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The Balance-of-Emissions Constraint on Growth: Pathways to Net-Zero Greenhouse Gas Emissions in a Simple Post-Keynesian Model

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Pathways to Net-Zero Greenhouse Gas Emissions in a Simple Post-Keynesian Model

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Abstract

Despite the scientific consensus on the need to achieve net-zero greenhouse gas (GHG) emissions by 2050 as a key environmental goal, there is little consensus among economists on the best pathway to achieve this crucial goal. Particularly contentious is what achieving net zero in time implies for the growth rate of the global economy. In the search for a post-Keynesian answer, we first review the related literature showing the divide between degrowth/post-growth authors, who argue that net zero implies a need for negative or zero growth, and Keynesian green growth advocates, who argue that positive growth rates are required. Motivated by these controversies, we develop a simple Sraffian supermultiplier model of the global economy, where GHG emissions depend on the stock of capital in production and absorption depends on the stock of natural capital, from which we can formally demonstrate that the goal of net-zero GHG emissions implies a constraint on the growth rate of the global economy. Crucially, this "balance-of-emissions constraint" on growth depends on a number of key parameters that are influenced by public policy, such as the share of public spending on natural capital, the share of investment in low-emission production capital, and the parameters that enter the supermultiplier, which determine the size of the rebound effect. From this, we model different pathways to net zero and argue for an interventionist policy mix, which we show brings about net zero emissions much more rapidly than any laissez-faire alternative scenario, even one with utmost optimism about future green technology.

Keywords: Degrowth, post-growth, green growth, net zero, structural change

JEL Codes: E12, O44, Q54

1. Introduction

In the last decade, post-Keynesian economists and their close collaborators have been increasingly interested in analysing different aspects regarding the green transition and the associated macroeconomic implications. The latter comes out of the recognition that the climate crisis is the most crucial economic and ecological challenge of the century, to the point that what happens in the next 25 years will set the course for the second half of the century. Although climate change is only one of the dimensions of the climate crisis, it is the most broadly discussed among the nine planetary boundaries, given its interconnectedness with other boundaries[1]. For this reason, there is broad consensus among economists regarding the need to decarbonise the economic system without any delay. There is less consensus, however, when it comes to *how* to achieve the established goal of net-zero greenhouse gas (GHG) emissions by 2050. Limiting global warming to a specific level implies adherence to a cumulative CO2 emissions budget. Broadly speaking, decarbonisation is possible through a reduction in the emission intensity of GDP, emphasised by proponents of green growth and/or a reduction of output growth, which has been the focus of those calling for degrowth or post-growth.

Constraining the CO2 intensity of production, which at the same time implies an increasing decoupling of GDP and GHG emissions, undoubtedly requires cleaner and more efficient capital and, therefore, the investment in green capital and technologies. For the latter, not only firms have an important role to play in developing and deploying new green technologies (Rozenberg et al., 2015), but also policymakers play a central role in steering the transition towards a net-zero emissions economy. From a mainstream perspective, the current economic system can be aligned with environmental goals through the price mechanism (Terzi, 2022).In mainstream analysis, tools such as carbon pricing and cap and trade, are commonly considered the main policy tools to address the climate crisis (Huwe and Rehm, 2022) and are often considered sufficient, to achieve green growth.From a heterodox perspective, such an approach is problematic for reasons such as the evidence of insufficient scaling up of green investment, the regressive and gendered impact of carbon taxes and in general the tendency to overlook structural challenges and the necessity of more profound systemic change (Dafermos et al., 2021).

Unsurprisingly, some heterodox economists emphasise that the government should play a much active role than often ascribed by mainstream authors, through for example, strong regulation and fiscal stimuli to accelerate the transition, all while keeping an eye on distributional and further socio-economic effects. From some heterodox perspectives, massive fiscal global stimuli are often envisioned if decoupling, and therefore, green growth is to be achieved. The main goal is often to achieve a "manufacturing boom in clean energy, overhauling infrastructure, creating jobs, spurring innovation in green technologies and bolstering 'energy security'" (Meaney, 2022), which would allow the transition to a decarbonised economy while ensuring full employment and rising living standards.

However, not all heterodox strands agree with the latter. Post-growth economists in particular are quite sceptical about the possibility of green growth, not only because of questions of scale but also because of the question of speed. In this respect, although there is some evidence of absolute

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[1] Such as biodiversity loss, land-system change, and biogeochemical flows (nitrogen and phosphorus cycles)

decoupling, it is not happening fast enough to achieve the goal of net-zero emissions by 2050. In the words of Jackson et al. (2024, p.2), "any binding carbon target sets up a non-negotiable relationship between […] the potential for economic decoupling and the allowable size of the economy. The bigger the economy (as measured by its GDP), the faster the decoupling rate needs to be, the slower the potential decoupling rate, the smaller the allowable size of the economy – if the carbon target is to be met". For this reason, the post-growth literature cautions against the reliance on technological solutions, presenting arguments backed up by evidence that should not be ignored. Hence, post-growth authors argue that a reduction of economic throughput and therefore output growth is a necessary channel to achieve decarbonisation in time. The arguments for this choice extend beyond the realm of ecological sustainability, with a wealth of sociological and anthropological evidence supporting the undesirability of further economic growth, particularly in the global north (as exemplified by Jackson, 2017; Hickel, 2022).

It is within this context that post-Keynesians and close collaborators have increasingly included ecological constraints in their analysis. Informed by the post-growth and heterodox green growth strands, they have analysed and discussed potential pathways for the ecological transition and hence the decarbonisation of the economy. Some of these contributions are clearly motivated by the arguments and evidence from the post-growth literature, while other contributions either disregard the issues around the compatibility of economic growth and ecological sustainability or they are more sceptical about the call for zero-growth or degrowth when discussing decarbonisation trajectories and, coming closer to the green growth literature, place a stronger focus on improving the emission intensity of production, arguing that at least some growth is necessary to decarbonise the world economy in the time left.

