or if the average resource share is falling. Thus, a structural shift toward sectors with lower resource intensity can drive average productivity growth above the rate of GDP growth.

Changes in the average resource share, ρ, result from structural change when resource cost shares differ between sectors. At equilibrium, sectoral resource cost shares are constant, so structural change is the the only reason the aggregate resource share might change. Growth rates of nominal value added need never be equal across sectors, but at some point the shares r_i and s_i for resource-intensive sectors will be sufficiently small that they make a negligible contribution to equation (24). Thus, we expect the effect of structural change to last only as long as the transition. Once the less resource-intensive sectors dominate, average resource productivity growth will again fall below the growth rate of GDP.

4 A general two-sector model

In this section we return to the two-sector model but go beyond the partial equilibrium analysis in the previous sections to a general equilibrium analysis. As before, we emphasize that the equilibrium in the post-Keynesian model is defined by constant cost shares and productivity growth rates, rather than prices. We maintain the notation for the resource cost share, ρ, and associated resource productivity, v, and introduce wage and profit shares ω and π, with associated labor and capital productivities λ and κ.

In a model of cost-share induced technological change, productivity growth rates respond to cost shares,

$$\hat{\lambda} = \ell(\omega, \pi, \rho), \tag{26}$$

$$\hat{\kappa} = k(\omega, \pi, \rho), \tag{27}$$

$$\hat{\nu} = r(\omega, \pi, \rho). \tag{28}$$

Using a subscript to indicate a partial derivative with respect to the argument, we can write the matrix of partial derivatives of the productivity growth rates, **M**, as

$$\mathbf{M} = \begin{pmatrix} \ell_\omega & \ell_\pi & \ell_\rho \\ k_\omega & k_\pi & k_\rho \\ r_\omega & r_\pi & r_\rho \end{pmatrix}. \tag{29}$$

Following the arguments in Kemp-Benedict (2017), if technological discovery is random, with a probability distribution that does not depend on the cost shares (at least in the short run), and firms adopt innovations that raise their return to capital within a period in which prices can be assumed fixed, then **M** is a positive semi-definite matrix. This property will help to establish the conditions for local stability in a general equilibrium setting.

To first order in variation of the cost shares, we can write the change in the productivity growth rates as

$$\Delta\hat{\lambda} = \ell_\omega \Delta\omega + \ell_\pi \Delta\pi + \ell_\rho \Delta\rho, \tag{30}$$

$$\Delta\hat{\kappa} = k_\omega \Delta\omega + k_\pi \Delta\pi + k_\rho \Delta\rho, \tag{31}$$

$$\Delta\hat{\nu} = r_\omega \Delta\omega + r_\pi \Delta\pi + r_\rho \Delta\rho. \tag{32}$$

Because shares must always add to one, their change must add to zero, so

$$\Delta\omega = -\left(\Delta\pi + \Delta\rho\right). \tag{33}$$

Substituting into the expressions above,

$$\Delta\hat{\lambda} = \left(\ell_\pi - \ell_\omega\right)\Delta\pi + \left(\ell_\rho - \ell_\omega\right)\Delta\rho, \tag{34}$$

$$\Delta\hat{\kappa} = \left(k_\pi - k_\omega\right)\Delta\pi + \left(k_\rho - k_\omega\right)\Delta\rho, \tag{35}$$

$$\Delta\hat{\nu} = \left(r_\pi - r_\omega\right)\Delta\pi + \left(r_\rho - r_\omega\right)\Delta\rho. \tag{36}$$

From this point forward, we focus on the system defined by capital and resource productivity, with the corresponding profit and resource cost shares, and drop equation (34). We assume that firms adopt target-return pricing, which means that the product of π and κ is maintained at a fixed value. That is, after prices are adjusted,

$$\Delta\left(\pi\kappa\right) = \kappa\Delta\pi + \pi\Delta\kappa = 0. \tag{37}$$

From this we see that

$$\Delta\pi = -\pi\hat{\kappa}. \tag{38}$$

Assuming the same pricing behavior as before for resources, we also have, from equation (8), that

$$\Delta\rho = \rho\left[\beta + \varepsilon\left(\hat{Y} - \hat{C}\right) - \left(1+\varepsilon\right)\hat{v}\right]. \tag{39}$$

