Unraveling the interplay of substitution elasticities and the green energy rebound effect☆

Verónica Acurio Vásconez [a,b] [ID],*, Mónica Pereira Henriques [a]

[a] *Université de Lorraine, France*
[b] *Université de Strasbourg, Centre National de la Recherche Scientifique (CNRS), Bureau d'Economie Théorique et Appliquée (BETA), 13 Place Carnot, CO No. 026, 54035 Nancy Cedex, France*

A B S T R A C T

This paper examines how technological progress in either green or fossil energy affects the consumption of both energy types within a neoclassical growth model that explicitly separates energy inputs—unlike the original Saunders (1992) framework. By incorporating substitution elasticities between production factors, we investigate whether improvements in one sector genuinely displace fossil fuels or instead generate structural rebound effects that increase total energy use. Using alternative functional forms—Cobb–Douglas and nested CES—we show that when the elasticity of substitution exceeds one, technological progress in either green or fossil energy can amplify the use of one or even both energy types, potentially triggering backfire effects, whereas low substitution elasticities moderate this impact. These findings highlight that the environmental effectiveness of technological change depends critically on production structures and substitution possibilities, offering policy-relevant insights for managing systemic rebound mechanisms.

1. Introduction

A central ambition of contemporary energy transition policies is to generate a structural productivity shock capable of reorienting economic activity towards low-carbon technologies—much like the structural shift induced by the Industrial Revolution. To this end, governments have deployed a range of instruments. Public investment in green R&D—such as *ARPA-E* in the U.S., *Horizon Europe* in the European Union (EU), and China's solar and battery programs—supports clean technology innovation. Industrial policies—like *France 2030* and the U.S. *Inflation Reduction Act*—aim to decarbonize key sectors. Mission-oriented initiatives—including the *EU's Green Deal* missions and *Mission Innovation*—seek to align stakeholders around strategic technological transitions. Collectively, these instruments aim to foster both technological progress and systemic change in energy and production systems.

Yet the effectiveness of these instruments hinges on a critical assumption: that green technological improvements will automatically displace polluting energy sources. However, empirical evidence increasingly challenges this view. For instance, in the context of household solar adoption, Galvin et al. (2022) show that so-called *"prosumers"*—households that produce their own solar electricity—consume, on average, 675.57 kWh/year more than comparable *non-prosumers* who rely solely on grid electricity. Rather than offsetting grid demand, green energy adoption may thus stimulate additional energy use—some of which continues to rely on fossil-based generation.

This phenomenon is known in the economic literature as the rebound effect—a set of mechanisms through which gains in energy efficiency are partially or fully offset by behavioral or economic responses that increase energy consumption.

The rebound effect, first articulated by Jevons (1865), has since been extensively examined in both theoretical and empirical literature. As shown by Missemer (2012), Jevons not only introduced the paradox that energy efficiency may increase total energy demand, but also framed early concerns about the limits of substituting natural resources in industrial production. These foundational insights have been further explored in debates on long-run sustainability, particularly through the Solow/Stiglitz versus Georgescu-Roegen/Daly controversy (Couix,

2019). While the neoclassical perspective allows for unbounded substitution between capital and natural resources through technical change, ecological economists emphasize the thermodynamic constraints that limit the decoupling of economic growth from energy use.

These divergent theoretical foundations inform contemporary models of energy rebound and influence how the rebound effect is incorporated in growth theory and climate policy. Building on this foundation, a second wave of research has sought to formalize rebound mechanisms within neoclassical growth models. Notably, Khazzoom (1980) uses partial equilibrium demand models for household appliances, while Brookes (1990) employs macroeconomic reasoning within a neoclassical production framework to show that efficiency gains may inadvertently increase total energy demand by stimulating economic output—a view encapsulated in the Khazzoom–Brookes postulate. These ideas motivated analytical models linking rebound intensity to production structures and technological change.

Another central contribution in this theoretical strand is Saunders (1992), who embeds energy efficiency improvements into a neoclassical growth model and demonstrates that the magnitude of rebound depends critically on the elasticity of substitution between energy and other factors. Later works (Saunders, 2000, 2008) extend this framework across different functional forms and technological scenarios. Berkhout et al. (2000) and Wei (2007) further clarify the typology of rebound effects—distinguishing direct, indirect, and economy-wide channels—and stress the importance of systemic feedbacks. Brockway et al. (2021) synthesize empirical estimates of rebound effects across sectors and highlight that structural and long-term rebounds are often substantial and underestimated. Böhringer and Rivers (2021) complement this by evaluating how computable general equilibrium (CGE) models simulate rebound effects in applied policy settings.

However, despite this rich literature, energy is almost always modeled as an aggregate input, without differentiating between fossil and green energy[1]—limiting our understanding of how green technological progress specifically affects the energy mix.

This lack of differentiation is especially problematic in the context of energy transitions, where the central policy objective is not merely to reduce overall energy use but to shift the composition of energy consumption away from fossil fuels. While recent microeconomic studies have begun to document rebound effects associated with green technologies—particularly in residential solar photovoltaic systems (e.g., Galvin et al., 2022, Qiu et al., 2019, Aydın et al., 2023)—these analyses remain localized and sector-specific. They point to a critical insight: that green energy adoption can stimulate additional energy consumption, rather than fully displacing fossil energy. However, these findings have not yet been systematically translated into macroeconomic frameworks capable of capturing long-run, economy-wide interactions. To our knowledge, no formal growth model exists that distinguishes between green and fossil energy to analyze how technological progress in one sector may affect the consumption dynamics of both. This limits our ability to assess whether green innovation genuinely displaces fossil energy or instead contributes to new patterns of energy demand that include continued reliance on carbon-intensive sources.