Rather than infer or presuppose that there is a net-zero constraint on long-run growth, this paper offers a formal demonstration of its existence and its determinants. Crucially, we show that this balance-of-emissions constraint depends on a number of parameters that may be influenced by policy. Hence, we argue that the precise limit on growth implied by the goal of net zero—and whether this limit is negative, zero, or positive—depends on the ambition of public policy around the world and the extent of international coordination. Moreover, by modelling various pathways to net zero, we show that the greater the extent of global government intervention, the faster the pace at which the transition occurs. Lastly, we show that even if all future private investment were in completely emissions-free production capital, this "techno-optimistic laissez-faire" transition to net zero would nonetheless likely take too long given our limited remaining carbon budget. We thus reaffirm the importance of public spending on the protection and restoration of natural capital in the transition to net zero.

The rest of the paper is structured as follows. In section 2, we review and compare the existing "green" post-Keynesian literature, elucidating in more detail the envisioned post-Keynesian decarbonisation pathways and the necessary policies to facilitate them. In section 3, we present a simple Sraffian supermultiplier model that allows for the consideration of structural change and hence different long-run pathways to global net zero emissions. Such pathways and the theoretical insights from this model are discussed in detail in section 4, with a suggested policy mix to achieve net zero emissions most urgently. Section 5 concludes.

2. Growth and decarbonisation: reviewing the post-Keynesian literature

Most models within post-Keynesian economics (PKE) operate in a context where resources are not considered to be scarce and, in the normal state, neither capital goods nor labour are fully employed. Traditionally, the focus of these models has been placed on increasing production and hence the rate of growth, considering the constraints coming from effective demand, with little regards to supply constraints (Lavoie, 2022, p. 25). However, informed by ecological macroeconomics, PKE has come to terms with the fact that output is not only limited by effective demand but also by ecological constraints. As a result, in the last decade there has been a significant surge in publications that operate at the intersection of post-Keynesian economics and ecological macroeconomics, reflecting the recognition of ecological limits and an awakened curiosity among post-Keynesians to explore their implications.[2] At the same time, ecological theories have incorporated (post-Keynesian) macroeconomic thinking (Rezai et al, 2013; Rezai and Stagl, 2016). As a result, many renowned ecological economists, such as Jackson and Victor (2015, 2020) have turned to the post-Keynesian theoretical toolbox for their macroeconomic analysis. [3]

2.1 Degrowth and zero growth post-Keynesian views

Within the post-Keynesian ecological literature, we can identify two strands that are relevant to the question of growth in the transition to net zero. The first strand makes use of a post-Keynesian framework to analyse the macroeconomic implications of zero growth or even de-growth, or the transition toward such a position, as called upon by post-growth authors. Among the first contributions are those by Fontana and Sawyer (2013; 2016; 2022), who informed by the post-growth literature, acknowledge that the post-Keynesian focus on speeding up growth to alleviate persistent macroeconomic issues, such as unemployment, can potentially lead to catastrophic environmental problems. Assuming that the growth rate of aggregate demand is higher than an ecologically sustainable growth rate, they explore the challenge of constraining the growth of demand. One of their main conclusions is that to achieve lower growth, there must be “control over the volume and composition of investment” (2016, p. 193), where government policies and social norms play an important role in driving net investment towards zero, including credit controls, restraints on investment and polices aimed at dampening animal spirits (2022, p,99). Similarly, Lange (2018) explores the conditions for sustainable economies without growth in different theories, including post-Keynesian, emphasizing many of the points brought up by Fontana and Sawyer. Monserand (2019) investigates the theoretical possibilities for a stable degrowth transition making use of a neo-Kaleckian growth and distribution model. The findings suggest that adding depreciation or any fixed cost allows for a stable equilibrium with a zero or negative accumulation rate. Using a Sraffian supermultiplier approach, Monserand (2019) shows that political action and a shift towards more ecological lifestyles allow for a degrowth transition while maintaining macroeconomic stability.

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[2] For earlier recognitions of ecological constraints, see Bird (1982), Eichner (1991, ch 13), and Stratmann-Mertens et al. (1991). For the reasons behind the lack of focus on ecological issues in PKE, see Mearman (2005), and for a discussion on the compatibility between ecological economics and PKE, see Gowdy (1991), Kronenberg (2010).

[3] See Hardt and O’Neill (2017) for a review of ecological macroeconomic models. In particular Table 3 and Figure 1 for a list of models and a categorization by modeling technique, respectively.

The analysis of growth imperatives has also been important within this strand, as touched upon by Fontana and Sawyer (2022) and analysed in detail by Cahen-Fourot and Lavoie (2016), who offer a post-Keynesian perspective to refute the supposed need for continuous growth tied to monetary systems and, concentrating on zero-growth economies (ZGEs), show that such economies are theoretically feasible with existing financial structures. Moreover, Hein and Jimenez (2022) analyse the conditions under which a stable ZGE allows for positive profits and a positive interest rate.[4] Focusing on the goods market equilibrium and on systemic financial stability, in the sense of constant and stable asset-capital or debt-capital ratios, the authors make use of an autonomous demand-led growth model driven by government expenditures and show that a stable stationary state, with zero growth, positive profits, and a positive interest rate is possible as long as specific maxima for the propensity to consume out of wealth and for the rate of interest are respected.

Lastly, since stimulating demand to lower unemployment is no longer possible in a ZGE , post-Keynesians have argued alongside ecological economists in favour of working time reduction (Rezai et.al, 2013; Fontana and Sawyer, 2016). In a dynamic context, a constant and stable employment rate has been shown to be theoretically possible in a ZGE if the negative effects on employment resulting from positive labour productivity growth are compensated by an appropriate reduction in working hours (Jimenez, 2023).

2.2 Positive growth and "Green New Deal" post-Keynesian views

A second strand in the literature is dubious about the desirability and/or feasibility of zero or de-growth for at least two reasons. First, it is argued that while zero growth may be possible from a macroeconomic-theoretic perspective, it is nonetheless inherently unlikely to be achieved in face of broader political economy considerations (Huwe and Rehm 2022; Cahen-Fourot 2022). After all, it seems difficult, if not outright impossible, that the stability conditions for a ZGE—such as no net investment, no saving by households nor firms, and a continuously balanced government budget—could be realistically achieved in a capitalist system in the present day or near future.