To simplify the notation in the following, we identify the first two terms in brackets as the external factors driving the resource price, and denote them *D*,

$$D \equiv \beta + \varepsilon\left(\hat{Y} - \hat{C}\right). \tag{40}$$

Substituting into equations (35) and (36), we have the system

$$\Delta\hat{\kappa} = \left(k_\rho - k_\omega\right)\rho D - \left(k_\pi - k_\omega\right)\pi\hat{\kappa} - \left(k_\rho - k_\omega\right)\left(1+\varepsilon\right)\rho\hat{v}, \tag{41}$$

$$\Delta\hat{v} = \left(r_\rho - r_\omega\right)\rho D - \left(r_\pi - r_\omega\right)\pi\hat{\kappa} - \left(r_\rho - r_\omega\right)\left(1+\varepsilon\right)\rho\hat{v}. \tag{42}$$

An equilibrium in the rate of productivity change is found by setting the left-hand side of this expression equal to zero. We can write the resulting equation in matrix form,

$$\begin{pmatrix} k_\pi - k_\omega & k_\rho - k_\omega \\ r_\pi - r_\omega & r_\rho - r_\omega \end{pmatrix}\begin{pmatrix} \pi\hat{\kappa}_{\text{eqm}} \\ \left(1+\varepsilon\right)\rho\hat{v}_{\text{eqm}} \end{pmatrix} = \begin{pmatrix} k_\rho - k_\omega \\ r_\rho - r_\omega \end{pmatrix}\rho D. \tag{43}$$

The (local) stability conditions are determined by the trace and determinant of the matrix of coefficients of the productivity growth rates, **C**, where

$$\mathbf{C} = \begin{pmatrix} -\left(k_\pi - k_\omega\right)\pi & -\left(k_\rho - k_\omega\right)\left(1+\varepsilon\right)\rho \\ -\left(r_\pi - r_\omega\right)\pi & -\left(r_\rho - r_\omega\right)\left(1+\varepsilon\right)\rho \end{pmatrix}. \tag{44}$$

For the system to be stable, this matrix must have two negative eigenvalues, which means that the trace (which equals the sum of the eigenvalues) must be negative and the determinant (which equals the product of the eigenvalues) positive. The trace is given by

$$\operatorname{Tr}\mathbf{C} = -\left(k_\pi - k_\omega\right)\pi - \left(r_\rho - r_\omega\right)\left(1+\varepsilon\right)\rho. \tag{45}$$

The broad historical trajectory of technology has been the replacement of people by resource-using machines. In terms of the model, this means that labor is substitutable by capital and resources, so we expect the partial derivatives k_ω and r_ω to be negative. We can therefore write

$$\operatorname{Tr}\mathbf{C} = -\left(k_\pi + \left|k_\omega\right|\right)\pi - \left(r_\rho + \left|r_\omega\right|\right)\left(1+\varepsilon\right)\rho. \tag{46}$$

From Kemp-Benedict (2017), the own-response to a change in the cost share must be positive, so k_π and r_ρ are both positive. We therefore find that the trace is negative, Tr **C** < 0, as required.

The determinant of **C** is given by

$$\operatorname{Det}\mathbf{C} = \left[\left(k_\pi - k_\omega\right)\left(r_\rho - r_\omega\right) - \left(r_\pi - r_\omega\right)\left(k_\rho - k_\omega\right)\right]\left(1+\varepsilon\right)\rho\pi. \tag{47}$$

The sign is determined by the expression in brackets, which we can expand and rearrange to find,

$$\left(k_\pi - k_\omega\right)\left(r_\rho - r_\omega\right) - \left(r_\pi - r_\omega\right)\left(k_\rho - k_\omega\right) = \left(k_\pi r_\rho - r_\pi k_\rho\right) + \left(k_\pi - k_\rho\right)\left|r_\omega\right| + \left(r_\rho - r_\pi\right)\left|k_\omega\right|. \quad (48)$$

In this expression, we have again assumed that labor is substitutable with capital and resources. The first term in parentheses on the right-hand side is nonnegative because of an inequality that applies to positive semi-definite matrices,

$$r_\pi, k_\rho \leq \sqrt{k_\pi r_\rho}. \quad (49)$$

As discussed in Kemp-Benedict (2017), at most one of the remaining terms can in principle be negative, which can occur only if capital and resources are complements. Even if one of the terms is negative, it may still not be of sufficient magnitude to overcome the other, positive, terms, but it does raise the possibility. The final term could plausibly be negative under conditions in which the resource cost share is very low, wage costs are high, and resource-intensive capital tends to replace labor. In that case the response of resource intensity to the profit share, r_π, could exceed the own-response, r_ρ. However, we do not expect that condition to persist, as it would drive resource costs progressively higher, until the cost share is no longer small. Once the cost share has risen sufficiently large, we expect firms to use more resource-efficient machinery and otherwise seek to reduce their resource costs. Thus, in mature economies we expect the determinant to be positive, Det **C** > 0.

