# Renewable energy investments, support schemes and the dirty option

**Abstract**

In a real options framework, we analyse the behaviour of a large energy producer who can invest in a portfolio of Renewable Energy Source (RES) and *dirty* energy source. Competitive fuel prices challenge the investments in RES. Given a budget constraint, the agent allocates the optimal capacities of both energy instalments and selects the optimal investment time. We use the model to compare the effectiveness of classical support schemes such as Feed-in Tariffs or Green Certificate with respect to forms of taxation of dirty technology such as Carbon Taxes or Carbon Permits. This paper proposes a conceptual framework and qualitative analysis to understand which support system enhances the attractiveness of renewable energy investments.

## 1 Introduction

The decarbonization of the energy sector, by means of stimuli of investments in Renewable Energy Sources (RES), is a central issue in the agenda of governments worldwide.

According to the International Energy Agency (IEA), renewable electrical capacity increases 50 % (1 220 GW) by 2024, from 2 502 GW in 2018 (IEA, 2019). Nearly two-thirds (64%) of net installations in 2018 were from renewable sources of energy, according to the latest annual Renewables Global Status Report (REN21, 2019). Nevertheless, one cannot deny the fact that fossil fuels made up 82 % of global primary energy in 2015 (Newell et al., 2019). Besides, the Global Energy Outlook (Newell et al., 2019) forecasts that the global energy demand will continue to rise, and most of the demand will be satisfied by fossil-based fuels. In this regard, carbon dioxide emissions from the global energy system are on a path to far exceed international targets of the Paris Agreement.

Due to the fact that the profitability of RES cannot compete with that of traditional fossil-based energy generators, policymakers have been implementing a variety of mechanisms to boost investments in RES. Broadly speaking, such policy mechanisms can be classified into two classes. The first class, which we refer to as subsidies, aims at reducing dioxide emission directly by giving monetary incentives to the energy produced with RES. The second class, which we refer to as carbon pricing, tries to boost investments in RES indirectly by fixing a price on emissions of fossil fuels.

Among the bundle of subsidies implemented worldwide, two prominent examples are Feed-in Tariffs (FiT) and the combination of the quota system and Green Certificates (GC). A FiT is a price-based policy mechanism with which a policymaker offers a fixed price to energy producers per unit of green power sold in the market for a given period of time. Launched for the first time in 1978 with the US National Energy Acts, these support schemes are still prevalent in many countries, and they are widely analysed in the academic literature. The combination of the quota system and green certificates is a quantity-based support scheme also active in many countries, especially Europe. A GC is a tradable asset, whose value fluctuates according to supply and demand, attesting that one unit of power (conventionally 1 MWh) has been generated by RES. Within the scheme, energy producers sell GCs to energy suppliers, who are required to buy a given number of GCs according to the quota system.

According to a recent article in the New York Times (Plumer and Popovich, 2019), as for February 2019, more than 40 countries have set some price on carbon. Important examples of implementations of carbon pricing around the world are Carbon Taxes (CT) and Carbon Emission Trading system, which we refer to simply as Carbon Permits (CP). A CT is a price-based tax for unit of emission of fossils' fuels. A CP is an asset that gives the right to emit one ton of dioxide. CPs are issued by the regulator, who also sets the maximum tons of emissions possible. Once issued, a CP is traded privately, and their value depends on current market conditions.

A recent ongoing debate is which of the two classes of decarbonization mechanisms is preferable in terms of effectiveness, implementation costs, and social fairness. While subsidies are still active in a large part of the world, economists are starting to ask whether or not a shift towards carbon pricing might provide a better decarbonization strategy. Two prominent examples are Bassi et al. (2017) and the *Economist' Statement on Carbon Dividends*, signed by dozens of economists (including 27 Nobel Laureate Economists, 4 former chairs of the Federal Reserve, 15 Former Chairs of the Council of Economic Advisers, and 2 Former Secretaries of the US Department of Treasury) and appeared on the Wall Street Journal in February 2019, in which carbon pricing is described as "the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary."

In this paper, we use the Real Options approach of Dixit and Pindyck (1994) to provide a comparative analysis of the effectiveness of carbon pricing and RES subsidies. To do so, we put ourselves on the side of a price-taker energy producer who, given a budget, has to decide the optimal time to invest and the optimal allocation of her budget on power generators based on two different technologies: the green and the dirty technology. We first analyze the baseline case in which no decarbonization schemes are active. Then we examine how the different carbon pricing schemes and RES subsidies affect the optimal allocation and the investment timing of the energy producers. More precisely, we provide two distinct comparisons: the case in which the effectiveness of Feed-in Tariffs is compared with that of carbon taxes; and the case in which green certificates are compared with carbon permits. The choice of these two different comparisons comes from the nature of uncertainty involved in different decarbonization schemes. In fact, while FiT and CT are mainly subject to policy uncertainty (PU), that is, uncertainty deriving from a possible sudden shift in the government's policy, GC and CP are both tradable assets subject to market risk. We focus on two main aspects that are described as follows. From a business perspective, we aim to provide guidance on the evolution of the profitability of RESs. On the other hand, from a regulation point of view, we aim to support regulators in drafting incentive plans in renewable energies.

