SEI STOCKHOLM ENVIRONMENT INSTITUTE

Stockholm Environment Institute, Working Paper 2014-08

Shifting to a green economy: Lock-in, path dependence, and policy options

Eric Kemp-Benedict

Stockholm Environment Institute
Linnégatan 87D
104 51 Stockholm
Sweden

Tel: +46 8 674 7070
Fax: +46 8 674 7020
Web: www.sei-international.org

Author contact:
Eric Kemp-Benedict
eric.kemp-benedict@sei-international.org

Stockholm Environment Institute
15th Floor, Witthyakit Building,
254 Chulalongkorn University,
Chulalongkorn Soi 64,
Phyathai Road, Pathumwan,
Bangkok, 10330, Thailand

Director of Communications: Robert Watt
Editor: Caspar Trimmer

Cover photo: Natures economy © = Heine Christiansen / flickr

About SEI Working Papers:
The SEI working paper series aims to expand and accelerate the availability of our research, stimulate discussion, and elicit feedback. SEI working papers are work in progress and typically contain preliminary research, analysis, findings, and recommendations. Many SEI working papers are drafts that will be subsequently revised for a refereed journal or book. Other papers share timely and innovative knowledge that we consider valuable and policy-relevant, but which may not be intended for later publication.

STOCKHOLM ENVIRONMENT INSTITUTE
WORKING PAPER NO. 2014-08

Shifting to a Green Economy: Lock-in, Path Dependence, and Policy Options

Eric Kemp-Benedict
STOCKHOLM ENVIRONMENT INSTITUTE

ABSTRACT

In the face of increasingly likely dangerous climate change, many developing countries are designing green economy or low-emissions development strategies, but are simultaneously on a course of investment locking them into high-emission infrastructure. Meanwhile, many high-income countries are working to reduce their emissions but are hampered by the cost of switching from an existing capital stock designed for a fossil fuel-based economy. This paper looks at economic aspects of the challenge of escaping carbon lock-in using a "brown-green capital" model. In the model, brown capital is more productive than green capital in a brown capital-dominated economy, while green capital is more productive in a green capital-dominated economy; that is, the model allows for "carbon lock-out". We explore possible macroeconomic consequences of policies to drive a transition to a low-carbon economy and policy responses in the case that macroeconomic imbalances result. Three results are particularly interesting. First, the effect of policy instruments depends on whether the economy is wage-led or profit-led, a distinction that emerges from post-Keynesian theory. Second, if investors hedge against uncertainty over expected levels of green and brown investment, then there is likely to be underinvestment in green capital even at quite high levels of green capital penetration, creating a substantial challenge for policymakers. Third, the model suggests an unusual role for a carbon price, to control inflationary pressure arising from public green capital investment, in addition to its usual role of encouraging emissions reductions at the margin.

CONTENTS

Tables and figures

ACKNOWLEDGEMENTS

The author would like to thank Duncan Foley, Michael Lazarus, and Lance Taylor, who provided comments on earlier drafts of the paper that prompted substantial revisions.

This work was funded by the Swedish International Development Cooperation Agency (Sida). Sida does not necessarily share the views expressed in the paper; responsibility for its contents rest entirely with the author.

1. INTRODUCTION

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) points out the benefits of action on climate today, and the costliness of delay (IPCC 2014a). While welcome, this is by no means a new idea. As Ha-Duong et al. (1997) pointed out nearly two decades ago in a letter to *Nature*, a low-carbon future is cheaper and easier to achieve in the long run if new capital is designed with that future in mind, rather than matching the needs of the present economy. More than a decade and half later, den Elzen et al. (2010) found it necessary to make the argument again, pointing out that due to inertia in economies, the success of emissions-reduction targets depend on the paths taken to reach them. Moreover, the recent New Climate Economy report argues that the costs of a low-carbon transition are likely to be modest at best, and offer benefits in the near term that often exceed the costs (Global Commission on the Economy and Climate 2014). This raises the question of why these opportunities have not led to a widespread shift towards low-carbon economies. There have, indeed, been some notable initiatives to lower emissions, such as Germany's *Energiewende* (energy transition) policy (Dehmer 2013) and China's efforts to curb its emissions (Garnaut 2014). Yet these examples stand out because they are rare, and the *Energiewende* in particular is facing technical, social, and political challenges (Buchan 2012). Those challenges can be met, and likely will be, but they illustrate the difficulties that can arise when moving to a low-carbon path.

Slow and halting action on climate mitigation despite demonstrable economic benefits is consistent with the "carbon lock-in" hypothesis (Unruh 2000; Mattauch et al. 2012), which proposes that modern industrial economies have put in place strong stabilizing forces that reinforce dominant technologies with a built-in commitment to high emissions. The carbon lock-in argument refers to institutional, social, and economic processes. Considering the economic aspects, and using the language of economic externalities – that is, of actions with benefits or harms that are not reflected in market prices – the environmental externalities arising from climate change are accompanied by a network externality that leads to underinvestment (den Butter and Hofkes 2006; Schmidt and Marschinski 2009). In this paper we assume the existence of carbon lock-in and explore the macroeconomic consequences of a major effort to escape it. We further assume the possibility of "carbon lock-out" (Lehmann et al. 2012) or "green lock-in", in which mutually reinforcing technologies, practices, and policies favour low-carbon investment. While controversial, this is a feature of some of the integrated assessment models used for climate mitigation scenarios when they are modified to include induced technological change (Edenhofer et al. 2006, p. 97). Such models assume "spillover" benefits from new technologies that make complementary technologies more attractive.

To explore a low-carbon transition we use an aggregate "green-brown capital" model. In such models, "green" capital (capital with low associated environmental impacts) contributes much less to climate change than "brown" capital (capital with high associated environmental impacts), in the sense that when operated at a normal level, greenhouse gas emissions from a given quantity of green capital are much smaller than those from the same quantity of brown capital.[1] Crucially, the capital productivity of green capital is assumed to be less than that of brown capital in a brown capital-dominated economy, but more in a green capital-dominated economy if there is green lock-in. We capture the fact that most technologies are neither green nor brown by positing that both types of capital are productive to some degree regardless of which type of capital dominates in the economy. Green-brown capital models have been explored by Ploeg and Withagen (1991), Rozenberg et al. (2013b), Ackerman et al. (2013), and Nordhaus (2010), although not all of the papers use the terms "green"

[1] "Quantity of capital" is a problematic concept (Sraffa 1960; Cohen and Harcourt 2003). For the present paper it is defined as the accumulated value of capital stocks as calculated by summing investment at constant prices, net of depreciation, in which capital of all vintages depreciates at the same rate (the perpetual inventory method).

and "brown" to describe different types of investments. Each of these papers treats investment as a problem of finding an optimal future path given knowledge of the probability of all future states of the world. As we argue below, this is a questionable assumption at the best of times, and highly questionable in the case of a major economic transition. We therefore assume that investors try to make the best guesses they can, arriving at an investment orientation that is "bearish", "bullish", or "neutral" regarding the prospects of a low-carbon transition.

With other authors, we conclude that a low-carbon transition cannot be achieved through prices alone, but must be accompanied by targeted investment (Stern 2006; den Butter and Hofkes 2006; Jaffe 2012; Lecocq and Shalizi 2014; Global Commission on the Economy and Climate 2014). We also find three other, apparently novel, results. First, the effect of policy instruments depends on whether the economy is wage-led or profit-led, a distinction that is not made in mainstream economic theory, but emerges from non-mainstream post-Keynesian theory. In general, we find that a push towards a green economy is likely to be stimulating in most economies. Second, if investors take a neutral position on a low-carbon economy, then there is likely to be underinvestment in green capital even at quite high levels of green-capital penetration. As we discuss, this raises substantial challenges for setting policy. Third, the model suggests an unusual role for a carbon price. Given the coexistence of environmental and network externalities, it is not clear how to set the "right" price. We argue instead that the price (actually, the rate of change of the price) can be set so as to control inflationary pressure arising from public green capital investment. At the same time, the carbon price encourages emissions reductions at the margin and stimulates the development of niche technologies that can eventually replace currently dominant technologies.

Prices

The peculiar role for the carbon price follows partly from the way that prices are treated in this paper. We take post-Keynesian economics as a theoretical frame. Of the several differences between mainstream and post-Keynesian economics (Holt and Pressman 2001), two are particularly relevant: the calculation of prices and the treatment of uncertainty, which is discussed below. In mainstream economic models, prices are set actively in competitive markets and reflect scarcity of goods and services. In post-Keynesian models, most prices are set as a mark-up on costs at a normal level of operation, and most goods and services are not scarce (Lavoie 2001). Admittedly, some sectors are highly competitive, and some prices, such as those for raw materials, do reflect at least temporary scarcity, but they are not typical.

In both mainstream and post-Keynesian economics, prices can drive technological change because innovation is biased toward saving costs. In the case of a carbon price this leads to marginal changes in emissions with existing equipment, larger changes with periodic major new investment, and the possibility of transformative change by stimulating the creation of niche technologies. The post-Keynesian assumption of mark-ups also implies that a carbon price will increase profits at the expense of wages, which leads to macroeconomic consequences. This topic is taken up in detail later in the paper.

Technological lock-in and socio-technological regimes

Carbon lock-in is an example of the broader phenomenon of technological lock-in. Lock-in can occur at the scale of a particular technology, but carbon lock-in is more fundamental, characterizing a broad socio-technological regime (Unruh 2000; Mattauch et al. 2012). Such regimes feature ramified and self-reinforcing social, institutional, and technological elements (Geels 2002; Geels and Schot 2007; Haxeltine et al. 2008). Socio-technological regimes are necessary for economies at any significant level of complexity, as they provide sufficient certainty – whether over access to materials and components, social roles and norms, or the nature and scope of regulations – to encourage investment in physical, social, natural, and human capital. The self-reinforcing elements within a regime make it difficult to shift out of it, while allowing innovation within it. Innovations can align with or against the dominant regime. Those aligned with it give rise to self-reinforcing technological trajectories reflecting a dominant technological paradigm (Dosi 1982). Those aligned against it take place in niches that can eventually expand and replace the currently dominant regime in a socio-technological transition (Geels and Schot 2007; Haxeltine et al. 2008).

Lock-in can be beneficial in complex economies; however, to address the climate challenge it must be overcome (Westley et al. 2011). For that to happen, societies must pursue, and governments must promote, novel technological and societal changes with uncertain benefits. Such a path requires experimentation and learning-by-doing. Thus, changes must be made through intentional, policy-driven, efforts that increase uncertainties for private investors and citizens. Rapid changes are likely to be resisted by institutions, firms, and individuals with a stake in the current socio-technological regime, as well as by those who do not want their lives disturbed and do not understand the need for urgency. Actors invested in the current regime typically have considerable resources at their disposal that they can deploy to influence opinion, and in the case of a policy-driven transition, they can cast doubt on the benefits and political sustainability of the program. A central issue in a low-carbon transition is the economic, social, and political role of fundamental uncertainty.

Risk and uncertainty

Following Keynes and earlier writings by Frank Knight (1921), post-Keynesians distinguish between risk, which can be quantified as known probabilities, and true uncertainty, which cannot. Keynes is worth quoting at length on the topic (Keynes 1937, pp. 213–214):

> By "uncertain" knowledge, let me explain, I do not mean merely to distinguish what is known for certain from what is only probable. The game of roulette is not subject, in this sense, to uncertainty; nor is the prospect of a Victory bond being drawn. Or, again, the expectation of life is only slightly uncertain. Even the weather is only moderately uncertain. The sense in which I am using the term is that in which the prospect of a European war is uncertain, or the price of copper and the rate of interest twenty years hence, or the obsolescence of a new invention, or the position of private wealth owners in the social system in 1970. About these matters there is no scientific basis on which to form any calculable probability whatever. We simply do not know.

In this paper we focus on uncertainties associated with a low-carbon transition. For climate change *per se*, on some questions there is a scientific basis on which to form a calculable probability. For example, the Intergovernmental Panel on Climate Change (IPCC) Working Group I (IPCC 2013) was able to conclude that it is "extremely likely" – that is, with an assessed probability of between 95% and 100% – that more than half of the rise in average global temperature between 1951 and 2010 was due to human influence. Most future drivers of climate change, in contrast, are truly uncertain, as are many climate impacts. IPCC Working Group II concluded, with "high confidence", that there is large uncertainty over future vulnerability and exposure (IPCC 2014b). Climate damages are nevertheless sometimes assigned probabilities in economic models, but even if this done, slowly declining probabilities for extremely high damage costs defeat calculations of risk (Weitzman 2009; Weitzman 2011).

The uncertainties associated with a low-carbon transition are those faced by investors, business owners, entrepreneurs, consumers, and workers in any intentional socio-technological transition: whether government policies will be sustained; what competitors and trading partners will do; whether one's current job is in danger; and whether good jobs will be available. Within a socio-technological regime and in tranquil times it is sometimes possible to assign probabilities to these sorts of question, but when the economy is in flux, in particular in the middle of a major transition, it is not.

Fundamental uncertainty can be addressed using the techniques of strategic foresight (Glenn and Gordon 2009). These techniques have been used by business leaders, policy-makers, and others to plan in the face of a fundamentally uncertain future (Burt 2007). At the centre of most foresight exercises is a set of narratives about the future (Wack 1985; Schwartz 1996), and a number of techniques have been introduced to structure narrative development. Taking a minimal strategic foresight approach, we use narratives to illustrate possible courses of action, and use the model developed in the paper to ensure a degree of consistency.