Because the trace of **C** is negative, and the determinant is expected to be positive in mature economies, we conclude that the equilibrium defined by equation (43) is stable.

Next, we consider cost shares. From equation (38), the equilibrium rate of change of the profit share is

$$\Delta\pi_{\text{eqm}} = -\pi\hat{\kappa}_{\text{eqm}}. \quad (50)$$

The equilibrium rate of change of the resource share is, from equation (39) and the definition of D in equation (40),

$$\Delta\rho_{\text{eqm}} = \rho D - \rho\left(1+\varepsilon\right)\hat{\nu}_{\text{eqm}}. \quad (51)$$

Substituting these expressions into the equilibrium condition in equation (43) and cancelling a common term on each side, we find

$$\begin{pmatrix} k_\pi - k_\omega & k_\rho - k_\omega \\ r_\pi - r_\omega & r_\rho - r_\omega \end{pmatrix}\begin{pmatrix} \Delta\pi_{\text{eqm}} \\ \Delta\rho_{\text{eqm}} \end{pmatrix} = 0. \quad (52)$$

This equation implies constant cost shares, $\Delta\pi_{\text{eqm}} = \Delta\rho_{\text{eqm}} = 0$, unless the determinant of the matrix is equal to zero. It is straightforward to show that the determinant of this matrix is the expression in brackets in equation (47) for Det **C**. That is, this determinant can be zero only if Det **C** is zero. But we have already argued that Det **C** should be positive. We therefore conclude that, at equilibrium, the cost shares are not changing.

In the general equilibrium two-sector model, we recover the same equilibrium condition as in the partial-equilibrium two-sector model. In addition, under target-return pricing, a constant resource share and steady rate of resource productivity growth is accompanied by a steady profit share and constant capital productivity.

5 Economic growth with and without resource constraints

With the two-sector model, in either the partial or full equilibrium case, the equilibrium rate of productivity change satisfies equation (10), repeated here for convenience,

$$\hat{v}_{\mathrm{eqm}} = \frac{\beta}{1+\varepsilon} + \frac{\varepsilon}{1+\varepsilon}\left(\hat{Y} - \hat{C}\right). \tag{53}$$

We can characterize the price response of resource costs in the two cases in terms of the elasticity, ε, with

$$\varepsilon \to \begin{cases} 0, & \text{resource abundant case,} \\ \infty, & \text{resource constrained case.} \end{cases} \tag{54}$$

We then have

$$\hat{v}_{\mathrm{eqm}} \to \begin{cases} \beta, & \text{resource abundant case,} \\ \hat{Y} - \hat{C}, & \text{resource constrained case.} \end{cases} \tag{55}$$

The direction of causality in the resource abundant case is from economic growth to resource use. This is the causal structure behind the environmental Kuznets curve (EKC) hypothesis. Our basic result is that we should not expect absolute decoupling, with the implication that we should not expect an EKC. Absolute decoupling can be stimulated over the short run if the supply price curve shifts abruptly or during a structural transition toward sectors with lower resource intensity. However, in either case the fall in resource intensity will not last. When the supply price curve stops shifting, the productivity growth rate falls below the GDP growth rate, while a structural shift will eventually end, leading at best to a sideways-s curve, first rising, then falling, and then rising again. These conclusions appear consistent with the empirical literature, which has found no robust evidence for an EKC (Stern 2004).

The resource constrained case corresponds to the conditions of Jevons' paradox. Here, the causality is reversed relative to the resource abundant case, which we express by moving the GDP growth rate to the left-hand side of the equation,

$$\hat{Y} = \hat{C} + \hat{v}_{\mathrm{eqm}}. \tag{56}$$

Reading causality from the right-hand side of this equation to the left-hand side, GDP growth is limited by the rate at which resource capacity can be expanded or resource productivity increased. The equilibrium level of resource productivity growth should here be interpreted as the maximum technically feasible rate. This is, effectively, Jevons' paradox: when new resources are made available, or the efficiency with which existing resources are used increases, output increases so as to take advantage of the new capacity.