A second reason for doubt among these authors is connected to the concern that a negative or zero growth rate will ultimately delay the transition to net zero. Sceptical of the potential of zero-growth or degrowth to decarbonise the economy, Priewe (2022) argues that it would only take a short time to use up the residual CO2 budget if a considerable improvement in emission intensity does not accompany zero growth. After considering eight different scenarios, Priewe suggests that low growth in the Global North should suffice, if coupled with substantial technological advances in decarbonisation. He emphasises that while slowing economic growth can help to achieve net-zero emissions, zero growth alone is not necessarily effective unless combined with significant reductions in emission intensity. Hence, this second strand places a stronger focus on the emission intensity channel, recognizing that the latter is a technology variable, but one which can be influenced by both behavioural and regulation changes. Additionally, the question of the speed of such changes is also emphasised. The crucial argument however is that the technological channel and associated policies

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[4] The monetary growth imperative is based on the argument that debt-money bearing interest triggers real GDP growth (Cahen-Fourot, 2022). It should not be confused with the more general term growth imperative, which is the need for growth in real GDP to be "socially and politically stable and to reproduce itself coherently over time, i.e., to foster social cohesion, and individual and collective wellbeing" (Cahen-Fourot, 2022, p.2).

are considered more feasible from both a macroeconomic and a political economy perspective than a zero or degrowth agenda, not only because of the perceived difficulty of aspects such as the generalisation of voluntary simplicity, but also considering the strong conditions for stability elucidated by the first strand mentioned in this section and thus the set of uncertainties and challenges associated with it.

Authors such as Pollin (2019) and Storm (2020) exemplify the post-Keynesian case for a Green New Deal. Despite also agreeing with many of the arguments presented in the degrowth literature, Pollin (2019) argues that a major problem with degrowth is that, "in concerning itself primarily with very broad themes, it actually gives almost no detailed attention to developing an effective climate-stabilization program" (2019, p.312). Hence, instead of degrowth, Pollin advocates for a "Green New Deal" to dismantle the fossil-fuel-dominant infrastructure.[5] The envisioned worldwide climate-stabilization project aims at the absolute decoupling of fossil fuel consumption from economic activity. According to his calculations, the latter is possible within a timeframe of 40 to 50 years through a 1.5-2% investment of global GDP per year in clean energy (Pollin, 2019, p.313). Similarly, Storm (2020) criticises the European Green Deal for being underfunded and overly optimistic about private finance and de-risking, instead arguing for public investment of a much more ambitious scale of around 3.5 - 4.5% of European Union GDP. In these post-Keynesian Green New Deal approaches, ambitious public investment is aimed at dramatically reducing the emission intensity of production through higher energy efficiency and the expanded supply of green energy, all while boosting output and employment.

Despite the differences in the two strands presented, some common ground exists among them. The most obvious one is the recognition of an imperative need for different policy interventions for a successful transition towards net zero. In this respect, policies that change the composition of investment are crucial, where the goal is to ensure that "brown" investment shrinks massively while green investments expand. The latter is true even from a degrowth perspective, as it has been recognised that policies that accelerate "the adoption of the cleanest technologies should always be welcome, even if the corresponding investments cause additional economic activity, as long as the overall effect is environmentally beneficial" (Monserand, 2019, p.8-9). Another point to highlight is that many of the contributions either directly recognise that there is a limit to growth, or they emphasise that there is a strong assumption regarding the possibility to decouple growth from GHG emissions.

Nonetheless, there exists a considerable degree of disagreement and ambiguity in the literature about whether growth is compatible with the goal of reaching net zero with the degree of urgency required. With this in mind, we develop a macroeconomic model with net emissions expressed over historical (rather than logical) time in the next section to help shed light on the matter. In doing so, the goal is to keep this model as simple as possible, in order to emphasise a few key theoretical insights. Moreover, we will show how this model can be fruitfully employed to understand various pathways to net zero.

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[5] Although the discrepancy with degrowth is perhaps not as strong as suggested, as this strand also suggest the importance of expand specific forms of production (see for example Hickel and Sullivan, 2024).

3. A Simple Model of the Pathways to Global Net Zero Emissions

In order to simplify the analysis of what is otherwise an inherently complex matter, we will focus on the long-run equilibria of the global economy rather than short-run adjustment processes.

3.1 A Basic Long-Run Macroeconomic Model of the Global Economy

In the analysis that follows, we adopt the standard post-Keynesian supply-side assumption that production follows a Leontief production function, where firms use the smallest amount (as determined by the fixed labour and capital coefficients a and v) of labour (L) and capital (K) required to produce the level of homogenous output (Y) determined by effective demand (D), as described in Equation 1

$$D = Y = \min\left(\frac{L}{a}, \frac{K}{v}\right). \tag{1}$$

We also follow the standard assumption that the amount of labour and capital employed is usually below the total amount available, such that involuntary unemployment and capacity underutilisation exist in the normal state. Firms are thus assumed to make efficient use of labour and capital as further labour and capital would be redundant and costly given the technical coefficients of production. However, firms do not minimise emissions as they can pollute without bearing any cost, reflected in the absence of emissions or a “unit emissions requirement” in the Leontief production function.

Turning to the demand side, output is determined by effective demand,

$$Y = C + I + G, \tag{2}$$

where the components of aggregate demand for the global economy are consumption (C), investment (I), and government spending (G). More specifically, we adopt a highly simplified Sraffian supermultiplier (SSM) approach, where consumption is the product of the propensity to consume (c) and income net of tax, where τ is the tax rate on all income, and investment depends on the level of output and the propensity to invest, h,

$$C = c(1 - \tau)Y \tag{3}$$

$$I = hY. \tag{4}$$

Government spending, on the other hand, is fully autonomous and grows at the rate g,

$$\hat{G} = g, \tag{5}$$

where hats denote a growth rate. We assume there is sufficient coordination between the national governments of the world via international organisations to allow us to speak meaningfully of global governmental spending and policy goals. To keep our focus on the matter at hand, we assume no limitations on public deficit financing or the level of public debt, which is made possible through money emission or zero-interest on privately held public bonds. We note that the more detailed, related macroeconomic models find that the stability of such a model is ensured under reasonable conditions (Freitas & Christianes 2020, Hein & Woodgate 2021, Morlin 2022, Woodgate et al. 2023). Given this, and that the focus of our model here is on ecological matters, we take the stability of the macroeconomic model as granted.