2. PRODUCTION, DISTRIBUTION, AND INVESTMENT IN A GREEN-BROWN CAPITAL MODEL

The economic model developed and applied in this paper is presented in mathematical form in four appendices. Only one equation appears in the body of the text. In this section we first consider the macroeconomic consequences of a particular level of investment in green capital and second we ask how total investment might be allocated to either green or brown investment, given total investment. For most of the paper we work with a closed-economy model. Although a shift toward a green economy will require flows of money and goods between countries, a closed-economy macroeconomic model is nevertheless a useful start to an analysis of a low-carbon transition. In part this is because all of the world's economies cannot, for example, simultaneously go into debt, or all become exporters – for a global problem, a closed-economy model helps focus on global macroeconomic constraints. More pragmatically, a closed economy model helps focus on the issues of greatest importance for the current paper: lock-in, uncertainty, and investment. We consider policies for a small open economy later in the paper.

Production

In this paper we assume that brown and green capital are made of the same "stuff", but the choice to make one or the other is irreversible – one type of capital cannot be converted into another. Put another way, we construct a "putty-clay" (Miller 2001) investment model. Putty can be moulded and re-moulded, while clay can be moulded once but then, after it is fired, it cannot be changed again. In a putty-clay model, the materials used to make capital goods – steel, rubber, silicon, and components made out of these and similar materials – can be used flexibly to produce any sort of capital good; for example, steel could be used to construct a boiler for a coal-fired power plant or to make a pylon for a wind turbine. But once the boiler is built it cannot be turned into a pylon, and vice versa, although it can be used more or less effectively. Hence the materials are putty-like at the investment stage and clay-like once the investment is made.

Mainstream models typically (but not always) assume putty-putty capital, in that firms can switch capital from one task to another and vary the mix of labour and capital smoothly and regularly. Firms are presumed to do this in order to maximize their profits given wages, costs of inputs, and the price for their products. Firms are also assumed to face a rising cost curve, so that marginal increases in output lead to higher costs per unit. These assumptions provide a unique equilibrium level of production, at which the marginal cost of production equals the going price for the good. However, the behaviour of actual firms does not match mainstream assumptions. Rather, firms make a combination of lumpy and smooth adjustments to both capital and labour utilization (Sakellaris 2004). The smooth adjustments typically take place within tight constraints given the existing capital stock, while lumpy adjustments allow for substantial changes in the proportions of capital, labour, and other inputs. Firms may leave some slack for planned downtime or to enable the firm to take advantage of surges in demand (Miller 2001). Generally, excess capacity allows firms to operate in a regime where the variable cost curve is horizontal, in contrast to the mainstream model (Miller 2000). A firm's strategy typically depends on its shut-down and start-up costs (Corrado and Mattey 1997; Mattey and Strongin 1997). Only when the plant is run at close to full capacity, or in industries where continuous operation is the norm, does increasing production lead to rising costs (Corrado and Mattey 1997). Thus the services of productive factors vary from one technique to another, but for a given technique it is a good approximation to treat them as entering in fixed proportions (Miller 2000, p. 121).

In post-Keynesian models, output is proportional to the capital stock, where the coefficient of proportionality may change over time, both in the short and the long run. This is captured by writing output, X, as

$$X = u\kappa K.$$

In this expression, the capital productivity κ is a long-run relationship that changes on the timescale of the turnover of long-lived capital stocks; that is, a timescale greater than 15 years (Lecocq and Shalizi 2014). The utilization, u, is a short-run relationship that varies over a business cycle. Capital productivity exhibits considerable variation (Maddison 1994), and can trend upward or downward for periods of time (Piketty 2014), but remains bounded over the long run.

In the model presented in this paper, total capital, K, is the sum of brown capital and green capital. We capture this assumption by requiring environmental impacts of green capital to always be lower than those of brown capital. In the case of carbon emissions, if the capital stock expands during the transition, then unit emissions must be considerably lower than they are today if we are to avoid dangerous climate change. This is physically possible – indeed, it is possible for net emissions to be negative – but very challenging. In this paper we assume that the needed technologies either are or will become available. We further assume either that brown and green capital depreciate at the same rate, or that brown capital depreciates more quickly through early retirement.

During a transition from a brown to a green economy, the share of green capital in the total capital stock will increase from a low value to 100%. We represent lock-in by assuming that increasing penetration of green capital decreases the productivity of brown capital while increasing that of green capital, such that brown capital in a brown capital-dominated economy is more productive than green capital, while the opposite is true in a green capital-dominated economy. We further assume that a green capital-dominated economy is never more productive than one dominated by brown capital, and might be less productive, because some green investment may be for abatement or other non-productive purposes. Thus, we assume that for the same level of capital stock, as measured by cumulative net investment at constant prices, a fully brown capital economy will produce either the same or more goods than a fully green capital economy.

We assume that green capital is more labour-intensive to operate than brown capital initially, although they are expected to converge over time. This assumption follows in part from the common observation that labour intensity is relatively high with new technologies, and that it falls with accumulated hours of use (Yelle 1979; Hall and Howell 1985). It also follows from the literature on the net employment effect of green investment (Bowen 2012). Several studies, in particular one by the United Nations Environment Program (UNEP 2011), have claimed that green capital is associated with a net increase in jobs, but the comparisons are not always in the same sector. For example, UNEP cites studies that compare jobs created in the green building sector to jobs lost in the energy sector due to reduced energy consumption. Others compare jobs in the same sector, in particular the energy sector, and claim higher labour intensity for non-fossil energy sources (Wei et al. 2010). As noted by Fankhauser et al. (2008), this means higher costs, as well as more jobs, which will play an important role in the model results discussed in this paper.

Policy instruments can affect the environmental impacts of brown and green capital. For example, an environmental tax may induce faster reductions in carbon dioxide emissions or energy intensity (Goulder and Schneider 1999; Gritsevskyi and Nakićenovi 2000; Edenhofer et al. 2006; Kumar and Managi 2009). Alternatively, mandated performance standards could drive emissions or energy use downward. However, such improvements are typically limited to rates of 1% to 2% per year; higher rates are possible for new capital and equipment, perhaps reaching 5% per year, depending on the rate of replacement of old capital and with a substantial push for innovation (Blok 2004). That is, a high rate of improvement requires the large-scale replacement of existing capital rather than marginal improvements to existing stock.

Distribution

Post-Keynesian theory assumes that different groups of economic actors have different behaviours (Taylor 2004). In particular, people whose main source of income is a pay cheque make different saving and consumption choices from those whose main source of income is the return on their investments, in large part because their incomes are usually substantially smaller. Even if individuals pool their income from wages or salary, rents, and capital gains to spend mainly on consumption goods, most rents and capital gains are retained by corporations or distributed to pension funds, and are subsequently reinvested. The net effect is more consumption out of salaries and wages and more investment out of capital income. For this reason, the functional income distribution – the distribution of national income between wages and profits – is an important determinant of growth and consumption.

In post-Keynesian models, profits are determined by the pricing behaviour of firms, who apply a mark-up on a “normal” level of costs (Lavoie 2001) that changes over the medium to long run. Long-term or anticipated changes in costs are eventually passed on to consumers, as appears to have happened with the European Emissions Trading Scheme (EU ETS) (Sijm et al. 2006; Zachmann and von Hirschhausen 2008). The typical firm changes its prices infrequently; Blinder (1994) reports a median frequency of once per year. This pricing behaviour creates a buffer that dampens abrupt changes in prices. As costs fluctuate so do profits, with a delayed impact on the costs of goods, and when costs are passed on to consumers real wages fall, even if nominal wages do not. Whether this is a problem for wage earners or not depends on the pace of change and whether the change in price is due to changes in wages or some other source. If firms’ costs are proportional to their wage bill then a rise in the nominal wage initially increases purchasing power but is eventually undermined if the costs are passed on to consumers – if employment levels and mark-ups do not change, then the rise in price exactly cancels out the rise in wages. The only way this cancellation would not occur is if firms were to apply lower mark-ups over the long run. Non-wage inflation, as occurred in the 1970s and 1980s oil price crises in the USA (Hooker 2002), is a different matter. In this case, profits tend to fall initially; after costs are passed on, real wages fall and profits rise.

With fixed levels of utilization, the real wage can only increase at the expense of the return on capital, and vice versa (along the “wage-profit frontier”). However, if the economy is in a slump, with low levels of utilization, it is possible for the real wage and the return on capital to both increase (Taylor 2004; Palley 2007). In a depression, the shift from a brown capital-dominated economy to one dominated by green capital can be stimulating – because labour productivity in the green capital sector is expected to be initially lower than in the brown capital sector, labour demand is expected to rise with increasing penetration of green capital. Also, modestly high levels of utilization can spur innovation (Juniper 2009). If the labour market is already tight, then a rise in labour demand can lead to inflation and distributional conflict between either falling wages or falling returns on capital.

Investment

In the context of a green-brown capital model, two quantities are relevant to investment: the total volume of investment, and its allocation between green and brown capital. The first of these is a standard topic of post-Keynesian analysis, while the second is not.

Total investment and utilization

In a closed economy, investment must, of necessity, equal savings. However, as discussed above, savings and investment are carried out by distinct social groups and governed by different behavioural rules. These social and personal dynamics are captured by marginal propensities to save out of wages or profits.

The question then becomes how the model is closed – that is, how savings and investment become equal at the level of the whole economy. Neoclassical models assume more or less flexible wages that adjust in an active labour market; firms modify their mix of capital and labour until the marginal productivity of labour equals the market-clearing wage and the marginal productivity of capital equals the return on capital at that wage. The labour market is assumed to clear more or less rapidly in different neoclassical models, with New Classical variants assuming rapid adjustment and New Keynesian variants assuming slower adjustment with "sticky" wages.

In contrast, post-Keynesian models (such as the one developed for this paper) are closed by adjusting the utilization rate. A falling utilization rate signals a slump, while a rising rate signals either a recovery or a period of stimulation. Changes in utilization drive investors' expectations: a slump can become self-perpetuating, possibly for many years, if it leads to a loss of investor confidence, while a stimulated economy can lead to several possible outcomes. If demand or wages rise, the economy can experience wage-push or demand-pull inflation. Rising demand or wages can also encourage firms to innovate in order to reduce costs or meet new demand, with potential benefits to the economy (Juniper 2009). If rising utilization leads investors to anticipate further increases, they might invest in new ventures; if they expect asset prices to rise, they may engage in speculation, buying an interest in a firm or a derivative in the expectation of selling it again at a profit, from a few milliseconds to a few weeks later. Speculation is usually beneficial when the fundamentals of a market are widely agreed and stable, but if expectations are unrealistically optimistic then speculation can lead to a bubble (Reinhart and Rogoff 2009). A reasonable policy goal is therefore to maintain steady levels of utilization at close to the full potential of the economy.

In the standard post-Keynesian model, savings rates are determined by wage and profit income and marginal propensities to save. Investment is determined by the utilization rate and the return on capital. The return on capital also depends on the utilization rate, as well as the profit rate and capital productivity. Setting savings equal to investment fixes the utilization rate as a function of the profit rate and other variables. Economies can then be broadly separated based on how utilization rates respond to changes in the profit share of total income. If utilization falls with a rising profit share then the economy is said to be "wage-led" or "stagnationist". If utilization rises when profits increase it is said to be "profit-led" or "exhilarationist" (Blecker 2002; Stockhammer 2011). Economies can be in either regime at different times. For example, Marglin and Bhaduri (1988) argued that in the 1970s the US economy transitioned from a wage-led to a profit-led domain; Hein and Krämer (1997) confirm their findings, but argue that in the 1980s conditions shifted back to a wage-led domain. Using an open-economy model and data from 1960–2005 (or 1970–2005 in the case of the UK), Hein and Vogel (2008) found that France, Germany, the UK and the USA are wage-led, while Austria and the Netherlands are profit-led. Stockhammer and Onaran (2013), reviewing the evidence from several studies, including their own major study for the International Labour Office, concluded that most countries are domestically wage-led, and so is the world as a whole. That is, ignoring the effect of changing prices of their exports, a rise in the profit share tends to depress output. Countries are typically profit-led only if the export effect is large enough to offset the tendency toward a wage-led regime. The implication is that countries with large domestic markets, such as the USA, Japan, the Euro area as a whole, and large European countries, are typically wage-led. Large developing economies, such as India and China, are domestically wage-led but are sufficiently export-oriented to be profit-led when exports are taken into account. The distinction between domestically wage-led and profit-led economies will become important when we discuss small open economies later in the paper.

Table 1: Response of utilization to increasing penetration of green capital with normal inflation in brown capital-dominated and green capital-dominated economies

	Brown capital-dominated		Green capital-dominated	
Effect of increasing penetration of green capital	Profit-led	Wage-led	Profit-led	Wage-led
Direct	+	+	-	-
Indirect via profits	-	+	+	-
Combined	?	+	?	-

In the model presented in this paper, the variable that changes across the transition to a green economy is the penetration of green capital. A changing share of green capital in the total capital stock affects capital and labour productivity because green and brown capitals have different productivities. The result is that investment in green capital drives an increase in labour required to produce the same volume of goods. The changing productivity also affects prices. We assume that prices are set as a mark-up on costs in the lowest-cost sector – in a brown capital-dominated economy, the price leader is the brown capital sector while it is the green capital sector in a green capital-dominated economy. The price follower has lower profits, so aggregate profits fall initially as green capital increases from a low level, but they rise with increasing green capital penetration if green capital is dominant. This gives rise to two impacts on utilization: a direct effect from changing productivity and an indirect effect through the profit share. The consequences for the utilization rate are shown in Table 1.