This paper seeks to fill that gap by examining how technological shocks affect long-term GDP growth and the consumption dynamics of green and fossil energy. To do so, we develop an extension of the theoretical framework introduced by Saunders (1992, 2000), grounded in the (Solow, 1956) growth model. However, unlike the original (Saunders, 1992) framework, which treats energy as a single

undifferentiated input, we explicitly disaggregate it into green and fossil components. This distinction enables us to explore not only the overall response of energy demand to technological change, but also the evolving composition of energy use—an essential consideration in the context of energy transitions. In this framework, we consider several functional forms for the production function—including Cobb–Douglas and constant elasticity of substitution (CES) that allow us to examine how various types of technological shocks—whether in green or fossil energy—propagate through the economy and influence energy use.

As for (Saunders, 1992), central to our analysis is the concept of the elasticity of substitution between production factors. Saunders (1992) found that when the elasticity between energy and other factors (capital and labor) is below one, energy efficiency gains tend to reduce energy consumption. Conversely, when the elasticity exceeds one, such gains can lead to increased energy use. Our aim is to investigate whether these results hold when distinguishing explicitly between green and fossil energy inputs.

Our results suggest that technological progress in either green or fossil energy leads to a rebound effect within a Cobb–Douglas framework, where the elasticity of substitution is fixed at one. In this case, any productivity improvement systematically results in a proportional increase in the consumption of the corresponding energy type. In contrast, when we consider alternative functional forms that allow for substitution elasticities different from one, the response of energy consumption to technological shocks becomes more nuanced.

We first analyze a structure in which capital, labor, and total energy are combined using a Cobb–Douglas function, while fossil and green energy are nested within a CES subfunction. In this configuration, when the substitutability between green and fossil energy is low (elasticity below one), technological progress in either energy type leads to a slower increase in the consumption of the improved energy source relative to labor. However, when green and fossil energy are easily substitutable (elasticity above one), a technological shock in either energy type accelerates the consumption of the improved energy source—highlighting the potential for a *backfire effect,* an extreme form of the rebound effect in which efficiency improvements lead to a rise in total energy consumption that exceeds the initial energy savings.

We then consider a nested CES structure in which production is organized around two composite factors: one comprising capital and labor, and the other combining green and fossil energy. Each composite is internally governed by a Cobb–Douglas function. In this setting, we find that when the elasticity of substitution between the two composites is below one—implying limited substitutability—technological progress in green (or fossil) energy leads to a slower increase in its consumption relative to labor growth. Conversely, when this elasticity exceeds one—indicating easier substitution—the same technological shock results in a faster increase in green (or fossil) energy use.

Our paper contributes to what Lange et al. (2021) define as the analysis of structural rebound effects at the macroeconomic and long-term level. By explicitly distinguishing between green and fossil energy within a theoretical growth model, we provide a structured framework to assess how technological progress and substitution mechanisms jointly shape energy consumption trajectories. In doing so, we contribute to the macroeconomic literature on the rebound effect by clarifying how substitution elasticities influence the environmental effectiveness of green technological change. This approach bridges long-run growth theory with policy-relevant insights for the low-carbon transition.

The remainder of the paper is organized as follows. Section 2 presents the extended (Saunders, 1992) model with disaggregated energy inputs and alternative production structures. Section 3 discusses the main results and their implications for understanding rebound effects under different substitution regimes. Section 4 concludes and outlines directions for future research.

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[1] Throughout this paper, we use the term green energy to refer to energy sources that include both renewable energies—defined as energy derived from natural processes that are constantly replenished, such as solar, wind, hydro, geothermal or marine energy—and biofuels. We use the term fossil energy to refer to conventional carbon-based sources like coal, oil, and natural gas.

2. A neoclassical growth model with energy

This paper presents a neoclassical growth model with energy, referred to as the NGME model, originally developed by Saunders (1992). This class of models extends the traditional Solow framework by explicitly integrating energy as a production factor alongside capital and labor. We adopt this approach because it offers a transparent and analytically tractable structure to study the interaction between technological shocks and economic growth. Its flexibility in allowing different substitution patterns among production inputs makes it particularly well-suited for assessing the effects of technological shocks on the energy transition. By extending the original model of Saunders (1992) to distinguish between fossil and green energy sources, we are able to examine how technological progress in each sector influences long-term GDP trajectories and to characterize the resulting rebound effects under varying degrees of substitutability. This framework thus provides a robust theoretical basis for analyzing the structural dynamics of energy consumption in the wake of technological advancements.

We assume that at each date t output Y_t is produced using four inputs: capital K_t, labor L_t, green energy $E_{g,t}$, and fossil energy $E_{b,t}$. We define green energy as energy generated from renewable sources that do not emit greenhouse gases—such as solar, wind, hydro and biofuels—while fossil energy refers to energy derived from carbon-intensive sources like coal, oil, or natural gas.

Production is given by the following function:

$$Y_t := F\left(K_t, L_t, E_{g,t}, E_{b,t}\right), \tag{1}$$

where F is a neoclassical production function, increasing and concave in all its arguments, and satisfying the Inada conditions.[2]

We consider a small open economy in which, at each period, green and brown energy are imported at exogenous prices $p_{g,t}$ and $p_{b,t}$, respectively. The trade balance is assumed to be balanced, and output is domestically allocated to consumption C_t and investment I_t. This leads to the following resource constraint:

$$Y_t = C_t + I_t. \tag{2}$$

In line with the Solow model, we assume that households do not optimize intertemporally but instead allocate a constant fraction s of their income to investment:

$$s = \frac{I_t}{Y_t}. \tag{3}$$

Capital accumulates without depreciation, according to:

$$K_{t+1} = I_t + K_t. \tag{4}$$

Labor grows at a constant exogenous rate n.

