Sustainable growth with renewable and fossil fuels energy sources: a DSGE approach

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Abstract
How to control climate change and to spur clean energy are among the most important challenges facing the world today. Governments are active player in solving the problems associated with pollution. We doubt the effectiveness of current policies to implement renewable based on the use of a flow of monetary subsidies: such a short-run policy leads investment in renewables to be suboptimal since investors do not perceive climate change policies as a long lasting government commitment. The aim of this paper is to show, through a DSGE model, the effectiveness of an incentive mechanism based both on a carbon tax and a stock of public capital which captures intensity of government long term commitment to support new technology developments in renewable energy, instead of a flow of monetary subsidy to renewables. Our key findings show that alternative measures of public support in the renewable energy sector based on a stock of public capital may produce better effects on implementation of renewables on the long run than a monetary subside. Finally, we simulate the model under a shock on the stock of public capital and on human capital to evaluate the dynamic behavior of the key variables .

JEL codes: D58, O44, Q48.
Keywords: economic growth, energy, innovation

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1. Introduction

There is an ongoing debate on the effectiveness of environmental policies into action to tackle climate change. In a business-as-usual scenario, which gives economic and environmental assessments of a world in which the economy continues on its current course without polluting emission reduction policies, fossil fuel use is projected to grow, and the dirtiest fuel, i.e. coal, is expanding its share to face the rising in energy demand driven by developing countries. The global response to climate change started with the so called Rio Earth Summit in 1992: governments realized the need to work together for an environmental and sustainable economic development. The Summit was a first move towards both environmental and energy policies at global level, by setting emission reduction targets for developed countries and establishing a framework of wider reduction for future from a sustainable development point of view. Its weak point was that the Summit promised a lot and cost little, since it was an agreement without stringent measures (Helm, 2008). The Summit has been followed by several discussions with the purpose of finding optimal common environmental policy for facing climate change. Afterwards, the Kyoto Protocol, an international agreement adopted in Kyoto on December 1997, has committed (instead of encouraging) 37 industrialized countries and the European Union (EU) to reduce GHG emissions through national measures. The search for a consensus among countries worldwide is tricky since energy policies advocated both by developed and developing countries differ widely. The primary objective of the strategies implemented so far lies in increasing the use of renewable energy in order to enjoy environmental benefits and for energy security reasons. The bulk of literature on environmental regulation policies (Acemoglu et al., 2011; Grimaud and Rouge, 2008; Nordhaus, 2008; Quiggin and Horowitz, 2003) focuses on the need of a carbon tax and monetary subsidies for the development and diffusion of environmental-friendly technologies. The carbon tax takes generally the form of a tax on the carbon content of fuels and it has several advantages over other economic incentives (Chen and Tseng, 2011). First, it corrects a distortion that is the polluting emissions generated by firms; secondly, given the widespread use of fossil fuels, the carbon tax is revenue raising and governments may use such revenues for other purposes to partially offset distortionary taxes. Moreover, carbon taxes act as a spur to adopt cleaner technology since polluters want to reduce their costs related to pollution production (Pearce, 1991). Even though a carbon tax would by itself discourage the use of fossil fuels, using this tax both to reduce polluting emissions and to stimulate research and development (R&D) activities in renewable energy would lead to excessive distortions (Acemoglu et al, 2011). Because of such distortions in the economy and limitations for public actions, governments rely on other instruments in addition to carbon tax to achieve environmental goals stated by international environmental agreements, like subsidies to renewable energies.

Renewables are still young technologies and their cost depends mainly on investment. As for investment cost of almost every technology that becomes lower with mass production and technological development, renewable energy sector needs investment to encourage innovation and to achieve their potential (Goswami, 2007). The use of renewables involves many benefits, some of which are not appropriated to the extent that there is no practical way in which producers may exclude special agents from consuming goods or services. Such inability is related to the difficulty to impose and receive a price that leads to competitive returns for the producer (Aschauer, 1989). Moreover, there is uncertainty within the energy industry about the level of investment in renewables made by firms themselves, so that it might be that no one invests in the production of energy from renewable resources. Consequently, there is a low incentive for the representative firm operating in renewable energy sector to bear expenses of investment. Public intervention is then necessary because private market economy is unable to accomplish the task of developing renewables.

The main policy instruments used by countries are generally classified as price-oriented or quantity-oriented; some of them are claimed to be more market conform than others, while other schemes are claimed to be more efficient in promoting the development of renewable energy (Meyer, 2003). Actually, there is no general agreement on the effectiveness of each scheme; such assessment is made difficult even by the fact that renewable energies differ among countries: two countries may offer the same support scheme but they face heterogeneous quality of the energy sources. It translates in different production costs incurred by renewable energies that might lead to misleading evaluations of support instruments (Held et al., 2006). All mechanisms introduced up to now are meant to promote use of renewable energy sources, but such variety of options may risk of not reaching the target of developing renewable energies (Klessmann, 2009).

