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Interplaying demand-led growth and energy supply constraints a Sraffian Supermultiplier Model with Energy Sector

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a Sraffian Supermultiplier Model with Energy Sector

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Abstract

This work aims to develop an analytical model that addresses the transition to a low-carbon economy by interplaying demand-driven dynamics and energy supply constraints. As the modeling of energy production in the ecological macroeconomics literature has been addressed within supply-driven growth models, the novelty of this article lies in integrating the energy sector into a demand-led growth framework. On the growth side, our model follows the Sraffian supermultiplier literature (Serrano, 1995). On the energy side, it draws inspiration from Bernardo and D'Alessandro (2016), explicitly modeling energy production from renewable sources. We assume business-as-usual and green government expenditures are sources of autonomous demand, with investment and capital stock composed of green and conventional components, respectively. The growth and energy sides of the model are connected through a green investment equation, which embodies a constraint on green capital stock accumulation given by the availability of renewable energy. Therefore, the growth dynamics are demand-driven, but the feasibility of the ecological transition is supply-constrained. Numerical simulations demonstrate that scenarios combining green fiscal policy and low growth are more conducive to promoting the energy transition, aligned with post-growth approaches.

Keywords: Ecological macroeconomics; demand-led growth; energy transition; mission-oriented policy.

JEL Codes: Q57; E11; E12; E62; P28

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1 Introduction

Transitioning from fossil fuels to renewable sources is at the forefront of efforts to confront climate change, prevent natural resource depletion, and potentially decouple economic growth from carbon emissions. Enhancing the capacity of renewable energy production is key in this context. Although several macroeconomic modeling tools have been devised to enhance comprehension of the connections between energy consumption and macroeconomic aggregates, the renewable energy production side is often overlooked in the ecological macroeconomics literature.

The post-Keynesian ecological macroeconomics literature has developed and expanded in recent decades to cover a broader range of issues. However, the modeling of energy production is typically addressed within supply-driven growth models (Hardt and O'Neill, 2017). Although there are ecological stock-flow consistent models (eco-SFC) that differentiate between renewable and fossil energy, its production is not specifically addressed (Dafermos et al., 2017; Carnevali et al., 2024; Jacques et al., 2023). In Dafermos et al. (2017) and Carnevali et al. (2024), the share of renewable energy consumed in production increases with the share of green capital stock, while the availability of renewable energy supply is not explicitly considered. In Jacques et al. (2023), the share of renewable energy in the total energy supply is exogenously determined.

Increasing renewable energy supply is essential to unlocking the energy transition, highlighting the importance of incorporating energy production into ecological macroeconomic modeling. Therefore, this work aims to build an analytical model to address the transition to a low-carbon economy based on a framework in which economic growth is demand-driven, but the feasibility of the green transition is supply-constrained by the availability of renewable energy. To do so, we develop a framework that integrates the energy sector into a demand-led growth model. On the growth side, the model is based on the Sraffian supermultiplier literature (Serrano, 1995), while on the energy side, it draws inspiration from Bernardo and D'Alessandro (2016).

The World Energy Investment Report revealed that public spending on energy research and development (R&D) rose by 7% globally in 2023, highlighting that governmental efforts to cut emissions while maintaining economic growth are inducing more corporate R&D and fostering the establishment of more innovative energy companies (IEA, 2024, pp. 150-176). This evidence aligns with the concept of a 'mission-oriented innovation policy of public spending' proposed by Mazzucato (2018), which argues that these spending have positive spillovers resulting from their inter-sectoral character and mobilize a crowd-in of private innovation spending. Building on the mission-oriented innovation approach and drawing from recent literature contributions that developed the Sraffian supermultiplier model with two autonomous demand sources (Freitas and Christianes, 2020; Morlin, 2022; Pedrosa et al., 2023), we propose two kinds of government expenditures as components of autonomous demand: business as usual expenditures and green innovation expenditures. Moreover, we introduce two types of capital and investment—green and conventional—while preserving the standard capital adjustment principle of the Sraffian supermultiplier model.

In the supply-driven growth models developed by D'Alessandro et al. (2010) and Bernardo and D'Alessandro (2016), the energy sector is modeled by explicitly addressing energy production from renewable sources. Building upon their approach, we integrate the energy sector into the Sraffian supermultiplier growth model by introducing a green investment function in which increasing the stock of green capital is only possible with sufficient renewable energy capacity. Hence, by integrating the energy production side, we impose an endogenously determined constraint on green capital accumulation, which differs substantially from the 'energy-constrained output' approach commonly proposed in ecological models, where production and output are constrained by an exogenously given finite stock of fossil energy reserves.

The introduction of the green investment function affects the composition of the capital stock, while it does not deal with the determination of total investment and capital stock growth rates in the Sraffian supermultiplier model. Therefore, its applicability is not limited to this class of models but is also compatible with alternative determinations of aggregate investment. Thus, this theoretically simple mechanism can be extended to different demand-led growth models, enabling them to address the energy transition, tackle environmental variables and relationships, and provide insights into pathways to sustainable development.

The article comprises three sections in addition to this introduction and the conclusion. Section 2 discusses the emergence of ecological macroeconomics alongside the 'post-growth' approaches, highlighting its complementarity with the post-Keynesian framework and clarifying our contribution to this literature. Section 3 presents the model, going through its growth side, the energy sector, and the environmental variables and relationships incorporated. Section 4 discusses the results of numerical simulations under distinct scenarios. The results highlight the role of public spending in green innovation and show that the cases with relatively lower economic growth are more conducive to the energy transition. Finally, the conclusion section closes the article.

2 The emergence of ecological macroeconomics

In recent decades, concerns over climate change have arisen due to widespread environmental degradation and a rapid increase in greenhouse gas (GHG) emissions in the atmosphere, challenging the economic system's production and consumption patterns. The rising global atmospheric temperatures due to the extensive GHG emissions threaten the ecosystems and current living standards as it could unleash extreme climate events with severe impacts if the threshold of 1.5°C above pre-industrial levels is crossed (on Climate Change), 2018). The primary goal of the Paris Agreement, the main international treaty on climate change, is to keep the global average temperature rise this century well below the critical limit of 2°C and as close as possible to 1.5°C. To achieve this goal, the treaty stipulates that GHG emissions must peak before 2025 and decline by 43 percent by 2030 with respect to 2015 levels.

Fossil fuels are the primary source of carbon emissions, accounting for around 76 percent of total GHG emissions (IEA, 2020). As the time horizon to stay within the limits imposed by the Paris Agreement narrows, the urgency of a low-carbon transition as the pathway to reduce emissions is stressed. The low-carbon transition is the process aimed at shifting the energy resources and technologies that society relies upon, currently heavily dependent on fossil fuels, towards a state where zero or low-carbon emissions are required to sustain the socioeconomic system (Nieto et al., 2020).

Based on the idea of scarcity of natural resources, the concept of 'green growth' arose in the early 2010s. Its policy agenda is intrinsically related to neoclassical economics foundations and aims to optimize resource allocation through market incentives – green subsidies and carbon taxes to correct market externalities, i.e., to enhance productivity through more efficient use of natural resources, waste reduction and lower energy consumption. The idea is that the harmful impacts on economic performance due to environmental degradation could be mapped, and the efforts to mitigate such effects represent an opportunity to improve economic growth (Reilly, 2012).

So far, the set of policies put forward on the green growth agenda failed to achieve relevant outcomes in terms of environmental sustainability (Jackson and Victor, 2019). Moreover, this approach also presents an inherent logical problem. Even if the production optimizes its efficiency, i.e., if the economy produces the same output at the highest productivity level possible and, consequently, without wasting resources, a unit of additional production would require new resources (Crist, 2019). Therefore, although optimizing the use of scarce resources is the fundamental problem in this framework, there is no optimal allocation capable of solving the scarcity issue in a growing economy. This logical problem has a second layer: the primary threat is not resource scarcity but global warming, as highlighted by the Paris Agreement's goal to limit rising atmospheric temperatures. Although both are related, in this context, it is more likely that the depletion of natural resources is a consequence of global warming rather than the immediate risk to humanity's living standards. Therefore, improving resource allocation alone cannot be a plausible solution to fight climate change.

From a theoretical point of view, several ecological economists have been arguing that the neoclassical approach ignores the principles of thermodynamics, such as the principle of mass balance and the entropy law (Georgescu-Roegen, 1971).[1] Moreover, underlying

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[1] The former states that the mass of the outputs must be equal to the mass of inputs, suggesting

assumptions of orthodox models such as the rational maximization behavior in markets and the optimal equilibrium growth path are considered flawed in addressing environment-economy interactions and "inconsistent with some of the basic premises about systems function derived from ecology" (Spash and Ryan, 2012, p. 8). In addition, Rezai et al. (2013) point out that the rationality of agents and the perfect foresight are incompatible with the fundamental social change necessary to avoid environmental collapse.

Considering the significant coupling between resource use and economic activity (Wiedmann et al., 2015), the continuous pursuit of growth is contested with the emergence of 'post-growth' approaches, which developed a conception of an environmentally sustainable and prosperous economy that does not rely on economic growth. The post-growth approaches are not homogeneous,[2] but converge to a common claim that continuous growth is incompatible with the finite nature of resources, advocating for reducing or stabilizing material and energy use within ecological limits (Hardt and O'Neill, 2017).

Although an overall economic decline is not a direct claim, the post-growth guidelines might imply slowing down, stabilizing, or even reducing GDP. Hence, post-growth approaches must deal with potential negative socioeconomic impacts. In this respect, the absence of economic growth is particularly critical for developing countries that have not yet attained a certain level of material well-being. This conflictual perspective around economic growth has been referred to in the ecological macroeconomics literature as a 'double-edged sword' (Fontana and Sawyer, 2016) and 'the twin problem of global dependencies' Gräbner-Radkowitsch and Strunk (2023), the latter explicitly addressing degrowth and the Global South.

This challenge faced by post-growth approaches highlighted the need for a macroeconomic framework to evaluate the aggregate socioeconomic effects of their proposals, paving the way for the emergence of ecological macroeconomics literature. Ecological macroeconomics aims to create robust analytical and empirical simulation frameworks to analyze the conflict between the social imperative of growth and biophysical constraints, understand the interactions between the economy and the environment on a macro level, and provide strategies for transitioning to a sustainable economy (Rezai et al., 2013; Hardt and O'Neill, 2017).

Hence, rejecting the existing mainstream approaches to integrate macroeconomic and environmental processes, the ecological macroeconomics literature emerges as a synthesis of ecological economics and post-Keynesian approaches (Hardt and O'Neill, 2017). Despite being accused by ecological economists of historically neglecting environmental issues (Daly, 2007), the post-Keynesian compatibility with the thermodynamic principles – due to the path-dependency and non-substitutability between production inputs –

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non-substitutability between material and non-material inputs. The latter implies that production is irreversible, rejecting the neoclassical assumption of malleable capital and highlighting the importance of path dependence (Kronenberg, 2010).