Under these assumptions, it can be shown that output and capital grow at the same rate in the long run (see Appendix A.1):

$$\frac{\dot{Y}_t}{Y_t} = \frac{\dot{K}_t}{K_t}. \tag{5}$$

Let w_t, r_t, $p_{g,t}$, and $p_{b,t}$ denote the real prices of labor, capital, green, and fossil energy, respectively. Following Saunders (1992), we assume these energy prices remain constant over time[3]:

$$\frac{\dot{p}_{g,t}}{p_{g,t}} = \frac{\dot{p}_{b,t}}{p_{b,t}} = 0. \tag{6}$$

In what follows, we introduce several production functions involving the four production factors described above, combined in different ways to reflect varying degrees of substitutability among them.

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[2] The Inada conditions ensure that the marginal productivity of each input becomes arbitrarily large as its quantity approaches zero, and arbitrarily small as its quantity becomes very large.

[3] Since we consider a small open economy, it is reasonable to assume that domestic choices do not influence international energy prices. However, to provide a more comprehensive analysis of the rebound effect, this assumption should eventually be relaxed.

Table 1
Factor growth rates without technological progress.

	Annual growth rate[a]							
	$\frac{\dot{Y}_t}{Y_t}$	$\frac{\dot{K}_t}{K_t}$	$\frac{\dot{L}_t}{L_t}$	$\frac{\dot{E}_{g,t}}{E_{g,t}}$	$\frac{\dot{E}_{b,t}}{E_{b,t}}$	$\frac{\dot{w}_t}{w_t}$	$\frac{\dot{p}_{e,t}}{p_{e,t}}$	$\frac{\frac{\dot{C}_t}{L_t}}{\frac{C_t}{L_t}}$
None	0.6	0.6	0.6	0.6	0.6	0.0	0.0	0.0

[a] % per year. $\alpha_l = 0.6214$, $\alpha_k = 0.316$, $\alpha_g = 0.0141$, $\alpha_b = 0.0484$.

For each of these specifications, we simulate the trajectories of production factors and GDP following technological shocks, starting from the steady state. These simulations define our set of scenarios. In each scenario, we focus on how the trajectories of green and fossil energy change in response to different values of the elasticity of substitution among factors.

To enable meaningful comparisons across scenarios, we first analyze a baseline case in which production factors are substitutable and no technological efficiency gains are assumed.

2.1. An NGME without efficiency gains

We begin by assuming that the production function links the production factors through a Cobb–Douglas specification, without incorporating technological progress, such that:

$$Y_t = K_t^{\alpha_k} L_t^{\alpha_l} E_{g,t}^{\alpha_g} E_{b,t}^{\alpha_b} \tag{7}$$

where each $\alpha_i, i \in \{k, l, g, b\}$ represents the elasticity of production with respect to factor i. Since firms operate in a perfectly competitive market, it can be shown that these elasticities correspond to factor shares (see Appendix A.2 for details). This equality allows us to properly calibrate these parameters for the simulations (see Appendix B for details).

We assume a labor growth rate of $n = 0.6\%$, consistent with the average annual growth of the French labor force over 1990–2024. For the technological progress introduced in the later models, we assume a constant growth rate of 1.04% per year, consistent with historical estimates of total factor productivity (TFP) growth in the French economy over the period 1960–2019[4]. These values provide a realistic calibration for studying long-run dynamics within our model. Under these assumptions, it can be shown that the growth rates of endogenous variables are those of Table 1 (see Appendix A.2 for derivation).

By assuming a Cobb–Douglas function without technical progress and fixed energy prices, we observe uniform growth rates across energy, capital, and real output, equal to the growth rate of labor. The simultaneous growth of all factors and output leads to the stabilization of the E_g/Y and E_b/Y ratios, maintaining a constant energy intensity in both sectors. Furthermore, as all real prices are constants over time, it can be shown that the real consumption per worker remains constant.

Having established our baseline NGME without technological progress, we proceed to contrast this growth pattern with alternative scenarios involving technological progress and the application of CES functions.

2.2. An NGME with efficiency gains

2.2.1. The Cobb–Douglas production function
In contrast to the previous scenario, let us assume here that the production function incorporates technological progress and is expressed as follows:

$$Y_t = \tau_n (\tau_k K_t)^{\alpha_k} (\tau_l L_t)^{\alpha_l} (\tau_g E_{g,t})^{\alpha_g} (\tau_b E_{b,t})^{\alpha_b} \tag{8}$$

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[4] See Table 5 in the Appendix for a description of the data series used to calibrate these parameters.

Table 2

Factor growth rates with technological progress: Cobb–Douglas.

Type of technological progress	Annual growth rate[a]								Technology-to-non-technology Energy Ratio
	$\frac{\dot{Y}_t}{Y_t}$	$\frac{\dot{K}_t}{K_t}$	$\frac{\dot{L}_t}{L_t}$	$\frac{\dot{E}_{g,t}}{E_{g,t}}$	$\frac{\dot{E}_{b,t}}{E_{b,t}}$	$\frac{\dot{w}_t}{w_t}$	$\frac{\dot{p}_{e,t}}{p_{e,t}}$	$\frac{\dot{\frac{C_t}{L_t}}}{\frac{C_t}{L_t}}$	$\frac{E_{b,t}}{E_{b,t,\text{no tech}}}$
None	0.6	0.6	0.6	0.6	0.6	0.0	0.0	0.0	1.0
Neutral	2.27	2.27	0.6	2.27	2.27	1.67	0.0	1.67	5.18
Capital	1.13	1.13	0.6	1.13	1.13	0.53	0.0	0.53	1.69
Labor	1.64	1.64	0.6	1.64	1.64	1.04	0.0	1.04	2.8
Green	0.62	0.62	0.6	0.62	0.62	0.02	0.0	0.02	1.02
Fossil	0.68	0.68	0.6	0.68	0.68	0.08	0.0	0.08	1.08