Both the resource abundant and resource constrained cases can be expressed in terms of a post-Keynesian Leontief production function. In standard post-Keynesian theory, output can be either capital or labor-constrained. With the possibility for limited natural resources, the production function is,

$$Y \le \min\left(\kappa K, \lambda L, \nu C\right). \tag{57}$$

When resources are abundant, and there is excess labor, GDP growth is constrained by the pace of capital accumulation. If labor is not abundant, as in a mature industrial economy, GDP growth can be limited by the growth in labor productivity as well as the rate of capital accumulation. In a resource-constrained economy, output can only grow as fast as resource capacity or resource productivity; this is the condition expressed by equation (56). Resource constraints characterized the young industrial economy that Jevons described. We may be entering such an era again, reflected in what Galbraith (2014, 108) calls the “choke-chain effect”. The economy has free rein within the limits placed by resource availability, but is sharply curtailed when it reaches the limits.

6 Stimulating absolute decoupling

The central result of this paper is essentially negative: unless resource supply is completely inelastic, we cannot expect sustained absolute decoupling, because the search for profitable innovation does not bring resource productivity growth above the rate of GDP growth. However, equation (55) suggests a way to stimulate absolute decoupling through policy. The goal of the policy would be to continually raise unit resource prices, as reflected in the parameter β. Given a target dematerialization rate, m, where

$$\hat{R} = -m, \tag{58}$$

the resource supply price schedule must shift vertically at a rate β^*, where

$$\beta^* = \hat{Y} + m. \tag{59}$$

Whether the dematerialization target can in fact be reached depends on the underlying physical processes. Human societies, including the economies embedded within them, require a steady flow of energy and materials, and produce wastes. Some energy and materials sources are fully renewable, so the only energy input is from the sun; some materials, such as steel, can be recycled with high efficiency. But some materials are very difficult to substitute (Ayres 2007), while today’s renewable technologies (such as biofuels) consume non-renewable inputs (such as synthetic fertilizers). Dematerialization then involves questions of substitution (renewable energy sources, bio-based materials) as well as more effective use of the existing inputs.

Technical studies typically show large potential for improving resource efficiency (e.g., for energy: Nadel, Shipley, and Elliott 2004). For the purposes of this paper, we presume that substantial dematerialization can occur over a policy-relevant time horizon, but for economic reasons it has not. In this case, equation (59) can guide resource pricing policy. For example, a resource tax could be assessed, which would steadily grow over time at a pace benchmarked to the realized rate of GDP growth. The tax revenues could be allocated in such a way as to ease the transition, for example through a revenue-neutral redistribution.

The proposal for stimulating decoupling as suggested by the model in this paper can be contrasted with conventional neoclassical theory, in which resources may be priced to correct an externality; that is, a social cost that is not borne directly by the participants in a market exchange. From this standpoint, the goal of policy is to internalize the externality by “getting the prices right”. In contrast, under a policy consistent with equation (59), the price is always changing, so there is no “right price” to which to adjust. Rather, the goal is to continually push resource costs up, even as firms drive them down through technological innovation. The policy target is specified on a purely physical basis, through the dematerialization target rate m.

The difference reflects divergent approaches to policy analysis. In conventional policy analysis, the policy goal is to maximize aggregate welfare. Markets are seen as the best tool for the job (on the strength of the “welfare theorems”), so if a market is absent or incomplete then one should be introduced. Despite developments within neoclassical theory itself that invalidate the premises behind the welfare theorems, they remain the guiding principles of practical economic policy analysis (Gowdy and Erickson 2005). In practice, an optimal solution is sought using cost-benefit analysis, which brings the problems identified by Gowdy and Erickson to the surface. As applied to environmental policy, cost-benefit analysis suffers from: implausible and inappropriate valuations; application of discounting outside its domain of validity; problems of fairness and morality when making decisions based on aggregate monetized costs and benefits; and the subtle introduction of values into a putatively objective process (Ackerman and Heinzerling 2002, 1563).

In this paper we take a different approach. Taking it as given that the political and legal spheres are the appropriate arenas for normative debate, an economic analysis should take as inputs the goals emerging from those debates. The purpose of the economic analysis is to answer whether the goal can be reached through a specifically economic mechanism. If it can, the proposed mechanism can be assessed against other proposals on the table. That assessment nearly always involves a political calculation. The subsequent policy design and implementation is then a combination of more localized policy decisions, including public consultation, and technical exercises. The process might be guided by the “four E’s” of traditional public administration: economy, efficiency, effectiveness, and equity. Aside from “effectiveness”, each of these criteria has been given multiple definitions, and the emphasis has shifted over time (Howlett, Mukherjee, and Rayner 2015), with equity a relatively recent entrant (Norman-Major 2011). Nevertheless, some broad regularities can be discerned. *Economy* is generally taken to mean that staff and budget are aligned with available resources, while policy goals are achieved without undue expense. *Efficiency* refers to implementation, in that the number, composition and sequencing of policy instruments is consonant with the intended goal. *Effectiveness* means the proposed policy achieves its goal. *Equity* addresses the perceived fairness and justice of outcomes, as well as inclusive policy design.

