Sustainable growth with renewable and fossil fuels energy sources

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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. So far, a large strand of literature on climate change states that we need several economic policy instruments to correct for existing types of market failures, for instance, an environmental tax on the carbon emissions and a research subsidy for research and development (R&D) in the renewable energy sector. We think that the failure of the existing policies on climate change is the fact that implementation of renewable energy is spurred by flow of monetary subsidies to renewables' price. 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. 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. To this end, the novelty of this paper is constituted by modeling a stock of public capital which captures intensity of government long term commitment to support new technology developments. We consider a Schumpeterian model of endogenous growth to take into account that production emit pollutants. The final good is produced employing labour and energy services from renewable energy and fossil fuels that are imperfect substitutes. The quantity of energy from fossil fuels is a function of investment and the amount of resources extracted. In our framework, 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. For doing so, we construct two variants since we take into account two different channels for government intervention. In the first variant, 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. In the second variant, the quantity of renewable energy depends on the stock of knowledge and investment, which in turn depends on policy intervention. 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. Next, we show how the optimum can be implemented by an appropriate flow of public capital, comparing

the relative effectiveness of current monetary subsidies and government reputation and commitments, in order to enable policy strategies.

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. The concentration of greenhouse gases (GHG) in the atmosphere was at 438 parts per million (ppm) of CO_2 equivalent in 2008, that is almost twice the pre-Industrial Revolution level (IEA, 2009). Such an increase is mainly caused by fossil fuel combustion for energy purposes in the power, industry, building and transport sectors (Stern, 2006). In a business-as-usual scenario, 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. 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 the emission reduction targets for developed countries and establishing a framework of wider reduction for the 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.

A large strand of literature on climate change states that we need two economic instruments to correct for the two types of market failures: an environmental tax on the carbon emissions and a research subsidy for research and development (R&D) spillovers in the renewable energy sector (Bosetti et al., 2009; Grimaud and Rougé, 2008). The carbon tax is needed because governments must increase the cost of pollution in order to reduce pollution generation, so that if it becomes more costly, firms will produce less pollution. Since there are distortions in the economy and limitations for government actions, we need other instruments in addition to carbon tax to achieve the environmental goals stated by international environmental agreements, like subsidies to renewable energy. The renewable energy sector needs investment to encourage innovation in technologies and to achieve their potential. It is expected that such investment will lead to a reduction of production costs so that renewable energies will be competitive with fossil fuels in the long run. In the renewable energy sector, every firm benefits both from its own investment and from the knowledge spillovers that come from the industry. The benefits from R&D activities made by the representative firm may not be appropriable in that there is no way to exclude other firms within the industry from the new technologies. Consequently, there is no incentive for the representative firm to bear the expenses of investment. Moreover, there is the uncertainty within the energy industry about the level of investment in renewables made by the firms themselves, so that it might be that no one invests in the production of energy from renewable resources.

The reasons for public intervention are then straightforward. 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). Currently, there is no general agreement on the effectiveness of each scheme and we are still far from enjoying the environmental benefits coming from the use of renewable energy (Held et al., 2006).

The bulk of literature on environmental regulation policies (Acemoglu et al., 2009; Grimaud and Rouge, 2008; Nordhaus, 2008; Quiggin and Horowitz, 2003) focuses on the need of a carbon tax and a research subsidy to implement the optimal environmental policy. The model we propose get underway from the one proposed by Grimaud et al. (2010) in which they basically 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 the price of renewables. 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 flow of public capital which captures intensity of government long term commitment to support new technology developments instead of a subsidy to the price of renewables. To our knowledge, there is not a significant literature on this issue.

We model an economy that is made up of four production sectors: the final output, the energy services, the fossil-fuel sector and the renewable one. The combustion of fossil fuels generates carbon dioxide (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, because fossil fuels are exhaustible and polluting. 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 green 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.

We construct two variants since we take into account two different production functions. In the first variant, the quantity of renewable energy depends on investment and the stock of knowledge. The second variant evaluates an "alternative" production function where a stock of public capital enter the production function as an input, with 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. The model

The main features of 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 ***final output*** Y is produced using not-skilled labor, L_{1t}, and energy services E_t: $Y_t = Y(L^Y, E_t)$, where Y is increasing and concave in each argument. We denote by p_E and w_t respectively the price of energy services and the real wage. The price of the final output is normalized to one. The profit of the representative producer is $\pi_{Y,t} = Y_t - w_t L_t^Y - p_{E,t} E_t$.