[a] % per year. $\alpha_l = 0.6214$, $\alpha_k = 0.316$, $\alpha_g = 0.0141$, $\alpha_b = 0.0484$.
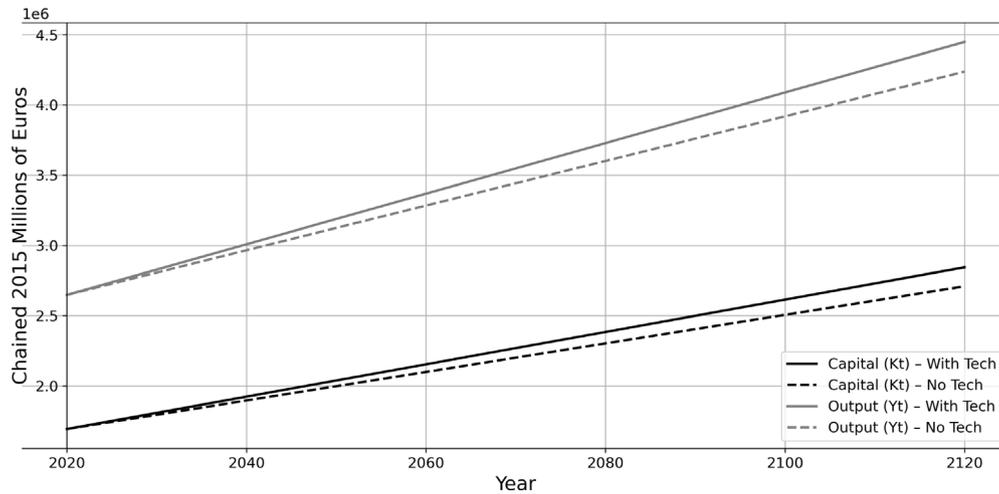

Fig. 1. Trajectories of capital (K) and output (Y) following a fossil-energy-augmenting technological shock. This figure compares the dynamic paths of capital and output under two scenarios: with and without fossil energy-augmenting technological progress. The dashed lines represent the baseline scenario (No Tech), in which no technological improvement occurs. The solid lines correspond to the scenario with fossil energy-augmenting progress (With Tech). As shown, both capital (black lines) and output (gray lines) grow more rapidly under the technological shock, illustrating the rebound effect—where improved energy efficiency leads to higher overall economic activity.

In this context, τ_i, with $i \in \{k, l, g, b\}$ denotes the level of technological progress for the respective factor i. Specifically, τ_n signifies neutral technological progress—a development that uniformly affects all production factors without favoring one input over another. This underscores the diverse forms that technological advancements can take, whether they augment capital, labor, green energy, or fossil energy or exhibit neutrality.

Note that in each scenario, we incorporate only one form of technological progress at a time. For instance, when we study the neutral technological progress case, we assume a constant growth rate for this variable and hold the other constants at a value of one over time.

Having incorporated technological progress, we define the rebound effect as in Saunders (1992): Under a fixed real energy price, a rebound effect appears when efficiency gains propel energy consumption to levels surpassing those achievable without such improvements.

As before, we assume that labor grows at a constant rate of 0.6% per year. Additionally, we assume that each technology type grows at a constant rate of 1.04% per year. The derivation of results can be found in Appendix A.3.

Table 2 summarizes our results. We observe that production, capital, green energy, and fossil energy all exhibit parallel growth rates above the growth rate of labor, in instances of efficiency gains resulting from technological progress. For instance, with a neutral-augmenting gain, production, capital, green energy, and fossil energy experience a growth rate of 2.27%, surpassing the rates observed in the absence of technological progress (0.6%).

The critical observation here is that "pure" energy efficiency gains also lead to an uptick in energy consumption. In the case of fossil energy-augmenting technological progress, we note an increase in both types of energy consumption (0.68% compared to 0.6%), indicating that efficiency gains in fossil energy contribute to an actual rise in fossil and green energy usage. In the case of green energy-augmenting technological progress, we also note an increase in both types of energy consumption, but this increase is smaller than the one observed with the fossil energy-augmenting technology (0.62%).

This result can be explained by the predominant role of fossil energy in energy consumption relative to green energy ($\alpha_{e,b} > \alpha_{e,g}$). This disparity underscores the greater influence of fossil energy over green energy in the production process. These observations are more clearly depicted in Figs. 1 through 4. Solid lines represent variable trajectory without technological shock, and discontinued lines represent variable trajectory with technological change in each scenario.

Fig. 2 particularly illustrates that enhancements in fossil energy efficiency lead to heightened consumption of both fossil and green energy (as well as capital and production) compared to the no technological case, depicted by the slight gap between the solid and dotted lines. In contrast, when there is an improvement in green energy efficiency, Fig. 4, the graphs depict a steady level of consumption over the years. Here, it is evident that the solid and dotted lines are combined.

