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Financing the energy transition: exploring the role of public green bonds in promoting sustainability and economic growth

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Abstract

This paper develops an endogenous growth model that explores the role of public green bonds as a tool for financing the energy transition. By subsidizing renewable energy generation and research and development (R&D) in renewable technologies, green bonds offer a viable approach to accelerate the deployment of sustainable energy sources. The main objective of this study is to analyze the dynamics of green reforms facilitated by green bonds, wherein subsidies to the renewable sector can be increased without necessitating additional taxes. The research findings highlight that the issuance of public green bonds can effectively subsidize renewable energy production and stimulate R&D activities in the renewable sector. By examining various structural parameters and conducting sensitivity analysis, the study identifies factors that widen the range of self-financed green reforms, such as a higher share of renewables in energy production, increased substitutability of inputs, and greater probability of successful innovations in the R&D sector. Importantly, the paper reveals that these green reforms can lead to both decarbonization of the energy system and enhanced economic growth, thereby achieving the dual objectives of sustainability and prosperity.

Keywords: energy transition, green bonds, Schumpeterian growth, green bonds, renewable energy, R&D investment, public financing.

JEL Classification: C68, E62, O44, Q43, Q55

1. Introduction

A successful energy transition requires three critical ingredients: a massive and rapid deployment of low carbon technologies, a global approach with all countries putting in place stringent climate polices simultaneously, and sufficient economic resources to finance those policies and technologies. The Energy Transitions Commission (2023) estimates that the world needs to invest in low carbon technologies around $3.5 trillion a year on average between now and 2050 to achieve a decarbonised energy system, implying a threefold increase in current investment. In the same sense, IRENA (2023) states that global investment needs quadruple to remain on track to achieve a global warming of 1.5°C. This amount, $3.5 trillion, is material. According to the World Bank database (https://data.worldbank.org/), global gross domestic product in 2021 was $96.5 trillion and, therefore, the investment needed to transition to a low carbon economy is around 3.6% of GDP. The message of this paragraph is clear: new financial sources, including public and private resources, are needed for a successful energy transition.

In this context, the aim of this paper is to explore the role of public green bonds as a tool to finance the energy transition. In our view the energy transition is not only a technological change to reduce carbon emissions, but also a tool to promote economic growth and prosperity. The incremental economic growth generated by new low carbon technologies provides an opportunity to increase public spending and to finance green energy projects, creating a virtuous circle of higher growth and lower carbon emissions.

To explore this link between the energy transition, public green bonds, and economic growth, we develop an endogenous growth model in which technological innovations boost the competitiveness of low-carbon energies. Technological progress increases the competitiveness of renewable energy at the cost of fossil sources. We propose a Schumpeterian mechanism of creative destruction, *à la* Aghion and Howitt (1992, 1998). In this context, governments can finance additional research and development programs (R&D) to accelerate technological progress in the renewable energy sector only, accelerating the transition and boosting economic growth. Furthermore, governments can directly subsidise the investment cost of renewable energy, accelerating its deployment.

The economic rationality of the model is simple. Renewable energy is gaining economic competitiveness thanks to technological innovations. The deployment of this new technology generates economic growth and decarbonises the energy mix simultaneously. The government can issue debt (green bonds) to subsidise the generation of renewable energy and/or to finance additional R&D in the renewable sector accelerating both, growth, and decarbonisation. In technical words, the government faces a Dynamic Laffer curve that could accelerate the energy transition without additional cost on taxpayers. This means that the increase in future tax revenues, due to stronger economic activity, is large enough to pay for the initial deficit caused by the increase in financial support to the renewable sector. By increasing financial support to the production of renewable energy, we assess under which technological and fiscal conditions it is possible to achieve an increase in growth, as well as agents' welfare, while carbon emissions decrease without any need to increase any tax rate or set a new tax in the future. This result has potential implications for policymakers that are facing financial constraints. For example, the European Union, which has committed to achieve net zero emissions by 2050, has a public debt that accounts for 85% of GDP in September 2022[1]. Adding public resources to accelerate the energy transition could be challenging from a policy point of view, given the limited room of financial manoeuvre.

It is well-known that renewable energy has significantly benefited from technological progress in the last decade. According to IRENA (2022), the global levelized cost of electricity of newly

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[1] Eurostat. Euro indicators January 2023. https://ec.europa.eu/eurostat/news/euro-indicators

commissioned utility-scale solar photovoltaic projects declined in 2010-2021 by 88%, the cost of onshore wind projects declined by 35%, and the cost of offshore wind declined by 41%.

The structure of the paper is the following. Section two reviews the existing academic literature. Section three describes the data used, the model, and calibration of parameters. Section four discusses the results, including a detailed characterization of the policies and sensitivity analysis. Section five concludes.

2. Literature review

As it has been explained in the Introduction, financing the energy transition is a key element of climate policies. Academic literature has focused on financial tools such as feed-in tariff and feed-in premium, tax incentives and credits, carbon taxes, and tradable green certificates among others (Abolhosseini, 2014). In this sense, green public bonds are a relatively less explored financial tool in general equilibrium models.

The main idea underlying previous academic literature on green bonds is the convenience of an intertemporal compensation mechanism between current generations and future generations. In standard models, green debt is issued today to finance the energy transition and future generations pay higher taxes to repay that green debt.

The study on green bonds closest to our paper is the one by Kotlikoff et al. (2022). They use a large-scale, multi-region, overlapping generations model of climate change and carbon policy. One major conclusion of their analysis is that coupling carbon taxes with debt allows for a correct balancing the costs and benefits of the different regions and generations. The work of Kotlikoff et al. (2022) and Kotlikoff et al. (2021) relies on seminal papers dealing with the use of public debt to mitigate adverse climate change (Bovenberg and Heijdra, 1998 and 2002; Heijdra et al., 2006; and more recently Karp and Rezai, 2014).

However, there is a growing set of research focused on the role of corporate green bonds, and the role that financial intermediaries and central banks have in investment. Carattini et al. (2021), Ferrari and Landi (2023), and Giovanardi et al. (2022), among others, are good examples of how to explore the links between climate polices, macroprudential policies, and corporate green bonds.

The dynamic Laffer effect has been studied in endogenous growth models without environmental externalities (Ireland, 1994; Pecorino, 1995; Milesi-Ferretti and Roubini, 1998; Agell and Persson, 2001; Novales and Ruiz, 2002; Novales, Fernandez and Ruiz, 2009). In the context of endogenous growth models with environmental externalities, Fernandez, Perez and Ruiz (2010, 2011) explore the possibility of the so-called *double dividend*, this is, simultaneous increases in economic growth and a decrease in in cleaner environmental pollution.

In this context and to the best of our knowledge, our paper is the first to explore the role of public green bonds as a tool to accelerate a self-financed energy transition, using a general equilibrium model where investment in renewable energy favors simultaneously economic growth and a cleaner energy mix.

3. Data and Methodology

3.1. Data

To calibrate the model, we used *BP Statistical Review of the World Energy 2020* for CO_2 emissions, energy prices, and consumption of fossil fuels for the European Union in 2019. The macroeconomic variables capital stock, total number of hours worked, population, and gross domestic product in real and nominal terms are from European Commission database AMECO[2]. Therefore, the analysis reflects the situation of the European economies in 2019[3].

3.2. The Model

We developed a discrete time model where endogenous growth is driven by innovation in the renewable sector. Innovation is a technological advance that leads to an increase economic returns, which are modeled as transitory monopolistic profits. Innovation makes renewable technology more efficient reducing its economic cost and making previous technology obsolete. This is a Schumpeterian growth model in which new renewable companies with innovative technology replace exiting renewable companies based on obsolete technologies.

3.2.1 The representative Household

There is a representative household that maximizes utility defined over sequences of consumption (C_t) and labor (n_t) subject to the budget constraint[4]

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[2] https://economy-finance.ec.europa.eu/economic-research-and-databases/economic-databases/ameco-database_en#:~:text=AMECO%20is%20the%20annual%20macro,produced%20by%20the%20directorate%20general.

[3] We think that 2019 is better than 2020 or 2021.The reason is that the Covid crisis in 2021 and post pandemic recovery in 2021 distorted energy consumption in the European Union due to the impact of lockdowns policies.

[4] Note that energy services are embedded in the utility function of the household through private consumption. The model considers the different forms of energy as intermediate inputs used to produce final energy services, which in turn is used as input to produce the final product (Y_t). In this sense, part of this production goes to private consumption; so, these energy services are already implicitly incorporated in the variable $C_t$that appears in the utility function.

$$\max_{\{C_t, N_t, A_{t+1}, B_{t+1}\}} \left\{ \sum_{t=0}^{\infty} \rho^t \frac{1}{1-\sigma} \left[\left(C_t - \Psi A_{R,t} n_t^{\nu} \right)^{1-\sigma} \right] - 1 \right\}$$

Subject to: (1)

$$(1+\tau^c)C_t + A_{t+1} - A_t + \frac{B_{t+1}}{(1+r_t^b)} = (1-\tau^w)W_t n_t + (1-\tau^r) r_t A_t + \overline{\Pi}_{R,t}^m + T_t^b + B_t$$

Also, $\Psi > 1, \sigma > 0$, r is the intertemporal subjective discount rate, σ is the risk aversion parameter, $1/(\nu - 1)$ is the intertemporal elasticity of substitution for the labor supply, $\Psi A_{R,t} n_t$ measures the disutility associated to labor.[5] We will explain below that $A_{R,t}$ is also the productivity coefficient that is determined in the R&D sector.