The first-order conditions are:

$$Y_{L^Y} - w_t = 0 \quad (1)$$

$$Y_E - p_{E,t} = 0 \quad (2)$$

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

The energy services sector

The amount of energy E_t is produced from two imperfect substitutes, that are fossil fuels EF_t and renewables ER_t: $E_t = E(EF_t, ER_t)$ where E is increasing and concave in each argument.

Energy efficiency technologies allow to reduce the content of CO_2 from fossil fuels for an amount which is equivalent, in energy units, to $Z_t = Z(I_t^E)$, where $0 < Z_t < EF_t$.

Denoting by $p_{EF,t}$ and $p_{ER,t}$ the prices respectively of fossil fuels and renewables, the profit function of the representative energy services producer is: $\pi_{E,t} = p_{E,t}E_t - p_{EF,t}EF - p_{ER,t}ER_t - I_t^E - \tau(EF_t - Z_t)$, where τ is the tax paid by the energy producer in proportion to the polluting emissions $(EF_t - Z_t)$. The first order conditions lead to:

$$p_E E_{EF} - p_{EF} - \tau(1 - Z_{EF}) = 0 \tag{3}$$

$$p_E E_{ER} - p_{ER} = 0 \tag{4}$$

$$-1 + \tau Z_{I^E} = 0 \tag{5}$$

The last one condition allow us to evaluate the carbon tax τ that is equal to $\tau = \frac{1}{Z_{I^E}}$, that is the pollution tax depends upon the effort made by the representative firm to reduce emissions.

The fossil fuel sector

The fossil fuel sector depends on investment I_t^{EF} in the fossil fuel sector, and on the amount of resources S_t extracted from time 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 $EF_t = EF(I_t^{EF}, S_t)$, where EF is increasing in I and decreasing in S. The profit of the fossil fuel producer is $\pi_t^{EF} = p_{EF}EF - I_t^{EF}$.

The maximization of the profit function subject to the constraint (6) leads to the lagrangian $L = p_{EF}EF - I^{EF} - \lambda EF$ and so the first-order conditions are as follows:

$$p_{EF}EF_{I_{EF}} - 1 - \lambda_t EF_{I_{EF}} = 0 \tag{7}$$

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

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 $p_{EF} = \frac{1}{EF_{I^{EF}}} - \lambda_t$; differentiating it with respect to time, we get $\dot{p}_{EF} = -\frac{\dot{EF}_{I_{EF}}}{EF_I^2} + \dot{\lambda}_t$ and through eq. (8) we obtain $\dot{p}_{EF} = -\frac{\dot{EF}_{I_{EF}}}{EF_I^2} - p_{EF} EF_S$ that is the classic Hotelling rule.

The renewable energy sector

We analyze two different renewable energy production functions variants in order to study the effectiveness of two different government instruments to implement renewables among energy portfolio. In both variants there exists an **R&D sector** where the knowledge production function is the same. 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 $\bar{a}_{ER,t} = \bar{a}^{ER}_{ER,t} + \bar{a}^{H_{ER}}_{ER,t}$ that is the sum of the marginal profitability in the renewables sector plus the marginal profitability of this innovation in the renewables R&D sector. By integrating the instantaneous social value of an innovation through time, we get the optimal value of a patent $\bar{A}_{ER,t} = \int_t^{\infty} \bar{a}_{ER,s} e^{-\int_t^s r_x dx} ds$ (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:

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

$$r_t = \frac{\dot{A}_t}{A_t} + \frac{a_t}{A_t} \qquad (11)$$

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 $\dot{H}_t^{ER}$ is a function $\dot{H}_t^{ER}\left(I_t^{ER}, H_t^{ER}\right)$ of the investment I_t^{ER} - the effort - in R&D sector, plus the stock of specific knowledge. The profit function in the R&D sector is $\pi_t^{H^{ER}} = A_t \dot{H}_t^{ER} - I_t^{ER}$ which means that the R&D sector supplies innovations $\dot{H}_t^{ER}$ at price A_t and demands some investment that is I_t^{ER}.