Table 1 summarizes the first of the important results in this paper. It shows that in a wage-led regime, rising penetration of green capital will always be stimulating in a brown capital-dominated economy and depressing in a green capital-dominated economy. In a profit-led regime, the direct and indirect effects have opposite signs, so whether increasing green capital is stimulating or depressing depends on the relative size of the two terms. As the global economy is wage-led, this suggests that a coordinated global push will be stimulating, but if countries act independently then the results for any particular country will depend on whether that country is wage-led or profit-led and, if profit-led, whether that is due to trade or to domestic conditions. This suggests different policy responses depending on the nature of the economy and the actions of other countries.

Portfolio allocation

In this section we take up the question of the allocation between green and brown capital. The simple rule is that if the share of green capital in total capital stock is to expand, then the share of green capital in new investment must exceed the share in the economy as a whole, or brown capital must be retired early. Suppose, for example, that initially 5% of all new investment is in green capital. In a fully brown economy this will increase the stock of green capital, but only up to the point at which the penetration of green capital in the economy is equal to 5%, where it will remain unless the share of green capital in new investment is increased or brown capital is retired early. Whether or not the share of green capital can expand therefore depends on how investors view green and brown capital investments, as well as the level of public investment.

There is no established post-Keynesian theory of how investment is allocated between assets of equal liquidity. Post-Keynesian finance theory focuses on the allocation of investment toward more or less liquid assets, specifically the choice between money, bonds, and equity. As argued by Poitras (2002), there may never be the equivalent of the neoclassical capital asset pricing model for post-Keynesian theory because such a model would be antithetical to basic post-Keynesian ideas. Nevertheless, there are common elements to most post-Keynesian discussions of finance (Davidson 1972; Crotty 1992; Gordon 1992; Poitras 2002), and Taylor (2004) identifies the makings of a general theory from the work of Minsky (2008). Most important is the recognition that the future is fundamentally uncertain; that is, it cannot be reduced to an assessment of risk given a known probability distribution of future states. Uncertainty is compounded by an assumption that, for firms, investments are difficult to reverse. The observation that investors make decisions in the face of fundamental uncertainty poses a challenge for investment theory. In this paper we address it by identifying a “neutral” position with respect to the prospects for a green economy and then discuss, in narrative form, possible reactions from investors that may make them “bullish” or “bearish” on the green economy, thereby placing them above or below the neutral line.

Tangible assets have (at least) two prices in post-Keynesian theory: a cost price, set by mark-up, and an asset price, which reflects expectations about how others will value the asset in the future. The two prices are linked, in that asset prices must be consistent with prices in the market for goods (Minsky 2008), but because of asymmetric information and uncertainty, the asset price can depart from what “fundamentals” would suggest. Investments are driven by expectations of changes in prices, which gives the own-rate of a return on an asset (Taylor 2004). Because profits may be reinvested to expand the business, the value of owner equity may rise over time as long as the equity is not diluted by issuing more shares. We assume that businesses and entrepreneurs seek funding for projects that they expect to yield a reasonable net income over coming years. If that expected income results in a profit rate higher than normal, then the entrepreneur will be willing to offer higher returns to external investors. If the asset price is less than the cost price, then no investment will take place. The volume of investment in either brown or green capital is determined by investors’ expectations; those expectations, as reflected in own-rates of return, shape investment decisions.

We allow outcomes to depend on the sequence of investments. That is, we allow for path-dependence. Specifically, we assume that in a brown capital-dominated economy, if the share of green capital is increasing then output will be higher if brown capital investments are made first, and green capital investments are delayed, while the opposite is true in a green capital-dominated economy. In the context of climate change this may seem surprising given the sound arguments for early action to avoid paying a higher price later in costly retooling or losing output through climate damages. However, those costs only become evident over the passage of year or decades, whereas investment can take place over much shorter timescales, from less than a year to a few years. Also, unlike firms, which must work with their installed capital, portfolio investors can buy and sell assets, or derivatives of assets, and are concerned with changes in their market value, rather than social costs and benefits. Presumably, if there were a private benefit to increasing green capital then it would occur spontaneously.

Asset prices in a low-carbon transition will be affected by a complex and shifting mix of factors: the penetration of green capital, productivity and costs, and investor sentiment, among others. Among these factors is a contribution that depends on relative productivities of green and brown capital and investors’ expectations of the direction and magnitude of the potential change in the share of green capital. As shown in Appendix 2, it is possible to construct a portfolio such that this term is zero; that is, it makes the portfolio insensitive to beliefs about the direction and magnitude of change in the share of green capital. We call this the "neutral portfolio" – it is the portfolio that should be chosen by a prudent investor who is unsure of the prospects for a green economy. Another possible portfolio consists entirely of the highest-performing asset, whether green or brown. This "most profitable" portfolio is shown together with the neutral portfolio for a hypothetical green-brown capital economy in Figure 1. As seen in the figure, path dependence means that the location of the most profitable or neutral portfolio depends on whether green capital is increasing or decreasing. Also, the figure is not symmetrical, on the assumption that to some extent green capital is inherently less productive than brown capital because it does not all contribute to producing goods (e.g., some of it may be for abatement).

Figure 1 summarizes the second of the important results in this paper. Indeed, it holds several implications. To see them, first note that the shaded triangle in the upper left of the figure is the region where green capital is expanding. In a brown capital-dominated economy (that is, on the left-hand side of the figure), both the most profitable and neutral portfolios lie below this line. An investor who truly believes that a green economy will not materialize would adopt the most profitable portfolio, which would be fully brown (curve a1 in the figure). However, if this investor bets wrongly then the costs could be substantial, as he or she would be left with financial assets of falling value that eventually would be backed by physical assets that are worthless except as scrap – that is, stranded assets. This suggests that even sceptical investors may wish to hedge their bets against the possibility of a green economy, adopting something close to the neutral portfolio (curve b1 in the figure).

For private investment to raise green investment above the diagonal would require investors to be sufficiently bearish on the green economy. Moreover, the gap between the neutral portfolio and the diagonal increases with increasing penetration, at least initially, so that investors must not only sustain, but also increase, their green investments over a portfolio where they hedge their bets. To do this, they must believe strongly that a green economy is a likely outcome. If the share of green capital in new investment does not expand, then the shift toward a green economy will stall, and if confidence weakens then investors may reduce the amount of green capital in their portfolios, driving green investment downward. Bullish sentiment must be sustained until the economy is in the ambiguous zone between curves a1 and a2 in the figure. In this region, continued increases in green capital are not favourable, but neither is a return to brown capital. A self-sustaining drive towards a fully green capital economy does not develop until green capital has substantially penetrated into the capital stock.

These dynamics illustrate lock-in, as the brown capital economy is strongly self-stabilizing. More positively, in this model the green economy is also self-stabilizing. The policy question is how to get over the "hump" between the brown and green capital regimes.

3. POLICY CHALLENGES, POLICY INSTRUMENTS, POLICY NARRATIVES

Switching to a green capital-dominated economy is socially desirable but privately unprofitable, a situation calling for public intervention. The main policy implication of the model presented in the appendices is that a successful transition to a green economy will require a sustained commitment backed by a continually changing policy mix over the course of the transition. If public policies are to receive continued support, then the citizenry must have evidence (or at least confidence) that they are headed in a positive direction, even if they must make sacrifices in the near term. It is easier to feel positive if the economy is providing employment and opportunities for gain, so a relevant policy goal is to aim for close to full utilization of capital and labour while restraining inflation. The success of the policies depends on how people – as consumers, workers, investors, and citizens – react to them. We therefore present policies in combination with one or more narratives illustrating responses of economic actors.

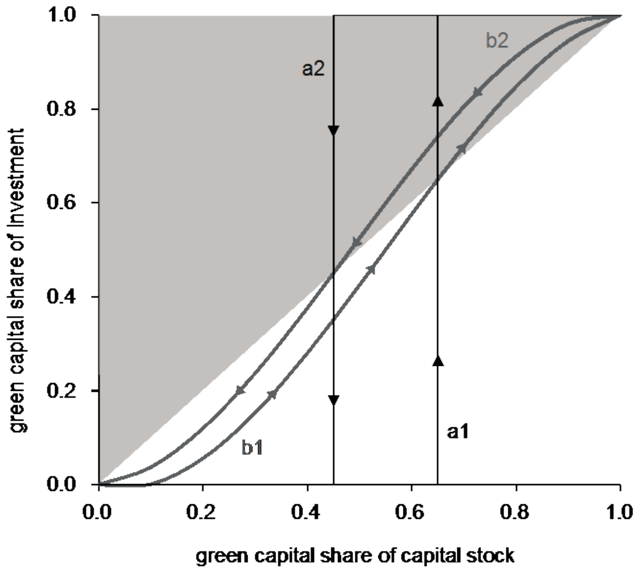

Figure 1: Illustrative alternative investment portfolios. a1 and a2 invest fully in the most profitable option; b1 and b2 are the neutral portfolio; due to path dependence, the curves depend on whether the share of green capital is increasing or decreasing; in the shaded area, the green capital share will increase.

Public investment and interest rates

Suppose that the government decides to invest strongly in the green economy. If this happens then public investment can either crowd out or crowd in private investment. In general, if public funds are used to purchase the same sort of capital goods that private investors would have bought, then it will tend to crowd out private investment. However, if public monies are invested in infrastructure, subsidizing costly retrofitting, and providing services to streamline green investment, then they complement private investment and can stimulate it. We assume that public investment is of the second kind. Thus the government does not have to fully make up the gap between the neutral portfolio and a level of investment at which green capital is expanding. Instead, the gap is made up through a combination of public investment and the private green investment that it induces.

If taxes are not raised for this purpose, the government deficit will grow, which is stimulating, although not sustainable in the long run. Alternatively, taxes may be adjusted so that total investment does not change, but from Table 1, even in this case the shift toward a green economy will be stimulating in a wage-led economy because a lower capital-to-labour ratio causes employment to expand. If the economy is in recession then stimulation is desirable, but if it is not then stimulation can drive inflation, leading investors and consumers to doubt the wisdom and sustainability of the government's policy. If inflation remains under control, but policies to promote a shift toward a green economy raise expectations of rising financial returns, then there may be over-investment, risking a bubble; that is, the result may be asset price inflation rather than inflation of the price of goods. A bubble will ultimately burst, which can sour both investors and consumers on the prospects for a green economy.

A policy of substantial green public investment therefore carries risks: of crowding out private investment; of driving inflation; and of stimulating an investment bubble. As discussed above, crowding out can be avoided by making complementary investments, supportive of the green economy, that are unlikely to be undertaken by private investors. The other two risks are conventionally addressed by the central bank, which dampens investment by raising interest rates, thereby lowering the price of existing assets and raising the cost of borrowing to pay for new ones. However, raising interest rates is a problematic policy option because it dampens green and brown investment equally. In general, if total investment is to be curbed, it is better if brown investment is reduced more than green investment. Rozenberg, Hallegatte, et al. (2013) argue that this could be accomplished by issuing “carbon credits” that can be accepted as legal reserves by commercial banks. In this paper we argue that a carbon price can also accomplish this goal.

Carbon price

In this post-Keynesian model, the carbon price plays a somewhat unusual role. Carbon prices do, as in neoclassical theory, influence behaviour at the margin, but that is not the dominant macroeconomic effect. Instead, in a brown capital-dominated economy as firms pass through costs to consumers – as in the EU ETS (Sijm et al. 2006; Zachmann and von Hirschhausen 2008) – it tends to increase profits at the expense of wages. This happens because mark-ups accumulate across supply chains (Kemp-Benedict 2014), creating a multiplier over input costs to firms, where the gain is realized as profit. In a wage-led economy an increase in profits tends to depress output. If the economy is not in recession, a carbon price thus has the same qualitative effect as raising interest rates, so it can help moderate the inflationary effects of increasing green investment. If the economy is in recession, then it can have the undesired effect of dampening the otherwise stimulating effect of green investment.

Using the language of economic externalities, the “right” carbon price would be based on the network externality associated with lock-in, rather than on costs from carbon emissions. However, a carbon price high enough to make low-carbon investment inherently more cost-effective than conventional investment is likely to be punishing. For example, the DICE model (Nordhaus 2010) treats green capital as entirely unproductive, so the marginal productivity of green capital is zero. The CRED model (Ackerman et al. 2013) assumes that green capital is one-half as productive as brown capital. Taking the CRED assumption as the marginal productivity of green capital, and assuming similar labour productivities in the brown and green sectors, an environmental tax must be large enough to roughly double the costs of production in the brown capital sector. If such an increase were implemented quickly then it would lead to rapid non-wage inflation. Likewise, in the New Keynesian green-brown capital model of Rozenberg (2013b), without the use of capital instruments utilization falls sharply and dramatically after the emissions tax is applied. More detailed studies reach the same conclusion. Foxon (2010, p. 3477) notes that a carbon tax large enough to shift investment is likely to be socially and politically unacceptable. Perhaps for this reason, the IEA, in a study of the electricity generation sector (2013, pp. 35–36), pointed out that the most established carbon market, the EU ETS, has shifted some production from coal to gas, but not enough to decarbonize the electricity supply. They argue that prices are too low and permit periods extend over too short a horizon (through 2020) to drive changes in long-lived capital stocks.