[2] See Kallis et al. (2012) for a differentiation among the strains of post-growth literature.

and the assumptions of fundamental uncertainty, the rejection of the notion of rational agents, the endogenous money creation, and the existence of involuntary unemployment, make the framework well-suited to complement – and be complemented by – ecological economics to address socio-economic-environmental relations (Fontana and Sawyer, 2016; Victor and Jackson, 2020).[3]

Reflecting the field's interdisciplinarity and pluralism, the ecological macroeconomics literature models are eclectic (Hardt and O'Neill, 2017; Jacques et al., 2023). As an attempt to define the scope of ecological macroeconomics, Hardt and O'Neill (2017, p. 208) identify one strain in the literature that focuses more on integrating ecological aspects into an existing macroeconomic framework without necessarily redefining the goals of the macroeconomy (Taylor et al., 2016). Meanwhile, a broader approach to ecological macroeconomics involves developing an extensive framework to comprehensively tackle the social, economic, and ecological dimensions (Jackson et al., 2014). Consequently, the visions of economic growth are not homogeneous, and not all works in the field adhere integrally to the post-growth principles.

Rather than delving into the normative debate about whether growth is desirable, we engage with the positive side of the discussion, precisely acknowledging that growth is ultimately inherent in capitalist economies. Consequently, growth models remain relevant in the literature and should be adapted to embody environmental relations and address aspects of the ecological transition. Recognizing the contentious aspects of economic growth, we have a more nuanced approach towards the notion – initially proposed by ecological economists (Kronenberg, 2010) and reflected in post-growth theories – that growth no longer enhances welfare globally. This stance does not promote 'growth-mania' (Fontana and Sawyer, 2016) but recognizes that the relevance of economic growth cannot be neglected, particularly for low-income countries facing high unemployment. Therefore, this work aims to build an analytical model to address the transition to a low-carbon economy by integrating the energy sector into a demand-led growth framework, interplaying demand-driven dynamics and energetic supply constraints.[4]

Given the high uncertainty surrounding the investments needed to decarbonize the economy and the urgency of the climate crisis, the State emerges as a potential agent for planning and coordinating efforts to mobilize the economy toward a low-carbon transition (Feij et al., 2023). Moreover, the private financial sector often fails to meet the credit demands of specific economic segments and geographic areas (Feil and Feijó, 2021), which highlights the limitations of relying majorly on market mechanisms to drive the green transition that requires a large volume of investments with high risk and uncertain return. Therefore, on the growth side, we build on the mission-oriented innovation

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[3] See Saes and Romeiro (2019) for an extensive methodological review of the foundations of the ecological macroeconomics framework.

[4] The necessity of interplaying demand-led and supply-constrained in ecological macroeconomics analytically solvable models is stressed in Hardt and O'Neill (2017, p. 134).

approach (Mazzucato, 2018; Deleidi and Mazzucato, 2021) and propose a Sraffian supermultiplier model with two autonomous demand sources, namely business as usual and green innovation government expenditures.

Among the twenty-two ecological macroeconomics articles surveyed in Hardt and O'Neill (2017), there are only two where the energy sector is modeled, precisely in the supply-driven growth models developed in D'Alessandro et al. (2010) and Bernardo and D'Alessandro (2016). Since then, a few eco-SFC models considered the energy transition from fossil fuel to renewable energy (Dafermos et al., 2017; Carnevali et al., 2024), although the energy production sector was overlooked (see Jacques et al. (2023)). Usually, the models within the ecological macroeconomics literature that integrate the environment do so by including energy, resources, or waste as proportional to the total output of the economy given some exogenous intensity parameter (Hardt and O'Neill, 2017).[5]

Building on the energy sector modeled in Bernardo and D'Alessandro (2016), we step forward by embodying renewable energy production in the growth model, allowing the changes in the composition of total energy from renewable and fossil sources to be determined endogenously. Simultaneously, renewable energy availability is integrated into the green investment function, representing a supply constraint to green capital stock accumulation. Therefore, the growth dynamics are demand-driven, but the feasibility of the ecological transition is supply-constrained. Moreover, it is noteworthy that two post-growth policy themes are integrated as elements of our model.[6] First, we relate the economic side of the model with the ecosystem and interact it with environmental limits. Second, by disaggregating the energy sector production between renewable and fossil fuel sources, we incorporate the ability of industries to produce goods with different environmental impacts. Figure 1 presents a simplified diagram that illustrates the model's primary relationships.

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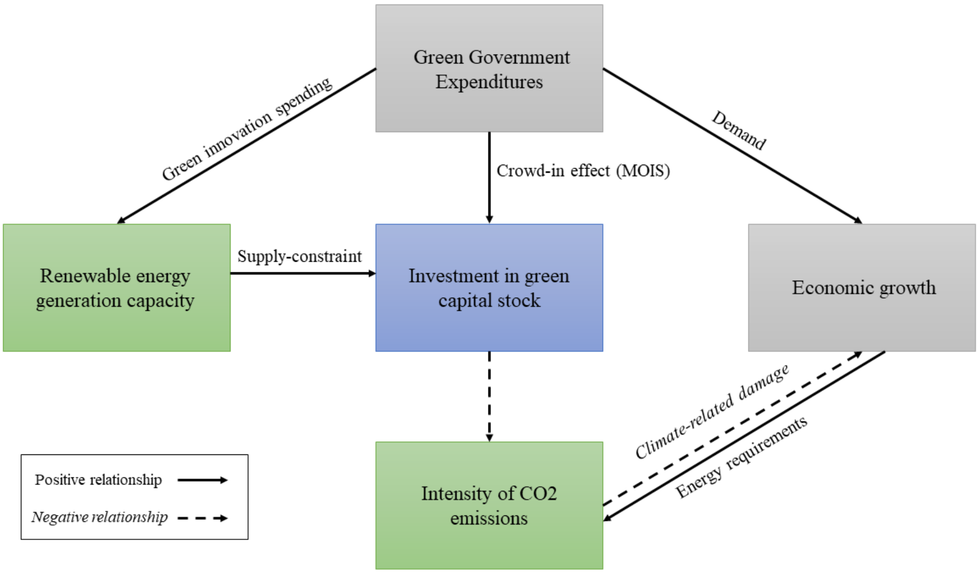
[5] Here, we refer specifically to analytical models. Integrated Assessment Models (IAM) such as MEDEAS (Capellán-Pérez et al., 2020), E3ME (Econometrics, 2022), and the EUROGREEN (D'Alessandro et al., 2020), are simulation models that rely on a different approach (see Nieto et al. (2020, p. 2).

[6] See Table 2 in Hardt and O'Neill (2017, p. 202) for a summary of post-growth policy themes potentially incorporated into models within the ecological macroeconomics literature.

Figure 1: Simplified model diagram



As the next section demonstrates, a valuable feature of the green investment function introduced in this article is its ability to allow changes in the composition of the capital stock while preserving aggregate investment determination. For this reason, the mechanism is not limited to the Sraffian supermultiplier model, and it is also compatible with alternative demand-led growth models, enabling them to address the energy transition, incorporate environmental variables and relationships, and provide insights into pathways for sustainable development.

3 The model

Consider a closed two-sector economy that produces, with a given technology,[7] one single final good and energy as an intermediary good. We employ a Leontief production function with capital (K) and energy (E) as inputs, which, by definition, assumes no substitutability between factors – an approach consistent with the thermodynamic principles discussed in the previous section. We assume that there is no labor scarcity, so it is never a constraint to production. The production function is presented in the Equation 1.

$$Y^{(K,E)} = \min\left(\frac{K}{v}, \frac{E}{\varepsilon}\right) \tag{1}$$

Where v denotes the capital-output ratio and ε is the energy intensity of output. Both are treated as fixed exogenous parameters, as technical progress is not addressed.

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[7] For the sake of simplicity, it is assumed that there is no technical progress.

Firms can produce either with brown or green capital, which differ based on the source of energy they use, respectively fossil and renewable energy.

3.1 Growth side

The structure of the growth dynamics follows a standard Sraffian Supermultiplier model in discrete time. In our model, autonomous demand (Z) is composed of two kinds of non-capacity-creating government expenditures, while the induced components are characterized by their respective propensities. The demand components are described by the equations from 2 to 8.

$$Y_t = G_t + C_t + I_t + I_t^R + I_t^Q \tag{2}$$

$$G_t = G_t^{bau} + G_t^{gr} = Z_t \tag{3}$$

$$C_t = c_t Y_t \tag{4}$$

$$I_t = h_t Y_t \tag{5}$$

$$I_t^R = e_t Y_t \tag{6}$$

$$I_t^Q = q Y_t \tag{7}$$

$$Y_t = \frac{1}{1 - c_t - h_t - e_t - q} Z_t = \alpha_t Z_t \tag{8}$$

Where Eq. 2 describes the equilibrium in the goods market, given by the equality between the output Y and aggregate demand; Eq. 3 denotes the government expenditures (G_t) and, consequently, autonomous demand (Z_t) as the sum of 'business-as-usual' (G_t^{bau}) and 'green' government expenditures ($G_t^g r$); Eq. 4 indicate the propensity to consume (c_t); Eq. 5 stand for the propensity to invest in the final sector (h_t); given that it is a two-sector model, we account for the investment in the energy sector, where Eq. 6 specifies the propensity to invest in the renewable energy (e_t) and Eq. 7 the exogenously given propensity to invest in fossil energy (q); finally, Eq. 8 expresses output in terms of the supermultiplier (α) and autonomous demand (Z).[8]

The potential output (Y_t^K) (Eq. 9) is the level of output at full capacity, depending on the capital stock (K_t) and on the fixed capital-output ratio (v), since there is no substitution between production inputs. So, the current capacity utilization level (u_t) is given by the ratio between Y_t and Y_t^K (Eq. 10).

$$Y_t^K = \left(\frac{1}{v}\right) K_t \tag{9}$$

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[8] As showed in Freitas and Serrano (2015), the model is stable as long as the so-called Keynesian stability condition holds, i.e., the expanded marginal propensity to spend is lower than 1. Therefore, stability requires that $(\bar{c} + \bar{h} + \bar{e} + q) < 1$.

$$u_t = \frac{Y_t}{Y_t^K} \tag{10}$$

Next, we can introduce the main relations of the Sraffian supermultiplier model, which are described by the equations from 11 to 13.

$$\hat{h} = \gamma \left(u_{t-1} - u_n\right) \tag{11}$$

$$g_t^K = \frac{h_{t-1}}{v} u_{t-1} - \delta \tag{12}$$

$$\hat{u} = \frac{g_y^Y - g_t^K}{1 + g_t^K} \tag{13}$$

The rate of change of investment $\hat{h}$ follows the flexible accelerator principle, which posits that whenever the current capacity utilization deviates from the normal level desired by firms (u_n), the propensity to investment slowly adjusts to bring the current capacity back to the target. The mechanism is described in Eq. 11,[9] where $\gamma > 0$ is a fixed coefficient indicating the speed at which h responds to deviations in u_t. The growth rate of capital stock (g_t^K) is given by Eq. 12, where δ is the fixed depreciation rate. Finally, Eq. 13 indicates the rate of change in capacity utilization ($\hat{u}$).[10]

To adapt the model to tackle the ecological transition, we distinguish capital and investment in the final goods sector into green and conventional (brown) components (Equations 14-16). Regarding capital, this differentiation hinges solely on the energy source employed. Green capital ($K^g r$) operates on renewable energy, whereas conventional capital (K^c) relies on fossil fuel. For the sake of simplicity, considering that v and ε are fixed parameters, it is assumed that green and conventional capital are technically perfect substitutes, having identical productivity and energy efficiency. This means they share the same capital-to-output ratios and require the same amount of energy to produce one output unit.

$$K_t = K_t^c + K_t^{gr} \tag{14}$$

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[9] Eq. 12 is obtained from the law of motion of capital, given by: $g_t^K = \frac{K_t - K_{t-1}}{K_{t-1}} = \frac{I_{t-1}}{K_{t-1}} - \delta$. We first divide both terms of the fraction by Y_{t-1}^K. Then, we multiply the numerator by Y_{t-1}/Y_{t-1}, which doesn't imply any changes in its value. We obtain the following expression: $\frac{I_{t-1} Y_{t-1} / Y_{t-1}^K Y_{t-1}}{K_{t-1} / Y_{t-1}^K}$. Finally, we can rewrite I_{t-1}/Y_{t-1}, $Y_{t-1}/Y_{t-1}^K/Y_{t-1}^K$, and K_{t-1}/Y_{t-1}^K respectively as h_{t-1}, u_{t-1} and v.