From this setup, we arrive at the usual SSM equation form, where output in any period is determined by the product of the steady-state supermultiplier, μ^*, and autonomous demand, in this case government spending,

$$Y = \mu^* G, \tag{6}$$

$$\mu^* = \frac{1}{\lambda - h^*}, \tag{7}$$

where $\lambda = 1 - c(1 - \tau)$ represents the leakages from aggregate demand imposed by saving (reflected in $1 - c$) and taxation (reflected in $c\tau$). We follow the usual Keynesian stability assumption that supposes that total demand leakages are greater than the propensity to invest and hence the supermultiplier and output cannot be negative

$$\lambda > h^*. \tag{8}$$

While the propensity to invest and thus the supermultiplier may vary in the short run given deviations of capacity utilisation from its normal rate, given the objective of this paper, we are only interested in long-run equilibria and so here we treat h and thus μ as constants equal to their long-run values h^* and μ^*. Given how h is defined, it is easy to show that its long-run value is determined by

$$h^* = \frac{gK}{Y} = \frac{gv}{u_n}, \tag{9}$$

where v is the capital-potential output ratio and u_n is the normal rate of capacity utilisation. The long-run growth rate of output, the capital stock, and labour employed is the same as and driven by the growth rate of government spending, g:

$$\hat{Y} = \widehat{K} = \hat{L} = g. \tag{10}$$

With this basic SSM model in place, we can now consider how levels of greenhouse gas (GHG) emissions and absorption relate to macroeconomic activity.

3.2 Net Greenhouse Gas Emissions due to Macroeconomic Activity

Equation 11 defines net GHG emissions (E_N) as the difference between annual global gross GHG emissions (E) and absorption (A) measured in CO_2-equivalent levels

$$E_N = E - A. \tag{11}$$

Analogous to the usual technical coefficients of production seen in Equation 1, throughout this paper we will make use of the concept of the *emissions intensity of capital* (ϵ) or *emissions intensity*, for short. The emissions intensity tells us the level of gross GHG emissions released by the capital used in production in any given period,

$$E = \epsilon K. \tag{12}$$

Hence, *decoupling* can be said to occur when technical change leads to shrinkage of the emissions intensity, i.e when $\hat{\epsilon} < 0$. [6]

Just as gross emissions depend on the level of capital stock in production, we can view absorbed emissions as dependent upon the ecosystem services provided by the stock of *natural* capital, N.[7]

$$A = \alpha N, \tag{13}$$

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[6] For relative decoupling, it is sufficient that the growth rate of gross emissions is lower than the output growth ($\hat{\epsilon} < 0 \Rightarrow \hat{E} < g, where\ g > 0$). For absolute decoupling however, we require a degrowth in GHG emissions, despite positive growth ($\widehat{E} < 0$ and $g > 0$).

[7] Natural capital takes or acts in several forms simultaneously. These forms include: *sources* such as raw materials, *functions* such as critical life support, and *sinks* such as waste absorption capacity (Winters, 1995). Quite important for our purposes are the sinks, which include the absorption of carbon dioxide from the atmosphere, highlighting the importance of maintenance and restoration (Farley and Brown Gaddis, 2007, p.18).

where α is an exogenous and constant parameter that tells us the absorption capacity of each unit of natural capital per year. We make use of another key variable, η, which denotes the ratio of natural capital to production capital,

$$\eta = \frac{N}{K}. \tag{14}$$

Given Equations 12-14, we can express net emissions in Equation 11 as

$$E_N = (\epsilon - \alpha\eta)K. \tag{15}$$

Net emissions thus depend upon the three key variables in our model: The emissions intensity (ϵ), the ratio of natural-to-production capital (η), and the level of production capital (K).

We will model the green transition as follows. In the initial position of the model, all firms default to the emission-intensive "brown" technique of production, denoted by ϵ_B. The transformation of the economy to a low emission "green" technique of production, where $\epsilon_G < \epsilon_B$, begins in period $t = 0$. We assume that the green technique of production has the same unit labour requirement and unit capital requirement as the brown technique of production. This modelling approach, which takes inspiration from the model of structural change implied by offshoring seen in Woodgate (2023), is naturally a large simplification, but one that will allow us to focus on the crux of the matter at hand, namely a scenario where firms can switch technique of production and prevent substantial emissions without having to employ more labour or capital but are hesitant to do so purely due to inertia. Capital is "clay-like" and switching technique is in itself costly. Firms may use the green technique in new plants, if only to stay in line with regulation or to tout their "green credentials" to consumers since we assume there are no greater cost efficiencies from doing so. However, they are unlikely to replace or retrofit old plants that use the brown technique of their own accord. Hence, without further government intervention in place, the greening of production occurs at the pace of new investment and the replacement of depreciated and scrapped capital associated with the brown technique of production.