Getting the price “right” may therefore not be an appropriate policy goal. Instead, we suggest that a rising carbon price can be used in a wage-led economy to counteract the effect of increasing penetration of green capital. It shifts the functional income distribution toward profits, having a depressing effect on the economy. At the same time, it encourages emissions reductions at the margin. This improves the performance of brown capital, and can also stimulate niche innovation. A carbon price is unlikely to be transformative, but it can support a transformation through both microeconomic and macroeconomic channels.

A closed, wage-led economy

The effects of an interest rate and environmental price are shown in Table 2. As seen in the table, raising interest rates is always depressing. In contrast, in a wage-led economy a rising carbon price acts counter to the effect of rising green investment: it is depressing in a brown capital-dominated economy and stimulating in a green capital-dominated economy. However, it is only effective if there is some green capital in the economy, so at low levels of penetration of green capital interest rates must be raised to restrain inflation. Importantly, a rising carbon price always acts opposite to the effect of increasing green capital penetration, so it can be used consistently across the transition. This helps to make policy appear more coherent and easier to justify. We now offer a policy narrative for a wage-led economy.

Table 2: Response of utilization to increasing green capital and policy instruments in brown capital-dominated and green capital-dominated economies

	Brown capital-dominated		Green capital-dominated	
Effect of increasing penetration of green capital	Profit-led	Wage-led	Profit-led	Wage-led
Direct	+	+	-	-
Indirect via profits	-	+	+	-
Interest rate	-	-	-	-
Carbon price	+	-	-	+

When the economy is dominated by brown capital, the government can begin investing in green infrastructure and other complementary assets, perhaps financed by green bonds (Reichelt 2010), while offering tax incentives, preferential interest rates, and other schemes to encourage private green investment and brown disinvestment. This is likely to be stimulating, which can be counteracted by raising interest rates, at least initially, while maintaining preferential rates for green investment or by using carbon credits (Rozenberg, Hallegatte, et al. 2013). As the stock of green capital increases, interest rates can be eased back while the carbon price is gradually raised. However, as green capital increasingly penetrates into the economy, problems emerge. Investors begin to see their brown investments losing value, while green investments are not yet paying off. Meanwhile, the government is finding it necessary to increase its contribution to total green investment in order to sustain the shift towards a green economy, but without obvious benefits to its citizens. If investors either lose confidence in the government's ability to manage the transition or act to protect the value of their brown capital investments, the government may find it very difficult to maintain its green investment policies. However, by this time a great deal of green infrastructure is in place, so opportunities for complementary, facilitating, investment are shrinking. This suggests that additional green investment is best supplied from the private sector, which could be encouraged by shifting to a policy of buying back brown capital at higher than market rates. That is, the government would at least partly compensate firms and investors for the loss of value of their assets. The retired assets would then provide a reservoir of scrap materials, such as steel, which could be used for green physical investment.

By this point the government has been running deficits for some time, so in a closed economy some other sector must be running surpluses. Much production, and much demand, has been going towards investment goods, and the profit share has been rising, so consumption has fallen. It is therefore the household sector that is running surpluses – they are building up savings by investing in the green economy.[2] If the government and citizens can move the economy over the hump, then the value of those green investments will begin to appreciate. As doubts about the feasibility of a green transition

[2] This situation could be compared to that of the US economy after World War II. During the war, consumption was restrained, while workers invested in war bonds. After the war, those private savings contributed to the subsequent boom.

fade, nearly all investment will be in green capital and the transition will become self-sustaining. In this case, continuing increases in the share of green capital will tend to depress output in a wage-led economy. To counteract this, the environmental price can be raised further. In a green capital-dominated economy, but one with some brown capital still in place, this now has a stimulating effect because it reduces profits in the brown capital sector. Once the economy is essentially all green, environmental prices can be left at high levels, where they internalize environmental costs and further stabilize the green economy.

A small open economy

So far we have applied a model for a closed economy. In this section we discuss the important case of a small open economy, focusing on differences from the closed economy case. Details are provided in Appendix 4. In an open economy, the domestic price compared to foreign prices affects the balance of trade, and therefore aggregate demand. Also, if foreign investment opportunities are more attractive and capital is mobile, investors may move their investments abroad. Both of these dynamics affect the trade balance. In the long run, there is evidence that growth is constrained by a country's trade balance (Thirlwall 1979; Thirlwall and Hussain 1982; Perraton 2003), but in the short and intermediate run it is possible for it to deviate from its long-run level while maintaining relatively high growth, if investment is forthcoming.

Table 3: Response of utilization to increasing green capital penetration in small open brown capital-dominated and green capital-dominated economies

	Brown capital-dominated		Green capital-dominated	
Effect of increasing penetration of green capital	Profit-led*	Wage-led*	Profit-led*	Wage-led*
Direct	+	+	-	-
Indirect via profits	-	+	+	-
Domestic price: profit effect**	-/+	+/-	+/-	-/+
Domestic price: trade effect	-	-	-	-
Foreign price	+	+	+	+
Foreign investment	-	-	-	-

** In all cases, the response is domestically wage-led or profit-led.*

*** Close to a fully brown or green capital-dominated regime, the sign before the "/" prevails. It is the opposite of the closed economy case. If domestic profits are not very sensitive to relative prices the sign can change at intermediate levels of green capital penetration.*

Small open economies are likely to be domestically wage-led, but can become profit-led through trade (Blecker 2002; Stockhammer and Onaran 2013). However, this occurs by changing a desired, or target, mark-up, or by changing wages, while we leave these factors fixed in order to focus on changes in penetration of green capital. The result is that in a domestically wage-led economy – regardless of whether it is overall profit-led – a push towards a green economy remains stimulating. Because most economies are domestically wage-led, this extends the closed-economy result to most economies. However, the effect of a rising carbon price is ambiguous. It now operates through two channels: the domestic effect and the effect on the balance of trade. The rise in profits from an increase in the carbon price is offset to some degree by the loss of profits due to a loss of international competitiveness, so that profits can either rise or fall. However, the rise in prices is always dampening through its effect on the balance of trade. If foreign prices rise – for example, if trading partners raise their own carbon price – then the effect is stimulating. In the context of a global push toward a green economy, with rising carbon prices, the macroeconomic performance of small open economies therefore depends on the actions of trading partners.

4. DISCUSSION

The results presented above suggest that if lock-in is preventing a transition to a low-carbon economy, then a carbon price will be an insufficient stimulus for a low-carbon transition. The analysis suggests a changing policy mix over the transition that combines direct public investment, promotion of private investment in green capital, and price-based, monetary, and fiscal instruments. Policies must be credible, and must be sustained over a long enough time for the economy to move into the region where a shift towards a low-carbon economy becomes self-sustaining. Whether that will be possible depends on the beliefs and personal motivations of investors: a bullish attitude toward the prospects for a green economy is necessary for the transition, while strong enough efforts to protect existing investments could undermine public policies.

The framing of the problem in this paper is somewhat similar to that in the papers of Rozenberg and colleagues (Rozenberg, Vogt-Schilb, et al. 2013a; 2013b; Rozenberg, Hallegatte, et al. 2013), and the policy prescriptions are complementary to theirs. In both their papers and this one, the goal is to maintain utilization of capital in order to maintain employment and encourage the investment that will be needed for a transition to a green economy. Rozenberg et al. also argue, as in this paper, against the use of a carbon price as the cost of an externality, while we in addition identify a macroeconomic role for a carbon price. The recommendations differ in that Rozenberg et al. propose policies aimed at individual, micro-level, behaviour, while this paper focuses on macro-level policy. Analytical attention must be paid to both levels: the macro level to capture the sometimes surprising implications of macroeconomic constraints and the micro level to better understand individual incentives.

While acknowledging this necessity and the value of Rozenberg et al.'s policy proposals, we argue that conventional economic models, as used by Rozenberg et al. among others, are inappropriate for analysing a low-carbon transition because they assume a degree of knowledge about the future that is implausible in a major economic transition. Indeed, conventional models may be inappropriate at any time, as argued by Solow (2008). As governments begin to implement low-carbon strategies, investors do not face a future with reasonably certain policies, prices, and environmental costs, but must instead place a mix of short-term and long-term bets in an environment dominated by fundamental uncertainty.

The messages suggested by the model in this paper are consistent with the requirements identified by private investors in the report "Investment-grade Climate Change Policy" (Sullivan 2011). Among other tasks it sets for governments, that report identified comprehensive policies that accelerate the deployment of technologies and infrastructure; policies supporting investment in renewables; financial incentives that "shift the risk reward balance in favour of low-carbon assets"; policies that help absorb the risk inherent in renewables and energy efficiency investments; aiming to take advantage of scale economies; and providing long-term policy certainty. That is, policies must plan for, and support, economy-wide changes, address risk, plan for positive externalities arising from increasing scale, and be both credible and politically sustainable. We argue that for governments to achieve these goals, they must examine and anticipate the macroeconomic implications of their policies, while international funders must understand and accommodate the challenges governments face in managing the transition.

The model could be extended in several ways. Few governments plan to implement a carbon price directly. Rather, they will put in place carbon markets and allow the price to be determined on those markets, and it would add to the realism of the model to explicitly represent carbon markets. Also, the government and banking sectors could be treated explicitly to explore the effect of taxes, government expenditure, and money. An expanded model could also incorporate induced technological change, in which an evolutionary perspective could focus attention on the development and expansion of new, disruptive technologies (Howarth 2012; Safarzyńska et al. 2012). The treatment of small open developing economies could be extended to cover the variety of fiscal, inflation, savings, or foreign exchange constraints they can face. These are best analysed using gap models (Bacha 1990; Sen 1991; Taylor 1994).[3] Finally, the separation of capital into "brown" and "green" varieties does not do justice to the complexity of real economies. A more nuanced picture with retrofitting, green-field investment, and neutral technologies would help to move the model from high-level generalizations to specific applications.

The simple narratives provided in this paper could also be expanded. Economic changes take place in a complex social, institutional, and political milieu and a transition would involve changes in all of these systems. This invites a qualitative treatment, which could be used to support alternative scenario narratives with a macroeconomic model playing a supporting role. Narrative and other techniques of strategic foresight could also be used to represent the wide range of possible technological trajectories. This could address an essential challenge for an intentional, policy-driven transition: that of picking the "winning" technology. To supporters of free market policies, this is a fundamental problem with state intervention. While there is truth in this critique, in the presence of lock-in, free market policies will tend to keep us on our current, frankly disastrous, path. The methods of strategic foresight provide structured approaches to thinking about a fundamentally uncertain future.

5. CONCLUSION

Current emissions and climate trajectories are deeply troubling (New et al. 2011; World Bank 2013). There are many reasons for this, including political and ideological ones. In this paper we focus on economic contributions to lock-in into a high-emission regime. Using a simplified model of an economy seeking to transition from a brown to a green capital-dominated state, we argue that governments must provide a changing mix of public investment and incentives for private investment in green capital accompanied by price-based, fiscal, and monetary instruments to maintain capacity utilization. The success of the policies depends on the attitudes of investors and the credibility and durability of the government's commitment to making the change.

The path of transition presents a series of substantial hurdles. Large-scale and fundamental changes to an economy will have macroeconomic consequences that will be reflected in changing employment and investment levels, inflation rates, balance of payments, and government and private debt. Maintaining a credible commitment in the face of such changes will be challenging. Most worryingly, the model in this paper suggests that the first stages are relatively easy compared to the subsequent period, during which public support must expand before the expected benefits have materialized and while those most heavily invested in the brown economy are seeing the value of their investments fall. However, many countries have experienced potentially destabilizing and rapid changes in their economies, and nevertheless managed to do well. With commitment, forethought, a pragmatic outlook, and common expectations on the part of governments, citizens, investors, development cooperation agencies, and international banks, a transition to a green economy is possible.

[3] Those familiar with Easterly's (1999) blistering critique of financing gap models may recall that he exempts the three-gap models as described by Bacha and Taylor (p. 428).

REFERENCES

Ackerman, F., Stanton, E. A. and Bueno, R. (2013). CRED: A new model of climate and development. *Ecological Economics,* 85. 166–76. DOI:10.1016/j.ecolecon.2011.04.006.

Bacha, E. L. (1990). A three-gap model of foreign transfers and the GDP growth rate in developing countries. *Journal of Development Economics*, 32(2). 279–96. DOI:10.1016/0304-3878(90)90039-E.

Blecker, R. A. (2002). Distribution, demand, and growth in Neo-Kaleckian macro models. In *The Economics of Demand-led Growth: Challenging the Supply-side Vision of the Long Run*. M. Setterfield (ed.). Edward Elgar, Cheltenham, UK.

Blinder, A. S. (1994). On sticky prices: academic theories meet the real world. In *Monetary Policy*. N. G. Mankiw (ed.). University of Chicago Press, Chicago, IL. 117–54.

Blok, K. (2004). Improving energy efficiency by five percent and more per year? *Journal of Industrial Ecology*, 8(4). 87–99. DOI:10.1162/1088198043630478.

Bowen, A. (2012). *'Green' Growth, 'Green' Jobs and Labor Markets*. Policy Research Working Paper. World Bank, Washington, DC. http://papers.ssrn.com.ezproxy.library.tufts.edu/abstract=2018164.

Buchan, D. (2012). *The Energiewende: Germany's Gamble*. Study Paper, SP 26. Oxford Institute for Energy Studies, Oxford, UK.

Burt, G. (2007). Why are we surprised at surprises? Integrating disruption theory and system analysis with the scenario methodology to help identify disruptions and discontinuities. *Technological Forecasting and Social Change*, 74(6). 731–49. DOI:10.1016/j.techfore.2006.08.010.