[10] To obtain Eq. 13 we depart from $\hat{u} = \left(u_t - u_{t-1}\right)/u_{t-1}$. By substituting u as given by Eq. 10 and rearranging, we obtain: $\frac{Y_t Y_{t-1}^K}{Y_t^K Y_{t-1}} - 1$. Then, we substitute Y_t/Y_{t-1} and Y_{t-1}^K/Y_t^K respectively by $1 + g_t^Y$ and $1/(1 + g_t^{Y^K})$ and simplify the expression. Finally, since the capital-output ratio v is constant, we replace the growth rate of potential output by the growth rate of capital to obtain Eq. 13.

$$K_t = \left[K^c_{t-1}(1-\delta) + I^c_{t-1}\right] + \left[K^{gr}_{t-1}(1-\delta) + I^{gr}_{t-1}\right] \tag{15}$$

$$I_t = I^c_t + I^{gr}_t \tag{16}$$

Enhancing energy efficiency is undeniably an essential aspect of the transition to a low-carbon economy. However, considering the purposes of this article, although an eventual increase in energy efficiency would reduce the energy required per unit of output, this improvement would not alter the model's underlying constraint: that the availability of renewable energy generation capacity limits green capital accumulation. The same reasoning applies if hybrid capital was considered, i.e., capital capable of operating either with fossil or renewable services. Ultimately, the share of capital effectively operating with renewable energy (green capital) would still be constrained by the availability of renewable energy capacity. Therefore, two simplifying assumptions are adopted for analytical tractability: constant energy efficiency and the absence of hybrid capital stock. Future versions of the model, however, could incorporate these potential improvements.

Recall that Eq. 16 represents the investment in the final sector, while the investment in the energy sector is described in Eq. 6 and 7. The decomposition of capital and investment does not alter the aggregate behavior of total investment, as defined in Eq. 11, or the total capital growth rate, as in Eq. 12, but rather allows for changes in its composition shares, which enables the model to consider aspects regarding the ecological transition explicitly. The changes in composition stem from the green investment (I^{gr}) equation, while the conventional investment (I^c) is residual, accounting for the portion of total investment not allocated to green investment. The equations will be introduced in the next section.

Given that we have two sources of autonomous demand, Eq. 17 introduces σ as the share of government expenditures in green innovation over total government expenditures. Eq. 18 gives the growth rate of autonomous demand, which is precisely the growth rate of government expenditures.[11]

$$\sigma_t = \frac{G^{gr}_t}{G_t} = \frac{G^{gr}_t}{Z_t} \tag{17}$$

$$g^Z_t = \sigma_{t-1} g^{G^{gr}} + (1-\sigma_{t-1}) g^{G^{bau}} \tag{18}$$

We assume that public expenditures are financed out of public debt, although the financial side of the economy is not explicitly addressed in this study. However, public

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[11] Although in our model the autonomous demand (Z) is represented solely by government expenditures (G), we use the notation Z to follow the pattern in the literature and clarify that the properties discussed apply to autonomous expenditures in general, regardless they consist solely of government expenditures, as in our case, or different sources.

debt's growth rate converges with government expenditures' growth rate. Pariboni (2016) presents formal proof for an analogous case in which it is shown that the growth rate of autonomous consumption tends to coincide with the growth rate of consumer debt (Pariboni, 2016, p. 225). In our model, this means that the debt-to-output ratio is stable in equilibrium. In models with a second source of autonomous demand besides government expenditures, the long-run stability of the debt-to-output ratio requires that the equilibrium growth rate is higher than the interest rate and that both autonomous expenditures do not grow persistently at different rates (Freitas and Christianes, 2020; Morlin, 2022).

Finally, we outline the energy and ecological-related variables on the growth side of the model by determining the propensities to consume c_t (Eq. 19) and to invest in renewable energy sector e_t (Eq. 21).

$$c_t = p_c(1 - D_t) \tag{19}$$

$$\Delta c_t = p_c(D_{t-1} - D_t) \tag{20}$$

$$e_t = e_{t-1} + \Delta e_t \tag{21}$$

$$\Delta e_t = e_{t-1}\left(g^{Ggr}_{t-1} - g^{Z}_{t-1}\right) \tag{22}$$

Where p_c is a fixed propensity to consume which is affected negatively by D_t, a damage coefficient between 0 and 1. As described in Eq. 20, the propensity to consume is assumed to be sensitive to climate-related damages which is a function of the atmospheric temperatures. In response to these damages, households may act cautiously, leading to a higher propensity to save (Dafermos et al., 2017). The damage function will be described in the next section. Equations 21 and 22 show that the propensity to invest in the renewable energy sector increases if the government adopts a more aggressive ecological policy by increasing green expenditures' growth (g^{Ggr}_t) beyond the growth trend of the economy, represented by g^Z. It signals to the private sector its intention to accelerate the expansion of renewable energy capacity and guide the economy towards greener production. Therefore, aligned with the mission-oriented innovation spending, it generates a crowd-in effect, captured by increasing the private sector's propensity to invest in renewable energy capacity. As shown in the World Energy Investment Report (IEA, 2024), the rise in government spending to tackle climate change and policies promoting the adoption of low-emission technologies have been inducing corporate spending on energy R&D. Since 2019, this spending has grown by an average of 7% per year, more than three times faster than global GDP (IEA, 2024, p. 163).

3.1.1 The fully adjusted position

Before outlining the model's convergence to the fully adjusted position, we emphasize that the dynamics of the variables outside of equilibrium reveal more about the underlying processes of the ecological transition, beyond just the long-run equilibrium values. Accordingly, in Section 4, we conduct a numerical simulation to explore these transitional behaviors. Nonetheless, the convergence to the fully adjusted position ensures the stability of the framework, allowing the transitional dynamics to be meaningfully analyzed.

In the standard Sraffian supermultiplier model, the fully adjusted position is achieved when the capacity utilization converges to the normal rate desired by firms ($u_t = u_n$), stabilizing the propensity to invest ($\Delta h = 0$) and consequently the level of capacity utilization itself ($\Delta u = 0$). Since, in equilibrium, the output growth is the autonomous demand growth, a persistently stable growth of autonomous demand is required to obtain the fully adjusted position of the model (Freitas and Serrano, 2015). In a version with two sources of autonomous demand, this condition requires that both expenditures grow at the same rate (see Morlin (2022)). If the growth rates of two sources of autonomous demand differ persistently, σ will tend toward 0 or 1. Therefore, the fully adjusted position requires a constant ratio between the autonomous expenditures ($\Delta\sigma = 0$).

Since we are dealing with two types of government expenditures, it is reasonable to assume that neither will disappear. The divergence in growth rates for each type of expenditure is significant for the analysis, as they lead to different long-run equilibrium paths. However, we consider this variation as a temporary policy measure, assuming that the government sets a single long-run growth rate for its spending, ensuring that both G^{bau} and G^{gr} will ultimately grow at the same pace and stabilizes.

Moreover, recalling Eq. 8, the output growth will converge to the autonomous demand growth only when the propensities that compose the supermultiplier α are constant.[12] Besides h that was already discussed, we have two additional endogenous variables c and e. In sum, the convergence to the fully adjusted position requires that $\Delta u = \Delta h = \Delta\sigma = \Delta c = \Delta e = 0$.

Regarding e, Eq. 22 shows that $\Delta e = 0$ when $g^{G^{gr}} = g^{Z}$, which is precisely the condition that stabilizes σ. In this case, the private investment in renewable energy sector simply follows the output and the propensity e remains constant. Finally, as of c, Eq. 20 shows that the propensity to consume is stable when the damage coefficient D is constant. The conditions to meet this requirement will be discussed in the environment subsection.

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[12] See Appendix B for the derivation of output growth.

3.2 Energy sector

We build upon the work of Bernardo and D'Alessandro (2016) to model the energy sector with a specific focus on renewable energy production capacity. Their macroeconomic framework analyzes the impacts on employment and inequality of various strategies for reducing carbon emissions, including the expansion of renewable energy capacity.