Throughout all that follows, we will use "brown capital" (K_B) and "green capital" (K_G) as shorthand for capital that is employed using the brown and green techniques respectively. It should be kept in mind, however, that this is a simple homogenous good model, so there is no difference in the capital goods themselves but rather in the way they are put to work.[8]

At any point in time after the transition begins ($t \geq 0$), then, the overall emission intensity of capital ϵ is an average of ϵ_B and ϵ_G weighted by κ, the share of green capital in the total capital stock

$$\epsilon = \epsilon_B(1 - \kappa) + \kappa\epsilon_G. \tag{16}$$

Defining $\epsilon_\Delta = \epsilon_B - \epsilon_G$, which is always strictly positive, we can express Equation 16 as

$$\epsilon = \epsilon_B - \epsilon_\Delta\kappa. \tag{17}$$

Let us suppose the share of green investment ϕ, where $0 \leq \phi \leq 1$, reflects the extent to which total net investment is added to the green capital stock. We will also suppose this fraction determines the extent to which depreciated and scrapped capital is replaced by green capital, where δ is the rate of capital replacement. Hence, we get the following expression for net investment into green capital (I_G)

$$I_G = \phi(I + \delta K) - \delta K_G. \tag{18}$$

The growth rate (denoted by a hat) of the share of green capital in total production capital is

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[8] While abstract, this is akin to many if not most other simple models of technical change where, for example, growth in labour productivity implies the same homogenous output good can be produced by somehow employing less labour in combination with the same capital good rather than some new capital good.

$$\hat{\kappa} = \frac{I_G}{K_G} - g = \frac{\phi(I + \delta K) - \delta K_G}{\kappa K} - g = (g + \delta)\left(\frac{\phi}{\kappa} - 1\right), \tag{19}$$

and the time rate of change (denoted by a dot) is thus

$$\dot{\kappa} = (g + \delta)(\phi - \kappa). \tag{20}$$

The long-run equilibrium value of the share of green production capital in total capital is,

$$\kappa^* = \phi, \tag{21}$$

i.e., determined by the share of green investment. While the rate of growth and depreciation do not affect the long-run value of the share of green capital, we note from Equations 19 and 20 that higher values of g and δ accelerate the transition to the steady state. Solving the differential equation implied by Equation 20,

$$\kappa(t) \;=\; \int \dot{\kappa}\, dt \;=\; \phi\left(1 - e^{-(g+\delta)t}\right). \tag{22}$$

we see that κ is bound between zero at $t = 0$ and tends to its upper bound of ϕ as $t \to \infty$.

Moving on to the next key variable in Equation 15, the ratio of natural-to-production capital η, we start our analysis with the simplifying assumption that increases in the stock of natural capital follow exclusively from government spending. Policies towards the goal of increasing total GHG absorption capacity (e.g. afforestation and reforestation, wetland restoration, the promotion of sustainable agriculture, urban greening, etc.) if not also other ecological goals imply an expansive role for public investment on top of protective regulation. Suppose, then, that G_N denotes the amount of global government spending dedicated to protecting and restoring the stock of natural capital, referred onwards as ecological government spending. If the cost of maintaining each unit of natural capital is ρ, then the time rate of change of the stock of natural capital can be specified as

$$\dot{N} = G_N - \rho N. \tag{23}$$

Equation 23 says that ecological government spending must equal to ρN just to protect and maintain the current level of natural capital, and greater than ρN to expand the stock of natural capital and therefore absorption.[9] Supposing that the share of ecological government spending in total government spending is

$$\gamma = \frac{G_N}{G}, \tag{24}$$

then the growth rate of the ratio of natural-to-production capital is

$$\hat{\eta} = \hat{N} - g = \frac{\gamma G}{\eta K} - \rho - g = \frac{\gamma}{\eta}\left(\frac{\lambda u_n}{v} - g\right) - \rho - g, \tag{25}$$

where here we make use of Equations 6, 7, and 9. It follows that the long-run steady state value of the natural-production capital ratio is

$$\eta^* = \frac{\gamma}{\rho + g}\left(\frac{\lambda u_n}{v} - g\right), \tag{26}$$

which is strictly positive given the Keynesian stability assumption, and its time rate of change is

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[9] Following Smith et al. (2017) natural capital's capacity to provide ecosystem services depends on variables such as the physical amount of vegetations and the biological diversity, making crucial to keep natural capital diverse and resilient to continue delivering ecosystem services in the long term. Such services include of course climate regulation and carbon sequestration (Daba and Dejene, 2018). At the same time the conservation of natural capital is costly since it depreciates as a result of human activities, as well as climate events such as droughts, wildfires, and floods.

$$\dot{\eta} = (\rho + g)(\eta^* - \eta). \tag{27}$$

From this we can find the state variable η as a function of time

$$\eta(t) \;=\; \int \dot{\eta}\, dt \;=\; \eta^* - (\eta^* - \eta_0)e^{-(\rho+g)t}, \tag{28}$$

where η_0 is the ratio of natural to production capital when the green transition begins at $t = 0$.

The last key variable in Equation 15, the total stock of production capital, is the most straightforward. Supposing K_0 represents the total level of capital in the year the transition begins, then its value in any year after is given by

$$K(t) \;=\; K_0 e^{gt}. \tag{29}$$

We are finally able to understand the evolution of net GHG emissions over time. First, it is useful to define the *net* emissions intensity of capital as

$$\epsilon_N(t) \;=\; \epsilon(t) - \alpha\eta(t) \;=\; \epsilon_B - \epsilon_\Delta \kappa(t) - \alpha\eta(t) \tag{30}$$

The net emissions intensity ultimately determines the sign of total net emissions, given that

$$E_N(t) = \epsilon_N(t)K(t) \tag{31}$$

where $K(t)$ is always positive. The steady state value of the net emissions intensity is

$$\epsilon_N^* \;= \epsilon_B - \epsilon_\Delta\phi - \alpha\eta^* \tag{32}$$

which, it can be shown, enters into the expression for the level of net emissions at any point in time *t*

$$E_N(t) = \left[\epsilon_N^* + \epsilon_\Delta \phi e^{-(g+\delta)t} + \alpha(\eta^* - \eta_0)e^{-(g+\rho)t}\right]K_0 e^{gt}. \tag{33}$$

To reach net zero emissions thus requires that

$$\epsilon_N^* \leq 0, \tag{34}$$

and since the time rate of change of net emissions is

$$\dot{E_N}(t) = K_0\left[g\epsilon_N^* e^{gt} - \left(\delta\epsilon_\Delta\phi e^{-\delta t} + \alpha\rho(\eta^* - \eta_0)e^{-\rho t}\right)\right], \tag{35}$$

it follows that the goal of net zero is reached more quickly the more negative the equilibrium net emissions intensity. Thus ϵ_N^* is doubly important in the transition to net zero as it not only defines the long-run position but also partly determines the pace with which that steady state is brought about.