2.2.2. Cobb–Douglas function with CES energy

Let us take the following form for the production function:

$$Y_t = \tau_n (\tau_k K_t)^{\alpha_k} (\tau_l L_t)^{\alpha_l} (a(\tau_g E_{g,t})^\rho + (1-a)(\tau_b E_{b,t})^\rho)^{\frac{\alpha_e}{\rho}} \qquad (9)$$

Remark that in this functional form, capital, labor, and total energy are linked in a Cobb–Douglas function, while both forms of energy
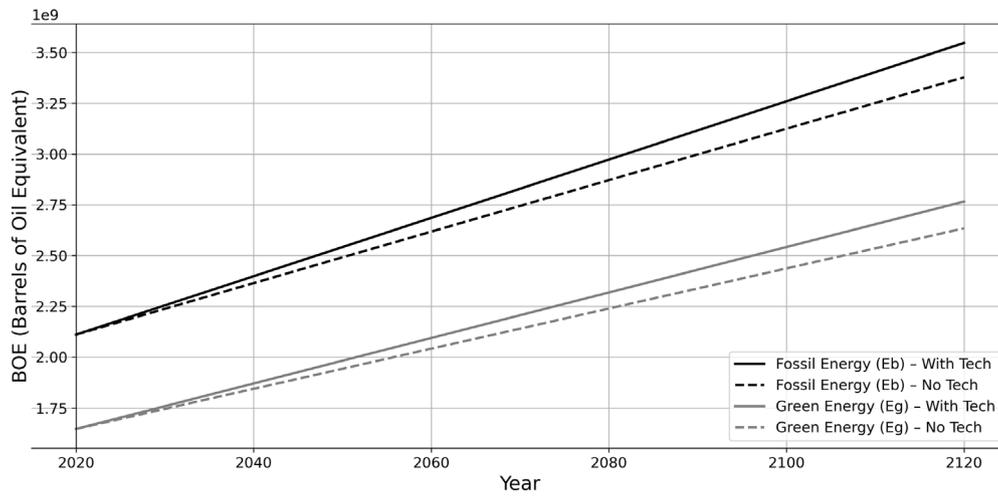
Fig. 2. Cobb–Douglas: Fossil Energy-Augmenting Tech. Prog. on E_g and E_f.
Both fossil energy (E_f, black lines) and green energy (E_g, gray lines) consumption rise under the fossil tech shock. The rebound effect is stronger for fossil energy, illustrating the dominant role of fossil input in the production process.
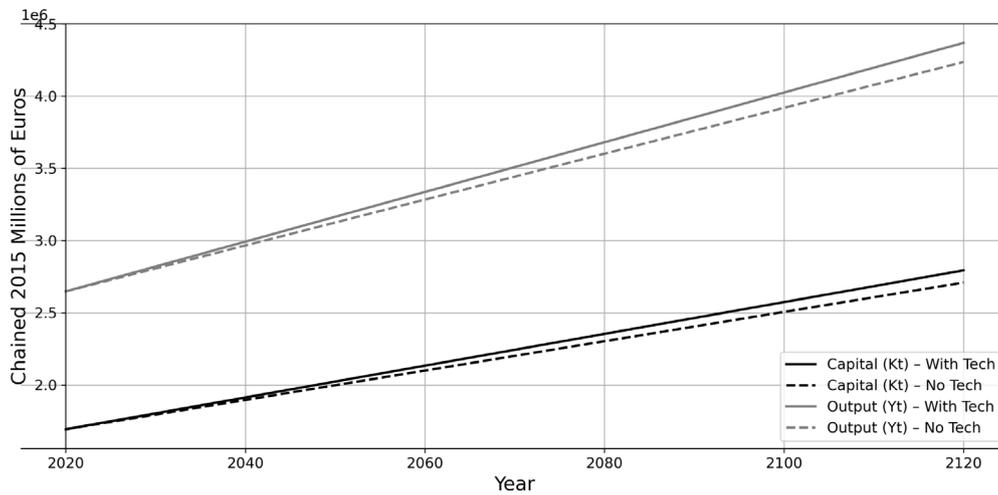

Fig. 3. Cobb–Douglas: Green Energy-Augmenting Tech. Prog. on K and Y.
Capital (K) and output (Y) grow modestly faster under green energy-augmenting progress, reflecting a relatively smaller rebound effect compared to fossil energy improvements.
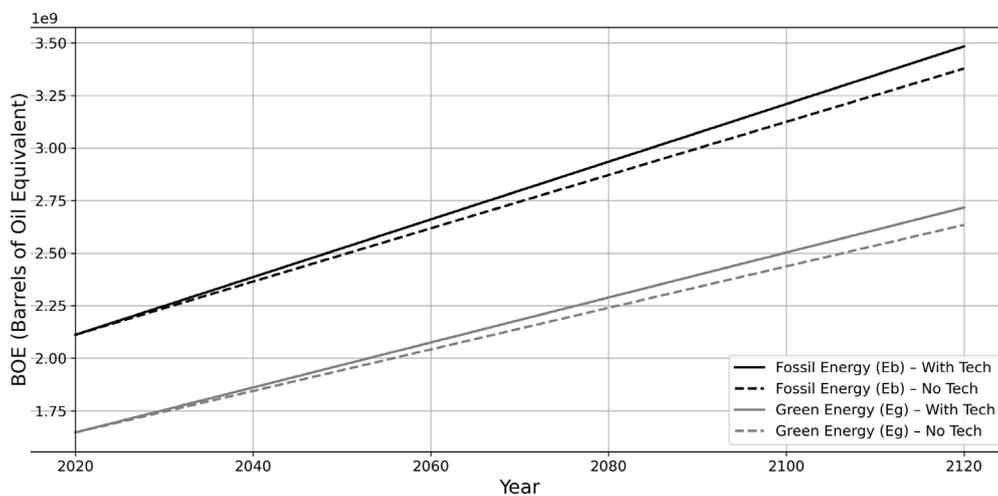

Fig. 4. Cobb–Douglas: Green Energy-Augmenting Tech. Prog. on E_g and E_f.
Green energy (E_g, gray lines) increases under the shock, while fossil energy (E_f, black lines) also grows slightly, indicating a cross-factor rebound effect driven by substitution dynamics.