Equation 23 represents the equilibrium in the final energy sector. On the supply side, the total energy flow available (E_t) consists of the fossil energy flow (X_t) and the renewable energy flow (L_t). On the demand side, total energy required for production is the product of output (Y) and energy intensity coefficient, denoted by the fixed parameter ε. The energy intensity measures the energy needed to produce one unit of output and is typically expressed in kilowatt-hours per dollar.

$$E_t = X_t + L_t = Y_t \varepsilon \tag{23}$$

In our model, we assume that the economy's intermediary sector, precisely the energy production sector, produces its own energy requirements. In this sense, the capital in the intermediary sector consumes part of the energy it produces. The relation between the net energy output and energy input throughout the energy production process is evaluated by the concept of energy-return-to-investment (EROI). The EROI is a ratio between the net energy produced and the energy invested directly and indirectly in the process (Eq. 24).

$$EROI = \frac{\text{net energy output}}{\text{energy input}} \tag{24}$$

Recent estimations suggest that the final stage EROI of fossil fuels and renewables ranges within overlapping intervals (Brockway et al., 2019). So, for simplicity, we assume they are equal. Considering that the net energy output of fossil and renewable energies is given respectively by X and L, we define the energy consumed in the intermediary sector in equations 25 and 26.

$$X^{int} = \frac{X}{EROI} \tag{25}$$

$$E^{int} = \frac{E}{EROI} \tag{26}$$

Therefore, E can be understood as a net energy production, which is also the energy available for the final sector. Still, the energy consumed in the intermediary sector will be taken into account to address pollutant emissions.[13]

Since the shares of fossil and renewable energy within total energy are determined

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[13] Following Brockway et al. (2019), we assume a final stage EROI of 6:1.

by the capital composition, we first have to define the amount of energy required by the operating capital stock. By playing with equations 10, 9 and 23, we can express both the capital stock (K) and energy (E) in terms of output (Y). Starting with Eq. 10, we isolate Y_t to arrive at $Y_t = u_t Y_t^K$. Substituting Y_t^K with its expression from Eq. 9 results in $Y_t = \frac{u_t K_t}{v}$. Similarly, isolating Y_t in Eq. 23 gives $Y_t = \varepsilon E_t$. Since both equations are expressed in terms of Y_t, equating them leads to $\frac{E_t}{\varepsilon} = \frac{u_t K_t}{v}$. Finally, by isolating E_t, we obtain Eq. 27, which represents the total energy demanded by the capital stock, considering the level of capacity utilization.

$$E_t = \frac{u_t \varepsilon}{v} K_t \tag{27}$$

Since green and conventional capital are technically perfect substitutes,[14] Kt can be decomposed into green and conventional capital components (as expressed in Eq. 15). This allows us to explicitly calculate the renewable and fossil energy required for production, given by equations 28 and 29, respectively.

$$L_t = \frac{u_t \varepsilon}{v} K_t^{gr} \tag{28}$$

$$X_t = \frac{u_t \varepsilon}{v} K_t^{c} \tag{29}$$

The fossil energy flow is treated as a residual variable in the model, so it adjusts to meet the technical efficiency of production ($X_t = Y_t \varepsilon - L_t$). In sum, the composition of investment alters the share of green and conventional capital, thereby determining the composition of energy consumed. The flows of renewable and fossil energy are limited to R_t and Q_t, their respective production capacities during the period, as shown in Eq. (LR) and Eq. (XQ).

$$L_t = l R_t \tag{30}$$

$$X_t = x Q_t \tag{31}$$

Where l and x are coefficients ranging between 0 and 1. Since fossil fuel energy is treated as a residual variable, we assume that Q_t will consistently meet the demand for fossil energy. While we acknowledge the finite nature of fossil fuel reserves, our model does not address this aspect as we do not intend to analyze pathways for resource-constrained growth; rather, our focus is on pathways for a transition constrained by the availability renewable energy.

Hence, the underlying principle of the model is that the structural shift from con-

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[14] We assume that the target capacity utilization is identical for both types of capital. For simplicity, we also consider their current capacity utilization rates to be equal.

ventional to green capital and, consequently, the ecological transition is limited by the availability of renewable energy. Since in our model firms demand renewable energy (L) to fuel their green capital stock, the accumulation of the latter is constrained by the renewable energy capacity generation (R), whose accumulation function is adapted from Bernardo and D'Alessandro (2016) and described as follows.

$$R_t = R_{t-1} + \left[\left(I^R_{t-1} + rG^{gr}_{t-1}\right) f(R_t)\right] - \delta^R(R_{t-1}) \tag{32}$$

$$f(R_t) = \rho_0 + \frac{\rho_1}{1 + e^{-\rho_2(\rho_3 R_{t-1} - \rho_4)}} \tag{33}$$

Where r is a parameter between 0 and 1 that determines the share of green government expenditures specifically oriented to innovations to expand the renewable energy capacity. Following the concept of the mission-oriented innovation, the government expenditures in green innovation have a direct effect in expanding the renewable energy capacity, as depicted by the parameter r, and also indirect by generating a crowd in effect in green private investment (recall Eq. 23). Next, δ^R is the depreciation rate of the capacity; and $f(R_t)$ is a logistic function that captures the diffusion of knowledge to the extent that R increases (Eq. 33). In sum, it is the ability of investment to actually increase R (Bernardo and D'Alessandro, 2016).

Therefore, increasing the stock of green capital is only possible with sufficient renewable energy capacity, as any incremental unit of green capital beyond the energy generation capacity would be necessarily idle. Thus, this constraint must be embodied in our green investment function. Recalling Eq. 30, the flow of renewable energy L is limited by the renewable energy capacity generation R. When $L = R$, it signifies that the flow of renewable energy consumed during the period reaches its maximum potential given the capacity. Then, R represents the maximum supply of renewable energy in the period. Therefore, considering a scenario where $L = R$, substituting L by R in Eq. 28 leads to $\frac{u_t \varepsilon}{v} K^{gr}_t = R_t$. Then, by isolating K^{gr}, we obtain the maximum amount of green capital that the renewable energy capacity can accommodate, which we denote as K^{gr}_{max} in Eq. 34. In sum, K^{gr}_{max} represents the stock of green capital that would fully utilize the renewable energy capacity, implying that $L = R$.

$$K^{gr}_{max,t} = \frac{R_t v}{u_t \varepsilon} \tag{34}$$

The renewable energy supply constraint requires that $\left(\frac{\varepsilon K^{gr}}{uv}\right) \leq R$, ensuring that $0 \leq l \leq 1$.[15] This condition applies when $K^{gr} \leq K^{gr}_{max}$. If, eventually, $K^{gr} > K^{gr}_{max}$, the

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[15] If the demand is lower than the capacity $\left(R > \frac{\varepsilon K^{gr}}{uv}\right)$, then $l < 1$. If the demand for renewable energy is equal to the capacity $\left(\frac{\varepsilon K^{gr}}{uv} = R\right)$, then $l = 1$ Finally, if the demand for renewable energy exceeds the capacity, we would have idle green capital. However, it is not the case since the green capital accumulation is constrained by K^{gr}_{max} (see Eq. 35).

excess of green capital would be idle due to the lack of availability of renewable energy. Therefore, this constraint (Eq. 34) underpins the foundation of the green investment function, which is defined in Eq. 35. Since total investment in the final sector (I) is determined following the flexible accelerator principle (recall Eq. 11), the investment in conventional capital (I^c) is treated as a residual variable, representing the remainder of total investment not allocated to green investment (Eq. 36).

$$I_t^{gr} = \left(K_{max,t-1}^{gr} - K_{t-1}^{gr}\right)\lambda + K_{t-1}^{gr}\delta^{gr} \tag{35}$$

$$I_t^c = I_t - I_t^{gr} \tag{36}$$

The green investment function (Eq. 35) incorporates the spare capacity of renewable energy as both a trigger and a supply-constraint of green investment. The $K_{max,t-1}^{gr}$ is the maximum green capital held by the renewable energy capacity in the previous period, representing the renewable energy supply-constraint. If $K_{max,t-1}^{gr} = K_{t-1}^{gr}$, it means that there was no spare renewable energy capacity in the previous period. Thus, the terms cancel out and the share of green investment will simply be the one that compensates the green capital depreciation $\left(K_{t-1}^{gr}\delta^{gr}\right)$. On the other hand, if the renewable energy capacity was not fully used in the previous period $\left(K_{max,t-1}^{gr} > K_{t-1}^{gr}\right)$, the available margin to expand the stock of green capital increases the green investment. The speed of this adjustment is given by λ, an exogenous coefficient between 0 and 1.

The spare renewable energy encouraging investment in green capital and the treatment of conventional investment as residual embody the assumption that firms have incentives to prefer green capital over conventional capital. In the model, this assumption aligns with the fact that climate change negatively affects consumption through a damage function, implicitly favoring green capital since it is not a pollutant and does not impact the damage. Also, although energy storage is not explicitly addressed, it is taken into account that renewable energy is difficult to store. Hence, any unused capacity is essentially lost, wasting both the energy and the resources invested in expanding renewable energy capacity, represented by I^R in the model (see Eq. 6). Additionally, this assumption is supported by real-world legislation aligned with ecological transition objectives. For example, the European Union (EU) Renewable Energy Directive 2023/2413 prioritizes using renewable energy over fossil fuels.

3.2.1 The fully adjusted position

As previously emphasized, the decomposition of capital and investment into conventional and green categories does not alter the aggregate behavior of total investment and the capital accumulation rate. Similarly, including the energy sector does not alter the equilibrium and stability conditions of the model, as the energy variables converge to the exogenous growth rate set by the autonomous demand growth rate.

Regarding the renewable energy capacity R, once $f(R)$ reaches its maximum value and becomes constant, the rate of accumulation of R depends solely on the growth rate of both public and private investment in renewable energy capacity, expenditures whose growth rate converge to the autonomous demand growth rate (see section 3.1.1). In sum, when the rate of accumulation of R stabilizes, the entire energy side of the model converges to equilibrium.

Since the growth rate of K^{gr}_{max} depends on R, it also converges to the autonomous demand growth rate. Recalling Eq. 35, the green investment I^{gr} depends on K^{gr}_{max} and K^{gr}. However, since we have two K^{gr} terms with opposite signs, $-\lambda K^{gr}$ and $\delta^R K^{gr}$, the contributions to growth cancel out, resulting in $g^{I^{gr}} = g^{K^{gr}_{max}} = g^Z$. Consequently, since in the long run $\Delta h = 0$ and total investment is fully induced, we have that $g^{I^{gr}} = g^I$ and the share of green investment stabilizes.

Finally, this implies that the accumulation rate of green capital K^{gr} and, subsequently, the growth rate of renewable energy consumption L, also converge to g^Z. Thus, the share of green capital and, consequently, the share of renewable energy consumption out of total energy stabilize.

3.3 Environment

Once the energy sector was integrated to the growth model, we can address the ecological relations by introducing the environmental variables. We define pollution as function of carbon emissions (Eq. 37).

$$P_t = \phi \left(X_t + X_t^{int} \right) \tag{37}$$

Where ϕ is an exogenous parameter indicating the carbon emission by unit of fossil energy used in production. Recall that X_t is the fossil energy flow consumed in the final sector and X_t^{int} is the energy consumption in the intermediary sector Eq. 25, as the capital in the intermediary sector consumes part of the energy it produces. The consumption of renewable energy, L, is naturally non-polluting as it produces no waste or harmful emissions. Moreover, since the intermediary sector generates its own energy requirements, the renewable energy production is assumed as non-polluting in the model.