Cohen, A. J. and Harcourt, G. C. (2003). Retrospectives: Whatever happened to the Cambridge Capital Theory controversies? *Journal of Economic Perspectives*, 17(1). 199–214.

Corrado, C. and Mattey, J. (1997). Capacity utilization. *Journal of Economic Perspectives*, 11(1). 151–67.

Crotty, J. R. (1992). Neoclassical and Keynesian approaches to the theory of investment. *Journal of Post Keynesian Economics*, 14(4). 483–96.

Davidson, P. (1972). A Keynesian view of Friedman's theoretical framework for monetary analysis. *Journal of Political Economy*, 80(5). 864–82.

Dehmer, D. (2013). The German Energiewende: The first year. *The Electricity Journal*, 26(1). 71–78. DOI:10.1016/j.tej.2012.12.001.

Den Butter, F. A. and Hofkes, M. W. (2006). A neo-classical economic view on technological transitions. In *Understanding Industrial Transformation*. X. Olshoorn and A. J. Wieczorek (eds.). Springer, Dordrecht, Netherlands. 141–62. http://link.springer.com/content/pdf/10.1007/1-4020-4418-6_8.pdf.

Den Elzen, M. G. J., Vuuren, D. P. van and Vliet, J. van (2010). Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Climatic Change*, 99(1-2). 313–20. DOI:10.1007/s10584-010-9798-5.

Dosi, G. (1982). Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy,* 11(3). 147–62. DOI:10.1016/0048-7333(82)90016-6.

Easterly, W. (1999). The ghost of financing gap: Testing the growth model used in the international financial institutions. *Journal of Development Economics*, 60(2). 423–38. DOI:10.1016/S0304-3878(99)00047-4.

Edenhofer, O., Lessmann, K., Kemfert, C., Grubb, M. and Köhler, J. (2006). Induced technological change: Exploring its Implications for the economics of atmospheric stabilization: synthesis report from the innovation modeling comparison project. *The Energy Journal*, Endogenous Technological Change and the Economics of Atmospheric Stabilisation Special Issue. 57–107.

Fankhauser, S., Sehlleier, F. and Stern, N. (2008). Climate change, innovation and jobs. *Climate Policy*, 8(4). 421–29. DOI:10.3763/cpol.2008.0513.

Foxon, T. J. (2010). Stimulating investment in energy materials and technologies to combat climate change: an overview of learning curve analysis and niche market support. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 368(1923). 3469–83. DOI:10.1098/rsta.2010.0106.

Garnaut, R. (2014). China's role in global climate change mitigation. *China & World Economy*, 22(5). 2–18. DOI:10.1111/j.1749-124X.2014.12081.x.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, 31(8–9). 1257–74. DOI:10.1016/S0048-7333(02)00062-8.

Geels, F. W. and Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, 36(3). 399–417. DOI:10.1016/j.respol.2007.01.003.

Glenn, J. C. and Gordon, T. J., eds. (2009). *Futures Research Methodology Version 3.0*. The Millennium Project. http://www.millennium-project.org/millennium/FRM-V3.html.

Global Commission on the Economy and Climate (2014). *Better Growth, Better Climate: The New Climate Economy Report: Executive Summary*. World Resources Institute, Washington, DC.

Gordon, M. J. (1992). The Neoclassical and a Post Keynesian theory of investment. *Journal of Post Keynesian Economics*, 14(4). 425–43.

Goulder, L. H. and Schneider, S. H. (1999). Induced technological change and the attractiveness of CO2 abatement policies. *Resource and Energy Economics*, 21(3–4). 211–53. DOI:10.1016/S0928-7655(99)00004-4.

Gritsevskyi, A. and Nakićenovi, N. (2000). Modeling uncertainty of induced technological change. *Energy Policy*, 28(13). 907–21. DOI:10.1016/S0301-4215(00)00082-3.

Ha-Duong, M., Grubb, M. J. and Hourcade, J.-C. (1997). Influence of socioeconomic inertia and uncertainty on optimal CO2-emission abatement. *Nature*, 390(6657). 270–73. DOI:10.1038/36825.

Hall, G. and Howell, S. (1985). The experience curve from the economist's perspective. *Strategic Management Journal*, 6(3). 197–212. DOI:10.1002/smj.4250060302.

Haxeltine, A., Whitmarsh, L., Bergman, N., Rotmans, J., Schilperoord, M. and Kohlder, J. (2008). A conceptual framework for transition modelling. *International Journal of Innovation and Sustainable Development*, 3. 93–114.

Hein, E. and Krämer, H. (1997). Income shares and capital formation: patterns of recent developments. *Journal of Income Distribution*, 7(1). 5–28. DOI:10.1016/S0926-6437(97)80002-9.

Hein, E. and Vogel, L. (2008). Distribution and growth reconsidered: empirical results for six OECD countries. *Cambridge Journal of Economics*, 32(3). 479–511. DOI:10.1093/cje/bem047.

Holt, R. P. F. and Pressman, S. (2001). What is Post Keynesian Economics? In *A New Guide to post Keynesian Economics*. R. P. F. Holt and S. Pressman (eds.). Contemporary Political Economy series. Routledge, London ; New York. 1–10.

Hooker, M. A. (2002). Are oil shocks inflationary?: Asymmetric and nonlinear specifications versus changes in regime. *Journal of Money, Credit, and Banking*, 34(2). 540–61. DOI:10.1353/mcb.2002.0041.

Howarth, N. (2012). Clean energy technology and the role of non-carbon price-based policy: An evolutionary economics perspective. *European Planning Studies*, 20(5). 871–91. DOI:10.1080/09654313.2012.667930.

IEA (2013). *Electricity in a Climate-Constrained World*. Organisation for Economic Co-operation and Development, Paris. http://www.oecd-ilibrary.org/content/book/ 9789264175556-en.

IPCC (2014a). Summary for policymakers. In *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, et al. (eds.). Cambridge University Press, Cambridge, UK, and New York. http://www.mitigation2014.org.

IPCC (2014b). Summary for policymakers. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastandrea, et al. (eds.). Cambridge University Press, Cambridge, UK, and New York. 1–32. https://www.ipcc.ch/report/ar5/wg2/.

IPCC (2013). Summary for policymakers. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, et al. (eds.). Cambridge University Press, Cambridge, UK, and New York. http://www.climate2013.org/spm.

Jaffe, A. B. (2012). Technology policy and climate change. *Climate Change Economics*, 3(4). 1250025. DOI:10.1142/S201000781250025X.

Juniper, J. (2009). Environmental innovation: a Post Keynesian interpretation. In *Post Keynesian and Ecological Economics: Confronting Environmental Issues*. R. P. F. Holt, S. Pressman, and C. L. Spash (eds.). Edward Elgar, Cheltenham, UK ; Northhampton, MA. 237–55.

Kemp-Benedict, E. (2014). The inverted pyramid: A neo-Ricardian view on the economy–environment relationship. *Ecological Economics*, 107. 230–41. DOI:10.1016/j.ecolecon.2014.08.012.

Keynes, J. M. (1937). The general theory of employment. *Quarterly Journal of Economics*, 51(2). 209–23. DOI:10.2307/1882087.

Knight, F. H. (1921). *Risk, Uncertainty and Profit*. Harper & Row, New York.

Kumar, S. and Managi, S. (2009). Energy price-induced and exogenous technological change: Assessing the economic and environmental outcomes. *Resource and Energy Economics*, 31(4). 334–53. DOI:10.1016/j.reseneeco.2009.05.001.

Lavoie, M. (2001). Pricing. In *A New Guide to Post Keynesian Economics*. R. P. F. Holt and S. Pressman (eds.). Contemporary Political Economy series. Routledge, London ; New York.

Lecocq, F. and Shalizi, Z. (2014). The economics of targeted mitigation in infrastructure. *Climate Policy*, 14(2). 187–208. DOI:10.1080/14693062.2014.861657.

Lehmann, P., Creutzig, F., Ehlers, M.-H., Friedrichsen, N., Heuson, C., Hirth, L. and Pietzcker, R. (2012). Carbon lock-out: Advancing renewable energy policy in Europe. *Energies*, 5(12). 323–54. DOI:10.3390/en5020323.

Maddison, A. (1994). *Standardised Estimates of Fixed Capital Stock: A Six Country Comparison*. 199409. Groningen Growth and Development Centre, University of Groningen, Groningen, Netherlands. http://ideas.repec.org/p/dgr/rugggd/199409.html.

Marglin, S. A. and Bhaduri, A. (1988). *Profit Squeeze and Keynesian Theory*. WIDER Working Paper, WP 39. World Institute for Development Economics Research, Helsinki, Finland.

Mattauch, L., Creutzig, F. and Edenhofer, O. (2012). *Avoiding Carbon Lock-In: Policy Options for Advancing Structural Change*. 1. Department of Climate Change Economics, TU Berlin. http://ideas.repec.org/p/ecc/wpaper/3.html.

Mattey, J. and Strongin, S. (1997). Factor utilization and margins for adjusting output: evidence from manufacturing plants. *Federal Reserve Board of San Francisco Economic Review*, 1997(2). http://www.frbsf.org/economic-research/publications/97-2/3-17-3.pdf.

Miller, R. A. (2001). Firms' cost functions: A reconstruction. *Review of Industrial Organization*, 18(2). 183–200. DOI:10.1023/A:1007853922900.

Miller, R. A. (2000). Ten cheaper spades: Production theory and cost curves in the short run. *Journal of Economic Education*, 31(2). 119–30. DOI:10.1080/00220480009596769.

Minsky, H. P. (2008). *Stabilizing an Unstable Economy*. McGraw-Hill, New York, NY.

New, M., Liverman, D., Schroder, H. and Anderson, K. (2011). Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369(1934). 6–19. DOI:10.1098/rsta.2010.0303.

Nordhaus, W. D. (2010). Economic aspects of global warming in a post-Copenhagen environment. *Proceedings of the National Academy of Sciences*, 107(26). 11721–26. DOI:10.1073/pnas.1005985107.

Palley, T. (2007). Macroeconomics and monetary policy: Competing theoretical frameworks. *Journal of Post Keynesian Economics*, 30(1). 61–78. DOI:10.2753/PKE0160-3477300103.

Perraton, J. (2003). Balance of payments constrained growth and developing countries: An examination of Thirlwall's hypothesis. *International Review of Applied Economics*, 17(1). 1–22. DOI:10.1080/713673169.

Piketty, T. (2014). *Capital in the Twenty-First Century*. Belknap Press, Cambridge, MA.

Ploeg, F. V. D. and Withagen, C. (1991). Pollution control and the Ramsey problem. *Environmental and Resource Economics*, 1(2). 215–36. DOI:10.1007/BF00310019.

Poitras, G. (2002). The philosophy of investment: A Post Keynesian perspective. *Journal of Post Keynesian Economics*, 25(1). 105–21.

Reichelt, H. (2010). Green bonds: a model to mobilise private capital to fund climate change mitigation and adaptation projects. In *The EuroMoney Environmental Finance Handbook*. Euromoney, London. 1–7.

Reinhart, C. M. and Rogoff, K. S. (2009). *This Time Is Different: Eight Centuries of Financial Folly*. Princeton University Press, Princeton, NJ.

Rozenberg, J., Hallegatte, S., Perrissin-Fabert, B. and Hourcade, J.-C. (2013). Funding low-carbon investments in the absence of a carbon tax. *Climate Policy*, 13(1). 134–41. DOI:10.1080/14693062.2012.691222.

Rozenberg, J., Vogt-Schilb, A. and Hallegatte, S. (2013a). Efficiency and acceptability of climate policies: Race against the lock-ins. *Review of Environment, Energy and Economics - Re3*. http://ideas.repec.org/a/fem/femre3/2013.11-03.html.

Rozenberg, J., Vogt-Schilb, A. and Hallegatte, S. (2013b). *How Capital-Based Instruments Facilitate the Transition Toward a Low-Carbon Economy: A Tradeoff between Optimality and Acceptability*. 6609. World Bank, Washington, DC. http://ideas.repec.org/p/ wbk/wbrwps/ 6609.html.

Safarzyńska, K., Frenken, K. and van den Bergh, J. C. J. M. (2012). Evolutionary theorizing and modeling of sustainability transitions. *Research Policy*, 41(6). 1011–24. DOI:10.1016/ j.respol.2011.10.014.

Sakellaris, P. (2004). Patterns of plant adjustment. *Journal of Monetary Economics*, 51(2). 425–50. DOI:10.1016/j.jmoneco.2003.03.002.

Schmidt, R. C. and Marschinski, R. (2009). A model of technological breakthrough in the renewable energy sector. *Ecological Economics*, 69(2). 435–44. DOI:10.1016/j.ecolecon. 2009.08.023.

Schwartz, P. (1996). *The Art of the Long View: Planning for the Future in an Uncertain World*. Currency Doubleday, New York.

Sen, P. (1991). Growth theories and development strategies: Lessons from Indian experience. *Economic and Political Weekly*, 26(30). PE62–72.

Sijm, J., Neuhoff, K. and Chen, Y. (2006). CO2 cost pass-through and windfall profits in the power sector. *Climate Policy*, 6(1). 49–72. DOI:10.1080/14693062.2006.9685588.

Solow, R. (2008). The state of macroeconomics. *The Journal of Economic Perspectives*, 22(1). 243–46.

Sraffa, P. (1960). *Production of Commodities by Means of Commodities: Prelude to a Critique of Economic Theory*. Indian Edition 1963. Vora & Co., Bombay, India.