The household income consists of five components: i) labor income $(W_t n_t)$ where W_t is the real wage, ii) the return on financial investment $(r_t A_t)$, where r_t is the real return on financial assets and A_t are the units of firm's stock owned by the representative household, iii) $\overline{\Pi}_t^m$ are the extraordinary profits distributed by the monopolist that produces renewable energy, net of investment in new renewable energies made by the outsiders entrepreneurs, iv) T_t^b are lump-sum transfers financed by taxes on consumption, on wages, and on financial capital, and v) the return from bonds, B_t which were bought the previous period.

On the other hand, this income can be used for: i) consumption (C_t), ii) financial investment $(I_t = A_{t+1} - A_t)$ and $\frac{B_{t+1}}{(1+r_t^b)}$ bonds at a price $1/(1+r_t^b)$, which pay a return r_t^b in the next period. The representative household also pays $\tau^c C_t$, $\tau^w W_t n_t$, and $\tau^r r_t A_t$ as taxes, where

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[5] Note that the second argument in the utility function, $A_{R,t} n_t^{\nu}$, grows at the same rate as C_t in the Balanced Growth Path.

τ^c, τ^w, τ^r denote, respectively, tax rates on consumption, on income from labor, and on returns from financial capital.

Then, from the agent's problem we obtain the following optimality conditions:

$$\nu\Psi A_{R,t} n_t^{\nu-1} = [(1-\tau^w)/(1+\tau^c)]W_t \tag{2}$$

$$\left(C_t - \Psi A_{R,t} n_t^{\nu}\right)^{-\sigma} = \rho\left[\left(C_{t+1} - \Psi A_{R,t+1} n_{t+1}^{\nu}\right)^{-\sigma}\left(1+(1-\tau^r)r_{t+1}\right)\right] \tag{3}$$

$$(1-\tau^r)r_{t+1} = r_t^b \tag{4}$$

$$\lim_{t\to\infty}\left(C_t - \Psi A_{R,t} n_t^{\nu}\right)^{-\sigma}(A_{t+1}+B_{t+1}) = 0 \tag{5}$$

3.2.2. The firms

(a) The final goods and services firm

There is a representative and competitive firm that produces the final output according to a Cobb-Douglas production function, combining capital, labor, and final energy as inputs. The firm solves the following problem:

$$\underset{\{n_t, K_{F,t}, e_t\}}{\text{Max}}\ p_t Y_t - W_t n_t - (r_t+\delta)K_{F,t} - p_{e_t}\left(A_{R,t} e_t\right),$$
$$\text{subject to:}\quad Y_t = \theta_t\left(A_{R,t} n_t\right)^{\alpha} K_{F,t}^{\beta}\left(A_{R,t} e_t\right)^{1-\alpha-\beta},$$

where p_t is normalized to 1, Y_t is the final good, n_t represent labor, $K_{F,t}$ is the stock of capital used in the production of the final goods and services, $\left(A_{R,t} e_t\right)$ stands for the effective units of final energy and θ_t is the total factor productivity. The first order conditions of the final good sector are:

$$W_t = \alpha\theta_t {n_t}^{\alpha-1} K_{F,t}^{\beta} {e_t}^{1-\alpha-\beta}\left[\frac{A_{R,t}}{A_{R,t-1}}\right]^{1-\beta} \tag{6}$$

$$r_t + \delta = \beta\theta_t {n_t}^{\alpha} K_{F,t}^{\beta-1} {e_t}^{1-\alpha-\beta}\left[\frac{A_{R,t}}{A_{R,t-1}}\right]^{1-\beta} \tag{7}$$

$$p_{e_t} = (1-\alpha-\beta)\theta_t {n_t}^{\alpha} K_{F,t}^{\beta} {e_t}^{-\alpha-\beta} \left[\frac{A_{R,t}}{A_{R,t-1}}\right]^{-\beta} \tag{8}$$

(b) The Energy Sector

Final Energy is generated from four energy sources: oil $e_{o,t}$, natural gas $e_{g,t}$, coal $e_{c,t}$ and renewable energy $e_{R,t}$. Natural gas, coal, and renewable energy are used as inputs to produce an intermediate input, label "intermediate energy" e_t^* according to a Constant Elasticity of Substitution (CES) technology of production with constant returns to scale. This aggrupation of variables reflects the fact that coal, natural gas, and renewable sources compete in the generation of electricity. In a second stage, "intermediate energy" and oil are combined to produce "final energy" e_t.[6]

The representative firm in this sector produces final energy in a competitive environment and solves the following problem:

$$\max_{\{e_{o,t}, e_{g,t}, e_{c,t}, e_{R,t}\}} \Pi_e = p_{e,t}e_t - \left(\bar{p}_{o,t} + \theta_o\xi_o\right) e_{o,t} - \left(\bar{p}_{g,t} + \theta_g\xi_g\right) e_{g,t} - \left(\bar{p}_{c,t} + \theta_c\xi_c\right) e_{c,t} - p_{R,t}e_{R,t}$$

subject to:

$$e_t = \left(a \cdot e_{o,t}^{\delta_E} + (1-a) \cdot \underbrace{\left[b e_{g,t}^{\gamma_E} + c e_{c,t}^{\gamma_E} + (1-b-c) e_{R,t}^{\gamma_E}\right]^{\delta_E/\gamma_E}}_{e_t^*}\right)^{1/\delta_E}$$

Where a is the participation of oil in e_t. The parameters *b*, *c* and (1-*b*-*c*) are the participation of natural gas, coal and renewable inputs on e_t^*, $1/(1-\gamma_E)$ is the interfuel elasticity of substitution between coal, natural gas and renewable inputs and $1/(1-\delta_E)$ is the interfuel elasticity of

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[6] Note that the energy variables do not grow, so we denote them in lower case letters. Additionally, all variables with no growth in the Balance Growth Path will also be represented in lower case letters.

substitution between oil and other energy sources. p_{e_t} is the price of final energy, while $\overline{p}_{o,t}, \overline{p}_{g,t}, \overline{p}_{c,t}$ are the internationally determined prices of imported fossil fuels[7] and $p_{R,t}$ is the endogenously determined price of renwable energy. Carbon taxes on fossil fuels set by the government are $\{\theta_o, \theta_g, \theta_c\}$ and revenues from those taxes are directly transferred to the renewable energy producer in the form of lump-sum transfer, net of the subsidies to the renewable sector and to the R&D sector. Finally, $\{\xi_o, \xi_g, \xi_c\}$ are the level of CO$_2$ emissions per calorific unit from oil, natural gas and coal.

The first order conditions of this problem are:

$$p_{R,t} = p_{e,t} \left[\frac{e_t}{e_t^*}\right]^{1-\delta_E} \left[\frac{e_t^*}{e_{R,t}}\right]^{1-\gamma_E} (1-a)(1-b-a) \tag{9}$$

$$a \cdot p_{e,t} \left[\frac{e_t}{e_{o,t}}\right]^{1-\delta_E} = \overline{p}_{o,t} + \theta_o \xi_o \tag{10}$$

$$(1-a) \cdot b \cdot p_{e,t} \left[\frac{e_t}{e_t^*}\right]^{1-\delta_E} \left[\frac{e_t^*}{e_{g,t}}\right]^{1-\gamma_E} = \overline{p}_{g,t} + \theta_g \xi_g \tag{11}$$

$$(1-a) \cdot c \cdot p_{e,t} \left[\frac{e_t}{e_t^*}\right]^{1-\delta_E} \left[\frac{e_t^*}{e_{c,t}}\right]^{1-\gamma_E} = \overline{p}_{c,t} + \theta_c \xi_c \tag{12}$$

(c) Renewable energy generation sector

Private agents in this economy have an incentive to innovate with the hope of obtaining monopolistic profits from renewable energy generation with the following production function:

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[7] Because the EU is a net importer of fossil fuels and at the same time has no capacity to impact in the international markets.

$$e_{R,t} = \left[\frac{K_{R,t}}{A_{R,t}}\right]^{\zeta} = x_{R,t}^{\zeta} \;\; with \;\; \zeta \, \epsilon \, (0,1]$$

where $K_{R,t}/A_{R,t}$ represents the capital per efficiency unit of the renewable energy. We assume that the monopolist' choice variable is the ratio $K_{R,t}/A_{R,t}$, which we denote by $x_{R,t}$, and also assume that the monopoly receives a subsidy, θ_R^m, from the government aimed at enhancing clean technology production. Then, the maximization problem of a monopolistic renewable energy producer is the following:

$$\max_{\{x_{R,t}\}} \Pi_{R,t}^m = \left[p_{R,t} \cdot (1+\theta_R^m) \cdot x_{R,t}^{\zeta} - (r_t + \delta) \cdot x_{R,t}\right] \cdot A_{R,t} + T_t,$$

where: $e_{R,t} = x_{R,t}^{\zeta}$, and $p_{R,t} = p_{e,t} \cdot \left[\frac{e_t}{e_t^*}\right]^{1-\delta_E} \left[\frac{e_t^*}{e_{R,t}}\right]^{1-\gamma_E} \cdot (1-a) \cdot (1-b-a)$, and T_t are lump-sum transfers financed by taxes on CO_2 emissions, net of the subsidies to the renewable and R&D sectors. Note that this producer uses a specific type of capital to produce renewable energy, such as windmills or PV solar plants to generate electricity.

The first order condition of this problem is:

$$p_{R,t}(1+\theta_R^m){x_{R,t}}^{2\zeta-1}\zeta\widetilde{\Omega}_t = (r_t + \delta) \, , \tag{13}$$

where:

$$\widetilde{\Omega}_t = (1-b-c)\left[\frac{e_t^*}{e_{R,t}}\right]^{1-\gamma_E}\left[(1-\delta_E)(1-a)\left[\frac{e_t}{e_t^*}\right]^{1-\delta_E}\frac{1}{e_t} + (\delta_E - \gamma_E)\frac{1}{e_t^*}\right] + \gamma_E\frac{1}{e_{R,t}}$$

Then the monopoly profits are:

$$\Pi_{R,t}^m = A_{R,t}\, p_{R,t}(1+\ \theta_R^m)x_{R,t}^{\zeta}(1-\zeta\Omega) \tag{14}$$

with $\Omega = x_{R,t}^{\zeta}\widetilde{\Omega}_t$

Notice that θ_R^m can be understood as a feed-in premium tariff, this is, a subsidy on top of the market price of renewable energy.