Pollutant emissions are the main driver of climate change, which, in our model, affects negatively the economic output through a harmful effect in household consumption. The effect was introduced in Eq. (20), where the determination of the propensity to consume was described as $c_t = p_c(1 - D_t)$. The propensity to consume is assumed to be sensitive to climate-related damages due to the increase in natural disasters, which can cause job losses, property destruction, and health issues driven by climate change. In response to these damages, households may act cautiously, leading to a higher propensity to save (Dafermos et al., 2017).[16] The magnitude of the effect is determined by a damage coefficient D, described in Eq. 38.

$$D_t = 1 - \frac{1}{1 + \eta_1 T_t + \eta_2 T_t^2 + \eta_3 T_t^{6.754}} \tag{38}$$

As proposed in Weitzman (2012) the function links the damage to the atmospheric temperature over pre-industrial levels (T). The coefficient D ranges between 0 and 1, and the parameters η were calibrated for $D = 0.5$ for an atmospheric temperature of 6º C above pre-industrial levels (Weitzman, 2012). The atmospheric temperature raises due to a higher concentration of CO2 in the atmosphere, so we determine T as a logistic function of pollution (Eq. 39).

$$T_t = \frac{\tau_1}{1 + e^{-\tau_2 (P_t \tau_3 - \tau_4)}} \tag{39}$$

According to the report *Climate Change 2021* released by the Intergovernmental Panel on Climate Change, the worst-case scenario estimates suggest an annual mean atmospheric temperature between 4°C and 4.8ºC above pre-industrial levels for the year 2100 (Lee et al., 2021, p. 572), which is incompatible with the ecological system. Therefore, the parameter τ_1 assumes the maximum value of T considering a worst-case scenario, and τ_2, τ_3, and τ_4 are calibrated to stem an initial value of 1º C, roughly the current level of atmospheric temperatures relative to pre-industrial period.

3.3.1 Fully adjusted position

As previously mentioned, the convergence to equilibrium requires a stable propensity to consume, which is achieved under a constant damage coefficient ($\Delta D_t = 0$). According to Eq. 38, this condition requires a stable atmospheric temperature (T), which can be achieved either by stabilizing the level of carbon emissions ($\Delta P_t = 0$), or when the atmospheric temperature achieves its maximum value. Therefore, unless the flow of fossil fuel energy stops rising, reaching the atmospheric temperature tipping point of 4.8°C can only be delayed, akin to buying time. Since the pollution is determined by the fossil energy consumed, which instead is function of the conventional capital used in production, the emissions-to-output ratio converge to an equilibrium value since the growth rate of conventional capital tends to coincide with the autonomous demand rate of growth.

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[16] Besides affecting the propensity to consume, the damage coefficient may also be related to investment decisions and capital depreciation (see Dafermos et al. (2017); Carnevali et al. (2024)).

4 Simulation scenarios and results

The main properties and relationships of the model can be analyzed through numerical simulations. In this study, our primary interest lies in the relative differences among distinct scenarios rather than the absolute values of the variables. Since the model does not rely on real-world data, the absolute values generated are not intended to represent any specific real-world quantities. Instead, these values serve as a means to explore the convergence dynamics and interactions within the model under different conditions. The model's equilibrium robustness is assessed through sensitivity analysis within the dynamic system, using Monte Carlo simulations to introduce random shocks to selected variables, with the results presented in Appendix C. At the same time, we argue that observing the behavior of the variables out of the fully-adjusted position provides more interesting insights than assessing the long-run equilibrium values.

All scenarios depart from a steady-state position, allowing us to isolate the effects of parameter changes in different scenarios.[17] Otherwise, it would be unclear whether variable behaviors result from exogenous shocks or the model's intrinsic convergence dynamics. Then, we create different scenarios by imposing shocks in the period t. The different scenarios are described in Table 1.

Table 1: Simulation scenarios

	Case 1	**Case 2**	**Case 3**	**Case 4**
Name	Baseline	Green G	Green G + low g^*	Case 3 + temporary shock
g^*	0.03	0.03	0.01	0.01
σ_t	-	0.1	0.1	0.1
Temporary shock	-	-	-	$gG^{gr}_{t:t+25} = 0.03$

We denote g^* as the equilibrium growth rate, which is determined by long-term growth rate of autonomous sources of demand, represented in our model by government expenditures. In the baselin/e scenario, we 'activate' the atmospheric temperature function, allowing the damage coefficient to be endogenously determined. Furthermore, we assume the absence of green policy ($\sigma = G^{gr}/G = 0$), characterized by a single business-as-usual government expenditure component. Hence, in the baseline scenario, any short-term deviations from equilibrium are specifically due to the impact of the increasing damage coefficient on consumption.

Based this on the pollution emissions in the baseline scenario, the atmospheric temperature function (Eq. 39) was calibrated to achieve 4°C above pre-industrial levels in t+80 periods, accordingly to the worst-case scenario forecasted by the IPCC Lee et al.

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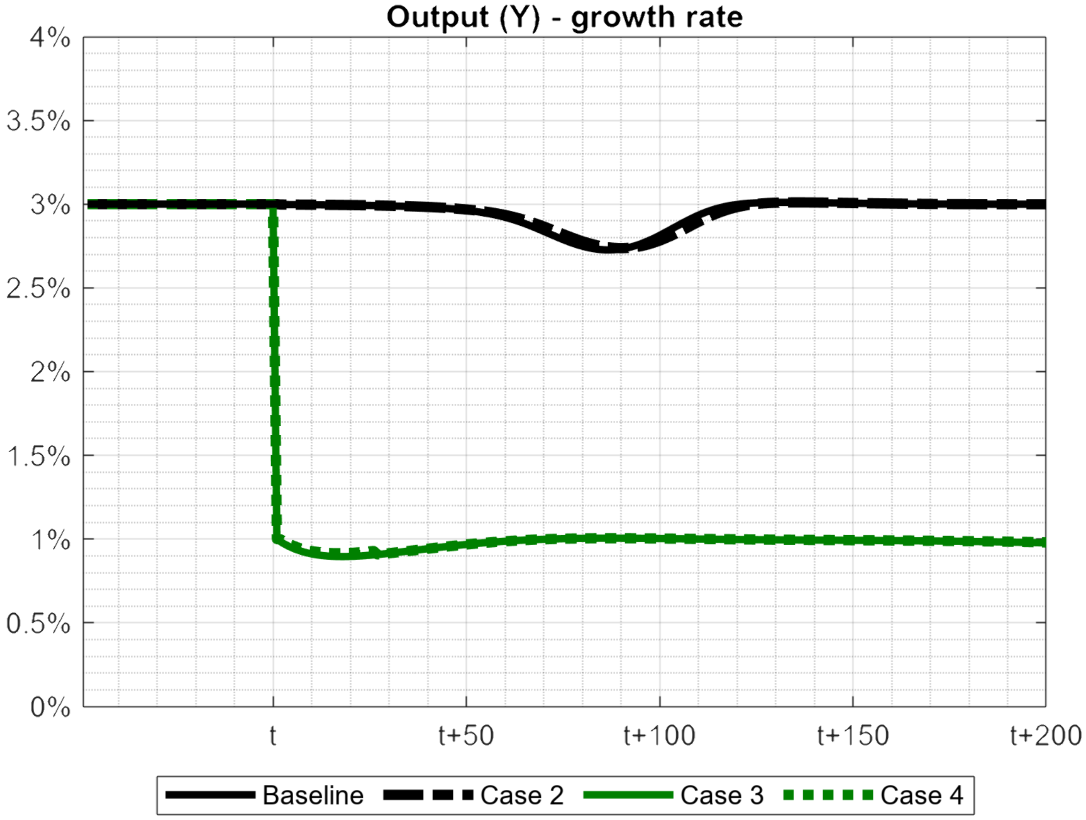
[17] We temporarily set the atmospheric temperature as fixed to depart from a steady-state position, implying a constant damage coefficient. Since the damage coefficient depends on pollution, and pollution grows at an exogenous rate in equilibrium, the damage coefficient would naturally increase, causing a variation in the propensity to consume and a deviation from the steady-state position.

(2021, p. 572). In our model, since the rate of change of pollutant emissions is greater than zero under all simulated scenarios, slowing down emissions only delays the rise in atmospheric temperature. Eventually, the temperature reaches its maximum value of 4.8°C. Consequently, the lower the rate of change in emissions, the longer it takes for the model to stabilize and converge to its fully adjusted position.

Case 2 introduces G^{gr} with an initial value set at 10 p.p. of total government expenditures ($\sigma_t = 0.1$), which applies to the subsequent scenarios. Case 3 simulates a 'low growth' scenario. The simulation reveals a relatively faster energy transition simply by reducing growth, which is coherent to post-growth approaches and will be discussed in further detail next.

In case 4, we implement a low growth scenario alongside an aggressive green fiscal policy. This involves temporarily accelerating the growth rate of G^{gr} relative to G^{bau}, which remains constant and equal to the economy's long-term trend g^*. The policy spans 25 periods,[18] such that $g^{G^{gr}} > g^{G^{bau}}$ from t to $t+25$, after which both rates equalize to g^*, ensuring the model converges to the long-run equilibrium. The resulting output growth rates for the different scenarios are depicted in Figure 2.

Figure 2: Output (Y) - growth rate %



In the real world, there is a significant coupling between resource use and economic

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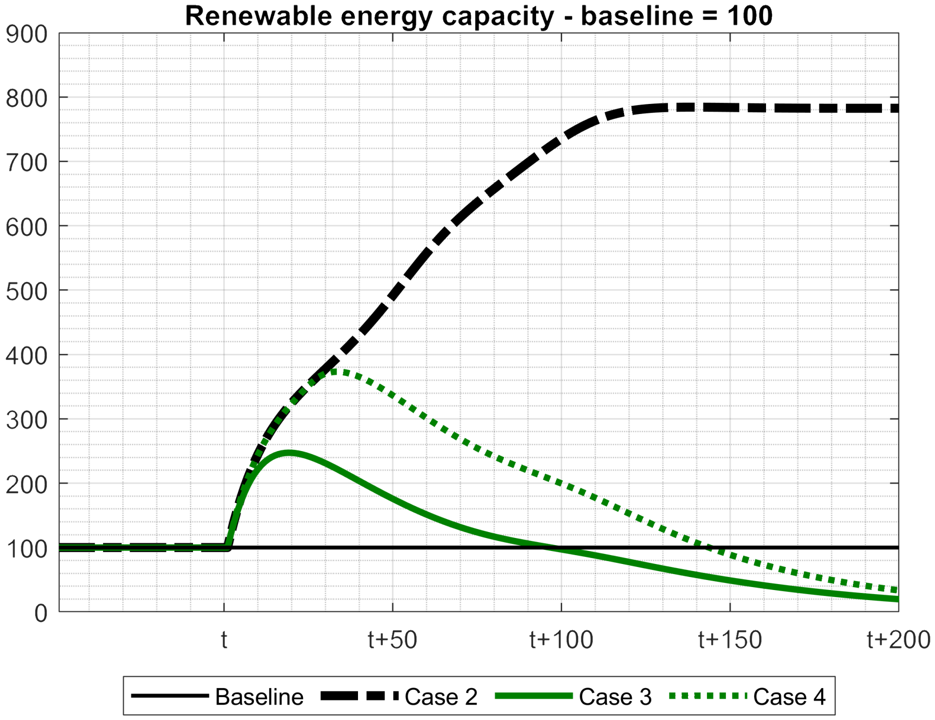
[18] Considering the periods as years, 25-years is the time-horizon for the long-term strategy of the EU Climate Action, which aims to be climate-neutral by 2050.

activity (Wiedmann et al., 2015). As discussed in Section 2, post-growth approaches emphasize the incompatibility of continuous economic growth with the finite nature of natural resources, advocating for reducing and stabilizing material and energy use within ecological limits. This perspective may entail lowering or stabilizing GDP or, in some cases, allowing it to decline. By simulating 'high' and 'low' growth scenarios, our model captures the effects of different growth rate levels on the energy transition and resource use.