Table 3

Factor growth rates with technological progress: CES Type 1.

Type of technological progress	Annual growth rate[a]								
	$\frac{\dot{Y_t}}{Y_t}$	$\frac{\dot{K_t}}{K_t}$	$\frac{\dot{L_t}}{L_t}$	$\frac{\dot{E_{g,t}}}{E_{g,t}}$			$\frac{\dot{E_{b,t}}}{E_{b,t}}$		
				$\sigma = 0.5$	$\sigma = 1$	$\sigma = 1.5$	$\sigma = 0.5$	$\sigma = 1$	$\sigma = 1.5$
None	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Neutral	2.27	2.27	0.6	2.27	2.27	2.27	2.27	2.27	2.27
Capital	1.13	1.13	0.6	1.13	1.13	1.13	1.13	1.13	1.13
Labor	1.64	1.64	0.6	1.64	1.64	1.64	1.64	1.64	1.64
Green	0.6	0.6	0.6	0.08	0.6	1.12	0.6	0.6	0.6
Fossil	0.6	0.6	0.6	0.6	0.6	0.6	0.08	0.6	1.12

[a] % per year. $\alpha_l = 0.6214$, $\alpha_k = 0.316$, $\alpha_e = 0.0626$.

are linked in a CES function. Accordingly, here, *a* denotes the share parameter between the two types of energy, and $\rho = \frac{\sigma-1}{\sigma}$, with σ indicating the elasticity of substitution between energy types.

This functional form allows for a flexible degree of substitutability between green and brown energy sources, while maintaining a Cobb–Douglas structure—i.e., a unitary elasticity of substitution—between capital, labor, and the aggregate energy input.

As before, the α_i parameters are equal to factor shares.

Results are shown in Table 3. When technological progress in labor increases, production, capital, and both fossil and green energy grow at a uniform rate of 1.64%. This outcome is consistent with those obtained using the Cobb–Douglas function.

The main distinction of this functional form, compared to the Cobb–Douglas specification, lies in how factors respond to technological advancements in fossil or green energy. A rebound effect—defined as the phenomenon whereby efficiency gains in fossil or green energy lead to increased consumption of the respective energy source—is observed when the growth rate of that energy source exceeds 0.6%, which corresponds to the baseline energy growth rate in the absence of a technological shock. A backfire effect—defined as the situation in which efficiency gains in fossil or green energy result in an increase in the consumption of that energy source that exceeds the rate of technological improvement itself—occurs when the growth rate of the energy source surpasses 1.04%, the assumed rate of technological progress for each type of energy.

In the case of efficiency gains in fossil energy, production, capital, labor, and green energy all experience identical growth rates. However, only the growth of fossil energy is affected by the elasticity of substitution (σ), and a backfire effect arises only when this elasticity exceeds one, pushing the fossil energy growth rate to 1.12%. Consequently, higher substitutability prompts increased consumption of fossil energy, while green energy consumption remains unchanged.

As an illustration of this case, consider a manufacturing facility that primarily relies on fossil fuels but incorporates a small amount of renewable energy whenever feasible, without being required to do so. Ignoring population growth, upgrading fossil fuel machinery would lead to increased fossil fuel consumption, as this factor becomes more productive and its use is not tied to green energy. Meanwhile, the utilization of green energy remains unchanged.

Alternatively, consider a region where industries rely primarily on natural gas for energy, but a newly introduced policy mandates a gradual increase in the share of renewable energy. In this setting, advancements in natural gas technology that improve efficiency may not necessarily lead to higher natural gas consumption, as firms face regulatory constraints and societal expectations pushing for a greener transition. However, the adoption of renewable energy sources such as wind and solar is unlikely to increase significantly, as existing infrastructure and financial incentives remain insufficient to support a large-scale shift away from fossil fuels.

Similarly, in the case of a green energy technological change, only the dynamics of green energy consumption depend upon the elasticity of substitution. Once again, higher substitution leads to increased consumption of green energy.

Consider a scenario where a city government encourages the adoption of renewable energy, leading to widespread installation of solar panels and wind turbines. In an environment with high energy substitutability, the increase in green energy consumption can occur despite the prevailing reliance on fossil fuels. This is because high substitutability allows for greater flexibility in replacing fossil fuels with green alternatives.

Conversely, in a situation with low substitution elasticity, even significant technological advancements in green energy production may not result in substantial reductions in fossil fuel usage. For instance, the development of more efficient solar panels or wind turbines might not lead to significant decreases in fossil fuel consumption if the potential for substitution is limited. As a result, despite improvements in green energy efficiency, constrained substitution elasticity may lead to stagnant or reduced green energy consumption, while fossil fuel consumption remains unchanged.

This highlights the significant impact of low substitution elasticity on consumption patterns.

2.2.3. CES function with nested (K,L) and (Eg,Eb) in Cobb–Douglas functions

Assume now that the production function is given by:

$$Y_t = \tau_n(a((\tau_k K_t)^{\alpha_k}(\tau_l L_t)^{\alpha_l})^\rho + (1-a)((\tau_g E_{g,t})^{\alpha_g}(\tau_b E_{b,t})^{\alpha_b})^\rho)^{1/\rho} \quad (10)$$

where parameter *a* represents the share parameter between two composite factors, one combining capital and labor and the other combining green and fossil energy, and $\rho = \frac{\sigma-1}{\sigma}$, with σ denoting the elasticity of substitution between the two composites.

We chose to group capital and labor on one hand, and fossil and green energy on the other, because—as shown by van-der Werf (2008)—the nesting structure that best fits the data is one in which capital and labor are first combined into a composite factor, which is then combined with energy (oil, in their case). While the author also finds that a nested specification of capital and labor is appropriate, we adopt a Cobb–Douglas formulation for this component in the interest of simplicity and because our focus is not on the imperfect substitutability between capital and labor.