(d) R&D Sector

The investment at time *t* in the renewable energy sector may have as a result an advancement in the corresponding good, whose productivity becomes, if research is successful:

$$A_{R,t} = (1+g)A_{R,t-1}$$

for some $g > 0$, which we assume to be constant over time in this sector. Otherwise, productivity remains invariant: $A_{R,t} = A_{R,t-1}$. We assume that the probability of time t research to be successful is given by

$$\phi_t = \lambda\left(\frac{H_{R,t}}{(1+g)A_{R,t-1}}\right)^{\eta}$$

This probability depends positively on investment in research, $H_{R,t}$. It also depends inversely on the level of productivity: improving productivity is harder the higher the level of productivity, making less likely that new research becomes successful. The parameter $\eta < 1$ indicates that an increase in $H_{R,t}/(1+g)A_{R,t-1}$ raises the probability of success less than proportionally. Finaly, λ is an indicator of productivity in the R&D sector that guarantees the probability of success to be between 0 and 1[8].

Therefore, the level of productivity $A_{R,t}$ follows a Bernoulli distribution:

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[8] λ can be equivalently interpreted as an index of the entrepreneurs' (intrinsic) ability to innovate.

$$A_{R,t} = \begin{cases} A_{R,t} = (1+g)A_{R,t-1}, & \text{with probability } \phi_t \\ A_{R,t} = A_{R,t-1}, & \text{with probability } 1-\phi_t \end{cases}$$

We define $h_{R,t}$ as $H_{R,t}/(1+g)A_{R,t-1}$ where $0 \leq h_{R,t} \leq 1$ captures the society's effort in R&D. So, in this economy, innovation is uncertain, but its size (g) is certain. Innovation is "patented"[9], and the innovator becomes a monopolist company and remains in this profitable situation until someone innovates again (it is assumed that "patents" do not expire). R&D rises innovation probability, having a positive impact on the whole economy, this is, R&D has a positive externality. Innovation crowds out the former renewable energy company that disappears (this effect is the Schumpeterian 'creative destruction').

Hereafter, we assume that the only the outsiders invest in R&D and have a chance to become the next innovator, not the incumbent monopolist. This assumption is without loss of generality as, we shall argue later, it always holds in equilibrium.

At all t, V_{t+1} is the net present value of becoming the next innovator for an outsider entrepreneur and π_{t+1} the profit associated of being a patent holder/monopolist in the intermediate good sector. Preferences are recursive, so that:

$$V_{t+1} = \Pi^{m}_{R,t+1} + \frac{1}{1+r_{t+1}} \mathbb{E}_t(V_{t+2})$$

Since the probability that someone (different form the incumbent at t) innovates at t+1 is $\phi_{t+1} = \lambda h^{\eta}_{R,t+1}$,

$$\mathbb{E}_t(V_{t+2}) = \lambda h^{\eta}_{R,t+1} \cdot 0 + \left(1 - \lambda h^{\eta}_{R,t+1}\right)V_{t+1} = \left(1 - \lambda h^{\eta}_{R,t+1}\right)V_{t+1}$$

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[9] We use patent in a restrictive way since patents are only valid for a period of time.

Keep in mind that if an innovator at *t*+1 remains an innovator in *t*+2, it means that no one has innovated, and she/he keeps obtaining V_{t+1}. We are focusing on cases in which the incumbent does not invest in R&D, this is we focus on situations in which the *t*+2-economy is identical to the one in *t*+1. Next, substituting the latest in V_{t+1},

$$V_{t+1} = \Pi^{m}_{R,t+1} + \frac{1}{1 + r_{t+1}}\left(1 - \lambda h^{\eta}_{R,t+1}\right)V_{t+1}$$

Collecting terms,

$$V_{t+1} = \frac{\Pi^{m}_{R,t+1}(1 + r_{t+1})}{r_{t+1} + \lambda h^{\eta}_{R,t+1}}$$

When research is successful in some *t* period, the innovator becomes a monopoly in the production of the renewable technology for that period.

Every period the outsider entrepreneur chooses her/his R&D level of investment $H_{R,t}$ to maximize the expected revenue from innovation minus the cost of R&D:

$$\max_{\{H_{R,t}\}} \mathbb{E}_t \left\{ \lambda \left(\frac{H_{R,t}}{(1+g)A_{R,t-1}} \right)^{\eta} \cdot V_{t+1} + \left[1 - \lambda \left(\frac{H_{R,t}}{(1+g)A_{R,t-1}} \right)^{\eta} \right] \cdot 0 - (1 - \theta^{e}_{R}) \cdot H_{R,t} \right\} =$$

$$\lambda \left(\frac{H_{R,t}}{(1+g)A_{R,t-1}} \right)^{\eta} \cdot \mathbb{E}_t \frac{\Pi^{m}_{R,t+1}(1 + r_{t+1})}{r_{t+1} + \lambda \left(\frac{H_{R,t}}{(1+g)A_{R,t-1}} \right)^{\eta}} - (1 - \theta^{e}_{R}) \cdot H_{R,t} \,,$$

where θ^{e}_{R} is a subsidy received by the entrepreneur as a compensation for the innovation effort Notice that this subsidy θ^{e}_{R} is a direct reduction in the level of R&D spending.

The first order condition for this maximization problem:

$$\frac{1}{(1+g)A_{R,t-1}} \lambda \eta h^{\eta-1}_{R,t} \cdot \mathbb{E}_t \frac{\Pi^{m}_{R,t+1}(1+r_{t+1})}{r_{t+1} + \lambda h^{\eta}_{R,t}} = (1 - \theta^{e}_{R}) \qquad (15)$$

$$\text{with} \quad \begin{cases} \Pi^m_{R,t+1} = \left[p_{R,t+1}(1+\theta^m_R)e_{R,t+1}(1-\zeta\Omega_{t+1})\right] A_{R,t+1} \\ r_{t+1} = p_{R,t+1}(1+\theta^m_R)e_{R,t+1}^{\frac{\zeta-1}{\zeta}}\zeta\widetilde{\Omega}_{t+1} - \delta \\ h_{R,t} = \dfrac{H_{R,t}}{(1+g)A_{R,t-1}} \end{cases}$$

Note that both θ^e_R and θ^m_R enhance research effort, the first one because of the direct decrease in the cost of research and the latter because of the increase in the expected future revenue if research is successful.

3.2.3. The Government

For the sake of simplicity in the analysis, the government faces two budget constraints simultaneously. One constraint shows exogenous public spending as a percentage of GDP financed by taxes on consumption, labor and capital, which we call *non-energy* taxes, and the government keeps the budget balanced:

$$T^b_t = \tau^c C_t + \tau^w W_t n_t + \tau^r(r_t - \delta)K_t \, .$$

The second budget constraint shows two alternative types of subsidies to renewable energy. These are 1) subsidies to the monopoly producing renewable energy and 2) subsidies to the R&D spending. The aim of these subsidies is to promote innovation in the renewable sector because they increase future income. Such subsidies are financed by means of taxes on fossil energies. We call these *green* taxes.

Furthermore, we include the possibility that government issues the so-called *green bonds*. They are called *green* because they are used exclusively to finance the energy transition; in particular, they finance the subsidies to production of renewable energy and to R&D spending. The *green* budget constraint is:

$$B_t + T_t + \theta_R^e H_{R,t} + \theta_R^m e_{R,t} A_{R,t} = \left[\theta_o \xi_o e_{o,t} + \theta_g \xi_g e_{g,t} + \theta_c \xi_c e_{c,t}\right] A_{R,t} + \frac{B_{t+1}}{(1 + r_t^b)}$$

3.2.4. Competitive Equilibrium

Under competitive equilibrium each agent solves her/his optimization problem given the prices, tax rates, and subsidies to which she/he is subject. Households maximize their objective (discounted sum of utilities) subject to their budget constraint given wages, interest rates, and tax rates on consumption; the firm producing final goods maximizes its profits subject to its technology, given wages, interest rates, and final energy prices. Firms producing final energy (acting in a competitive environment) maximize their profits subject to their technology and given the prices at which they sell their final energy production, prices of oil, gas, coal[10], and prices of renewable energy set by the renewable energy company (since it is a monopoly). The firm producing renewable energy is monopoly and maximizes its profits subject to its technology, given interest rates and subsidies. As for the R&D sector, it maximizes its expected profits from its spending, given the endogenous structure of the probability of success, and subsidy to R&D activities.

Finally, the government balances its two budget constraints: the one in which tax revenues from consumption, labor and capital are equal to transfers to households, and the one in which revenues from fossil fuels finance subsidies to renewable energy generation and spending on R&D. In this budget constraint, the government can issue *green* bonds to finance these subsidies.

Since all agents satisfy their objective functions and labor, capital and goods markets are balanced, the aggregate resource constraint of the economy is:

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[10] These are determined in international markets and are taken as given by the final energy producing firms.

$$C_t + K_{t+1} + (1-\delta)K_t + H_{R,t} = Y_t - A_{R,t}\left[\overline{p}_{o,t}e_{o,t} + \overline{p}_{g,t}e_{g,t} + \overline{p}_{c,t}e_{c,t}\right] \tag{16}$$

this is, consumption plus investment in capital plus spending in innovation must be equal to the final output of the economy net of purchases of fossil fuels.