Recall that, in our model, the transition towards greener production relies fundamentally on the availability of renewable energy, which represents the supply constraint to green capital accumulation. In turn, renewable energy capacity accumulation is a function of public and private investments, implying that the cases with higher output growth rates present also a higher renewable energy capacity accumulation rate, as shown in Figure 3.

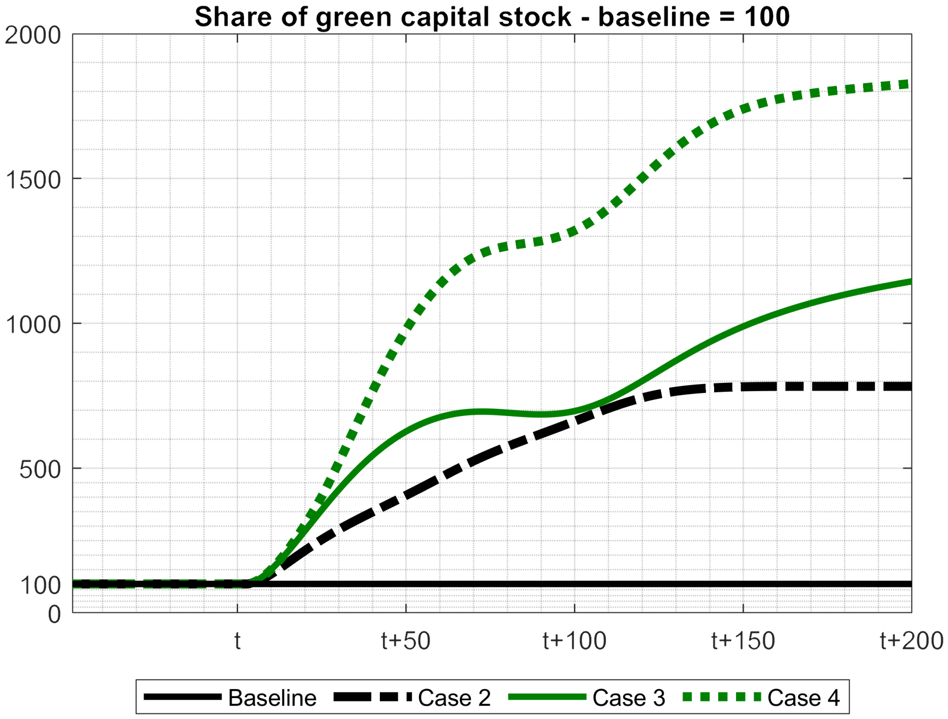
Figure 3: Renewable energy capacity generation (R)



We observe the shock in R caused by introducing green government expenditures for cases 2, 3, and 4 in period t. Even without G^{gr}, due to the higher g^*, the accumulation of R stemming from private expenditures I^R (recall Eq. 32) in the baseline scenario surpasses both low g^* cases after nearly 150 periods.

However, despite a greater renewable energy capacity in case 2, the simulations indicate that the ecological transition is less feasible in high growth scenarios. As shown in Figure 4, cases 3 and 4, characterized by lower growth rates, attain a higher share of green capital stock out of total capital and consequently a higher share of renewable energy consumption.

Figure 4: Share of green capital stock

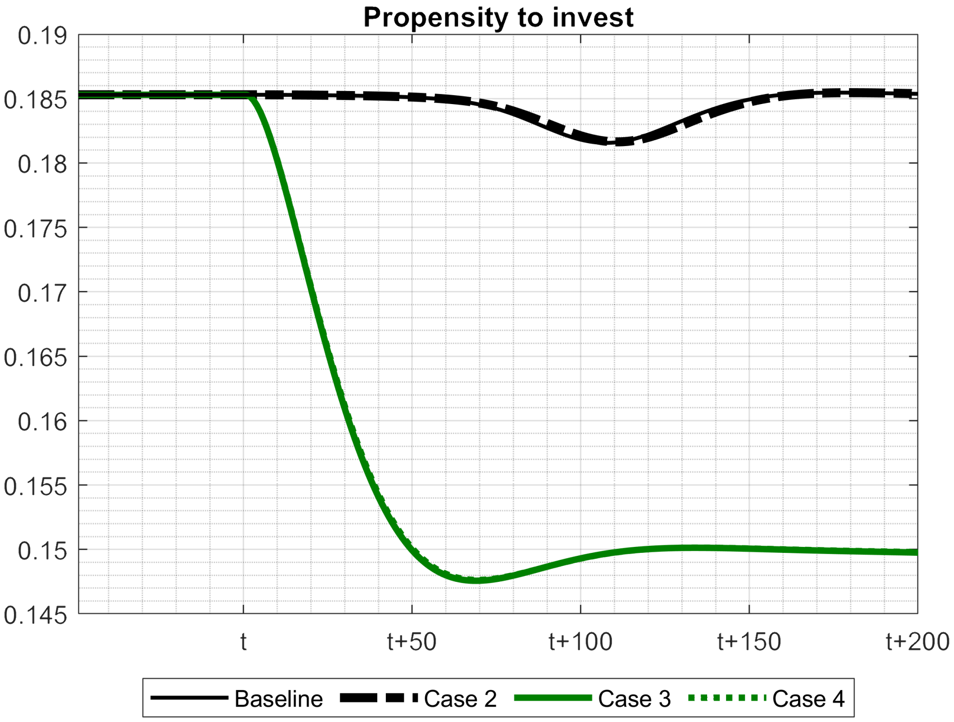


This property of the model arises from the renewable energy capacity constraint to green investment. In the simulation, once we introduce G^{gr} in cases 2, 3, and 4, there is a positive shock in the availability of renewable energy capacity, creating room to increase the green capital stock. However, for a given availability of renewable energy capacity, there is a maximum amount of new green capital stock that can be accommodated, setting a limit on green investment (recall Eq. 35). Consequently, the higher the total investment, the greater the stock of conventional capital required to complement green investment. Therefore, for a given availability of renewable energy, the share of green investment will be higher the lower the total investment is.

The difference observed between cases 3 and 4 stems from the aggressive green fiscal policy imposed in the latter. Since the growth of G^{gr} exceeds g^* for 25 periods, the renewable energy capacity grows faster than total investment during the policy period, resulting in greater spare renewable capacity in case 4 compared to case 3. Additionally, in cases 3 and 4, the shock from lowering g^* reduces the capacity utilization rate u and, consequently, the propensity to invest h. This is an important outcome of the Sraffian Supermultiplier model, which was empirically validated by Girardi and Pariboni (2020).

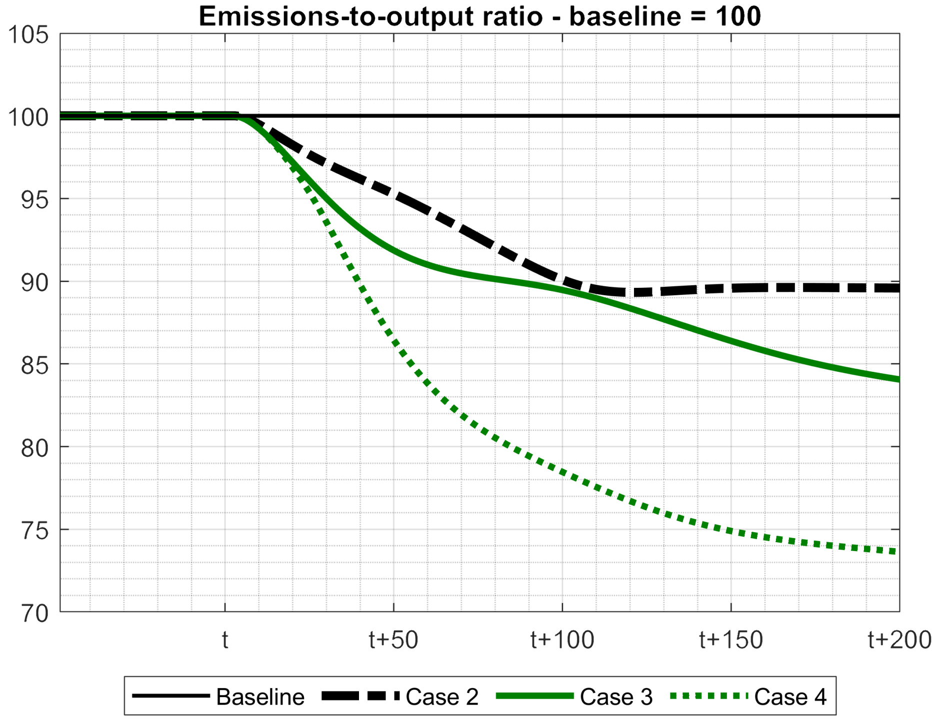
Figure 5 illustrates the evolution of h for the different scenarios.

Figure 5: Propensity to invest (h)



The model's intuition is straightforward, as slowing down economic growth effectively buys time to execute the energy transition. The energy transition takes time since the accumulation of renewable energy capacity is not an immediate process. Meanwhile, higher economic growth demands more fossil fuel energy to meet production requirements. This results in a lower share of renewable energy in the energy mix, but ultimately a higher absolute level of fossil energy consumption and consequently higher pollutant emissions. In the model, this aspect is also captured by the emissions-to-output ratio, as depicted in Figure 6.

Figure 6: Emissions-to-output ratio



In case 4, the relatively higher capacity for transitioning from fossil fuels to renewable energy is also reflected in a lower emissions-to-output ratio compared to the other cases. The scenario simulated in case 4 combines two fundamental aspects for the feasibility of the ecological transition. First, following the concept of the mission-oriented innovation policy of public spending (Mazzucato, 2018), the government expenditures in green innovation play a key role in expanding the renewable energy capacity and generating a crowd in effect in green private investment. Second, the economic growth is slowed down, increasing the feasibility of the energy transition and, consequently, the decoupling between economic growth and emissions.

Therefore, it is important to emphasize that continuous economic growth has negative implications that can hinder or delay the effectiveness of the energy transition in reducing CO2 emissions, aligning with post-growth principles. Since output growth induces also investment in the fossil energy sector, ongoing economic growth sustains investments in fossil fuels. Additionally, it implies that energy demand will continue to rise. Recalling the discussion in Section 2, while improvements in energy efficiency can soften increasing energy needs, efficiency gains cannot increase indefinitely. Even at maximum energy efficiency, any increase in output would still rise energy demand. Consequently, continuous economic growth inevitably expands energy requirements. Given that achieving near-zero CO2 emissions necessitates phasing out fossil fuel consumption, a necessary condition is that renewable energy generation capacity grows faster than overall energy demand. Therefore, the lower the economic growth rate and the faster the increase in renewable energy capacity generation, the more feasible is a rapid transition toward a low-carbon economy.