This article aims to evaluate the effectiveness of an incentive mechanism based both on a carbon tax and a stock of public capital which captures intensity of government long term commitment to support new technology developments in renewable energy through investment in infrastructures, instead of a flow of monetary subsidy to renewables. The model will get underway from the one proposed by Grimaud et al. (2010) in which they show that two instruments - an R&D subsidy and a carbon tax - are necessary to correct for the two market failures, i.e. R&D spillovers and pollution. We break with tradition in relation to the short-run policies based on monetary subsidies to the price of renewables. In our opinion, the failure of the existing policies on climate change is due to the fact that the implementation of renewable energy is spurred by the flow of monetary subsidies to the price of renewables. Such a short-run policy leads investment in renewables to be suboptimal since investors do not trust climate change policies: there are several turnabouts on climate change policies that support financially renewable energy in a shaky way, as it has happened recently in USA, Germany, Italy and Spain.

We believe that a more fruitful approach to tackle climate change should take into account that investors in renewable energy react positively to a stock of commitment and reputation of the policy makers on the long run. As an example of credible long-run investment, consider that the European Investment Bank has recently created the 2020 European Fund for Energy, Climate Change and Infrastructure ("Marguerite Fund") in partnership with national institutional investors with the aim of financing energy infrastructure on the long-run, with emphasis to renewables (European Investment Bank, 2010). The innovation of the “Marguerite Fund” consists of its aim that it is not speculative and it has a long-run horizon.

The objective of our paper is to show the effectiveness both of a carbon tax and a stock of public capital which captures intensity of government long term commitment to support new technology developments in renewable energy instead of a subsidy to the price of renewables. To our knowledge, there is not a significant literature tackling comprehensively the issue of effectiveness of Government intervention in favour of renewables. We recall that economic analysis has long modeled public capital stock as a key factor among inputs in the final output's production (e.g., see Aschauer 1989, 1990, 1993; Lynde and Richmond, 1992), considering the relation between aggregate productivity and public capital stock, both in the United States and in other developed countries. Main finding is that private sector productivity is positively related to the level of infrastructure (Aschauer, 1989).

In our model, the final good is produced employing labour and energy services from two imperfect substitutes that are renewable energies and fossil fuels. The quantity of energy from fossil fuels is a function of investment and the amount of resources extracted. The price of the non-renewable energy follows the generalized version of the Hotelling rule. Concerning the renewable energy policy intervention, we consider the effective value of an innovation paid to the inventor as an incentive for doing research in renewable energy in order to lower production costs and make it competitive in the energy market. In order to take into account government intervention we postulate that the production function depends on investment and existing specific knowledge, together with a stock of public capital which represents the cumulated government support to new technology. There is the perspective of a non-linear jump, that is, there is a critical R&D threshold beyond which renewable energy gains in importance with respect to the fossil fuels input. We first present the decentralized economy and study the behaviour of agents in each sector: the final good sector, the energy services, the consumers and the government. We characterize both the decentralized equilibrium and the first-best optimum solutions. Then, we show how the optimum can be implemented by an appropriate stock of public capital, determining the conditions of the relative effectiveness of the cumulated stock of government reputation and commitment, in order to enable policy strategies.

2. The Model

The main features of the model consist of a final output, which uses different forms of energy as inputs, investment in energy efficiency augmenting technologies, R&D producing sector, stocks of knowledge and stock of public capital which captures intensity of government long term commitment to support new technology developments. The combustion of fossil fuels generates polluting emissions, as CO_2, that damage the natural environments and then society. Furthermore, the producer of fossil fuels have a negative cost from polluting emissions, unless the government intervenes with market instruments like taxes. In our model, the carbon and capture storage (CCS) technology that allows for significant CO_2 emission reductions is included in the fossil-fuel sector. The productive capacity of fossil fuels is finite. According to the condition derived by Hotelling (1931), we describe the dynamic of the fossil fuels' price that is expected to grow over time.

We assume that there is research only in the renewable energy sector. There are two market failures: pollution and research spillovers. The former is corrected through a tax on the quantity of pollution from fossil fuels. Research spillovers are related to the benefits from new clean technologies shared between firms: innovation is a non-rival good and it implies the inability to exclude and to receive the social price of innovation.

The renewable production function includes as inputs a stock of public capital, investment and the existing specific knowledge. We work on the effective value of an innovation paid to the inventor as an incentive for doing research in renewable energy in order to lower production costs and make it competitive in the energy market. The effective value of the patent for innovation in the two variants proposed changes according to the production function of renewable energy.