To the extent that the theory in this paper reflects the real world, the policy suggested by equation (59) should be effective in driving decoupling at a rate specified in policy commitments. Further, it has the potential to be both economic and equitable. In broad outline, the policy could be implemented by assessing a revenue neutral tax at the wellhead (or at port of entry). The tax would be applied directly in only a few sectors, while the revenues could be distributed through a social dividend (Boyce and Riddle 2007) or similar scheme intended to be both fair and transparent. The proposed policy also has the potential to be efficient, in that, although it covers nearly all sectors of the economy, it requires only two policy instruments: a tax whose rate is the sum of a target rate of dematerialization and recent (e.g., previous quarter) estimated real GDP growth; and a revenue distribution policy.

Climate mitigation policy in practice is informed by neoclassical theory, and often includes a carbon price, whether as a tax, the price of an emissions credit in an emissions trading scheme, or an “internal” price used by government or business for planning purposes. The World Bank *State and Trends of Carbon Pricing 2016* (World Bank, Ecofys, and Vivid Economics 2016, 56) lists three sources for internal prices: estimates of the social cost of carbon (SCC); estimated marginal abatement cost; or current or anticipated market values of emissions allowances. The first and third approaches should, according to conventional analysis, yield values similar to each other, but the internal prices reported in the World Bank report varied over three orders of magnitude. Experience with SCC estimates (Tol 2011) offers one explanation. The SCC approach is closest in spirit to conventional theory, in that it is an estimate of the marginal cost or benefit that ought to be internalized. However, SCC estimates are challenging (Metcalf 2008); there are substantial uncertainties in the size of some impacts, and when these are taken into account, cost estimates can vary over a wide range (Ackerman and Stanton 2012). Conventional pricing theory faces a further challenge. Each of the three approaches listed above should generate prices that rise over time as greenhouse gas concentrations and global average temperatures rise, yet the European Emissions Trading Scheme (EU ETS) saw prices fall substantially in recent years, part of a longer downward trend with large fluctuations around the trend (Meadows, Slingenberg, and Zapfel 2015, fig. 2.5).

Thus, while existing pricing schemes may appear similar to the policy suggested by the theory in this paper, the similarities are superficial. No estimate of social cost or market-clearing price informs equation (59), and it does not rely on detailed calculation of marginal abatement costs. Rather, a physically-based mitigation goal determines m, which then determines β^*. In practice, countries specify their climate mitigation goals through politically-negotiated and physically-based targets, the nationally determined contributions (NDCs) arising from the Paris climate agreement. The NDCs have a direct analogue in equation (59) in the dematerialization target rate m.

7 Conclusions

The prospects for sustainability depend crucially on the ability to decouple material throughput from economic value. As this has not happened in the past, one may doubt whether it is possible in the future. In this paper we provide an explanation for why decoupling has not yet occurred, based on two assumptions – that resource prices rise with demand and that the pace of resource productivity improvement rises with the resource cost share.

The theory presented in this paper suggests that when resources are comparatively abundant, relative decoupling may occur, but absolute decoupling will not, except during periods when resource costs are rising faster than GDP. When resources are constrained, GDP growth is determined by the rate of expansion of resource supply and the technically feasible rate of resource productivity growth. In the latter half of the 19th century, when Jevons (1865) wrote *The Coal Question*, coal was a constraining resource, so any advances in extractive technology or efficiency of use led, paradoxically, to even greater resource use, rather than less.

We may be entering a new resource-constrained era, but even if we are, we are not bringing carbon-intensive energy consumption down fast enough to meet globally-agreed carbon mitigation goals (UNEP 2016). The theory presented here suggests that absolute decoupling can only be driven by a sufficiently rapidly rising resource price. By ensuring a steady and predictable rise in resource costs that exceeds the GDP growth rate, firms are encouraged to continually raise resource productivity at a rate sufficient to absolutely decoupling resource use from GDP. The proposed policy is more predictable than that suggested by conventional theory, which urges that a carbon price be set at a periodically updated social cost of carbon that reflects the damages inflicted by a marginal unit of carbon emissions. It is also more directly applicable to policy implementation, as the policy instrument directly incorporates the physical goal that the policy is meant to address.

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