Stern, N. (2006). *The Stern Review on the Economics of Climate Change*. Cambridge University Press, Cambridge, UK, and New York.

Stockhammer, E. (2011). Wage-led growth: An introduction. *International Journal of Labour Research*, 3(2). 167–87.

Stockhammer, E. and Onaran, O. (2013). Wage-led growth: theory, evidence, policy. *Review of Keynesian Economics*, 1(1). 61–78.

Sullivan, R. (2011). *Investment-Grade Climate Change Policy: Financing the Transition to the Low-Carbon Economy*. IIGCC, INCR, IGCC, and UNEP FI.

Taylor, L. (2004). *Reconstructing Macroeconomics: Structuralist Proposals and Critiques of the Mainstream*. Harvard University Press, Cambridge, MA. http://site.ebrary.com/ id/10328835.

Taylor, L. (1994). Gap models. *Journal of Development Economics*, 45(1). 17–34. DOI:10.1016/0304-3878(94)90057-4.

Thirlwall, A. P. (1979). The balance of payments constraint as an explanation of international growth rate differences. *BNL Quarterly Review*, 32(128). 45–53.

Thirlwall, A. P. and Hussain, M. N. (1982). The balance of payments constraint, capital flows and growth rate differences between developing countries. *Oxford Economic Papers*, 34(3). 498–510.

UNEP (2011). *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication.* UN Environment Programme, Nairobi.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, 28(12). 817–30. DOI:10.1016/S0301-4215(00)00070-7.

Wack, P. (1985). Scenarios: Shooting the rapids. *Harvard Business Review*, Nov-Dec. 139–50.

Wei, M., Patadia, S. and Kammen, D. M. (2010). Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US? *Energy Policy*, 38(2). 919–31. DOI:10.1016/j.enpol.2009.10.044.

Weitzman, M. L. (2011). Fat-tailed uncertainty in the economics of catastrophic climate change. *Review of Environmental Economics and Policy*, 5(2). 275–92. DOI:10.1093/reep/rer006.

Weitzman, M. L. (2009). On modeling and interpreting the economics of catastrophic climate change. *Review of Economics and Statistics*, 91(1). 1–19. DOI:10.1162/rest.91.1.1.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., et al. (2011). Tipping Toward Sustainability: Emerging Pathways of Transformation. *AMBIO*, 40(7). 762–80. DOI:10.1007/s13280-011-0186-9.

World Bank (2013). *Turn down the Heat : Climate Extremes, Regional Impacts, and the Case for Resilience*. World Bank, Washington, DC. http://documents.worldbank.org/curated/en/2013/06/17861350/turn-down-heat-climate-extremes-regional-impacts-case-resilience-executive-summary.

Yelle, L. E. (1979). The learning curve: Historical review and comprehensive survey. *Decision Sciences*, 10(2). 302–28. DOI:10.1111/j.1540-5915.1979.tb00026.x.

Zachmann, G. and von Hirschhausen, C. (2008). First evidence of asymmetric cost pass-through of EU emissions allowances: Examining wholesale electricity prices in Germany. *Economics Letters*, 99(3). 465–69. DOI:10.1016/j.econlet.2007.09.024.

APPENDIX 1: CLOSED ECONOMY MACROECONOMIC MODEL

In this appendix we focus on macroeconomic consequences. Portfolio allocation is addressed in Appendix 2, policy instruments in Appendix 3, and open economy extensions in Appendix 4. To keep the essential points clear, we do not explicitly treat taxes and the government sector, so that consumption and investment are the sums of private and public consumption and investment.

Output and capital productivity

We start with a standard post-Keynesian model, in which economic output X is proportional to capital K. We split the factor of proportionality into a utilization factor, which is close to one but can vary over short to medium times, and an average capital productivity κ, which can vary over longer times:

$$X = u\kappa K. \tag{1}$$

We now extend the standard post-Keynesian model to incorporate two types of capital – brown and green – by setting total capital equal to the sum of the two.

$$K = K_b + K_g. \tag{2}$$

The two types of capitals have different productivities, κ_b and κ_g, so we can rewrite equation (1) as

$$X = u\left(\kappa_b K_b + \kappa_g K_g\right). \tag{3}$$

The share of green capital in the total economy is the essential variable in this paper. As it rises from zero (or close to zero) to one, the economy passes from a brown capital-dominated state to a green capital-dominated one. We denote this variable by z, so that

$$z \equiv \frac{K_g}{K} = 1 - \frac{K_b}{K}. \tag{4}$$

The assumption that green and brown capital can be added together, as in equation (1), implies that they are made of the same "stuff". The distinction between them lies in their environmental impact and their compatibility with other types of capital. This assumption also implies that the variable z is dimensionless.

In terms of z, we recover equation (1) by defining the average capital intensity,

$$\kappa(z) \equiv (1-z)\kappa_b(z) + z\kappa_g(z). \tag{5}$$

As indicated in this equation, we allow the individual brown and green capital productivities to vary with z. This is an important feature of the model, in that it allows us to capture the network externality that is the central topic of this paper: the mix of green and brown capital in the economy affects the performance of both brown capital and green capital enterprises.

As noted above, we assume that each type of capital has a distinct productivity. Also, we allow brown capital to be retired earlier than normal, which we represent by a higher depreciation rate. Using an over-dot to indicate a time derivative, the change in capitals is given by

$$\dot{K}_b = -\delta_b K_b + I_b, \tag{6}$$

$$\dot{K}_g = -\delta_g K_g + I_g. \tag{7}$$

Adding these together, dividing through by K, and following convention by using a "hat" to represent a proportional rate of change over time,

$$\hat{K} = \frac{\dot{K}}{K} = -(1-z)\delta_b - z\delta_g + \frac{I}{K}. \tag{8}$$

Defining the average (and z-dependent) depreciation rate as

$$\delta(z) \equiv (1-z)\delta_b + z\delta_g, \tag{9}$$

equation (8) becomes the familiar formula

$$\hat{K} = -\delta + \frac{I}{K}. \tag{10}$$

Note that in this expression we suppress the dependence of δ on z to reduce clutter. We adopt a similar convention throughout the paper.

We assume that the individual labour intensities λ_b and λ_g and environmental impact intensities ε_b and ε_g are not affected by the mix of green capital, z, although as noted above they are liable to change over time through lumpy investments. In parallel with capital productivity, we write labour, L, as

$$L = u\left(\lambda_b K_b + \lambda_g K_g\right) = u\lambda K, \tag{11}$$

and emissions, E, as

$$E = u\left(\varepsilon_b K_b + \varepsilon_g K_g\right) = u\varepsilon K, \tag{12}$$

where the average environmental impact and labour intensities, ε and λ, depend on z,

$$\varepsilon(z) = (1-z)\varepsilon_b + z\varepsilon_g, \tag{13}$$

$$\lambda(z) = (1-z)\lambda_b + z\lambda_g. \tag{14}$$

Path dependence

We allow for path dependence to get a further constraint on brown and green capital productivities. Figure 2 shows a situation in which both green and brown capital increase in a brown capital-dominated economy. In this economy, z is not zero, but it is small. The change in output is given approximately by the first-order difference between output at point A and output at point B,

$$\Delta X = \kappa_b \Delta K_b + \kappa_g \Delta K_g + \left(K_b \kappa_b' + K_g \kappa_g'\right)\Delta z. \tag{15}$$

However, if there is path dependence then there will be a second-order effect due to the choice of path, and those incremental changes can accumulate over time.

In Figure 2 path ABC depicts a change in capital in which brown capital is increased first, and then green capital. Path AB'C depicts a change in which green capital is increased first. The first-order change in output is the same for either path. Most of the second-order terms are the same as well, leaving

$$\Delta X_{ABC} - \Delta X_{AB'C} = \left(\kappa_b' \frac{\partial z}{\partial K_g} - \kappa_g' \frac{\partial z}{\partial K_b}\right)\Delta K_b \Delta K_g. \tag{16}$$

This will be positive if GDP increases more when brown capital is increased (by a small amount) before green capital is increased (also by a small amount). It will be negative if the opposite is true and zero if the path does not matter. As discussed in the main text, we assume that in a brown capital-

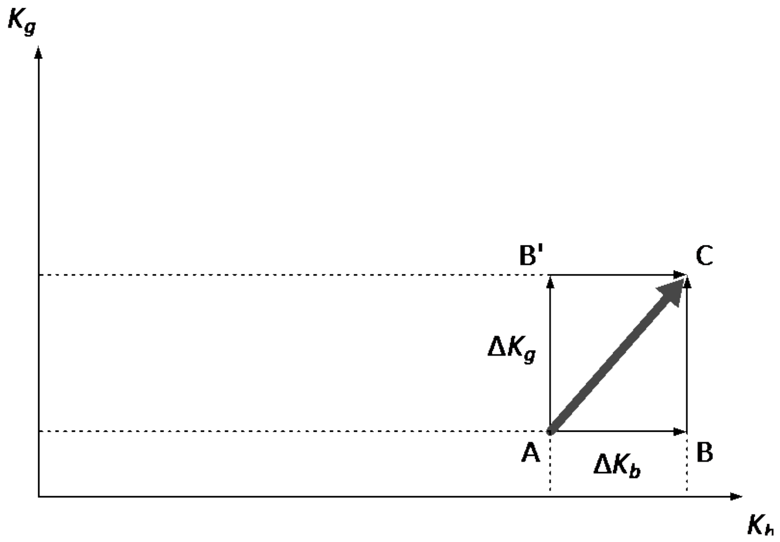

Figure 2: Increasing both green and brown capital: two paths

dominated economy there are private benefits to investing in brown capital first. This makes the expression in equation (16) either zero or positive in a brown capital-dominated economy, so that

$$\kappa_b' \frac{\partial z}{\partial K_g} \geq \kappa_g' \frac{\partial z}{\partial K_b}, \quad z \text{ close to zero.} \tag{17}$$

From the definition of *z*, this implies that

$$-\frac{\kappa_b'}{\kappa_g'} \leq \frac{z}{1-z}, \quad z \text{ close to 0.} \tag{18}$$

By a similar argument, we assume that it is not favourable to move away from a green capital-dominated state, so that

$$-\frac{\kappa_g'}{\kappa_b'} \leq \frac{1-z}{z}, \quad z \text{ close to 1.} \tag{19}$$

Dynamics in z

From here onward we suppress dependence on *z*, and use a prime to denote a derivative with respect to *z*. We show that we can mainly work in the *z* domain and convert from that to a change in time by computing the time rate of change in *z*. It is given by

$$\dot{z} = \frac{\dot{K}_g}{K} - \frac{K_g}{K}\frac{\dot{K}_g + \dot{K}_b}{K} = \frac{(1-z)\dot{K}_g - z\dot{K}_b}{K}. \tag{20}$$

From equations (6) and (7), the final expression is

$$\frac{(1-z)\dot{K}_g - z\dot{K}_b}{K} = z(1-z)\Delta\delta + \frac{(1-z)I_g - zI_b}{I}\frac{I}{K}, \tag{21}$$

where we have defined $\Delta\delta$ as the difference between the brown and green capital depreciation rates. It is either zero, if there is no early retirement of brown capital, or positive:

$$\Delta\delta \equiv \delta_b - \delta_g \geq 0. \tag{22}$$

Writing the green capital share of investment as $\varphi = I_g/I$, we can write the time rate of change in z as

$$\dot{z} = z(1-z)\Delta\delta + (\varphi - z)\frac{I}{K}. \tag{23}$$

The only time when it is not possible to work purely in the z domain is when variables change over time due to factors other than a change in the type of capital. This is true for labour and environmental impact intensities, which can change due to investment in new equipment and learning-by-doing with existing equipment.

Note that according to equation (23), the penetration of green capital expands only if the share of green capital in new investment exceeds the share of green capital in the economy ($\varphi > z$), brown capital is retired early ($\Delta\delta > 0$), or both. The early retirement effect is strongest at intermediate levels of green capital penetration.

Network externalities and trends

In symbols, the assumptions in the main text regarding productivity of green and brown capital can be written

$$\kappa_b' \leq 0, \quad \kappa_g' \geq 0, \quad \kappa_b(0) > \kappa_g(0), \quad \kappa_b(1) < \kappa_g(1), \quad \kappa_b(0) \geq \kappa_g(1). \tag{24}$$

With these assumptions it is possible to show that

$$\kappa'(0) \leq 0, \quad \kappa'(1) \geq 0. \tag{25}$$

The assumptions regarding environmental impacts, labour intensities, and depreciation rates become

$$\varepsilon_b > \varepsilon_g, \quad \lambda_b \leq \lambda_g, \quad \delta_b \geq \delta_g, \tag{26}$$

which imply

$$\varepsilon' < 0, \quad \lambda' \geq 0, \quad \delta' \leq 0. \tag{27}$$

That is, environmental impact per unit of capital falls with increasing penetration of green capital. The depreciation rate might also fall, if brown capital is retired early, or stay the same, while the labour intensity either increases or stays the same. Note that this is purely an effect of switching from brown to green capital. Individual labour intensities and environmental impacts for a particular type of capital, whether brown or green, typically decline over time. The total change in time is given by

$$\dot{\lambda} = \lambda'\dot{z} + \frac{\partial\lambda}{\partial t}, \quad \dot{\varepsilon} = \varepsilon'\dot{z} + \frac{\partial\varepsilon}{\partial t}. \tag{28}$$

Both the labour intensity and emissions intensity typically decline at a rate of about 1-3% per year, due in part to marginal improvements in capital equipment and processes and in part to learning-by-doing with existing equipment.