4. Implications: Limits to Growth and Policies to Achieve Net Zero Quickly

Analysis of the equilibrium net emissions intensity reveals an important limitation to the rate of growth in the transition to net zero. Since $\epsilon_N^* \leq 0$, it follows that

$$\epsilon_B - \epsilon_\Delta\phi - \alpha\frac{\gamma}{\rho+g}\left(\frac{\lambda u_n}{v} - g\right) \leq 0, \tag{36}$$

which, upon rearranging for g, gives

$$g \leq \frac{\alpha\gamma\lambda u_n - \rho v(\epsilon_B - \epsilon_\Delta\phi)}{v(\epsilon_B - \epsilon_\Delta\phi + \alpha\gamma)}. \tag{37}$$

This term may be referred to as the *net-zero constraint* on growth or, with an obvious nod to Thirlwall (1979), the *balance-of-emissions constraint*. It may be negative, of course, in which case there is no positive rate of growth compatible with the target of net zero emissions. It is also possible that growth exceeds this constraint while net emissions fall in the short run as the transition to using the green technique of production begins, as reflected in Scenario S1 of Figure 1. However, as is also shown in

S1, net emissions will then recontinue their rise in the long run if production cannot be completely decarbonised (i.e. if $\phi < 1$ and $\epsilon_G > 0$) and there is no government investment in natural capital ($\gamma = 0$). This "laissez-faire failed transition" scenario, as we have called it, is thus incompatible with net zero in the long run, just as in the baseline scenario also seen in Figure 1 where there is no transition to the green technique of production nor any government action ($\phi = 0, \gamma = 0$). Our model underlines further theoretical insights that are worth discussing in more detail.

4.1 The Insufficiency of Laissez-Faire Technological Optimism

What might be called the ideal laissez-faire scenario is reflected in the maximum share of green investment ($\phi = 1$) and emission intensity of green capital of zero ($\epsilon_G = 0$, and thus $\epsilon_\Delta = \epsilon_B$), implying that technology is sufficiently advanced such that the production of all products can fully decarbonise without additional cost nor restrictions on growth. This quixotic scenario implies that the limit to growth given techo-optimism (g_{TO}) is

$$g_{TO} \leq \lambda u_n / v, \tag{38}$$

which is simply the usual Keynesian stability assumption seen in Inequality 8. In other words, in the case of technological optimism so defined, there is no limitation placed on the growth rate by concerns about climate change, and net zero can be achieved without government investment in natural capital such that $\gamma = 0$. The corollary is that if the green technique of production is not completely emissions-free ($\epsilon_G > 0$) or cannot be applied to the production of all goods ($\phi < 1$), then there is a limitation upon the growth rate that is more pressing than the usual stability requirement. Given the difficulty involved in decarbonising many industries in the real world, such as aviation and concrete, assuming that $\phi = 1$ and $\epsilon_G = 0$ appears highly unreasonable, at least in the foreseeable future within which we must reach net zero.

Outside of this case of upmost technological optimism is the related case of technical change reducing the unit capital requirement, v. The smaller the v-parameter, the less capital needed to produce output and so the fewer emissions associated with production. Again, however, it appears a matter of unbridled optimism to suppose that the unit capital requirement could shrink fast enough within the short period of time remaining so as to be significant in the path to net zero.

Importantly, while the laissez-faire techno-optimism scenario may hypothetically achieve net zero—though doubts about the plausibility of the required assumptions abound—it likely cannot do so quickly enough. This scenario implies that $\phi = 1$, $\epsilon_G = 0$, $\gamma = 0$, $\eta^* = 0$ and $\epsilon_N^* = 0$, but the level of net emissions in Equation 33 will only slowly reach net zero after many years relative to other scenarios, as depicted in Scenario S2 in Figure 1. This in contrast to a reality in which estimates of the carbon budget imply a finite and short period remaining in which net GHG emissions may still be positive. In short, then, we find no support whatsoever for a laissez-faire techno-optimism pathway to net zero as it is a slow, if not completely quixotic, scenario.

Figure 1 *Evolution of Net GHG Emissions over Time in Key Selected Scenarios: Failed (S1), Delayed & Quixotic (S2), and Urgent & Interventionist (S3) Transitions*