2.1 The final output sector

The final output Y_t is produced using not-skilled labor *L*, capital *K* and energy services *E*: $Y_t = Y(L, K^Y, E)$, where Y is increasing and concave in each argument. We denote by p_E , w_t and r_t respectively the price of energy services, the real wage and the interest rate. The price of the final output is normalized to one. The profit of the representative producer is $\pi_t^Y = Y_t - w_t L_t^Y - p_{E,t} E_t - (r+\delta) K_t$, the rate at which depreciation causes *K* to fall is the amount of depreciation δK. For our convenience, we drop time notation henceforth.
The first-order conditions are:

$$Y_L - w = 0 \tag{1}$$

$$Y_E - p_E = 0 \tag{2}$$

$$Y_K - (r+\delta) = 0 \tag{3}$$

where F_x is the derivative of *F* with respect to *x*.

2.2 The energy services sector

The amount of energy E is produced from two imperfect substitutes, that are fossil fuels EF and renewable energy ER, that is $E = E(EF, ER)$ where *E* is increasing and concave in each argument.
Denoting by p_{EF} and p_{ER} the prices respectively of fossil fuels and renewables, the profit function of the representative energy services producer is: $\pi^E = p^E E - p^{ER} ER - \left(p^{EF} + \tau\right) EF$, where τ is the tax paid by the energy producer in proportion to the carbon emissions *EF*. The first order conditions lead to:

$$p^E E_{EF} - \left(p^{EF} + \tau\right) = 0 \tag{4}$$

$$p_E E_{ER} - p_{ER} = 0 \tag{5}$$

2.3 The fossil fuel sector

The fossil fuel sector depends on investment K^{EF} in the fossil fuel sector, and on the stock of non renewable resources S_t. The dynamic of S_t is as follows:

$$S_t = \int_0^t EF_s ds \leftrightarrow \dot{S}_t = -EF_t \tag{6}$$

The fossil fuel production function is $EF_t = EF(K_t^{EF}, S_t)$, where EF is increasing in *K* and *S*. The profit of the fossil fuel producer is $\pi_t^{EF} = p_{EF} EF - r_{K_{EF}} K_t^{EF}$ with $r_{K_{EF}}$ equals the interest rate of K^{EF} .

The maximization of the profit function subject to the constraint (6) leads to :

$$p^{EF} EF_{K^{EF}} - r_{K_{EF}} - \lambda_t EF_{K^{EF}} = 0 \tag{7}$$

$$p^{EF} EF_S + \lambda_t EF_S = -\dot{\lambda}_t \tag{8}$$

where λ is the multiplier associated with (6). The term λEF_S goes to zero due to the transversality condition. From equation (7) we get $p_{EF} = \frac{r_{K_{EF}}}{EF_{I^{EF}}} - \lambda_t$; differentiating it with respect to time, we get $\frac{\dot{p}_{EF}}{p_{EF}} = -\frac{\dot{EF}_{K^{EF}}}{EF_{K^{EF}}} + g_{K^{EF}} - \frac{\dot{\lambda}}{\lambda}$ and through eq. (8) we obtain $\dot{p}_{EF} = p_{EF}\left[-\frac{\dot{EF}_{K^{EF}}}{EF_{K^{EF}}} + g_{K^{EF}} + EF_S\left(1 + p_{EF}\frac{EF_{I^{EF}}}{p_E - EF_{I^{EF}}}\right)\right]$ that is the classic Hotelling rule.

2.4 The renewable energy sector

In the renewable energy production sector there exists an R&D sector with a knowledge production function. We analyze the R&D sector by focusing on the value of a patent for inventors of new green technologies as a chance to switch to renewables instead of fossil fuels.

Because of the nature of innovation that is a non-rival good, the price received by the inventor is different from the social value of innovation. The instantaneous social value of an innovation is $\bar{a}_{ER,t} = \bar{a}_t^{ER} + \bar{a}_t^{H_{ER}}$ that is the sum of the marginal profitability in the renewables sector and the marginal profitability of this innovation in the R&D sector. By integrating the instantaneous social value of an innovation through time, we get the optimal value of a patent:

$$\bar{A}_{ER,t} = \int_t^{\infty} \bar{a}_{ER,s} e^{-\int_t^s r_x dx} ds \tag{9}$$

Now, consider the effective value of the innovation as $a_{ER,t} = \mu_{ER} \bar{a}_{ER,t}$ where μ_{ER} is a share of the social value which is effectively paid to the innovator and $0 < \mu_{ER} < 1$.