We can rewrite the profit function as

$$\pi_t^{H_{ER}} = A_t H^{ER}(L_t^{ER}, H_t^{ER}) - I_t^{ER} \tag{12}$$

The first order condition leads to:

$$A_t H_{I^{ER}} - 1 = 0 \leftrightarrow A_t = \frac{1}{H_{I^{ER}}} \tag{13}$$

The marginal profitability of innovation is written combining the derivative of the profit function with respect to the knowledge stock, and equation (13):

$$\overline{a}^{H_{ER}} = \frac{\partial \pi^{H^{ER}}}{\partial H^{ER}} = A_t H_{H^{ER}} = \frac{H_{H^{ER}}}{H_{I^{ER}}} \tag{14}$$

So, in order to obtain the instantaneous effective value of the innovation in the renewables R&D sector, we need the marginal profitability in the renewable energy sector.

In the **first variant**, we consider that renewable energy production function is made up of three inputs: investment in renewables I^{ER}, stock of existing knowledge H^{ER} and public capital G_t. The production function writes $ER_t = ER(I^{ER}, G_t, H^{ER})$ with ER increasing and concave in each argument. G is the cumulated government effort to support in the long run renewable energy and 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.

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 I^{ER} and the public capital G_t.

The profit function in the renewable energy sector is

$$\pi^{ER} = p_{ER} ER(I^{ER}, G_t, H^{ER}) - I^{ER} \tag{15}$$

and the first-order condition with respect to the investment and yields:

$$\frac{\partial \pi^{ER}}{\partial I} = 0 \rightarrow p_{ER} ER_{I_{ER}} - 1 = 0 \leftrightarrow p_{ER} = \frac{1}{ER_{I_{ER}}} \qquad \text{and} \tag{16}$$

$$\frac{\partial \pi^{ER}}{\partial G} = 0 \rightarrow p_{ER} ER_G = \frac{ER_G}{ER_I} \tag{17}$$

Then, the effective value of the innovation in renewables R&D sector in the first variant of the model is:

$$a^1{}_{ER,t} = \mu_{ER} \left(\frac{ER_G}{ER_I} + \frac{H_H}{H_{I^H}} \right) \tag{18}$$

In the **second variant**, we discard the assumption about the existence of stock of public capital considered in the renewable energy production functions, so that this latter is no more using three inputs as before, but only two: investment in R&D activities I_t^{ER} and the stock of knowledge H_t^{ER} so that $ER_t = ER(I_t^{ER}, H_t^{ER})$.

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. We have already compute $\overline{a}^{H_{ER}}_{ER,t}$ in the first case; the mechanisms is more or less the same, but we have to take into account that the production function of renewable energy producers now is different. There is no more the public capital as an input, but the government intervention is modeled as a subsidy to investment, which is set $0 \le \sigma \le 1$. The profit function in the renewable sector is now:

$$\pi_t^{ER} = p_{ER} ER(I^{ER}, H^{ER}) - (1-\sigma) I^{ER} \tag{19}$$

The first-order condition is:

$$\frac{\partial \pi^{ER}}{\partial I} = 0 \rightarrow p_{ER} ER_I - (1-\sigma) = 0 \tag{20}$$

$$\frac{\partial \pi^{ER}}{\partial H} = 0 \rightarrow p_{ER} ER_H \tag{21}$$

and combining equations (20) and (21) we get the marginal profitability in the renewable energy sector:

$$\overline{a}^{ER}_{ER,t} = (1-\sigma) \frac{ER_H}{ER_I} \tag{22}$$

We can write the effective value of an innovation in renewables R&D sector when governments subsidize investment in renewable energy sector through a subsidy σ as:

$$a^2_{ER,t} = \mu_{ER}\left[\frac{ER_{H^{ER}}}{ER_{I^{ER}}}(1-\sigma)\right] + \left(\frac{H^{ER}_{H^{ER}}}{H^{ER}_{I^{ER}}}\right) \qquad (23)$$

We can now compare equation (18) that is the effective value of innovation paid to inventors in the first variant ($a^1_{ER,t}$) and (23), i.e. the effective value of innovation in the second variant ($a^2_{ER,t}$) 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 $a^1_{ER,t} \succ a^2_{ER,t}$:

$$\mu_{ER}\left[\left(\frac{ER_G}{ER_F} + \frac{H_H}{H_I}\right) - \frac{ER_H}{ER_I}(1-\sigma) - \frac{H_H}{H_I}\right] > 0 \qquad (23)$$

and by reducing we get

$$\frac{ER_G - ER_H(1-\sigma)}{ER_I} \geq 0 \quad \text{if} \quad \frac{ER_G}{ER_H} \geq (1-\sigma) \qquad (24)$$

Then, we study the derivative of the effective value of innovation with respect to the policy instrument (G in the first variant and σ in the second variant).