In this section, we assume as well that real capital prices are constant as energy prices (i.e. $\frac{\dot{r_t}}{r_t} = 0$).

In this case, both types of energies must have the same growth rates for the existence of a steady state, meaning that[5]:

$$\frac{\dot{E_{g,t}}}{E_{g,t}} = \frac{\dot{E_{b,t}}}{E_{b,t}} \quad (11)$$

As shown in Appendix A.5, within this framework the parameters α_i no longer correspond to the factor shares. However, it can be shown that:

$$\alpha_l = \frac{w_t L_t}{r_t K_t + w_t L_t} \quad (12)$$

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[5] See Appendix A.5 for derivation.

Table 4

Factor growth rates with technological progress: CES Type 2.

Type of technological progress	Annual growth rate[a]								
	$\frac{Y_t}{Y_t}$	$\frac{K_t}{K_t}$	$\frac{L_t}{L_t}$	$\frac{E_{g,t}}{E_{g,t}}$			$\frac{E_{b,t}}{E_{b,t}}$		
				$\sigma = 0.5$	$\sigma = 1$	$\sigma = 1.5$	$\sigma = 0.5$	$\sigma = 1$	$\sigma = 1.5$
None	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Neutral	2.28	2.28	0.6	1.76	2.28	2.8	1.76	2.28	2.8
Capital	1.24	1.24	0.6	1.24	1.24	1.24	1.24	1.24	1.24
Labor	1.64	1.64	0.6	1.64	1.64	1.64	1.64	1.64	1.64
Green	0.6	0.6	0.6	0.48	0.6	0.72	0.48	0.6	0.72
Fossil	0.6	0.6	0.6	0.2	0.6	1.0	0.2	0.6	1.0

[a] % per year. $\alpha_l = 0.618$, $\alpha_k = 0.382$, $\alpha_g = 0.2324$, $\alpha_b = 0.7676$.

$$\alpha_k = 1 - \alpha_l \tag{13}$$

$$\alpha_b = \frac{p_{b,t} E_{b,t}}{p_{g,t} E_{g,t} + p_{b,t} E_{b,t}} \tag{14}$$

$$\alpha_g = 1 - \alpha_b \tag{15}$$

Then in this framework, α_i are cost shares of input i in their respective composite. These equations help us with the calibration of these parameters for the simulations.

Results are summarized in Table 4. As before, for each case we assume that only one technological type grows at a constant rate of 1.04%, while the other rest are constant at a value of one. Labor growth at 0.6%.

Just like the Cobb–Douglas production function and the Cobb–Douglas function with CES energy, when there is technological progress favoring capital or labor, it results in uniform growth across all inputs and output at the same rate. However, in scenarios involving neutral, green energy-augmenting, and fossil energy-augmenting technological shocks, its impact depends on the value of the elasticity of substitution between composites. Interestingly, this dependency is apparent only in the growth rates of green and fossil energy, while other variables remain unaffected by the elasticity of substitution. This emphasizes the dynamic nature of energy growth rates influenced by the substitutability between inputs.

In these scenarios, as before, we observe that the higher the elasticity of substitution, the greater the growth rate of green and fossil energy following a technological shock. A higher value of σ implies greater flexibility in substituting capital and labor with green and fossil energy in the production process. This increased flexibility enables the economy to allocate resources more efficiently towards the inputs experiencing technological progress, resulting in higher growth rates of green and fossil energy use relative to output and capital. However, compared with the previous case, a technological shock in either energy type now affects the consumption of both.

Conversely, when the value of σ is lower than one, the consumption of either energy type increases at a lower rate than that of labor growth, indicating that technological progress results in reduced energy requirements for the same output level.

A rebound effect is also noticeable in scenarios involving neutral efficiency gains, and it is visible for any value of the elasticity of substitution.

Additionally, the growth rate for fossil energy remains higher than the growth rate of green energy, which again can be attributed to its predominant usage compared to green energy within the energy balance ($\alpha_b > \alpha_g$).

3. Results and discussion

These findings provide valuable insights for the development of effective policies aimed at improving our economy and transitioning to a greener economic model. Understanding the implications of the elasticity of substitution is crucial in anticipating the outcomes of

efficiency gains in green energy. In a general equilibrium framework, the form of the production function is crucial. In cases where the Cobb–Douglas function applies, efficiency gains in green or fossil energy lead to an increase in overall energy consumption due to technological advancements. Therefore, policymakers should exercise caution when confronted with a Cobb–Douglas production function as improving the efficiency of fossil energy may lead to a rebound effect, where the consumption of both fossil and green energy increases.

These results may change, however, when assuming an imperfect substitutability between factors in different forms.

For our initial analysis, we use a Cobb–Douglas function for capital, labor, and energy but assume that green and fossil energy are linked in a CES one.

Using this particular production function, we find that when there is technological advancement in green energy and the elasticity of substitution is below one, the technological green energy shock results in an increase in green energy consumption that is smaller than labor growth, while fossil energy consumption grows at the same rate as labor. This slower increase in green energy consumption warrants caution among policymakers. However, when the elasticity of substitution exceeds one, we witness a faster increase in green energy consumption while fossil energy grows at the same rate as labor. This is a promising outcome, as it signifies progress towards a greener future with increased green energy usage, without pushing fossil energy consumption.

Regarding technological advancements in fossil energy, we observe similar results. If the elasticity exceeds one, fossil energy consumption increases at a faster rate than labor, which is undesirable. However, when the elasticity is below one, fossil energy increases at a slower rate than green energy, with the latter growing at the rate of labor. This finding is in line with sustainability objectives, particularly the goal of reducing reliance on fossil fuels and promoting the growth of renewable energy sources.