5 Concluding remarks

In recent decades, the ecological macroeconomics literature has expanded to address a broader range of issues. We contribute to this literature by developing an analytical model that integrates the energy sector – and the constraints it imposes on the ecological transition – within a demand-led growth framework. The growth model is connected to the energy sector through a green investment equation, which incorporates a constraint given by the availability of renewable energy and affects investment and capital stock composition. Thus, we developed a framework capable of interplaying demand-driven dynamics and energetic supply constraints. By doing that, we also provide a simple and manageable analytical strategy that can be adapted for other demand-led growth models to address the energy sector constraints, environment-related variables, and the feasibility of the ecological transition.

The simulation results demonstrate that scenarios combining green government expenditures with lower output growth rates achieve a higher share of renewable energy consumption and lower emissions-to-output ratios. Despite scenarios with higher economic growth accumulating greater renewable capacity, the energy transition is hindered. This property of the model arises from the renewable energy capacity constraint to green investment. It implies that for a given availability of renewable energy, the share of green investment will be higher the lower the total investment is. At the same time, continuous economic growth implies a corresponding continuous increase in energy demand. Hence, expanding the renewable energy generation in a low-growth scenario is more conducive to promoting the energy transition. This characteristic is consistent with post-growth perspectives, where slowing economic growth effectively extends the timeframe available for executing the energy transition.

From a political economy perspective, the absence of economic growth is particularly critical for developing countries that have not yet attained a certain level of material well-being. As discussed in Section 2, this conflictual perspective around economic growth has been referred to in the ecological macroeconomics literature as a 'double-edged sword' (Fontana and Sawyer, 2016) and 'the twin problem of global dependencies' (Gräbner-Radkowitsch and Strunk, 2023), the latter specifically addressing degrowth and the Global South.

Moreover, engaging in the ecological transition implies that governments must confront the interests of large and economically significant industries that are heavily carbon-intensive. These industries include those directly related to fossil fuels, such as oil and gas exploration, intensive agriculture and land use, fashion, and transportation. Furthermore, the potentially harmful social impacts of shutting down carbon-intensive industries or simply degrowing the economy in general, such as rising unemployment, must be taken into account.

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Appendix

A Simulation parameters and initial values

Table A1: Model Parameters and Their Descriptions

Symbol	**Description**	**Value**	**Remarks**
u_n	Normal capacity utilization rate	0.85	Standard in the SSM literature.
pc	Propensity to consume	0.5	Model's baseline scenario.
q	Propensity to invest (fossil energy sector)	0.007	Based on IEA (2024).
γ	Speed of adjustment of investment to changes in the capacity utilization	0.05	Standard in the SSM literature.
v	Capital-output ratio	1.5	Standard in the SSM literature.
δ	Capital depreciation rate	0.075	Standard in the SSM literature.
ϵ	Energy intensity	8	As in Bernardo and D'Alessandro (2016).
r	Share of G^{gr} destined to investments in renewable energy sector	0.5	Model's baseline scenario.
λ	Speed of adjustment of green investment to spare renewable energy capacity	0.05	Assumed as equal to γ.
ϕ	Carbon intensity	1.28	As in Bernardo and D'Alessandro (2016).
EROI	Energy return to investment	6	Adapted from Brockway et al. (2019).
ρ_0	Parameter of $f(R)$	1	Adapted from Bernardo and D'Alessandro (2016).
ρ_1	Parameter of $f(R)$	5	Adapted from Bernardo and D'Alessandro (2016).
ρ_2	Parameter of $f(R)$	0.202	Adapted from Bernardo and D'Alessandro (2016).
ρ_3	Parameter of $f(R)$	$3.56 \cdot 10^{-6}$	Adapted from Bernardo and D'Alessandro (2016).
ρ_4	Parameter of $f(R)$	2.5	Adapted from Bernardo and D'Alessandro (2016).
τ_1	Parameter of atmospheric temperature function	4.8	Maximum value of T^{AT}.
τ_2	Parameter of atmospheric temperature function	0.702	Calibrated for an initial $T^{AT} = 1°C$.
τ_3	Parameter of atmospheric temperature function	$6.08 \cdot 10^{-8}$	Calibrated for an initial $T^{AT} = 1°C$.
τ_4	Parameter of atmospheric temperature function	2.4	Median reference value of T^{AT}.
η_1	Parameter of damage function	0	As in Dafermos et al. (2017).
η_2	Parameter of damage function	0.00284	As in Dafermos et al. (2017).
η_3	Parameter of damage function	0.000005	As in Dafermos et al. (2017).

Table A2: Initial Values

Symbol	Description	Value	Remarks
G	Government expenditures	50,000	Model's baseline scenario
σ	Share of G^{gr}/G	0	For cases 2, 3, and 4, we introduce $\sigma = 0.1$
h	Propensity to invest (final sector)	0.1853	Calibrated for steady state initial value
e	Propensity to invest (renewable energy sector)	0.003	Based in IEA (2024)
u	Capacity utilization	0.85	Calibrated for steady state initial value
K^{gr}/K	Share of K^{gr}	0.01503	Calibrated for steady state initial value
R	Renewable energy capacity	32,828.34	Calibrated for steady state initial value
$f(R)$	Renewable energy capacity logistic function	3.00	Obtained from the given parameters
T^{AT}	Atmospheric temperature above pre-industrial levels	1°C	Obtained from the given parameters
D	Damage coefficient	0.0028	Obtained from the given parameters

B Output growth derivation

To derive the output growth equation, we first suppose a simpler version of the Sraffian supermultiplier model for a closed economy Eq. B1. The propensity to consume is fixed, and the only endogenous component in the supermultiplier is the propensity to invest h.

$$Y_t = \frac{1}{1 - c - h_t} Z_t \tag{B1}$$

To obtain the output growth in a continuous-time system, we compute Eq. B2 by taking the logarithm and derivatives with respect to time t from both sides of Eq. B1:

$$\ln \frac{\partial Y_t}{\partial t} = \ln \frac{\partial Z_t}{\partial t} - \ln \frac{\partial (1 - c - h_t)}{\partial t} \tag{B2}$$

We know that the log-differences of Y_t and Z_t represent their respective growth rates, g and g^Z. Using the chain rule, we differentiate the term involving h_t as described in Eq. B3.

$$\ln \frac{\partial (1 - c - h_t)}{\partial t} = \frac{1}{1 - c - h(t)} \left(- \frac{\partial h(t)}{\partial t} \right) \tag{B3}$$

Denoting the derivative of h_t with respect to time as $\dot{h}$, we substitute Eq. B3 into Eq. B2 and express the output growth as described in Eq. B4.

$$g = \frac{\dot{h}}{1 - c - h_t} + g^Z \tag{B4}$$

Therefore, the output growth (g) is determined by the growth of autonomous demand

and changes in the supermultiplier stemming from variations in h.

In discrete time, it is known that if $A_t = B_t C_t$, the growth rate of A_t is determined by the sum of the growth rates of B and C plus the product of their growth rates, such that $(g^A = g^B + g^C + g^B g^C)$. We refer to this property as the discrete-time product growth rate rule. Accordingly, the output Y is the product of the autonomous demand Z and the supermultiplier α. Applying this property to calculate the output growth of Y in discrete time, we sum the growth rates of the autonomous and supermultiplier components plus their product. In the next steps, we calculate the growth rate of the supermultiplier component:

$$\hat{\alpha}_t = \frac{\frac{1}{1-c-h_t} - \frac{1}{1-c-h_{t-1}}}{\frac{1}{1-c-h_{t-1}}} \tag{B5}$$

The simplified expression of Eq. B5 is shown in Eq. B6.

$$\hat{\alpha}_t = \frac{h_t - h_{t-1}}{1 - c - h_t} \tag{B6}$$

To avoid complications stemming from the simultaneous determination between h_t and Y_t, we take advantage of the fact that we know $h_t = \gamma(u_{t-1} - u_n)$ (Eq. 11) to rearrange Eq. B6. The numerator can be expressed as $h_t - h_{t-1} = \Delta h_t = h_{t-1}\hat{h}_t$, and h_t in the denominator can be expressed as $h_{t-1}(1 + \hat{h})$. After performing these rearrangements, we obtain Eq. B7:

$$\hat{\alpha}_t = \frac{h_{t-1}\hat{h}_t}{1 - c - h_{t-1}(1 + \hat{h}_t)} \tag{B7}$$

Therefore, the growth rate of Y is determined as in Eq. B8:

$$g_t = g^Z + \frac{h_{t-1}\hat{h}_t}{1 - c - h_{t-1}(1 + \hat{h}_t)} + g^Z \left(\frac{h_{t-1}\hat{h}_t}{1 - c - h_{t-1}(1 + \hat{h}_t)} \right) \tag{B8}$$

In our model, we instead have three endogenous components in the supermultiplier (recall Eq. 8: the propensity to invest in the final sector h, the propensity to consume c, and the propensity to invest in the renewable energy sector e. The derivation of the output growth rate expression, however, follows the same steps. Hence, in continuous time, g_t is determined as in Eq. B9:

$$g_t = g_t^Z + \frac{\dot{h}}{1 - c_t - h_t - e_t - q} + \frac{\dot{c}}{1 - c_t - h_t - e_t - q} + \frac{\dot{e}}{1 - c_t - h_t - e_t - q} \tag{B9}$$

Accordingly, in discrete time, we will have a term for each endogenous component in the supermultiplier. Recall that from Eq. 19 we know that $\hat{c}_t = \frac{p_c(D_{t-1} - D_t)}{c_{t-1}}$ and from Eq. 21 we know that $\hat{e} = g^{G^{gr}_{t-1}} - g^{Z_{t-1}}$. To simplify the notation, we denote $\hat{\alpha}^h$, $\hat{\alpha}^c$, and $\hat{\alpha}^e$ as the respective terms for each component, as described in equations B10, B11, and B12:

$$\hat{\alpha}_t^c = \frac{c_{t-1}\hat{c}_t}{1 - c_{t-1}(1+\hat{c}_t) - h_{t-1}(1+\hat{h}_t) - e_{t-1}(1+\hat{e}) - q} \tag{B10}$$

$$\hat{\alpha}_t^h = \frac{h_{t-1}\hat{h}_t}{1 - c_{t-1}(1+\hat{c}_t) - h_{t-1}(1+\hat{h}_t) - e_{t-1}(1+\hat{e}) - q} \tag{B11}$$

$$\hat{\alpha}_t^e = \frac{e_{t-1}\hat{e}_t}{1 - c_{t-1}(1+\hat{c}_t) - h_{t-1}(1+\hat{h}_t) - e_{t-1}(1+\hat{e}) - q} \tag{B12}$$

Following the discrete-time product growth rate rule, we can calculate the output growth g as the sum of the rates of change of each component plus their cross-products. Finally, g is determined in Eq. B13:

$$\begin{aligned} g_t = g_t^Z + \hat{\alpha}_t^c + \hat{\alpha}_t^h + \hat{\alpha}_t^e + g_t^Z(\hat{\alpha}_t^c + \hat{\alpha}_t^h + \hat{\alpha}_t^e) + \hat{\alpha}_t^c(\hat{\alpha}_t^h + \hat{\alpha}_t^e) + \hat{\alpha}_t^h\hat{\alpha}_t^e \\ + g_t^Z(\hat{\alpha}_t^c\hat{\alpha}_t^h + \hat{\alpha}_t^c\hat{\alpha}_t^e + \hat{\alpha}_t^h\hat{\alpha}_t^e) + \hat{\alpha}_t^c\hat{\alpha}_t^h\hat{\alpha}_t^e + g_t^Z\hat{\alpha}_t^c\hat{\alpha}_t^h\hat{\alpha}_t^e \end{aligned} \tag{B13}$$

C Sensitivity analysis

To evaluate the robustness of the model's long-run equilibrium, we conduct a sensitivity analysis by randomly varying four key parameters within a range of 50% above and below their baseline values. The parameters are: i) the government expenditures growth rate (g^G); ii) the initial share of green government expenditures out of total government expenditures (σ), iii) the share of green government expenditures oriented to expand renewable energy capacity (r); and iv) the speed of adjustment of green investment to spare renewable energy capacity (λ).