Because in the long-run equilibrium, or Balanced Growth Path, the set of variables $\{C_t, K_t, K_{R,t}, K_{F,t}, W_t, \Pi^m_{R,t}, H_{R,t}\}$ grow at the same rate as $H_{R,t}$ does (the remaining variables do not grow in the long-run), it is possible to rewrite all the equations characterizing the competitive equilibrium in such a way that all the variables in the steady-state have a null growth rate. So, the detrended variables are defined as follows:

$$c_t \equiv \frac{C_t}{A_{R,t-1}}\ ;\ k_t \equiv \frac{K_t}{A_{R,t-1}};\ k_{F,t} \equiv \frac{K_{F,t}}{A_{R,t-1}};\ k_{R,t} \equiv \frac{K_{R,t}}{A_{R,t-1}};\ w_t \equiv \frac{W_t}{A_{R,t-1}};\ \pi^m_{R,t} \equiv \frac{\Pi^m_{R,t}}{A_{R,t-1}};$$

$$h_{R,t} \equiv \frac{H_{R,t}}{(1+g)A_{R,t-1}}$$

with $\frac{A_{R,t}}{A_{R,t-1}} \simeq 1 + \lambda g h^{\eta}_{R,t}$ being the growth rate in each period *t*.

The competitive equilibrium system of equations, written in terms of detrended variables is:

$$p_{R,t} = p_{e,t}e_t^{1-\delta_E}{e_t^*}^{\delta_E-\gamma_E}(1-a)(1-b-c)k_{R,t}^{\zeta(\gamma_E-1)}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{-\zeta(1-\gamma_E)} \tag{17}$$

$$\overline{p}_{o,t} + \theta_o\xi_o = p_{e,t}a\, e_t^{1-\delta_E}\, e_{o,t}^{\delta_E-1} \tag{18}$$

$$\overline{p}_{g,t} + \theta_g\xi_g = p_{e,t}(1-a)\left[\frac{e_t}{e_t^*}\right]^{1-\delta_E} b\left[\frac{e_t^*}{e_{g,t}}\right]^{1-\gamma_E} \tag{19}$$

$$\overline{p}_{c,t} + \theta_c\xi_c = p_{e,t}(1-a)\left[\frac{e_t}{e_t^*}\right]^{1-\delta_E} c\left[\frac{e_t^*}{e_{c,t}}\right]^{1-\gamma_E} \tag{20}$$

$$r_t = p_{R,t}(1+\theta_R^m)\zeta {k_{R,t}}^{(\zeta-1)}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{1-\zeta}\Omega_t - \delta \tag{21}$$

$$\alpha\theta_t n_t^{\alpha-1} k_{F,t}^{\beta} e_t^{1-\alpha-\beta}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{-\beta}\left(\frac{1-\tau^w}{1+\tau^c}\right) = \nu\Psi n_t^{\nu-1} \tag{22}$$

$$k_t = k_{R,t} + k_{F,t} \tag{23}$$

$$\left[c_t - \Psi n_t^{\nu}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)\right]^{-\sigma} = \rho\left[\left(c_{t+1} - \Psi n_{t+1}^{\nu}\left(\frac{A_{R,t+1}}{A_{R,t}}\right)\right)^{-\sigma}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{-\sigma}\left((1-\tau^r)r_{t+1}+1\right)\right] \tag{24}$$

$$c_t + \left(\frac{A_{R,t}}{A_{R,t-1}}\right)k_{t+1} - (1-\delta)k_t + (1+g)h_{R,t} =$$

$$= \theta_t n_t k_{F,t}^{\beta} e_t^{1-\alpha-\beta}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{1-\beta} - \left(\frac{A_{R,t}}{A_{R,t-1}}\right)\left[\overline{p}_{o,t}e_{o,t} + \overline{p}_{g,t}e_{g,t} + \overline{p}_{c,t}e_{c,t}\right] \tag{25}$$

$$e_{R,t} = k_{R,t}^{\zeta}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{-\zeta} \tag{26}$$

$$e_{R,t} = x_{R,t}^{\zeta} \tag{27}$$

$$e_t = \left[a e_{o,t}^{\delta_E} + (1-a)e_t^{*\delta_E}\right]^{1/\delta_E} \tag{28}$$

$$e_t^* = \left[b e_{g,t}^{\gamma_E} + c e_{c,t}^{\gamma_E} + (1-b-c)e_{R,t}^{\gamma_E}\right]^{1/\gamma_E} \tag{29}$$

$$r_t + \delta = \beta\theta_t\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{1-\beta} n_t^{\alpha} k_{F,t}^{\beta-1} e_t^{1-\alpha-\beta} \tag{30}$$

$$p_{e,t} = (1-\alpha-\beta)\theta_t\left(\frac{A_{R,t}}{A_{R,t-1}}\right)^{-\beta} n_t^{\alpha} k_{F,t}^{\beta} e_t^{-\alpha-\beta} \tag{31}$$

$$\frac{1}{1+g}\left(\frac{A_{R,t}}{A_{R,t-1}}\right)\lambda\eta h_{R,t}^{\eta-1}\left[\frac{\frac{\overline{\Pi}_{R,t+1}^{m}}{A_{R,t}}(1+r_{t+1})}{r_{t+1}+\lambda h_{R,t+1}^{\eta}}\right] = (1-\theta_R^e)\ , \tag{32}$$

$$\frac{\overline{\Pi}_{R,t}^{m}}{A_{R,t-1}} = \left(\frac{A_{R,t}}{A_{R,t-1}}\right)(1-\zeta\Omega)p_{R,t}(1+\theta_R^m)e_{R,t}\ , \tag{33}$$

where $\frac{\overline{\Pi}_{R,t}^{m}}{A_{R,t-1}} \equiv \pi_{R,t}^{m}$ and $\Omega = (1-b-c)e_t^{*1-\gamma_E}\left[e_{R,t}\right]^{\gamma_E}\left[(1-\delta_E)(1-a)\left[\frac{e_t}{e_t^*}\right]^{1-\delta_E}\frac{1}{e_t} + (\delta_E-\gamma_E)\frac{1}{e_t^*}\right] + \gamma_E$

$$T_t^b/A_{R,t-1} = \tau^c c_t + \tau^w \alpha y_t + \tau^r \left(\beta \frac{y_t}{k_{F,t}} - \delta\right) k_t \tag{34}$$

$$b_t + \tau_t + \theta_R^e (1+g) h_{R,t} + \theta_R^m e_{R,t} p_{R,t} \frac{A_{R,t}}{A_{R,t-1}} =$$

$$= \left[\theta_o \xi_o e_{o,t} + \theta_g \xi_g e_{g,t} + \theta_c \xi_c e_{c,t}\right] \frac{A_{R,t}}{A_{R,t-1}} + \frac{b_{t+1}}{(1+r_t^b)} \tag{35}$$

$$r_t^b = (1-\tau_r) r_t \tag{36}$$

So, the economy is characterized by a system of 20 equations with the following 20 variables:

$$\left\{p_{R,t}, p_{e,t}, e_t, e_t^*, k_{R,t}, k_{F,t}, k_t, c_t, h_{R,t}, e_{o,t}, e_{g,t}, e_{c,t}, r_t, r_t^b, x_{R,t}, e_{R,t}, n_t, \pi_{R,t}^m, \left(\frac{T_t}{A_{R,t-1}}\right), \left(\frac{T_t^b}{A_{R,t-1}}\right)\right\}$$

Which can be numerically computed, both in the transition dynamics and in the Balanced Growth Path.

3.2.5. Computing the Dynamic Laffer Effect

To analyze the Dynamic Laffer effect the following steps are taken: i) Assuming that the economy is currently placed in the Balanced Growth Path; ii) Assuming that initially the transfers to the renewable energy generators and R&D sector equal the revenue obtained from taxes on fossil fuels, i.e., no debt issuance is necessary and we assume that the current stock of outstanding debt is zero. Therefore, the volume of transfers before assessing the existence or not of a Dynamic Laffer effect of changes in subsidy θ_R^m is:

$$T_{t,0} = \left(1 + g\lambda h_{R,0}^\eta\right)^{t-1} A_{R,0} T_{0,0} \,,$$

where $T_{0,0} = \left[\theta_o \xi_o e_{o,0} + \theta_g \xi_g e_{g,0} + \theta_c \xi_c e_{c,0}\right]\left(1 + g\lambda h_{R,0}^\eta\right) + \cdots$

$$+\tau_c c_o + \tau_w \alpha y_o + \tau_r \left(\beta \frac{y_0}{k_{F,0}} - \delta\right) k_0 - \cdots$$

$$-\theta_R^e h_{R,0}(1+g) - \theta_R p_{R,0} e_{R,0}(1 + g\lambda h_{R,0}^{\eta}) ,$$

and $A_{R,0} = 1$

Note that the 0 subindex denotes the initial steady-state values before the change in θ_R^m . Denoting by $\widetilde{Rev}_{t,1}$ the green tax revenues net of subsidies after the change in θ_R^m, we obtain the dynamic path followed by these revenues:

$$\widetilde{Rev}_{t,1} = \left[\theta_o \xi_o e_{o,t} + \theta_g \xi_g e_{g,t} + \theta_c \xi_c e_{c,t}\right] * \left(1 + \mathrm{g}\lambda h_{R,t+1}^{\eta}\right)^t - \theta_R^e h_{R,t,1}(1+g)\left(1 + g\lambda h_{R,t-1,1}^{\eta}\right)^{t-1}$$

$$-\theta_R^m e_{R,t,1} p_{R,t,1}\left(1 + g\lambda h_{R,t,1}^{\eta}\right)^t, \;\; t = 0,1,2, \ldots.$$

Note that the 1 subindex denotes the values of variables after the change in θ_R^m. So, the *green* constraint of the government that must be satisfied is:

$$\left(\widetilde{Rev}_{t,1} - T_{t,0}\right) + \frac{B_{t+1,1}}{1+r_{t+1,1}^b} - B_{t,1} \;\; \geq 0 \qquad (37)$$

Or, equivalently

$$\left(\widetilde{Rev}_{0,1} - T_{0,0}\right) + \sum_{t=1}^{\infty}\left(\frac{1}{\prod_{s=0}^{t-1}(1+r_{s,1}^b)}\right)\left(\widetilde{Rev}_{t,1} - T_{t,0}\right) \;\; \geq 0 \qquad (37')$$

where $r_{t,1}^b = (1-\tau^r) r_{t,1} = (1-\tau^r)\left(\beta \frac{y_{t,1}}{k_{F,t,1} - \delta}\right)$

Hence, a Dynamic Laffer effect exists if future revenues net of subsidies offset initial deficits resulting from the increase in θ_R^m. To this end, the increase in θ_R^m should have a larger positive impact on economic growth than negative impact on the cost of debt. In the results discussion section, the fiscal mix leading to Dynamic Laffer effects are analyzed.