In view of these results, policymakers should consider adopting a "policy mix" approach when dealing with these types of functions. This entails focusing on technological progress in green energy sectors where the elasticity of substitution exceeds one, leading to increased green energy usage. Conversely, in sectors with an elasticity of substitution below one, policymakers should prioritize technological advancements in fossil energy, resulting in reduced fossil energy consumption. By combining these two strategies, policymakers can achieve the dual objective of boosting green energy while curbing fossil energy consumption, thus promoting a more sustainable energy landscape, while labor, capital and output growth stay constant.

For our next analysis, we use a CES function with two composite factors: one combining capital and labor, and the other combining green and fossil energy. When the elasticity of substitution between these composites falls below one, technological progress in either energy source results in lower growth rates for the consumption of both green and fossil energy compared to scenarios without technological progress. Consequently, the consumption of both green and fossil energy grows at a slower rate than labor. While a reduction in fossil energy consumption

may be beneficial for society, a significant slowdown in green energy consumption could impede the transition to a more sustainable future.

Nevertheless, if the substitution elasticity between composites exceeds one, an increase in any type of energy technology leads to an increase in the use of both energy types. This gives us a mixed outcome: while green energy rises after energy technological shocks, so does fossil energy.

It is crucial to note, however, that these last results stem from our assumption of constant energy prices, which implies in this case an equal growth rate for both types of energy. While this assumption allows for analytical tractability, it abstracts from market dynamics that could either dampen or amplify rebound and backfire effects. As such, the policy implications of our findings should be interpreted with caution, especially in contexts where energy prices are expected to vary significantly due to regulation, scarcity, or geopolitical factors.

In scenarios where the growth of fossil or green energy is influenced by the elasticity of substitution, our findings align with those of Saunders (1992). When the elasticity of substitution falls below one, it leads to a decrease in the consumption of the respective energy source or both energies. Conversely, if the elasticity of substitution exceeds one, it results in an increase in the consumption of the relevant energy source or both energies.

It is equally important to consider scenarios where the inputs are not substitutable. In such cases, an increase in green energy efficiency may not be beneficial. Instead of achieving a greener economy, this can lead to an undesirable outcome where fossil energy consumption grows at a faster rate than green energy consumption.

The dynamics we uncover may differ in economies with different energy mixes or production structures. For instance, in countries with a higher initial share of green energy, green technological progress could trigger stronger rebound effects, especially when substitution between energy types is easier. Similarly, differences in factor shares—such as higher energy intensity or lower reliance on labor—can amplify or mitigate the effects of technological change on energy consumption. These structural characteristics must therefore be taken into account when drawing policy conclusions from our model.

We hope that, armed with this knowledge, policymakers can design targeted policies to facilitate the transition towards a greener economy.

4. Conclusion

The findings of this study offer valuable insights for the design of more effective policies to support the energy transition. In particular, they highlight the crucial role of the elasticity of substitution between production factors—especially between different energy types—in shaping the environmental and economic outcomes of technological progress in green energy.

Our results show that energy consumption dynamics are highly sensitive to the underlying production structure, and especially to the degree of substitutability between inputs. In a Cobb–Douglas framework, where the elasticity of substitution is fixed at one, technological improvements in either green or fossil energy systematically trigger a rebound effect—that is, a proportional increase in the consumption of the respective energy type. By contrast, when we consider more flexible functional forms, where substitution elasticities can differ from one, the rebound effect becomes contingent on the magnitude of that elasticity. When the elasticity is below one—indicating limited substitutability—efficiency gains lead to more moderate increases in energy consumption relative to labor growth. Conversely, when the elasticity exceeds one—implying that inputs can be more easily substituted—technological progress results in faster increases in energy use, amplifying the rebound effect.

Understanding these substitution mechanisms is therefore essential for evaluating the environmental effectiveness of green innovation. Our results highlight that the success of green technological change depends not only on efficiency gains but also on the structure of production

and the degree to which inputs can be substituted. To translate these theoretical insights into actionable policy guidance, future research should prioritize the empirical estimation of substitution elasticities across sectors and technologies. These estimates are indispensable for anticipating where and when rebound or backfire effects are likely to occur, and for designing climate and energy policies that avoid unintended consequences.

From a theoretical standpoint, two extensions appear particularly relevant. First, future models should allow for endogenous energy prices, as assuming fixed prices over time can severely limit the accuracy of long-run projections. Second, incorporating explicit policy instruments—such as carbon pricing, renewable energy subsidies, or regulatory constraints—into macroeconomic models would enable a richer assessment of how technological progress interacts with policy design. Together, these extensions would provide a more comprehensive framework for analyzing the interplay between green innovation, energy demand, and policy effectiveness.

Lastly, while the current study focuses on the production side, households are also major energy consumers and play a central role in shaping aggregate energy demand. A natural extension of this work would involve incorporating household behavior into a dynamic macroeconomic framework—such as a Ramsey or Real Business Cycle (RBC) model—to examine how green energy efficiency affects total energy consumption when both producers and consumers are active agents.

We leave these questions for future research.

CRediT authorship contribution statement

Verónica Acurio Vásconez: Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Mónica Pereira Henriques:** Writing – original draft, Software, Investigation, Formal analysis, Data curation.

Declaration of competing interest

This work is original, has not been published elsewhere, and is not under consideration by any other journal. All sources and references have been properly acknowledged and cited. We declare that we have no conflicts of interest. All data used in this study can be provided upon reasonable request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.strueco.2025.10.007.

Data availability

Data will be made available on request.

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