The intertemporal effective value is $A_{ER,t} = A_t = \int_t^{\infty} a_{ER,s} e^{-\int_t^s r_x dx} ds$ (10)

Differentiating equation (10) with respect to time, we get:

$$\dot{A}_t = -a_t + \int_0^{\infty} a_s e^{-\int_t^s r_u du} \left(-(-r_t)\right) ds \leftrightarrow \dot{A}_t = -a_t + r_t A_t \ ,$$

that is

$$r_t = \frac{\dot{A}_t}{A_t} + \frac{a_t}{A_t} \tag{11}$$

Equation (11) equals the rate of return of the innovation on the financial market to the rate of return of R&D activities.

Reverting back to the R&D sector, the knowledge production function H_t^{ER} depends on investment K_t^H whose price is r_H, that is the effort in *R&D* sector: $H_t^{ER} = H\left(K^H\right)$. The profit function in the *R&D* sector is $\pi_t^{H^{ER}} = A_t H_t^{ER} - r_H K_t^H$ which means that the *R&D* sector supplies innovations H_t^{ER} at price A_t and demands some investment that is K_t^H.

We can rewrite the profit function as:

$$\pi_t^{H_{ER}} = A_t H(K^H) - r_H K^H \tag{12}$$

The first order condition leads to:

$$A_t H_{K^H} - r_H = 0 \leftrightarrow A_t = \frac{r_H}{H_{K^H}}$$

Then, the marginal profitability of innovation is:

$$\overline{a}_t^{H_{ER}} = \frac{\partial \pi^{H^{ER}}}{\partial K^H} = \frac{r_H}{H_{K^H}} \tag{13}$$

In order to obtain the instantaneous effective value of the innovation in the R&D sector, $a_{ER,t}$, we need the marginal profitability in the renewable energy sector. We consider that renewable energy production function is made up of three inputs: investment in renewables K^{ER}, stock of existing knowledge H^{ER} and public capital K^G; for the sake of simplicity, we assume that all firms are identical. The production function writes

$$ER_t = ER(K^{ER}, K^G{}_t, H^{ER}) \tag{13}$$

with *ER* increasing and concave in each argument. K^G is the cumulated government effort to support renewable energy in the long run and it includes both the actual value of policy commitment in monetary resource and the shadow value of the regulatory legislation, which creates a favorable administrative framework for investment decisions.

The production function of the renewable energy (13) differs from those used by most of the literature since it considers public capital as an input that enters the production function with private capital: the idea of including G separately from other inputs is that private inputs are not close substitute for public capital. Since public capital generates external economies, it is necessary to do some specifications on the interactions between private and public inputs. As in Otto and Voss (1994), we assume that ER(·) is homogeneous of degree one in private inputs, i.e. investment and knowledge, and exhibits increasing returns to scale in all three inputs with constant returns to scale over private inputs. Such a technology is defined by Aschauer (1989) as restricted increasing returns to scale. The assumption of constant returns to scale over private inputs is consistent with the theory according to which industries with increasing returns to scale are publicly operated (List and Zhou, 2007). More broadly, Arrow and Kurz (1970) state that if private inputs exhibit constant returns to scale technology and public capital and a private input, let's say effective labor, combine with increasing returns to scale, then the final output production function will exhibit increasing returns to scale. We discard the hypothesis that

ER(·) is constant returns to scale over all inputs, that is decreasing returns to scale over private inputs, because such a specification implies congestion in the use of public capital; we rule out the possibility of congestion in the use of K^G, because it ultimately represents the shadow value of policy commitment.

We get the marginal profitability in the renewable energy sector through the combination of the first order condition of the R&D profit function with respect to the investment K^{ER} and the public capital K^G.

The profit function in the renewable energy sector is a function of the value of output minus costs; thus the profit function is:

$$\pi^{ER} = p^{ER}ER(K^{ER}, K^G, H^{ER}) - r^{ER}K^{ER} - r^G K^G \tag{14}$$

and the first-order conditions yields:

$$\frac{\partial \pi^{ER}}{\partial K^{ER}} = 0 \rightarrow p^{ER}ER_{K^{ER}} - r^{ER} = 0 \leftrightarrow p_{ER} = \frac{r^{ER}}{ER_{K^{ER}}} \tag{15}$$

$$\frac{\partial \pi^{ER}}{\partial K^{G}} = 0 \rightarrow p^{ER}ER_{K^{G}} - r^{G} = 0 \rightarrow \frac{ER_{K^G}}{ER_{K^{ER}}} = r^G \tag{16}$$

Eq. (16) represents the marginal profitability of renewables since $\overline{a}_t^{ER} = \frac{\partial \pi^{ER}}{\partial K^G}$. The sum of eq. (16) and the marginal profitability of innovation (eq.13) gives the effective value of the innovation in the renewable energy sector:

$$a_{ER,t} = \mu_{ER}\left(\frac{r_H}{H_{K^H}} + \frac{ER_{K^G}}{ER_{K^{ER}}}\right) \tag{17}$$

In the Appendix we study the derivative of the effective value of innovation with respect to the policy instrument *G* and we compare it with the case of a government subsidy, denoted by *σ*.