3.2.6. Parameters Calibration

To carry out the analysis, we use the following baseline values characterizing European fiscal policy and the structural parameters of the economy:

Table 1: Parameter Calibration

$\delta_E =$	-0.200	$\sigma =$	1.400
$\gamma_E =$	0.450	$\rho =$	0.960
$\eta =$	0.180	$d =$	0.053
$\lambda =$	1.900	$\alpha =$	0.610
$g =$	0.045	$\beta =$	0.330
$\zeta =$	0.900	$\theta_R^m =$	0.050
$a =$	0.677	$\theta_R^e =$	0.050
$b =$	0.509	$\theta =$	2.200
$c =$	0.371	$\tau_c =$	0.100
$\xi_o/\xi_g =$	1.260	$\tau_w =$	0.200
$\xi_o/\xi_c =$	0.744	$\tau_r =$	0.300
$\psi =$	2.600	$p_o/p_g =$	1.544
$\theta_o =$	1.496	$p_c/p_g =$	0.685
$\theta_g =$	0.828	$\nu =$	2.000
$\theta_c =$	1.971		

This set of parameters replicate key empirical facts for the EU economy. Specifically, according to the values for $\{\lambda, \eta, g, \zeta, \theta, \nu, \Psi\}$, economic growth rate is 2.06%, time endowment allocated to work is N=0.31 and probability of success of the R&D activity is $\phi_t = 46\%$. These values are in line with the EU real GDP growth rate for 1970-2019 (2.11%), the percentage of time devoted to time is 31% (these data are both obtained from the database AMECO), and the probability of success for innovations in the renewable energy sector is also aligned to the results in Olsen (2020) and Salas-Fumás (2019).

On the other hand, the technological parameters b, c and γ_E are consistent with the estimations in Argentiero et al. (2018). The values for technological parameter a, and the tax rates on fossil fuels $\{\theta_o, \theta_c, \theta_g\}$ are calibrated to replicate the share of each fuel on fossil fuel consumption and carbon intensity in 2019[11]. Fossil fuel prices and emissions are taken from BP Statistical Review of the World Energy 2020. For δ_E we use the value -0.4 to replicate complementarity between oil and intermediate energy. With the complete set of parameters, the ratio of tax revenues to output in the model is 1.26, consistent with Eurostat data for 2019. Finally, the share of consumption of fossil fuels over output in the model is 4.1%, aligned with the actual ratio for the EU in 2019, according to the database AMECO.

Parameter values for the production function of final goods (α, β, d) follow the standard values in previous literature. The discount rate value (ρ) is consistent with gross real interest rate (net of depreciation) of 4%, which is also standard in economic literature.

Tax rates on consumption, labor, and capital $\{\tau_c, \tau_w, \tau_r\}$ are calibrated according to the standard values in academic literature on fiscal policy and Laffer effects (see for example Novales and Ruiz, 2002, Mankiw and Weinzierl, 2006, or Trabandt and Uhlig, 2011). Such tax rates generate revenues over GDP equal to 26%, similar to those observed for the EU.

Finally, the baseline values for subsidies θ_R^m and θ_R^e are intendedly low, to explore a potential dynamic Laffer curve in the following section.

4. Empirical results and discussion

4.1. Steady-state analysis

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[11] Carbon intensity is defined as carbon emissions over real GDP.

Starting from the baseline calibration, we change one fiscal instrument at a time and assess the effects on the steady state of the model. We analyze the impact on growth, probability of R&D innovation success, and revenues from energy taxes and non-energy taxes as a percentage of output. We call ***energy-tax revenues*** those obtained from taxes on fossil fuels, i.e. natural gas, oil and coal, net of the subsidies to renewable energy production and R&D. We call ***non-energy-tax revenues*** those obtained from taxes on capital, labor, and consumption. Results are depicted in Figures 1 and 2.

Figure 1 shows that economy growth rate is positively affected by increases in subsidies to the production of renewable energy. This is due to the increase in the success probability on the innovations in the research sector, induced by the larger incentives to innovate. When subsidies to the production of renewable energy are larger, the expected future profit of the monopolist obtaining the patent are larger, leading to higher R&D spending and higher probability of success. Second, non-energy taxes revenues increase as a result of the larger subsidies to renewable energy production, due to stronger economic growth, which expands the tax base for consumption and income taxes. Third, the ratio of energy taxes revenues to output is lower the larger the subsidy to renewable energy production because these revenues are net of subsidies to the renewable and R&D sectors. The increase in the subsidy offsets the mild increase in the taxes from oil, coal and gas.

Figure 2 shows that increasing subsidies to the R&D sector also has a positive impact on growth, because the probability of success increases. In this case, the incentive to increase the spending on R&D is direct and this translates into a larger probability of success. As a result of the stronger economic growth, the non-energy tax revenues increase. On the other hand, all energy sources to output ratios decrease, suggesting that this policy increases the energy efficiency of the economy. Finally, the consumption of energy and energy-tax revenues as a percentage of output are lower. These results are key to understand the Dynamic Laffer Effects in subsection 4.2.

Figure 1: Effects of subsidies to renewable energy production increases θ_R^m

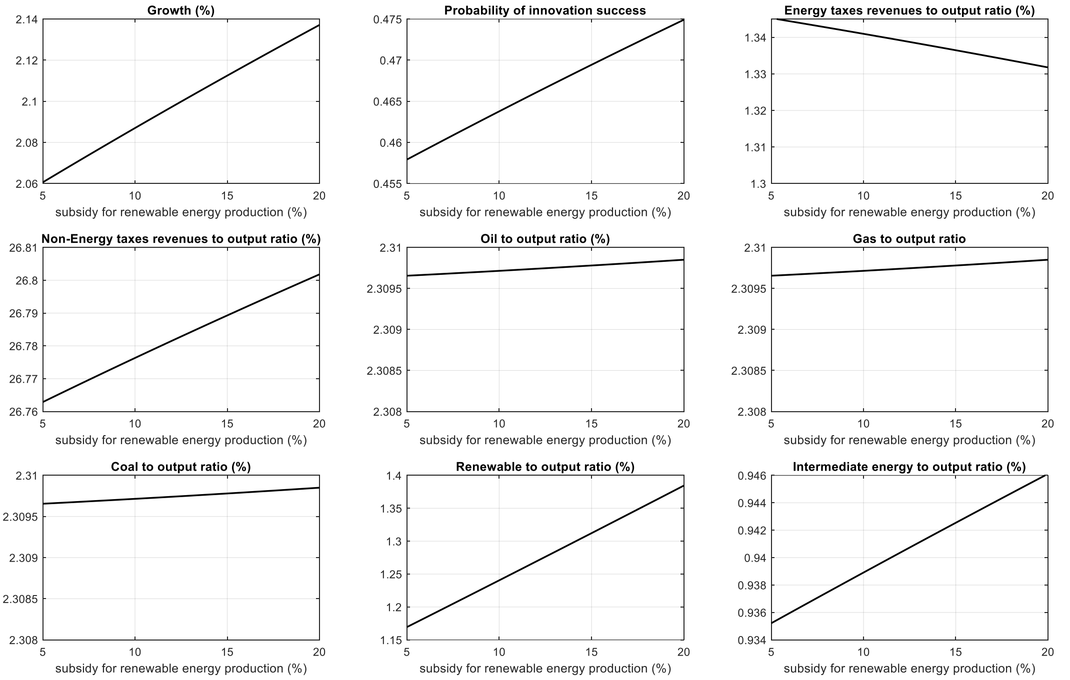
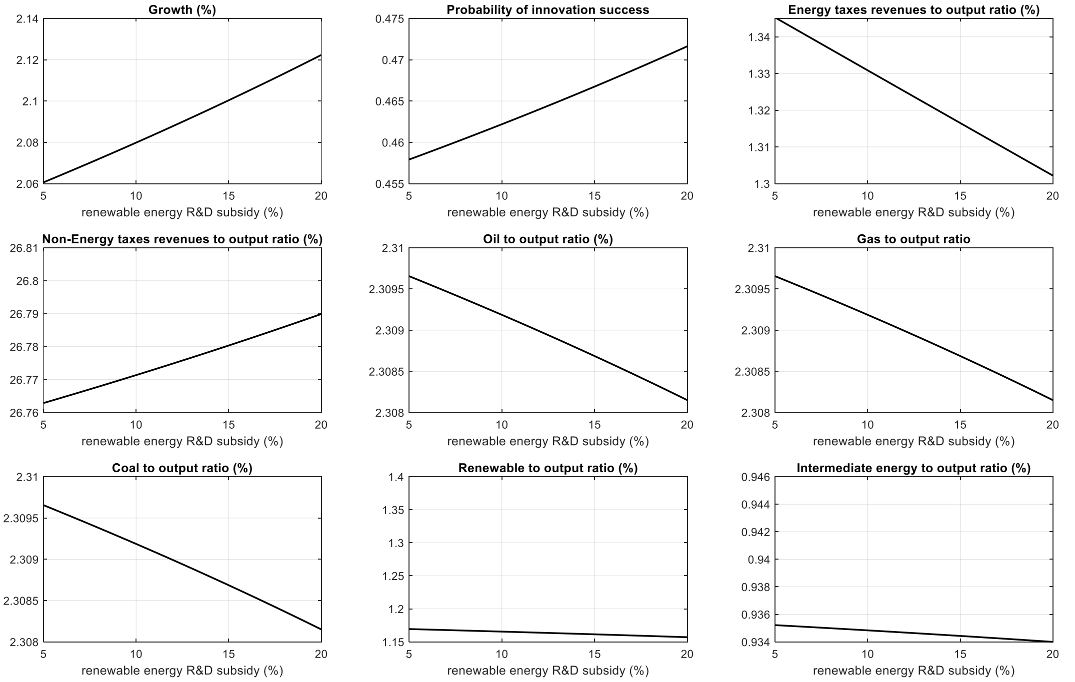