The functional income distribution

We assume a uniform price for all goods, P, which is set as a mark-up on costs per unit of output. The price is the same whether goods are produced from brown or green capital, so if their costs per unit of output are different, then the mark-ups of firms using different types of capital must also be different. Later we introduce an environmental price, but for now the only cost of production is wages, so costs per unit of capital employed are equal to

$$\boldsymbol{c_b = w\lambda_b}, \quad \boldsymbol{c_g = w\lambda_g}. \tag{29}$$

Costs per unit of output can be computed by dividing by the capital productivity. With mark-up ratios μ_b and μ_g, the price is equal to

$$P = \mu_b \frac{c_b}{\kappa_b} = \mu_g \frac{c_g}{\kappa_g}. \tag{30}$$

Profits are given by the difference between the value of goods sold and the costs required to produce them,

$$\pi PX = \left(\mu_b - 1\right) c_b K_b + \left(\mu_g - 1\right) c_g K_g. \tag{31}$$

After some manipulation, the profit share can be shown to be

$$\pi = \left(1 - z\right) \frac{\mu_b - 1}{\mu_b} + z \frac{\mu_g - 1}{\mu_g} = \left(1 - z\right) \pi_b + z \pi_g, \tag{32}$$

where π_b and π_g are the standard expressions for the profit rate in terms of mark-ups. A useful alternative expression for the average profit share, equivalent to the one above, can be found from the difference between the value of total output from total costs in terms of aggregate capital and output:

$$\pi PX = PX - cuK. \tag{33}$$

In this equation, parallel to the definitions above, the average cost c is given by

$$c = (1 - z) c_b + z c_g. \tag{34}$$

Dividing equation (33) by PX gives an expression for the profit share,

$$\pi = 1 - \frac{1}{P} \frac{c}{\kappa}. \tag{35}$$

We assume that the price P is set as a mark-up on costs in the most competitive (that is, lowest-cost) sector, so that

$$P = \frac{\mu}{\kappa} \begin{cases} c_b, & \text{brown capital-dominated} \\ c_g, & \text{green capital-dominated} \end{cases} \tag{36}$$

In a brown capital-dominated regime we then have

$$\pi = 1 - \frac{1}{\mu} \left(1 - z + z \frac{c_g}{c_b} \right), \quad \text{brown capital-dominated.} \tag{37}$$

Investors are interested only indirectly in the profit share of national income, π. More immediately, they care about how much they receive relative to what they have invested. The return on capital, or profit rate, r, is calculated as

$$r = \frac{\pi X}{K} = \pi u \kappa = u \left(\kappa - \frac{c}{P} \right). \tag{38}$$

Because wages are the only cost introduced so far, the profit rate is given by

$$r = u \left(\kappa - \frac{w}{P} \lambda \right). \tag{39}$$

From the inequalities (25) and (27), we see that λ either rises or stays the same as z begins to increase from zero, while κ falls. This drives r downward, unless there is inflation, driving P up, or utilization increases, so if there is inflation then the real wage will fall. This shows that if utilization is fixed, then equation (39) describes a wage-profit frontier, but it need not hold if utilization can change.

Macroeconomic balance for a closed economy

So far, we have introduced an equation relating capital to output and investment to capital. In this subsection we introduce a standard post-Keynesian (more narrowly, Kaleckian) closed economy model to determine utilization (see Blecker 2002; Taylor 2004, chap. 4). Total investment is given as the sum of investment in green and brown capital,

$$I = I_g + I_b. \tag{40}$$

We then impose macroeconomic balance between saving and investment,

$$g^i = g^s. \tag{41}$$

Each side of this equation is determined by a distinct behavioural relationship, and macroeconomic dynamics and policy prescriptions follow from the way in which this macroeconomic balance is resolved. Different resolutions result in different "closures" of the model. Following standard practice in post-Keynesian theory, we close the model by adjusting utilization.

Continuing to use a hat to represent growth rates, private investment is determined by the typically Kaleckian behavioural equation

$$g^i = \hat{K} + \delta = \frac{I}{K} = \gamma + \alpha r + \beta u = \gamma + \left(\alpha \pi \kappa + \beta\right) u. \tag{42}$$

In this equation, α and β measure the response of investors toward rising or falling profit and utilization rates, while δ is the depreciation rate. For the final equality, equation (38) is used to express the return on capital in terms of other model variables. Note that we can now write the expression for the time rate of change of z, from equation (23), as

$$\dot{z} = z(1-z)\Delta\delta + \left(\varphi - z\right) g^i. \tag{43}$$

As mentioned earlier, with this equation it is possible to express dynamics in terms of z rather than time t and then convert later.

Savings are given by a separate behavioural relationship based on savings propensities from wage and profit income. The relationship is

$$g^s = \left[(1-\pi)s_w + \pi s_\pi\right]\frac{X}{K} = \left[(1-\pi)s_w + \pi s_\pi\right]u\kappa. \tag{44}$$

Macroeconomic balance between investment and savings is achieved when equation (41) holds. Setting the investment growth rate, equation (42), equal to the savings growth rate, and solving for utilization, gives

$$u = \frac{\gamma}{\left[s_w + \left(s_\pi - s_w - \alpha\right)\pi\right]\kappa - \beta}. \tag{45}$$

This is a conventional Kaleckian result. In the standard Kaleckian model, utilization responds to a change in wage and profit shares, creating regimes of wage-led and profit-led growth (Blecker 2002, p. 138 ff.). In the present model, the driving variable is the share of green capital in total capital, z. We return to this Kaleckian model in Appendix 3.

Economic growth at full utilization

The policy goal pursued in the paper is to maintain full (or a normal level of) utilization. Assuming this is accomplished, economic output is given by

$$X = \kappa K. \tag{46}$$

The growth rate is then given by

$$\hat{X} = \frac{\kappa'}{\kappa}\dot{z} + \hat{K}. \tag{47}$$

Capital growth is given by equation (8) and the time rate of change of z by equation (43). The result is

$$\hat{X} = -\left(1 - z\frac{\kappa'}{\kappa}\right)(1-z)\Delta\delta - \delta_g + \left[1 + (\varphi - z)\frac{\kappa'}{\kappa}\right]\frac{I}{K}. \tag{48}$$

Given a target GDP growth rate of g^*, the needed level of investment as a share of GDP is then given by

$$\frac{I}{X} = \frac{I}{\kappa K} = \frac{g^* + \delta_g + \left(1 - z\kappa'/\kappa\right)(1-z)\Delta\delta}{\kappa + (\varphi - z)\kappa'}. \tag{49}$$

If $\kappa' = 0$ and $\Delta\delta = 0$, this becomes the familiar expression

$$\frac{I}{X} = \frac{g^* + \delta_g}{\kappa}. \tag{50}$$

That is, the investment rate is equal to the rate at which capital must be replaced plus the target growth rate in excess of the replacement rate, converted to GDP terms by dividing through by the capital productivity. The capital productivity declines as z increases from zero, eventually reaching a minimum and then rising again, although perhaps not as high as it was in a brown capital-dominated economy. This means that for a fixed GDP growth rate and depreciation rate, investment – and therefore savings – must initially increase as a share of GDP at the expense of consumption.

The additional term in the numerator of equation (49) is likely to always be positive if $\Delta\delta > 0$. At small z it must be positive because $\kappa' \leq 0$ close to $z = 0$. For z close to one, the term could potentially become negative, but only if the response of capital productivity to a change in z is greater than one – that is, if a 1-percentage point increase in z leads to a change in κ of greater than 1%. Assuming that the response is not so strong, the term will be positive at any value of z. This term has a straightforward interpretation: it is the additional capital replacement required to offset early retirement, and we assume that the increase in capital productivity from increasing penetration of green capital is not enough to make up for the loss of production from the retired brown capital.

The additional term in the denominator of equation (49) changes sign as z increases from zero to one. If green capital penetration is to increase, then the share of green capital in investment, φ, must exceed the share of green capital in the capital stock, z, so the sign of the term is given by the sign of κ', which is negative at small z and positive for z close to one. This further increases the needed investment rate at small z while decreasing it at larger z.

APPENDIX 2: PORTFOLIO ALLOCATION

We assume that the value of equity is proportional to profit per share. If k is capital per share and a is the constant of proportionality, then the value of equity, v, is

$$v = ak\left(P\kappa - c\right). \tag{51}$$

In this expression, κ is capital productivity of the enterprise and c is cost per unit of installed capital. The own-rate of return, ρ, is the expected rate of growth of the value from one time period to the next,

$$\rho = \frac{v_{+1}}{v} - 1 = \frac{k_{+1}\left(P_{+1}\kappa_{+1} - c_{+1}\right)}{k\left(P\kappa - c\right).} - 1. \tag{52}$$

We assume that investors expect prices to increase at the historical rate of inflation, and costs to increase at the same rate. In this case,

$$\rho = \left(1 + \hat{P}^e\right)\frac{k_{+1}\left(P\kappa_{+1} - c\right)}{k\left(P\kappa - c\right).} - 1, \tag{53}$$

where $\hat{P}^e$ is the expected rate of inflation. To first order, we then have

$$\rho \cong \hat{P}^e + \hat{k}^e + \frac{P\kappa}{P\kappa - c}\frac{\kappa'}{\kappa}\Delta z^e. \tag{54}$$

Note that

$$\frac{P\kappa}{P\kappa - c} = \frac{\mu}{1-\mu} = \frac{1}{\pi}, \tag{55}$$

so the own-rate of return can be written more succinctly as

$$\rho \cong \hat{P}^e + \hat{k}^e + \frac{1}{\pi\kappa}\kappa'\Delta z^e = \hat{P}^e + \hat{k}^e + \frac{1}{r}\kappa'\Delta z^e. \tag{56}$$

In the last expression, r is the return on capital at full utilization. For green and brown capital separately, we then find the real own-rates of return

$$\rho_b - \hat{P}^e = \hat{k}_b^e + \frac{1}{r_b}\kappa_b'\Delta z^e, \tag{57}$$

$$\rho_g - \hat{P}^e = \hat{k}_g^e + \frac{1}{r_g}\kappa_g'\Delta z^e. \tag{58}$$

Whether brown or green capital has a higher own-rate of return with a rise in z therefore depends on expectations regarding the growth potential of brown and green investments. It also depends on expectations for the change in z.

The neutral portfolio

We note that a particular mix of shares in brown and green capital investments can be used to hedge against uncertainty in the change in z. Specifically, if the proportion of green capital shares in the investment portfolio is φ, then choosing a portfolio such that

$$\left(1-\varphi\right)\frac{1}{r_b}\kappa_b' + \varphi\frac{1}{r_g}\kappa_g' = 0 \tag{59}$$

will eliminate the dependence on Δz^e. This is accomplished when

$$\varphi = -\frac{\Phi \kappa_b' / \kappa_g'}{1 - \Phi \kappa_b' / \kappa_g'}, \tag{60}$$

where

$$\Phi \equiv \frac{r_g}{r_b}. \tag{61}$$

From inequality (18), if z is close to zero, then we can write

$$-\frac{\kappa_b'}{\kappa_g'} = \sigma \frac{z}{1-z}, \quad 0 < \sigma \leq 1. \tag{62}$$

The parameter σ measures the effect on output of putting brown capital investment before green capital investment or vice versa. For the neutral portfolio, we then find

$$\varphi_{\mathrm{neut}} = \frac{\sigma \Phi z}{1 - (1 - \sigma \Phi) z}. \tag{63}$$

This is the share of green capital in the neutral portfolio. It is the portfolio that a risk-averse investor might pick who is uncertain of the future pathway for green vs brown capital in the economy.

The product $\sigma\Phi$ is a measure of the relative attractiveness of investment in green or brown capital compared to the shares prevailing in the economy. This can be seen by taking the ratio of the investment shares,

$$\frac{I_g}{I_b} = \frac{\varphi}{1-\varphi} = \frac{z}{1-z} \sigma \Phi. \tag{64}$$

There are three important considerations raised by this equation. First, if $z = 0$ initially, and investors build a neutral portfolio, then there will be no investment in green capital. Second, initially it can be expected that the asset price of green capital is less than that of brown capital. In that case, the ratio of investment in green capital to that of brown capital is less than the ratio of the shares of green and brown capital in the economy, so that near the point $z = 0$, the tendency will be to return to smaller values of z – that is, the brown capital-dominated world is locally stable. Similarly, a green capital-dominated economy near $z = 1$ is also stable. Finally, if investors expect the sequence of investment to matter, and it is better to invest in brown capital first, then green capital investment is further depressed through the factor σ.

APPENDIX 3: POLICY INSTRUMENTS

In this section we ask about the consequences of a particular level of investment in green capital for profits and utilization, and therefore for employment and inflation.

Response of utilization to a change in *z*

The total change of utilization with a change in z is given by the direct change plus an indirect change from an induced shift in the profit rate,

$$u' = \frac{\partial u}{\partial z} + \frac{\partial u}{\partial \pi}\pi'. \tag{65}$$

The change in u therefore depends on the sign and magnitude of each of these terms. If it is positive, then increasing penetration of green capital has an expansionary effect on the economy, which we refer to as "stimulating" in the body of the paper. (Conversely, we refer to a contractionary effect as "depressing".) From equation (45) we have

$$\frac{\partial u}{\partial z} = -\frac{u^2}{\gamma}\left[s_w + \left(s_\pi - s_w - \alpha\right)\pi\right]\kappa'. \tag{66}$$

We also impose the Keynesian stability condition, that an increase in utilization drives savings more strongly than investment. This condition enforces a rule that under normal circumstances temporary increases in utilization do not grow exponentially into investment booms. It is given by

$$\frac{\partial g^i}{\partial u} < \frac{\partial g^s}{\partial u}. \tag{67}$$

From this condition, the expression in brackets in equation (68) is positive, so its sign is determined entirely by the sign of κ'. It is positive for values of z close to zero, and negative for values of z close to one. Between those values it must change sign at least once, but might change sign multiple times.