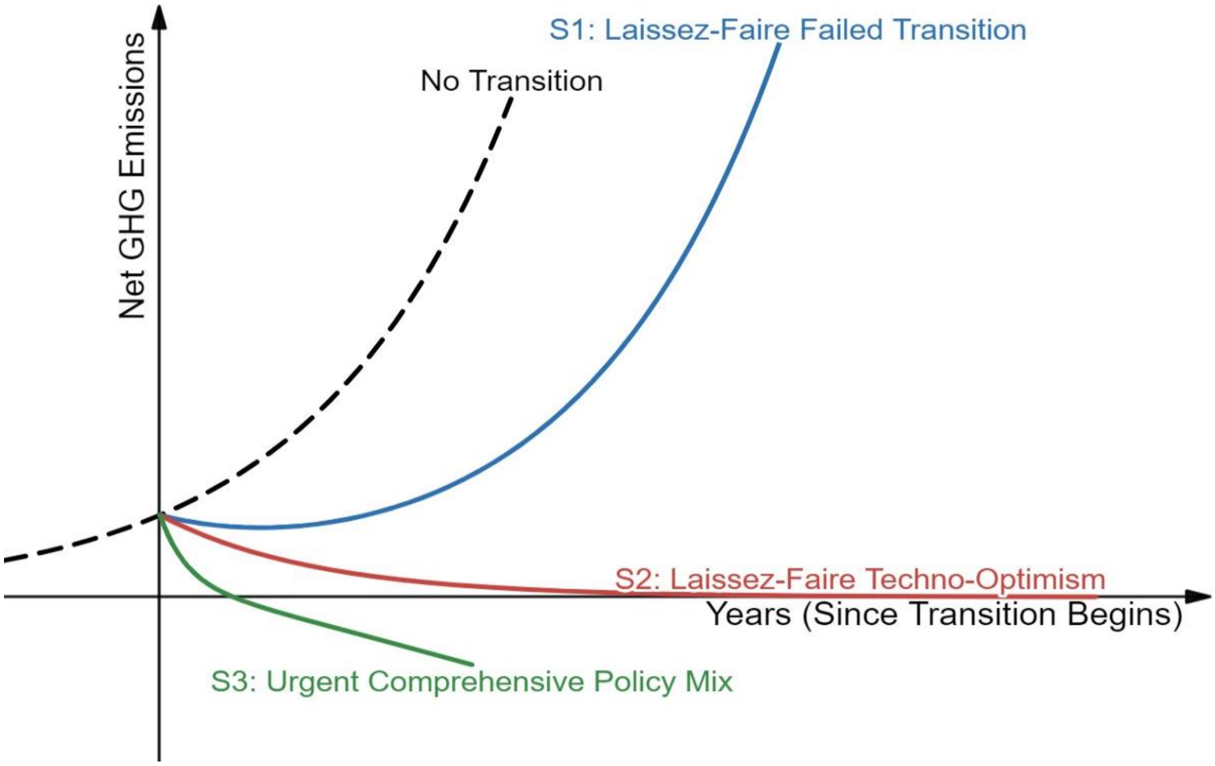

Figure 1 Legend	**Emission intensity of green capital, ϵ_G**	**Share of investment in green capital, ϕ**	**Share of green gov't spending, γ**	**Capital replacement rate, δ**	**Super-multiplier, μ**	**Growth rate, g**
Baseline (BL)	$\epsilon_G < \epsilon_B$	0	0	δ_{BL}	μ_{BL}	g_{BL}
S1	$\epsilon_G < \epsilon_B$	< 1	0	δ_{BL}	μ_{BL}	g_{BL}
S2	0	1	0	δ_{BL}	μ_{BL}	g_{BL}
S3	$\epsilon_G < \epsilon_B$	< 1	> 0	$\delta_{S3} > \delta_{BL}$	$\mu_{S3} < \mu_{BL}$	$g_{S3} < g_{BL}$

4.2 A Clear Ecological Purpose for Government Spending

Moving away from the unrealistic case of techno-optimism, it is clear the share of total government spending towards natural capital is crucially important. If $\gamma = 0$, there is no positive long-run rate of growth that is compatible with net zero GHG emissions, since that would imply the stock of emissions-absorbing natural capital forever shrinks relative to emission-producing production capital. If it were costless for public authorities to protect and maintain the stock of natural capital so that $\rho = 0$, we see there would be a less pressing limit on the long-run rate of growth, yet reality does not seem to lend any support to notion that it is easy or free to protect the commons (Barbier, 2014). The greater the extent to which government dedicate their spending towards ecological restoration, the higher the rate of growth the atmosphere can handle. This follows because the nature of growth is fundamentally different in a scenario with a significant share of public investment in ecological services than the business-as-usual growth of recent centuries. This comes with a caveat, however.

4.3 The (Super)Multiplier Effect is the Rebound Effect

While the multiplier effect is usually seen favourably, as it makes government spending or any other autonomous growth driver more effective in stimulating incomes and employment, here the corresponding supermultiplier only presents difficulties to the use of government spending to protect and expand the stock of natural capital relative to production capital. Referring back to the balance-of-emissions constraint, we see that a higher demand leakage parameter (λ) raises the growth constraint, as does a lower propensity to invest (h^*) caused by a higher normal rate of utilisation (u_n) or a lower unit capital requirement (v). Since the supermultiplier is determined by $1/(\lambda - h^*)$, this result reflects the fact that a smaller supermultiplier implies that the government spending that drives the growth of natural capital has smaller positive feedback effects on demand, output, and thus production-capital growth. In other words, we see that the supermultiplier captures the dreaded rebound effect, which lessens the effectiveness of public investment as a tool to reach net zero.[10]

With this in mind, if our primary goal is to transition to net zero and to do so quickly, the supermultiplier needs to be reduced to minimise the rebound effect. Reminding ourselves of the determinants of demand leakage parameter ($\lambda = 1 - c(1 - \tau)$), this implies a role for higher taxation and the discouragement of high overall propensities to consume through, for example, limitations on advertising or consumer credit. The difficulty in doing so lies in the fact there are possibly conflicting social goals. In particular, the overall propensity to consume depends negatively on the profit share, but higher inequality is an unnecessary and likely unacceptable means to achieve emission targets. Policies to minimise the propensity to invest could also aid in reducing the multiplier/rebound effect, in particular, an increase in the normal rate of capacity utilisation or a reduction in the unit capital requirement. However, the difficulty of using policy to achieve either outcome is likely much higher than affecting taxation, propensities to consume, or indeed the growth rate of public spending.

4.4 Depreciation and Capital Scrapping

The capital replacement rate (δ) does not influence the steady state value of the net emissions intensity, but does partly determine the speed of the transition to this steady state, as can be seen in Equations 33 and 35. This is also reflected in Figure 2, where all parameters are the same in both pathways except for the capital replacement rate, and so the pathway with the higher replacement rate reaches net zero before the other pathway, despite tending to the same long-run steady state. Since timing is of paramount importance in the pathway to net zero, it is thus also an important parameter that policy may be apt to target. Through mandating that brown capital can only be in use for a shorter period of time, policy may be used effectively to speed up the rate of capital scrapping and thus increase the replacement rate.