We show that K^G represents a better policy instrument than a subsidy to spur investment in innovation, that is in research, for the whole range of values of σ, i.e. both when subsidy is closed to zero (under-subsidization) and close to one (over-subsidization).

2.5 The Households and the Government sectors

We consider an economy populated by a continuum of individuals with utility function

$$U = \int_0^\infty u(c_t, z_t)e^{-\rho t}dt$$

where c_t is consumption per head, z_t is the pollution level, $\rho > 0$ is the constant rate of time preference and $u(c_t, z_t) = \frac{c^{1-\sigma} - 1}{1-\sigma} - z_t$ is the utility function with $\sigma > 0$.

The representative household seeks to maximize the utility *U* subject to the following constraints:

$$\dot{k}_t = r_t k_t + w_t L_t - T_t - C_t$$

$$\dot{z} = EF_t - \alpha z_t$$

where T is the lump sum tax and k is capital per worker. Then the Hamiltonian to be maximized is $H = u(c,z)e^{-\rho t} + \lambda(rK + wL - T - C) + \mu(EF - \alpha z)$. The first order condition for maximizing H with respect to the control variable c gives

$u_c e^{-\rho t} = \lambda$,

and the Euler equation with respect to the shadow value of capital is

$\lambda \mathrm{r} = -\dot{\lambda}$,

which can be converted into a consumption-growth equation:

$$\mathrm{g_c}\sigma - \rho = \mathrm{r_t} \tag{18}$$

with g_c equals the consumption growth rate.

This implies that there is positive growth in consumption if $r_t > \rho$.

The first order condition for maximizing H with respect to the control variable z gives

$\mathrm{u_z e^{-\rho t}} = -\dot{\mu}$ which leads to

$$\frac{\dot{\mu}}{\mu} = 1 + \alpha \tag{19}$$

We assume that the government provides services directly to private producers without employing user fees and then finances expenditures through taxes.

The government's budget constraint differs according to the variant we take into account; each year we have:

$$T_t + \tau EF = \Delta K_t^G \tag{20}$$

where ΔK^G is the annual stock of public capital increment, made available to the representative firm. It is true that at time T we have $K_t^G = \sum_{t=0}^{T} \Delta K_t^G$.

The balance equation of the final output writes $Y_t = C_t + K_t^E + K_t^{ER} + K_t^{EF} + K^H + K^G - \delta K$.

In our economy, the final output is devoted to aggregate consumption, fossil fuels production, renewable energies production and *R&D*.

3. Welfare Analysis

3.1 Characterization of optimum

We consider an economy populated by a continuum of infinitely lived individuals with utility function:

$$W = \int_0^\infty u(c,z)e^{-\rho t} dt$$

The Hamiltonian to be maximized is (we leave out time subscripts for our convenience):

$$H = u(c)e^{-\rho t} + \lambda \left\{ Y\left[L, K^Y, E(EF, ER)\right] - c - K^E - K^{ER} - K^{EF} - K^H - K^G - \delta K \right\}$$
$$+ \eta ER\left[K^{ER}, K^G, H(K^H)\right] - \varphi EF(K^{EF}, S) + \nu\left[EF - \alpha z\right]$$

The latter constrain in the Hamiltonian, that is $\dot{V} = -EF(I^{EF}, S) + Z(I^{E}) + bV$, formalizes the dynamic of clean environment ($\dot{V}$); b is the spontaneous regeneration rate according to which clean environment evolves.
The existence of an optimal solution is characterized by the following equations:

$$Y_E E_{EF} - \frac{1}{EF_{I^{EF}}} + \frac{1}{Z_{I^{EF}}} = \frac{1}{c^{-\sigma}e^{-\rho t}} \int_0^\infty c^{-\sigma} e^{-\rho s} \frac{EF_S}{EF_{I^{EF}}} ds \tag{23}$$

$$\frac{1}{Z_{I^E}} = \frac{1}{c^{-\sigma}e^{-\rho t}} b \int_0^\infty \frac{1}{c^{-\sigma}e^{-\rho s}} Z_{I^E} ds \tag{24}$$

$$Y_K - \delta = g_c + \rho \tag{25}$$

$$H_{I^H} \frac{ER_{H^{ER}}}{ER_{I^{ER}}} + H_{H^{ER}} - \frac{\dot{H}_{I^H}}{H_{I^H}} = \sigma g_c + \rho \tag{26}$$

Equation (23) equalizes the marginal net profit in terms of output due to the use of fossil fuels by additional extraction to the total marginal gain if there is no additional extraction, by a socially optimal point of view. Eq. (24) gives the optimal level of incentive in order to invest in energy efficiency technologies to reduce polluting emissions from fossil fuels. Equation (25) gives the optimal trade-off between capital and consumption. Finally, eq. (26) formalizes the trade-off between investment in renewable energies and consumption.