The results indicate that the output growth rate, capacity utilization level, and investment propensity converge to a steady-state long-run equilibrium. On the environment side, the share of green capital and the emission-to-output ratio also converge in the long run, although the different parameter value combinations lead to distinct outcomes with respect to the feasibility of the energy transition. The results of the Monte Carlo simulations are summarized in the figures below.

Figure C1: Sensitivity analysis - Output growth rate

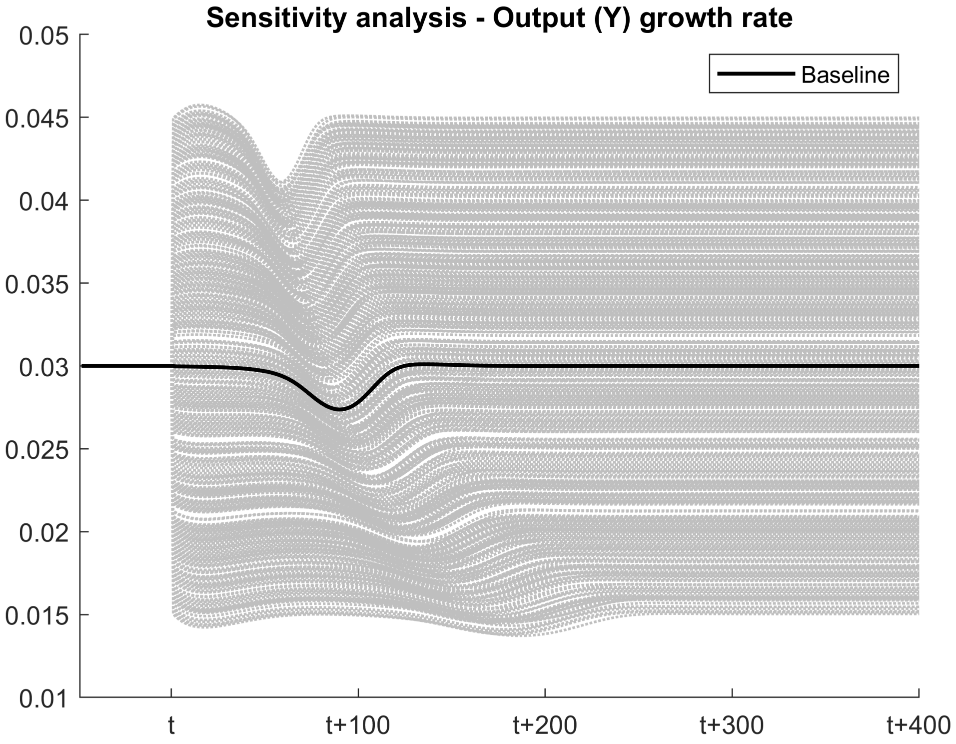

Figure C2: Sensitivity analysis - Capacity utilization

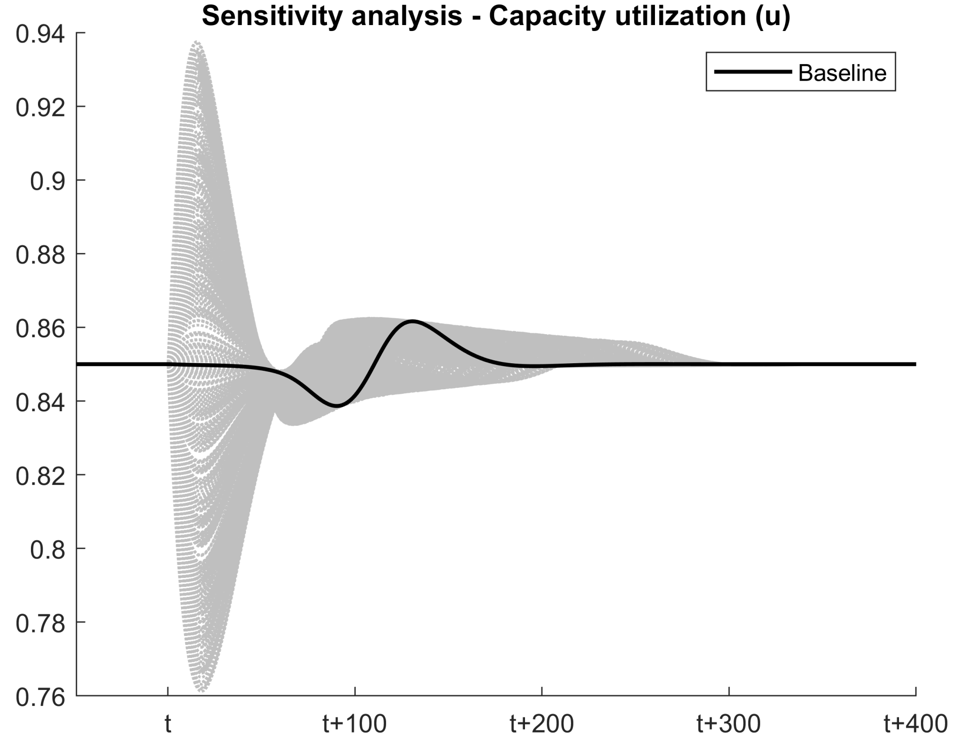

Figure C3: Sensitivity analysis - Propensity to invest

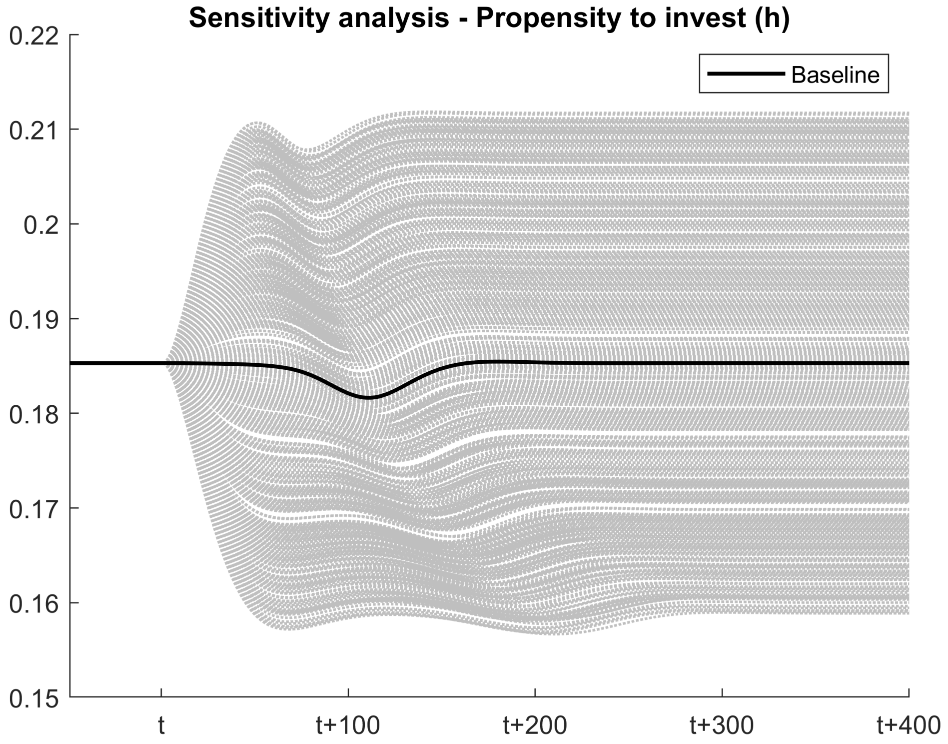

Figure C4: Sensitivity analysis - Share of green capital stock

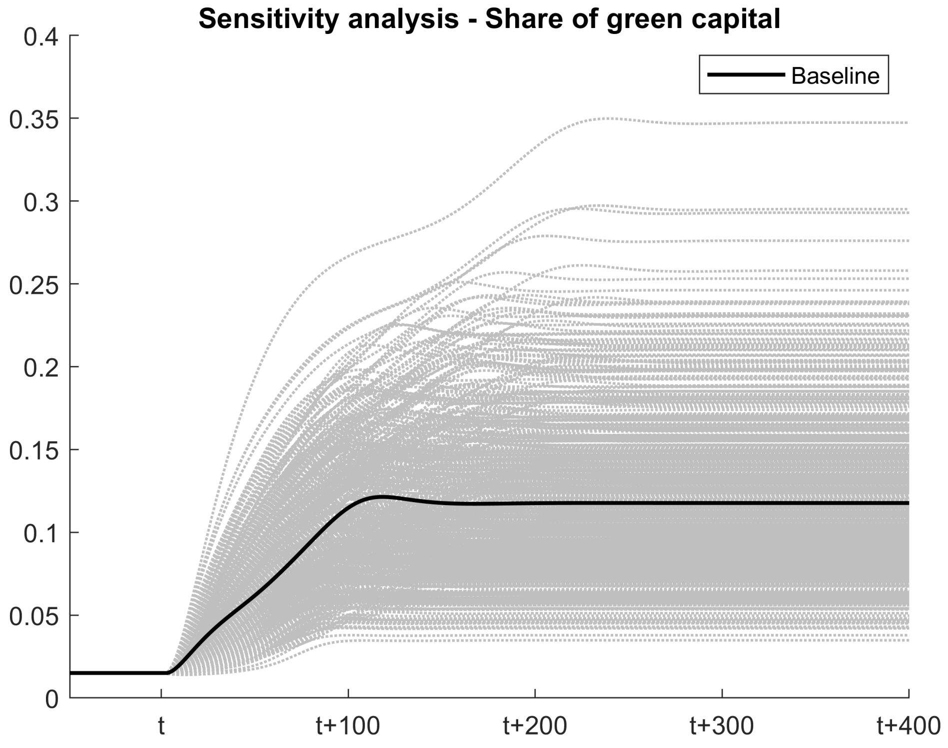

Figure C5: Sensitivity analysis - Emissions to output