Figure 2: Effects of subsidies to renewable energy R&D effort increases θ_R^e



4.2. Dynamic Feasible green reforms

Table 2 and Figures 3 and 4 describe the impact from policies supporting renewable energy. Table 2 shows the results when the *maximum-feasible* subsidy to the renewable energy generation θ_R^m is implemented. The we define the *maximum-feasible* subsidy as the maximum level in θ_R^m that is self-financed, i.e., the debt issued to finance the initial deficit caused by the increase in subsidies, $\Delta\theta_R^m$, is financed by the increase in economic growth without the need of higher taxes. The first row of the table corresponds to the simplest possible policy in which only this subsidy (θ_R^m) is modified. The second row shows an alternative policy-mix, in which both subsidies, θ_R^m and θ_R^e are modified.

Table 2. Laffer effects of maximum feasible increase in the subsidy θ_R^m above its initial value (θ_R^m=5%)

	Max θ_R^m	$Growth\ rate$	$Welfare$ $effect$	$\Delta\ (CO2/GDP)$ (Basis points)	$\Delta\ CO2$
Only θ_R^m changes	**16.21%**	**2.118%**	**0.57%**	**-0.403**	**-0.0126%**
$\Delta\theta_R^e = 0.1\%$	12.27%	2.099%	0.38%	-0.265	-0.008%

When only θ_R^m changes, this subsidy increases from the baseline 5.00% to 16.21%. For this maximum feasible increase, the economy grows by 0.058%, social welfare increases by 0.6%[12], carbon intensity[13] decline by 0.40%, and the level of emissions decreases by 0.013%. Hence, a climate improvement coupled with higher growth is achieved without cost for future generations in the form of higher tax burden.

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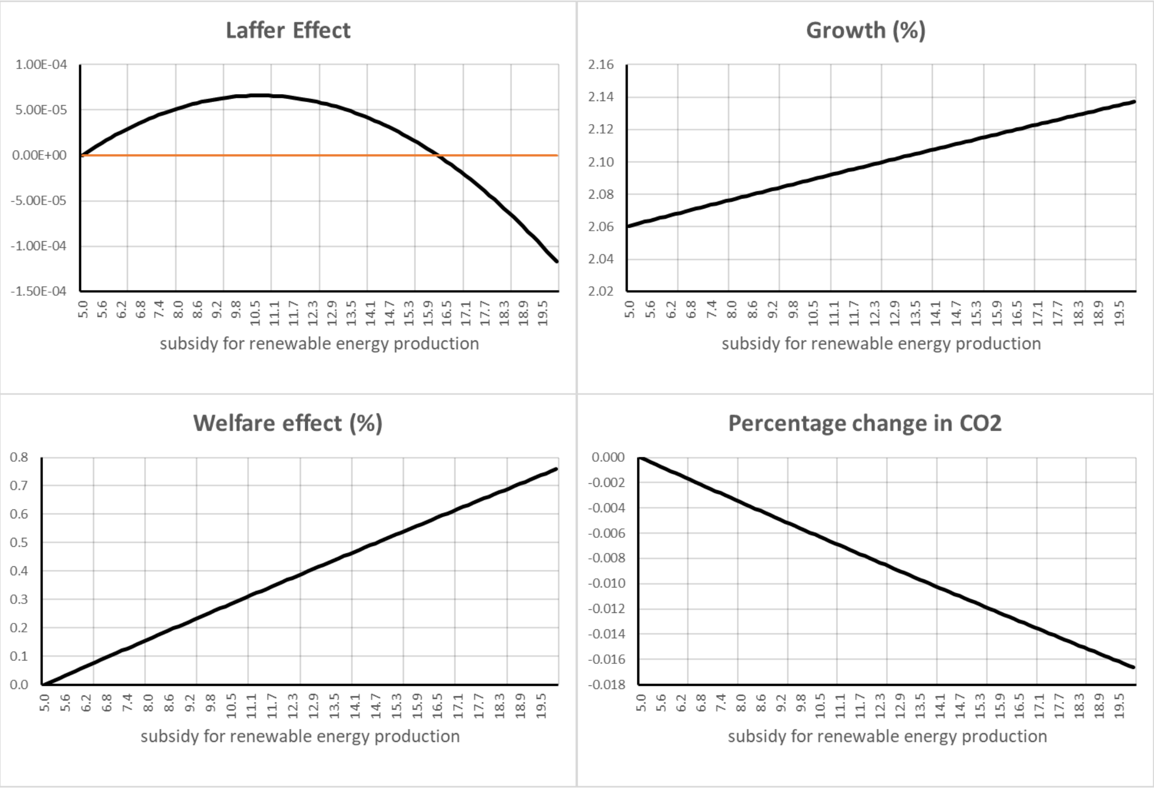
[12] Measured -as it is standard- by the percentage change in consumption which would make the household indifferent between the situations before and after the reform.

[13] In the model carbon intensity is defined as emissions over output.

Figure 3 provides economic intuition for these results. The figure depicting the Laffer Effect shows the computed value for the dynamic feasibility constraint in equations [37] or [37'] for incremental values of the subsidy. If the left-hand side [37] or [37'] is positive then higher subsidies are dynamically feasible, because discounted future government deficits are offset by discounted future government surpluses. The value of θ_R^m for which the inverse-U shaped curve intersects the X-axis shows the maximum feasible subsidy. Those values lying between the baseline level (5%) and the maximum (16.21%) generate a budget surplus from an intertemporal perspective, i.e., the discounted future surpluses exceed the discounted future deficits. Hence, in all these cases, the reduction in emissions is coupled with improvements in the government fiscal balance.

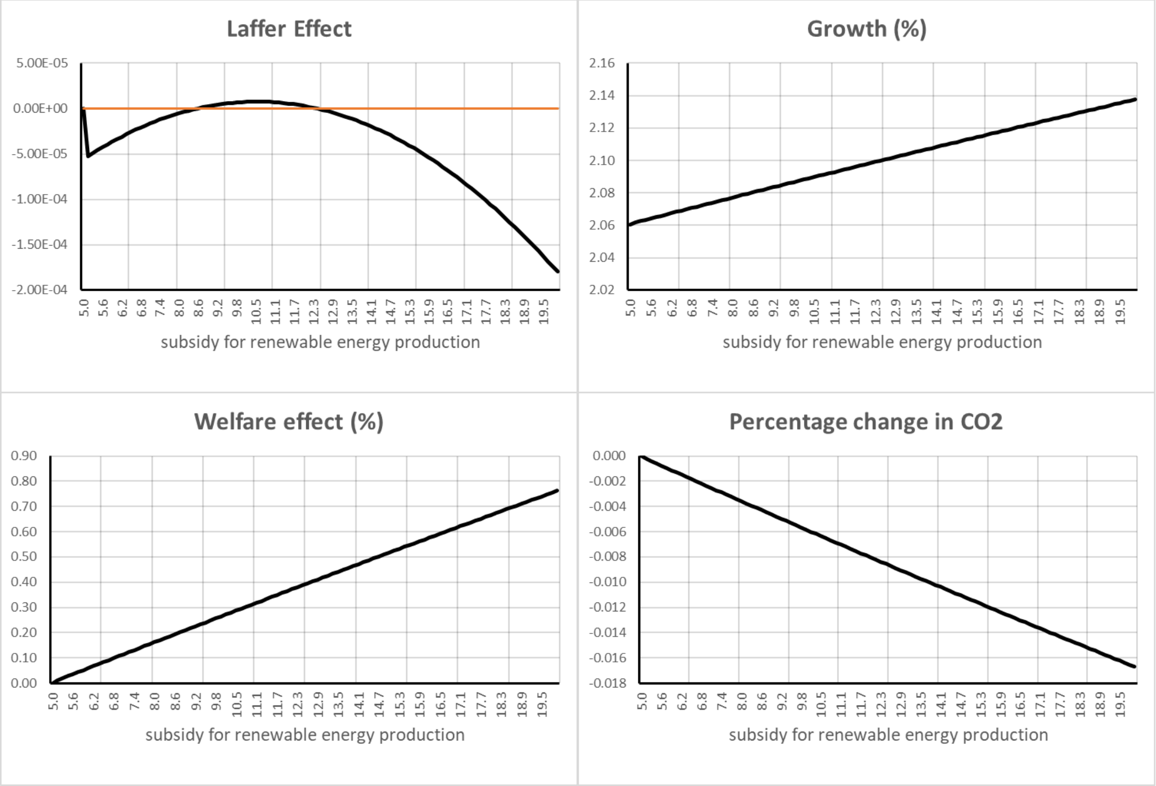
Figure 3: Baseline Laffer Effect (with θ_R^e =5%): only θ_R^m changes



In the second row of Table 2 the results from an alternative policy-mix exercise are presented. Starting from the baseline case $\theta_R^m = 5\%$, the successive increases in this policy variable are coupled with an increase in the subsidy to R&D spending equal to 0.1% ($\Delta\theta_R^e = 0.1\%$). In this case, government spending devoted to the renewable sector is higher, leading to a lower maximum feasible subsidy, (θ_R^m=12.27%) that is lower than before. For this new maximum level, economic activity increases by 0.0385%, welfare by 0.4%, carbon intensity decreases by 0.26%, and total emissions decrease by 0.008%.