3.2 Implementation of optimum

We now study conditions to implement the optimum, in order to find optimal levels for carbon tax and marginal productivity of renewables with respect to the stock of capital.

First, from the equilibrium condition in equation (6), the carbon tax is equal to $\tau_t = \frac{1}{Z_{I^E}}$, that is the carbon tax depends upon the effort made by the representative firm to reduce polluting emissions. Through eq. (6) and eq. (24), we can say that the value of the carbon tax is optimal if:

$$\tau_t = \frac{b}{c^{-\sigma}e^{-\rho t}} \int_0^\infty \frac{1}{c^{-\sigma}e^{-\rho t}} Z_{I^E} ds \tag{27}$$

Eq. (36) provides the optimal level of the carbon tax; since both $u'(c) > 0$ and $Z_{I^E} > 0$, then $\tau_t > 0$. This is a standard result as it is already stated in the main literature.
There follows the new result that we provide in the current literature with the present paper. Addressing now the implementation of equation (26), it is necessary to explain the equilibrium condition that characterizes the trade-off between investment in renewables and consumption. The log-differentiation of eq. (14) with respect to time leads to $\frac{\dot{A}_t}{A_t} = -\frac{\dot{H}_{I^H}}{H_{I^H}}$; by substituting the latter in eq. (12), we have that $r_t = -\frac{\dot{H}_{I^H}}{H_{I^H}} + \frac{a_t}{A_t}$. We make use eq (20) to state the effective value

of innovation, using the result that the effective value of innovation is more efficient in variant *A* that variant *B*, in order to characterize the equilibrium condition that characterizes investment in renewable energy and consumption is, using eq. (22):

$$\mu H_{I^H}\left(\frac{ER_G}{ER_{I^{ER}}}+H_{H^{ER}}\right)-\frac{\dot{H}_{I^H}}{H_{I^H}}=\sigma g_c+\rho \tag{28}$$

Then, by equating eq. (28) that characterizes the decentralized equilibrium with eq. (26), we obtain the optimal value of the trade-off between investment in renewable energies and consumption:

$$\frac{ER_G}{ER_{H^{ER}}}=\frac{1}{\mu}+d\,\frac{1-\mu}{\mu}\text{, that is}$$

$$\frac{ER_G}{ER_{H^{ER}}}=\frac{1+d(1-\mu)}{\mu} \tag{29}$$

where

$$d=\frac{H_{H^{ER}}}{H_{I^{ER}}}\frac{ER_{I^{ER}}}{ER_{H^{ER}}} \tag{30}$$

We can summarize the above results in the following proposition:

Proposition 1. The equilibrium is optimal if the carbon tax expressed in eq. (6) equals eq. (27), and if eq. (28) that characterizes the trade-off between investment in renewable energies and consumption in the decentralized equilibrium equals eq. (26) (see appendix).

Concerning eq. (29), we notice that if the share of the social value which is effectively paid to the innovator is total, that is $\mu=1$, then it must be the case that $ER_G=ER_{H^{ER}}$. The value $\mu=1$ implies that the social value of the innovation equals the effective value of the innovation itself and therefore the two marginal productivities ER_G and ER_H must be equal. Usually, this is not the case because of imperfection of market structure that reflects the state of imperfect information. At the opposite extreme case, if $\mu=0$, then $ER_G / ER_{H^{ER}}=+\infty$.

The lower the value of μ, the higher must be the relative productivity (ER_G) of the public capital *G* with respect to the marginal productivity of knowledge (ER_H) in the renewable energy production function. In this sense, the public intervention G must compensate the market imperfection (i.e. $\mu<1$), in order to attain the optimum equilibrium. In general, in terms of policy design, eq. (29) implies that if $0<\mu<1$, then $ER_G>ER_H$, i.e. the marginal productivity of public intervention must be higher than the marginal productivity of knowledge in the *ER* production function.

4. The model dynamics
[TO BE ADDED]

5. Conclusions

In this paper we have evaluated the effectiveness of an incentive mechanism based on two tools that are a carbon tax and a stock of public capital, in order to spur investment in renewable energies and then lower production costs. Most of the literature argues that carbon tax and monetary subsidies to renewables are needed for the development and diffusion of environmental-friendly technologies. We show that the latter instrument, i.e. monetary subsidies, should be replaced by a stock of public capital, because a short-run policy based on a flow of monetary subsidies leads investment to be suboptimal, since investors do not trust environmental policies. The stock of public capital captures both the actual value of policy commitment in monetary resources and the shadow value of regulatory legislation, which creates a favorable administrative framework for investment decisions. More generally, we recall that economic analysis has long modeled public capital stock as a key factor among inputs in the final output's production, and it turns out that private sector productivity is positively related to the level of infrastructure. We introduce this theoretical result in the environmental regulation framework and we analyze how the stock of public capital affects the evolution of renewable energy technologies.