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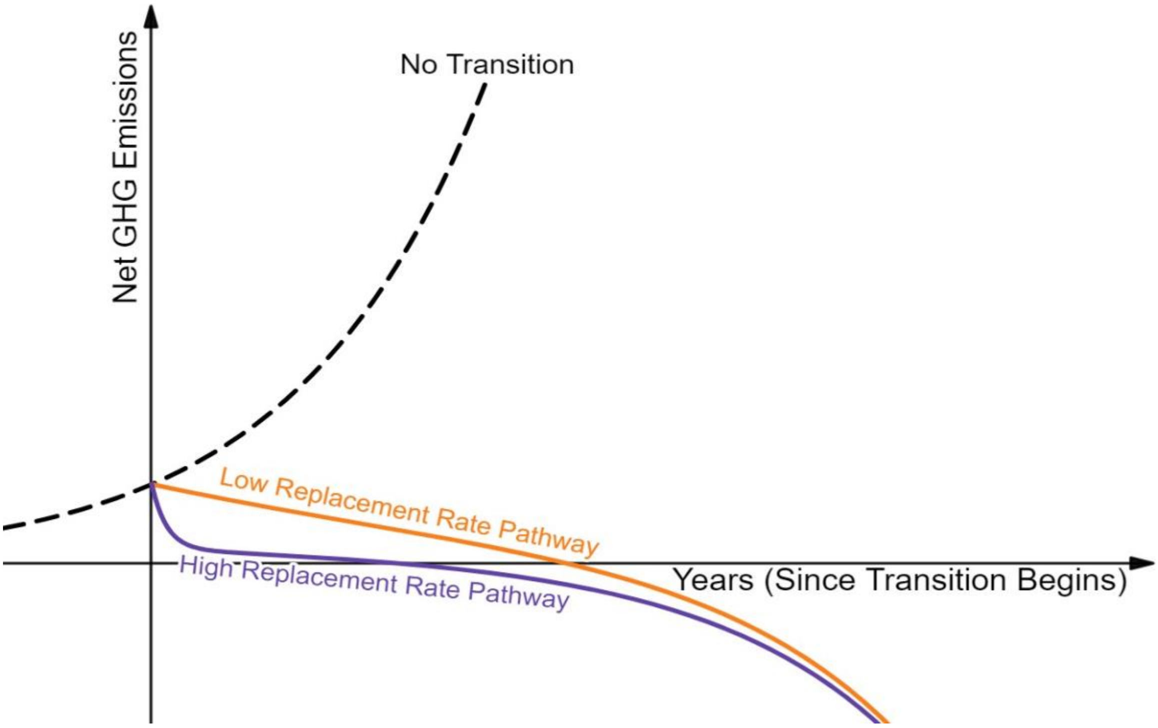
[10] Authors as Taylor et al (2016) have also warned about how higher mitigation expenditure (which includes expenditure on natural capital) boosts “output and thereby GHG emission, in a macroeconomic version of the “Jevons paradox” or “rebound effect” […]. Whether the induced increase in emission will overwhelm the reduction due to greater mitigation is ultimately an empirical question” (p.2)

Figure 2 *Effect of Capital Replacement Rate (δ) on the Speed of Achieving Net Zero*



4.5 An Urgent and Comprehensive Policy Mix for Net Zero

Based on the preceding results, we finish by describing a policy mix that can most quickly bring about net zero GHG emissions without relying on technological optimism, i.e. while maintaining the more realistic assumption that if $\phi < 1$ and $\epsilon_G > 0$. This pathway is depicted as S3 in Figure 1. This outcome requires the steady-state net emissions intensity to be as negative as possible, which implies a high share of government spending on natural capital and a low supermultiplier, i.e. high taxation and saving relative to the propensity to invest. In many ways, a lower rate of growth is also important, yet this rate of growth does not necessarily need to be non-positive, which is a valuable finding given the impossibility of a negative steady state rate of growth and the impracticality of zero growth given the aforementioned political economy considerations. Lastly, brown capital scrapping mandates, which increase the capital replacement rate, δ, further speed up the transition to net zero to the extent that they are implementable. Likewise, to the extent that regulation and policy may affect the share of green investment (ϕ) through green investment mandates or brown investment restrictions, or the emission intensity of green capital (ϵ_B) and the unit capital requirement (v) through research and development investment, these parameters may also be considered as useful policy variables rather than purely exogenous parameters.

5. Concluding Remarks

Recognising a gap in the literature, this paper offers a simple post-Keynesian model of various pathways to net zero GHG emissions. The model demonstrates that there exists a balance-of-emissions constraint on growth that must be respected if the goal of net zero is to be achieved. Our finding applies for growth rates at the global level, which need not be understood as a unified growth rate in all regions of the world. On the contrary, as envisioned in the post-growth literature, this average growth rate can encompass lower growth rates in high-income countries and higher growth rates in poorer regions in the world, which are far more reliant on economic growth to fight poverty, and to improve other socio-economic indicators.

Our findings are also in line with those who are sceptical of market-based solutions, as we have shown that, even if net zero can be achieved in the long run under a set of a highly optimistic assumptions, this long-run equilibrium would likely take too long to bring about in historical time. Instead, we have shown that net zero is more likely to be achieved with the required urgency if governments coordinate on an interventionist policy mix build upon three pillars. First, this policy mix should include regulation to maximise the investment into green capital and increase the replacement rate of brown capital. Second, higher shares of government spending on the restoration of the stock of natural capital are required to increase global absorption capacity. Third, the policy mix should aim to reduce the supermultiplier since it reflects the rebound effect. This may be achieved through higher taxation on those who can afford to pay, a lower growth rate of government spending so as to reduce firms' propensity to invest, and efforts to reduce propensities to consume through, for example, stricter limitations on advertising.

Final remarks are reserved for the limitations inherent in this highly simplified approach. First, parameters such as the green share of investment (ϕ) were assumed to be exogenous constants, whereas one might suppose they are likely inherently dynamic, increasing over time with new innovations. Similarly, the emission intensity of green capital (ϵ_G) may indeed fall over time for the same reason and do so at a higher pace given higher public and private research and development expenditures. We have abstracted away from any potential endogeneity of the absorption capacity of natural capital (α), which can be in fact a function of accumulated emissions given that increases in air temperature can affect plant carbon metabolism and hence absorption capacity (Dusenge et al, 2018), and we supposed neither the growth rate of physical capital, nor the accumulated emissions affect the growth rate of natural capital, and vice versa. Lastly, monetary policy is not considered here despite being another possible lever in the green transition. While we maintain these omissions were worthwhile to enable the development of this simple and tractable model, incorporating such considerations may prove fruitful in future work.

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