By doing the derivative of the effective value of an innovation in equations (18) and (23) we get respectively

$$\frac{\partial a_{ER}}{\partial G} = \mu_{ER}\frac{ER_{GG}}{ER_I} \qquad (25)$$

$$\frac{\partial a_{ER}}{\partial \sigma} = -\mu_{ER}\frac{ER_H}{ER_I} \qquad (26)$$

Eq (24) shows a quite plausible result, i.e. we get a better effect of the capital stock G with respect of 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), the higher is the subsidy share. In fact, if σ = 0 than a better effect of the capital stock is granted if the lhs ratio is > 1; conversely, if σ = 1 , then it suffices a very small positive ER_G to satisfy condition (24).

This latter result is rather obvious , because 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 expression (25) and (26) 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 (25) and (26) we can see that the negative invention value effect of the subsidy is less harmful in equation (25) than equation (26), if:

$$\left|ER_{GG}\right| < \left|ER_{H}\right| \tag{27}$$

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 (27) shows that G is an absolute best policy instrument to spur investment in innovation, that is in research.

3. Theoretical results

By taking into account the first variant proposed in the model that is more attractive than the second one, we want to show the dynamic system. Consider the social planner's problem: choose L^Y and E so as to:

$$\max \int_0^\infty U(C,V)e^{-\rho t}dt \quad \text{s.t.} \tag{21}$$

$$C_t = Y(L^Y, E) \tag{22}$$

$$\dot{S} = EF_t$$

$$\dot{H} = H(I^{ER}, H^{ER})$$

$$\dot{V} = -EF_t + Z_t + bV_T$$

$$0 \le L^Y \le L$$

where $\dot{V}$ represent the dynamic of clean environment which enters the utility function, and b is the spontaneous regeneration rate according to which clean environment evolves.

The current-value Hamiltonian for the maximization problem is:

$$H = U(C,V)e^{-\rho t} + \lambda_1\left[C - Y(L^Y, E)\right] - \lambda_2 EF + \lambda_3 H(I^{ER}, H^{ER}) - \lambda_4(-EF + Z + bV)$$

where λ_1, λ_2, λ_3 and λ_4 are the shadow prices of *l, S, H* and *V*. Necessary first order conditions for an interior optimal solution are:

$$\frac{\partial H}{\partial C} : U_C e^{-\rho t} = -\lambda_1$$

$$\frac{\partial H}{\partial L^Y} : U_C e^{-\rho t} = \lambda_1 Y_L$$

$$\frac{\partial H}{\partial S} : U_C e^{-\rho t} Y_E E_{EF} - \lambda_1 Y_E E_{EF} - \lambda_2 + \lambda_4 = -\dot{\lambda}_2$$

$$\frac{\partial H}{\partial H^{ER}} : \lambda_3 H_{H^{ER}} = -\dot{\lambda}_3$$

$$\frac{\partial H}{\partial V} : U_V e^{-\rho t} - \lambda_4 b = -\dot{\lambda}_4$$

Defining

$h \equiv \frac{\lambda_4}{\lambda_3}$, that is the shadow price of environmental quality in terms of knowledge in renewable sector, and $d = \frac{EF}{S}$ the depletion rate, we can derive the dynamic system:

$$\frac{\dot{\lambda}_4}{\dot{\lambda}_3} = \frac{U_V e^{-\rho t} - \lambda_4 b}{\lambda_3 H_{H^{ER}}} \rightarrow \dot{h} = \frac{U_V e^{-\rho t}}{\lambda_3 H_{H^{ER}}} - h \frac{b}{H_{H^{ER}}}$$

$$\dot{V} = Z_t + bV_t - dS$$

$$\dot{S} = dS$$

The equations above constitute a dynamic system in S, V and h.

4. Conclusion

Our analysis is relevant in the current debate on the optimal climate change policy to implement the use of renewable energy instead of fossil fuels. 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. Currently, there is no general agreement on the effectiveness of each scheme and we are still far from enjoying the environmental benefits coming from the use of renewable energy. We have shown 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. For this purpose, we model a stock of public capital which captures intensity of government long term commitment to support new technology developments. We focus on the effective value of innovation paid to inventors of new green technologies as an incentive for doing research in renewable energy that make it competitive in the energy market. Such value varies according to the renewables production function, and given the same burden in actual monetary terms for the Government, the main result of the paper is that policy is more effective when the flow of public capital enters the production function as a public stock compared to the monetary subsidies to energy prices.

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