In our analysis, we construct two variants since we take into account two different channels for government intervention, and then we compare them. The first variant evaluates a renewable energy production function where a stock of public capital enters the production function as an input, with investment and the existing knowledge; the second variant leaves out the stock of public capital, but the government intervention is modeled as a subsidy to investment. We work on the effective value of an innovation paid to the inventor as an incentive for doing research in renewable energy in order to lower production costs and make it competitive in the energy market. Our results show that the stock of public capital positively affects investment in renewable energy and is superior to a simple flow of monetary subsidy. Finally, we implement the optimal solutions, showing the optimal values for carbon tax and the stock of public capital. The policy implication is that policy must be designed in such a way that the marginal productivity of public intervention must be higher than the marginal productivity of knowledge in the renewable energy production function. In conclusion, public intervention emerges as a crucial element for accomplishing the task of developing renewable energies.

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Appendix

In order to assess the relative effectiveness of the stock of public capital G with respect to the more traditional subsidy, let us postulate a variant of the renewable energy production functions, with only two inputs: investment in R&D activities I_t^{ER} and the stock of knowledge H_t^{ER} so that $ER_t = ER(I_t^{ER}, H_t^{ER})$. Here, the government intervention is modeled as a subsidy σ to investment, which is set to: $0 \le \sigma \le 1$.

We want to compute the effective value of the innovation, that is the price paid to the inventor for doing research in renewable energy sector in order to substitute fossil fuels with renewables in the input portfolio energy services. The profit function in the renewable sector is now:

$$\pi_t^{ER} = p_{ER} ER(I^{ER}, H^{ER}) - (1-\sigma) I^{ER} \qquad \text{(A1)}$$

The first-order conditions are:

$$\frac{\partial \pi^{ER}}{\partial I^{ER}} = 0 \rightarrow p_{ER} ER_{I^{ER}} - (1-\sigma) = 0 \qquad \text{(A2)}$$

$$\frac{\partial \pi^{ER}}{\partial H^{ER}} = 0 \rightarrow p_{ER} ER_H \qquad \text{(A3)}$$

and combining equations (A2) and (A3) we get the marginal profitability in the renewable energy sector:

$$\overline{a}_{ER,t}^{ER} = (1-\sigma) \frac{ER_H}{ER_{I^{ER}}} \qquad \text{(A4)}$$

The effective value of an innovation in renewables sector in this variant, denoted by *B*, when governments subsidize investment in renewables through a monetary subsidy σ is:

$$a_{ER,t}^{B} = \mu_{ER} \left[\frac{ER_{H^{ER}}}{ER_{I^{ER}}} (1-\sigma) \right] + \left(\frac{H_{H^{ER}}^{ER}}{H_{I^{ER}}^{ER}} \right) \qquad \text{(A5)}$$

We can now compare equation (20) that is the effective value of innovation paid to inventors in the model, here denoted by A, $(a_{ER,t}^{A})$ and (A5), i.e. the effective value of innovation in this variant $(a_{ER,t}^{B})$ to evaluate the best instrument in terms of subsidy to be associated with the carbon tax so that renewables can overtake fossil fuels in the long term.

We first find the condition for $a_{ER,t}^{A} \succ a_{ER,t}^{B}$:

$$\mu_{ER} \left[\left(\frac{ER_G}{ER_{I^{ER}}} + \frac{H_{H^{ER}}}{H_{I^H}} \right) - \frac{ER_{H^{ER}}}{ER_{I^{ER}}} (1-\sigma) - \frac{H_{H^{ER}}}{H_{I^H}} \right] > 0 \qquad \text{(A6)}$$

and by reducing we get

$$\frac{ER_G - ER_{H^{ER}}(1-\sigma)}{ER_{I^{ER}}} \ge 0 \quad \text{if} \quad \frac{ER_G}{ER_{H^{ER}}} \ge (1-\sigma) \qquad \text{(A7)}$$

By computing the derivative of the effective value of an innovation in equations (20) and (A5) we get respectively:

$$\frac{\partial a_{ER,t}^{A}}{\partial G} = \mu_{ER} \frac{ER_{GG}}{ER_{I^{ER}}} \qquad \text{(A8)}$$

$$\frac{\partial a_{ER,t}^{B}}{\partial \sigma} = -\mu_{ER} \frac{ER_{H}}{ER_{I^{ER}}} \qquad \text{(A9)}$$