See Figure 4 for a better understanding of these results. The first chart shows that the Laffer effect is obtained for a narrower range of subsidies to renewable energy generators (θ_R^m) than in the first case: only from 8.6% to 12.3%. Therefore, this is the only range for dynamically feasible *green reforms*. We call *green reform* as the simultaneous and balanced increase in subsidies to the renewable sector financed through the issuance of green bonds. This smaller feasible set of reforms can be explained by analyzing the effects for the steady state. The increase in θ_R^e, reduces the energy-tax revenues more than the increase in the non-energy-tax revenues. As a consequence, the increase in θ_R^e reduces tax revenues as a percentage of output, making more difficult to finance the initial deficit caused by the *green reform*.

Figure 4: Laffer effect when $\Delta\theta_R^e = 0.1\%$



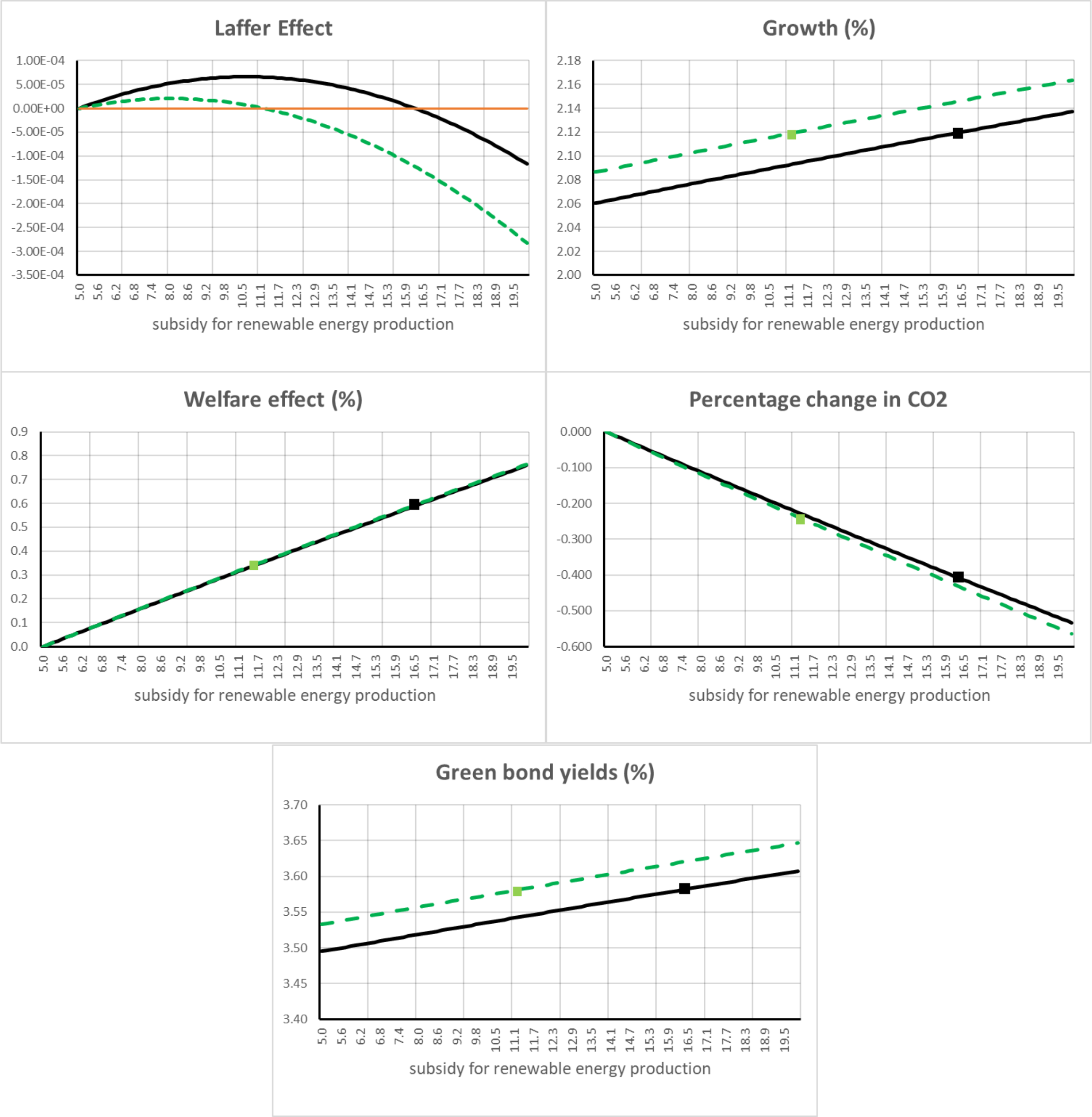
A key result of this study is that subsidizing renewable energy generation is more efficient from an economic point of view that subsidizing R&D in the renewable technology sector. The reason is that it generates greater future benefits. The renewable generation subsidy is in place year after year until another company creates an innovative technology that displaces the current monopolist from the market, while the direct subsidy to R&D only lasts for the period in which the spending was made. This implies that the positive long-term effect generated by generation subsidies are than bigger that those generated by R&D subsidies. Furthermore, the equilibrium interest rate is higher when subsidizing R&D because the risk associated with unsuccessful R&D spending has a greater impact on the interest rates. Therefore, the higher the interest rate, the more difficult it is for a Laffer effect to emerge, as future fiscal surpluses will have a lower present value than the accumulated initial deficits. This is the fundamental reason why subsidizing investment in innovation does not generate a Laffer effect.

5.3. Sensitivity analysis

We carry out a sensitivity analysis to explore how alternative technological parameters impact on these results (Figures 5 to 7 provide some insights). First, a decrease in $\delta_E$from -0.2 to -0.4, which increases complementarity between oil and intermediate energy (compound energy from natural gas, coal, and renewable energy) in the energy production function. This change diminishes -very remarkably- the Dynamic Laffer effect. The feasible subsidy to renewable energy generation decreases materially (see Figure 5). The maximum feasible subsidy to the renewable energy generators is now 11.1%, instead of 16.2%. As a result, the improvement in terms of growth, social welfare, and emissions is smaller: the increase in growth is now 0.032% instead of 0.058%, the increase in social welfare is 0.32% instead of 0.57%, and the decrease in carbon intensity is -0.23% instead of -0.40%, or -0.0071% and -0.0126%, respectively, when considering the level of emissions.

Figure 5 provides intuition for these results. When complementarity between oil and intermediate energy is large, the economic growth is higher -for any given subsidy to renewable energy production (θ_R^m), but bonds' yield is also higher, making more costly to repay outstanding debt and hence, making more difficult to obtain the Dynamic Laffer Effect. As a result, the maximum feasible subsidy is smaller than before.

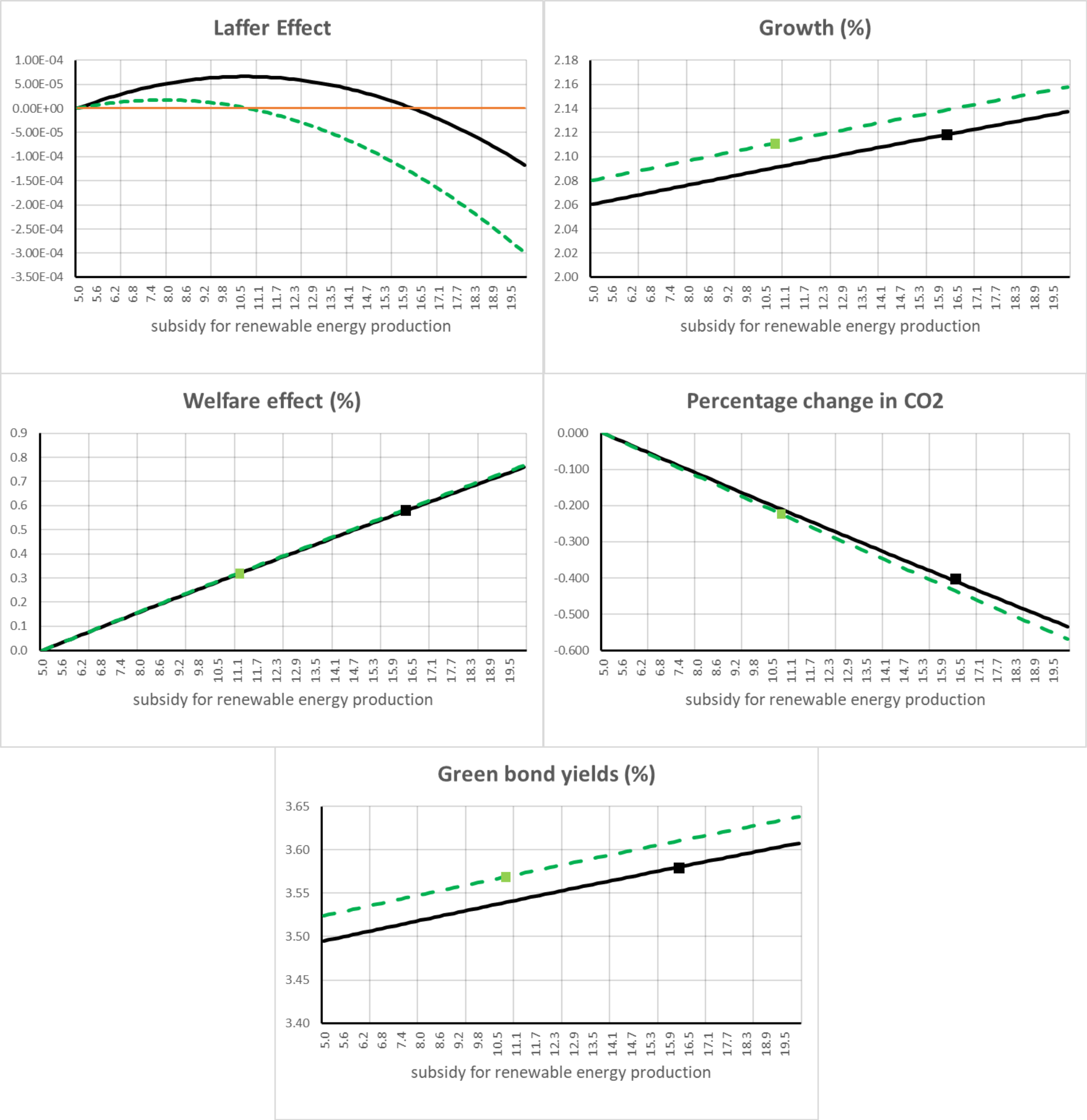
Figure 5. Sensitivity analysis to an increase in oil and intermediate energy (e_t^*) complementarity. Bold line: baseline scenario; dashed line: $\boldsymbol{\delta_E} \downarrow$