The change in utilization with a change in the profit share is given by the standard Kaleckian result,

$$\frac{\partial u}{\partial \pi} = -\frac{u^2}{\gamma}\left(s_\pi - s_w - \alpha\right)\kappa. \tag{68}$$

This expression is not affected by z. It can be negative, in a wage-led (or "stagnationist") economy or positive in a profit-led (or "exhilarationist") economy.

While the dependence of u on π in equation (68) does not depend on z, π' does. From equation (37), the profit share declines with increasing penetration of green capital in a brown capital-dominated economy,

$$\pi' = -\frac{1}{\mu}\left(\frac{c_g}{c_b} - 1\right) < 0, \quad \text{brown capital-dominated.} \tag{69}$$

In contrast, it rises in a green capital-dominated economy.

The total change in u with an increasing penetration of green capital is given by equation (68), which we can now write

$$u' = -\frac{u^2}{\gamma}\left[s_w\kappa' + \left(s_\pi - s_w - \alpha\right)(\pi\kappa)'\right]. \tag{70}$$

The sign of this expression is only definite in the case of a wage-led economy; otherwise it becomes ambiguous.

The different possibilities are shown in Table 1 on page 8. It can be seen from the table that in a wage-led regime an increasing penetration of green capital will always increase utilization in a brown capital-dominated economy, at least initially, and will always decrease utilization in a green capital-dominated economy. In a profit-led economy the outcome depends on the relative magnitudes of the two contributions to the change in utilization.

The subsequent trajectory can diverge from these patterns. If the economy is in a slump, then a rising utilization can help pull it out, but if it is not in a slump then it can drive inflation. Also, if the labour market is tight, then switching to more labour-intensive capital can also drive inflation. Rising inflation reduces the real wage and therefore, from equation (39), boosts profits. The effect might or might not be enough to change the sign of $\boldsymbol{\pi}'$, and if that sign does change it might or might not be enough to change the sign of $\boldsymbol{u}'$. Higher than normal inflation might change the sign of π' in a brown capital-dominated economy if the introduction of green capital is sufficiently slow and inflation is rapid, otherwise it will continue to be negative.

Interest rates

The effect of the interest rate can be captured in a straightforward way by adding a term to g^i (Taylor 2004),

$$g^i = \gamma + \left(\alpha\pi\kappa + \beta\right)u - \theta i. \tag{71}$$

If the coefficient θ is positive then an increase in the interest rate i will tend to depress investment. This can be seen empirically: lagged changes in the interest rate are negatively correlated with subsequent changes in the investment rate, with a coefficient of about 0.1.[4] Without a lag the correlation is positive, because of the central bank's reaction to rising investment rates.

Working through the implications for utilization, a rise in the interest rate will tend to depress utilization, other things remaining equal, as expected.

Carbon price

We now assume that firms pay a price p_E for the environmental impact of their production. The price might be imposed directly as a tax or indirectly through a cap and trade scheme. Regardless of how it is implemented, it adds to variable production costs, so that

$$c_b = w\lambda_b + p_E\varepsilon_b, \tag{72}$$

$$c_g = w\lambda_g + p_E\varepsilon_g. \tag{73}$$

The profit share, equation (35), then becomes

$$\pi = 1 - \frac{1}{P}\frac{w\lambda + p_E\varepsilon}{\kappa}. \tag{74}$$

As the penetration of green capital, z, increases in a brown capital-dominated economy, κ decreases, λ either increases or stays the same, and ε decreases.

The environmental price has inflationary implications. To see this, suppose that the environmental impact of green capital is negligible, and compute the value of p_E that makes the price based on green capital operating costs equal to that based on brown capital operating costs at the same mark-up. From equation (30), when mark-ups are equal,

[4] This estimate is from the author's calculations using US data.

$$\frac{c_b}{\kappa_b} = \frac{c_g}{\kappa_g}. \tag{75}$$

If the environmental impact of green capital can be ignored, then from equations (72) and (73), this implies

$$\frac{p_E \varepsilon_b}{w\lambda_b} = \frac{\kappa_b}{\kappa_g}\frac{\lambda_g}{\lambda_b} - 1. \tag{76}$$

As argued in the body of the paper, assuming the marginal productivity of green capital to be one-half that of brown capital, and maintaining the assumption that the labour intensity of green capital is at least as large as that of brown capital, then this equation shows that the environmental tax must be enough to at least double the costs of production in the brown capital sector. If such an increase were implemented quickly then it would lead to rapid inflation.

As in inequality (69), the profit share declines with increasing penetration of green capital because by assumption costs of green capital are higher than those of brown capital, and we cannot set the environmental price high enough to make brown capital more expensive. We also find

$$\frac{\partial \pi}{\partial p_E} = -\frac{z}{\mu}\left(\frac{\varepsilon_g}{c_g} - \frac{\varepsilon_b}{c_b}\right) > 0, \quad \text{brown capital-dominated, } z > 0. \tag{77}$$

This is positive because $\varepsilon_b > \varepsilon_g$ and $c_b < c_g$. It is equal to zero if (but only if) z is zero. The strength of the effect depends on the amount of green capital in the economy, and it strengthens with increasing penetration of green capital.

In a green capital-dominated economy, the signs of both π' and $\partial\pi/\partial p_E$ are opposite to that in a brown capital-dominated economy. This means that in either a brown or green capital-dominated economy a rise in the carbon price has an effect opposite to that of an increase in the penetration of green capital. The effect is strongest in a mixed economy with substantial amounts of green and brown capital. This is shown in Table 2 in the main text.

APPENDIX 4: OPEN ECONOMY EXTENSIONS

In this appendix we extend the Kaleckian model to include trade. The approach follows that of Blecker (2002). Prices continue to be set as a mark-up on costs of the least-cost option (either brown or green capital), but the mark-up now depends on relative prices:

$$P = \mu \frac{c_\bullet}{\kappa_\bullet}, \text{ where } \mu = \mu_0 \left(\frac{eP^*}{P} \right)^\varepsilon. \tag{78}$$

In this equation, μ_0 is the mark-up at price parity, which can be thought of as a "target" mark-up, e is the exchange rate, P^* the foreign price, and ε is a non-negative elasticity. The least-cost capital, whether brown or green, is indicated by a subscript dot. It is convenient to write the elasticity in terms of a parameter ξ, which sits between zero and one,

$$\varepsilon = \frac{1}{\xi} - 1. \tag{79}$$

It is also convenient to define a "competitiveness" parameter q as the ratio of foreign to domestic prices in domestic currency and a convenience parameter x as the ratio of foreign price to domestic costs,

$$q \equiv \frac{eP^*}{P}, \quad x \equiv \frac{eP^*}{c_\bullet / \kappa_\bullet} = q\mu. \tag{80}$$

In terms of these variables,

$$\mu = \mu_0^\xi x^{1-\xi}, \tag{81}$$

which then gives

$$q = \left(\frac{x}{\mu_0} \right)^\xi. \tag{82}$$

The profit rate is given by

$$\pi = 1 - \frac{1}{\mu} = 1 - \frac{1}{\mu_0} q^{(\xi-1)/\xi}. \tag{83}$$

Domestic investment continues to depend on the profit rate and utilization, as in equation (42), but allows for capital mobility, in that an increase in the foreign profit rate r^* leads to falling domestic investment,

$$g^i = \gamma + \alpha\left(r - r^*\right) + \beta u = \gamma - \alpha r^* + \left(\alpha\pi\kappa + \beta\right)u. \tag{84}$$

Domestic savings follows the same rule as before, given by equation (44), but domestic investment no longer needs to equal domestic savings. Instead,

$$g^s = g^i + b(q,u), \tag{85}$$

where $b(q,u)$ is the trade balance divided by the capital stock. Assuming that a depreciation (that is, an increase in q) tends to boost exports (the Marshall-Lerner condition), b is an increasing function of q. Assuming that increasing utilization leads to a greater influx of investment goods and intermediate goods, b is a decreasing function of u. That is,

$$b_q > 0, \quad b_u < 0. \tag{86}$$

We next find how utilization responds to changes in different parameters by differentiating equation (85). We assume that the target profit rate μ_0 does not change. Because the result involves many terms, we give some intermediate results and define some useful aggregate parameters.

The first of the intermediate results is that the variation in q can be written

$$\frac{dq}{q} = \xi \frac{dx}{x} = \xi \left[\frac{d\left(eP^*\right)}{eP^*} - \frac{dc_\bullet}{c_\bullet} \right]. \tag{87}$$

It is also convenient to define

$$\Lambda \equiv s_\pi - s_w - \alpha \tag{88}$$

and

$$\mathrm{M} \equiv s_w + \left(s_\pi - s_w - \alpha\right)\pi = s_w + \Lambda\pi. \tag{89}$$

We next compute the variation in equation (85) in terms of these variables, but keep in mind, from earlier discussions, that the profit share is affected by both the penetration of green capital and the carbon price, and so are costs, as seen in equations (72) and (73). The result is,

$$\left(\mathrm{M}\kappa - \beta - b_u\right)du = -\Lambda u\kappa\, d\pi - \mathrm{M}u\kappa' dz + qb_q\xi \left[\frac{d\left(eP^*\right)}{eP^*} - \frac{\varepsilon_\bullet}{c_\bullet} dp_E \right] - \alpha\, dr^*. \tag{90}$$

The profit share is affected by several factors,

$$d\pi = \pi' dz + \frac{\partial \pi}{\partial p_E} dp_E + \frac{1-\xi}{\mu} \frac{d\left(eP^*\right)}{eP^*}, \tag{91}$$

where the response of the profit share to a change in the carbon price now has an additional term from trade,

$$\frac{\partial \pi}{\partial p_E} = -\frac{z}{\mu}\frac{\varepsilon_g}{c_g} + \frac{\xi - (1-z)}{\mu}\frac{\varepsilon_b}{c_b}, \quad \text{brown capital dominated, } z > 0. \tag{92}$$

This expression is negative at low levels of green capital penetration, in contrast to the closed economy case. It can become positive at intermediate levels of green capital penetration if the mark-up is not very sensitive to changes in the competitiveness parameter (that is, if ξ) is close to one.

Our interest in this paper is in the signs of terms, rather than their absolute values. The factor in parentheses that multiplies du on the left-hand side of equation (90) is positive, assuming the Keynesian stability condition. Furthermore, we assume that the Keynesian stability condition holds domestically – that is, omitting the balance-of-trade term – implying that M is also positive. The parameter Λ is positive in a domestically wage-led regime and negative in a domestically profit-led regime. The parameters q and θ are both positive, and b_q is positive from the Marshall-Lerner condition. Note that setting b_q, b_u, and dr^* equal to zero and ξ equal to one gives the closed-economy result, so the effects of trade can be seen by focusing on those terms. The results are shown in Table 3 in the main text.

SEI - Headquarters
Stockholm
Sweden
Tel: +46 8 30 80 44
Executive Director: Johan L. Kuylenstierna
info@sei-international.org

Visitors and packages:
Linnégatan 87D
115 23 Stockholm, Sweden
Letters:
Box 24218
104 51 Stockholm, Sweden

SEI - Africa
World Agroforestry Centre
United Nations Avenue, Gigiri
P.O. Box 30677
Nairobi 00100
Kenya
Tel: +254 20 722 4886
Centre Director: Stacey Noel
info-Africa@sei-international.org

SEI - Asia
15th Floor
Witthyakit Building
254 Chulalongkorn University
Chulalongkorn Soi 64
Phyathai Road, Pathumwan
Bangkok 10330
Thailand
Tel: +(66) 2 251 4415
Centre Director: Eric Kemp-Benedict
info-Asia@sei-international.org

SEI - Oxford
Florence House
29 Grove Street
Summertown
Oxford, OX2 7JT
UK
Tel: +44 1865 42 6316
Centre Director: Ruth Butterfield
info-Oxford@sei-international.org

SEI - Stockholm
Linnégatan 87D, 115 23 Stockholm
(See HQ, above, for mailing address)
Sweden
Tel: +46 8 30 80 44
Centre Director: Jakob Granit
info-Stockholm@sei-international.org

SEI - Tallinn
Lai str 34
10133 Tallinn
Estonia
Tel: +372 627 6100
Centre Director: Tea Nõmmann
info-Tallinn@sei-international.org

SEI - U.S.
Main Office
11 Curtis Avenue
Somerville, MA 02144
USA
Tel: +1 617 627 3786
Centre Director: Charles Heaps
info-US@sei-international.org

Davis Office
400 F Street
Davis, CA 95616
USA
Tel: +1 530 753 3035

Seattle Office
1402 Third Avenue, Suite 900
Seattle, WA 98101
USA
Tel: +1 206 547 4000

SEI - York
University of York
Heslington
York, YO10 5DD
UK
Tel: +44 1904 32 2897
Centre Director: Lisa Emberson
info-York@sei-international.org

Stockholm Environment Institute

SEI is an independent international research institute that has been engaged in environment and development issues at local, national, regional and global policy levels for more than 25 years. SEI supports decision-making for sustainable development by bridging science and policy.

sei-international.org

Twitter: @SEIresearch, @SEIclimate