Eq. (A7) shows a quite plausible result, i.e. we get a better effect of the capital stock *G* with respect to the direct subsidy σ, when the productivity effect of the public stock *G* (ER_G) is relatively stronger than the productivity effect of knowledge stock (ER_H). In fact, if σ = 0 than a better effect of the capital stock is granted if the lhs ratio is higher than 1; conversely, if σ = 1 , then it suffices a very small positive ER_G to satisfy condition (A7).
This latter result is rather obvious: if the subsidy is covering the full amount of investment, than there is no effective value to innovation. We can appreciate this point noting that both expressions (A8) and (A9) are negative, i.e. an increase in public subsidy reduces the effective value of innovation, because firms will rather adopt existing technology if there is a subsidy.
Thus, comparing (A8) and (A9) we can see that the negative invention value effect of the subsidy is less harmful in equation (A8) than in equation (A9), if:

$$\left| ER_{GG} \right| < \left| ER_{H} \right| \qquad \text{(A10)}$$

We can interpret this latter result stating that the public stock G is relatively less likely than current subsidy σ to incur in the risk of choking innovation with over subsidization, because ER_{GG} is likely to be generally weaker than ER_H, being a second order effect (in fact, if ER is linear in G, than ER_{GG}=0 and so eq. (27) shows that G is an absolute best policy instrument to spur investment in innovation, that is in research.

In order to make a meaningful comparison between the model with G and the variant of this Appendix, we postulate that the long term amount of monetary resources disbursed by the government is the same as in the model. Thus, in this variant the government's budget constraint is, for each period:

$$T_t + \tau(EF_t - Z_t) = \sum_i \sigma_t I_t^{ER} \qquad \text{(A10)}$$

Comparing eq. (A10) with (22), we observe that, obviously, in every period it does not necessarily happen that $\sigma_t I_t^{ER} = \Delta G_t$, while it is true that at time T we impose that $G_T = \sum_{t=0}^{T} (\sigma_t I_t^{ER})$ where $G_T = \sum_{t=0}^{T} \Delta G_t$.

Proof of Proposition 1

Eq. (29) is derived from the following expressions:

$$H_{I^{ER}} \frac{ER_{H^{ER}}}{ER_{I^{ER}}} = \mu \left(H_{I^{ER}} \frac{ER_G}{ER_{I^{ER}}} + ER_{I^{ER}} \right);$$

The latter equation can be simplified as follows:

$$H_{I^{ER}}\frac{ER_{H^{ER}}}{ER_{I^{ER}}}+H_{H^{ER}}\frac{ER_{I^{ER}}}{ER_{I^{ER}}}=\mu\left(H_{I^{ER}}\frac{ER_{G}}{ER_{I^{ER}}}+H_{H^{ER}}\frac{ER_{I^{ER}}}{ER_{I^{ER}}}\right)$$

$$H_{I^{ER}}ER_{H^{ER}}+H_{H^{ER}}ER_{I^{ER}}=\mu(H_{I^{ER}}ER_{G}+H_{H^{ER}}ER_{I^{ER}})$$

$$H_{I^{ER}}ER_{H^{ER}}+H_{H^{ER}}ER_{I^{ER}}=\mu H_{I^{ER}}ER_{G}+\mu H_{H^{ER}}ER_{I^{ER}}$$

$$\mu H_{I^{ER}}ER_{G}=H_{I^{ER}}ER_{H^{ER}}+H_{H^{ER}}ER_{I^{ER}}-\mu H_{H^{ER}}ER_{I^{ER}}$$

$$\mu H_{I^{ER}}ER_{G}=H_{I^{ER}}ER_{H^{ER}}+(1-\mu)H_{H^{ER}}ER_{I^{ER}}$$

$$\mu\frac{ER_{G}}{ER_{H^{ER}}}=1+(1-\mu)\frac{H_{H^{ER}}}{H_{I^{ER}}}\frac{ER_{I^{ER}}}{ER_{H^{ER}}}$$

$$\frac{ER_{G}}{ER_{H^{ER}}}=\frac{1}{\mu}+\frac{(1-\mu)}{\mu}\frac{H_{H^{ER}}}{H_{I^{ER}}}\frac{ER_{I^{ER}}}{ER_{H^{ER}}}$$

and by defining $d=\frac{H_{H^{ER}}}{H_{I^{ER}}}\frac{ER_{I^{ER}}}{ER_{H^{ER}}}$

it turns out that

$\frac{ER_{G}}{ER_{H^{ER}}}=\frac{1}{\mu}+d\,\frac{1-\mu}{\mu}$ that is

$$\frac{ER_{G}}{ER_{H^{ER}}}=\frac{1+d(1-\mu)}{\mu}.$$

This result allows us to speculate on the value of μ.