The small squares in the chart show the level for the maximum feasible taxes.

We analyze the effect of a decrease in the share of oil in final energy production, captured by the a parameter. This change also diminishes remarkably the possibility to obtain the dynamic Laffer effect. For a value of this parameter equal to 0.65, the maximum feasible subsidy to renewable energy generation is 10.6%, nearly 6 percentage points less than in the baseline case (where $a = 0.677$). This result makes sense, because as the share of oil decreases, the energy-tax revenues decrease sharply, making more difficult to finance the initial deficit. In deep sense, fossil fuels are those that finance the energy transition. On the other hand, we observe that, a smaller a parameter leads to a higher bond yield, increasing the cost of debt. Accordingly, the positive effects of the *green reform* are smaller compared to the baseline calibration. The maximum increase in economic growth is 0.029% compared to 0.058% for the baseline, the corresponding increase in welfare is 0.29% compared to the 0.57 and the decrease in carbon emissions is -0.218% versus -0.403% for the baseline.

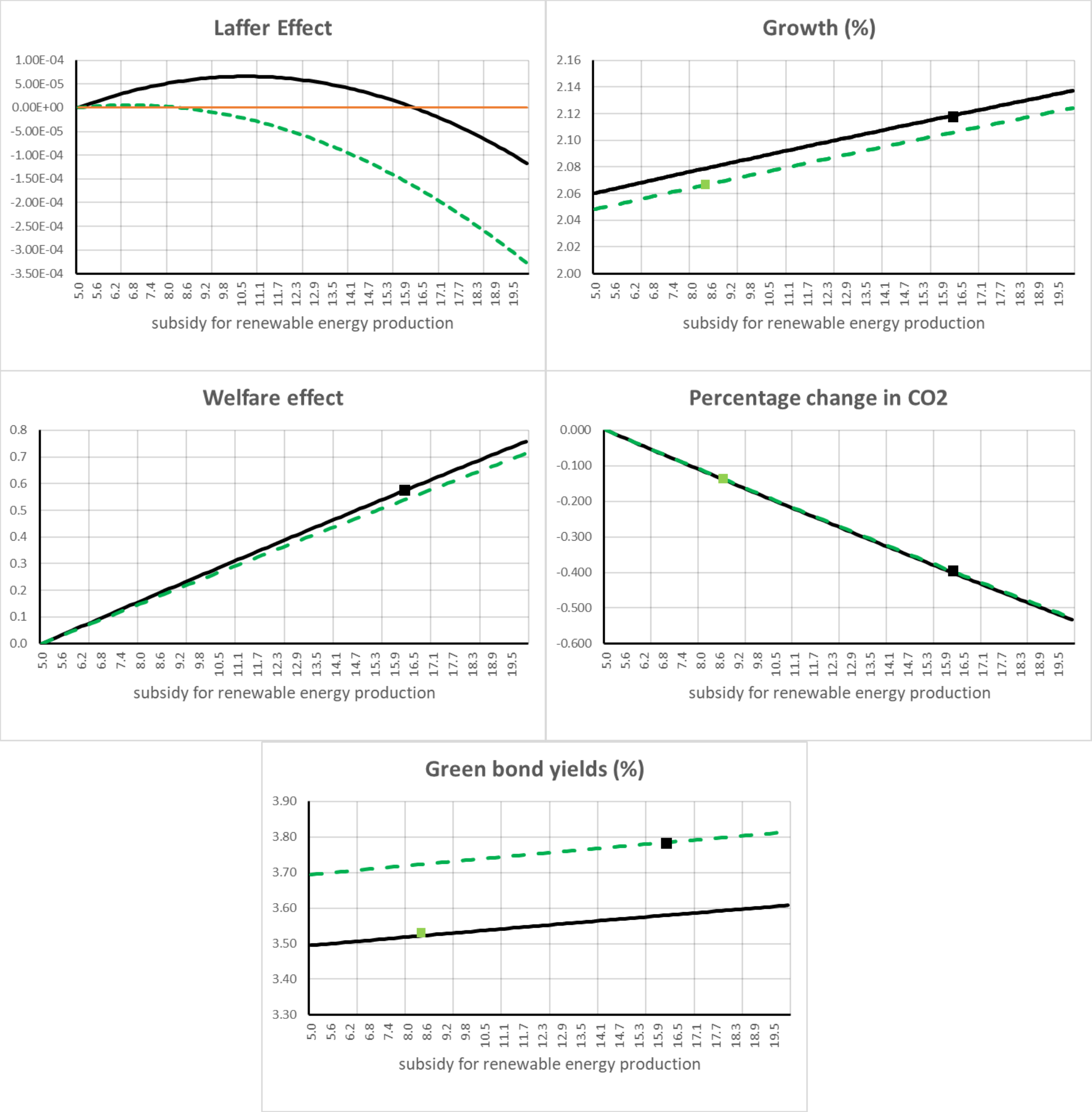
Figure 6: Sensitivity analysis to a decrease in the share of oil in final energy production. Bold line: benchmark; Dashed line: a ↓



The small squares in the chart show the level for the maximum feasible taxes.

Finally, Figure 7 explores the role of risk aversion. When σ increases from 1.4 to 1.5, the Dynamic Laffer Effect is also remarkably reduced. The subsidy to renewable energy can only be increased to 8.3%, 8 percentage points lower than in the baseline scenario. The explanation for this smaller room for maneuver for a green reform is that the increase in the risk aversion harms the potential growth of the economy, making more difficult the Dynamic Laffer Effect (see Novales and Ruiz, 2002, or Ireland, 1994, for a detailed analysis of this effect). We can observe this negative effect on growth in Figure 7. Bonds' yield is larger than in the baseline calibration, increasing the burden of debt and making more difficult to obtain the Dynamic Laffer Effect. Accordingly, the positive effects on growth, welfare, and emissions are also materially diminished. The increase in growth resulting from the green reform is 0.018% versus the 0.058% for the baseline; the increase in welfare is 0.16% compared to the 0.57% and, finally, the decrease in emissions is only -0.12% versus the -0.403%.

Figure 7: Sensitivity analysis to a decrease in the intertemporal elasticity of substitution. Bold line: benchmark; Dashed line: $\sigma \uparrow$



The small squares in the chart show the level for the maximum feasible taxes.

6. Conclusions

The urgent need to expedite the deployment of renewable technologies remains a critical policy objective to effectively address global warming and align with the targets set in the Paris Agreement. In this context, we have developed an endogenous growth model that explores the utilization of public green bonds as a key policy tool for financing the energy transition.

The primary focus of this paper is to examine the role of public green bonds in facilitating the financing of the energy transition. Specifically, these green bonds subsidize renewable energy generation through a feed-in premium scheme, as well as support research and development (R&D) efforts in renewable technologies through direct subsidies. A significant contribution of this study lies in demonstrating a range of viable *green reforms* that can be implemented dynamically. We define *green reform* as a simultaneous and balanced increase in subsidies to the renewable sector, financed through the issuance of green bonds. In essence, we demonstrate that it is feasible to enhance subsidies for renewable energy production without the necessity of raising other taxes. This is possible because the public debt incurred during the initial stages of subsidy establishment becomes self-financed due to its positive impact on economic growth.

One noteworthy academic contribution of this paper is that it is possible to simultaneously decarbonize the energy system while fostering economic growth. This is accomplished through an endogenous mechanism known as Schumpeterian creative destruction within the energy system.

The conducted sensitivity analysis indicates that a higher share of renewable sources in the production of final and intermediate energy, greater substitutability among productive inputs in energy production, or an increased probability of successful innovations in the R&D sector widen the range of self-financed green reforms. It is important to emphasize that even in cases where the economy's structural parameters do not permit a dynamic Laffer effect, the role of green bonds remains positive by reducing the need for increased taxation to maintain government budget balance over time.

A thought-provoking conclusion drawn from the model is that promoting a shift in society's utilization of renewables and fossil fuels from complementary inputs to substitutive inputs seems advantageous. Such a shift would yield more substantial emission reductions when implementing a green reform.

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