This paper belongs to the literature that studies the analysis of investors' behavior in response to the introduction of decarbonization schemes using the Real Options methodology, recently reviewed in Kozlova (2017). In this context, Boomsma et al. (2012) build a model with multiple sources of uncertainty to analyse optimal capacity and investment timing under Feed-in Tariffs and green certificates. They find that while under green certificates, firms invest in larger projects, Feed-in Tariffs promote earlier investments. Also using a setup with various sources of uncertainty, Boomsma and Linnerud (2015) and Adkins and Paxson (2016) analyse investment timing under different subsidies. They both focus on policy uncertainty and use quasi-analytical methods to solve their model. Policy uncertainty is also studied in Dalby et al. (2018), where the authors study a model of Bayesian learning for policy uncertainty. The focus of this prominent stream of the literature is on governments' incentive to RES. Kitzing et al. (2017) valued investments in offshore wind energy in the Baltic Sea amid uncertainties regarding FiT, Feed-In Premiums and tradable GC, and Zhang et al. (2017) focus on the optimal design of subsidies. However, we observe that comparisons between subsidies and carbon pricing are absent and that the mentioned studies ignore the possibility of investing in traditional energy.

Some papers incorporate fuel price uncertainty into the valuation design by analysing various aspects. Siddiqui and Fleten (2010) use a Real Options model to show how a policymaker should allocate funds to boost the development of new technologies. Martinez Cesena and Mutale (2011) analyse a Real Options model for the design of an off-grid photovoltaic generator. In a model with random evolution of fuel prices, Fuss and Szolgayova (2010) analyse how technological uncertainty affects the optimal time of replacement of traditional technologies with new less fuel-intensive power generators. Along the same line, but without technological uncertainty, Li et al. (2015); Xian et al. (2015) build a real options model to analyse the optimal investment time in new fuel-based technologies. This piece of literature recognizes fuel price as an essential factor driving investors' choices, although the focus on decarbonization schemes is absent.

With this paper, we aim to complement the literature on Real Options for energy investments in two aspects. First, we give the decision-maker the option of investing not only in renewable energy but also in conventional energy, thus giving more flexibility to the decision-makers. We refer to this additional flexibility as *the Dirty Option.* To the best of our knowledge, this is done for the first time in the described context, bringing the analysis closer to real investment problems. Last, we provide a comparative analysis of the effectiveness of subsidies and carbon pricing. Consequently, we aim to determine at what point the RES become so attractive (or profitable) as conventional energy. Besides, we intend to present a practical model for the evaluation of the project that is convenient and understandable for both researchers and practitioners.

The article is organized as follows. In section 2, we describe our model. We explore the investment timing and capacity selection options in Section 3. In Section 4, we discuss the results of sensitivity analysis. Finally, in section 5, we conclude.

## 2 Model's setup

We use a continuous-time infinite-horizon real options framework, in which a price-taking energy producer contemplates the installation of new energy production plants. Two alternative technologies are available: the traditional (dirty) fossil-based technology, denoted by $D$ and the renewable (green) technology such as wind or solar power, denoted by $G$. Given an available budget $B$, the firm's problem consists in determining the optimal capacity in dirty ($D$) and green ($G$) energy source, denoted by $x_D$ and $x_G$, respectively, and the optimal time to expand the production capacity. We measure capacity in terms of power, that is one unit of capacity corresponds to one Megawatt (MW). Let $I_h$ be the cost of installation of one unit of power of technology $h$, $h = D, G$. The equation $I_D x_D + I_G x_G = B$ describes the budget constraint faced by the producer. Without loss of generality, we assume for simplicity that once installed, both technologies are capable of producing energy for $T$ years. After $T$ years of use, the power plants do not produce efficiently and are dismissed.

The production function of dirty technology is $Q_D(x_D) = A_D \cdot h_D \cdot x_D$, where $A_D$ is total hours in a year, $h_D$ is heat rate for traditional technology. The production function of green technology is $Q_G(x_G) = A_G \cdot h_G \cdot x_G^\gamma$, where $A_G$ is total hours in a year, $h_G$ is heat rate for renewable technology and $\gamma \in (0, 1)$. Our assumption about the concavity of the production function of green technology is in line with the literature. For instance, Boomsma et al. (2012) justify diminishing marginal production resulting from increasing capacities by wake effects. We refer to Boomsma et al. (2012) for further details.

Following the literature on Real Options, we assume that electricity prices ($E_t$) and fuel prices ($F_t$) follow two GBM [1]:

$$\begin{aligned} \frac{dE_t}{E_t} &= \mu^E dt + \sigma^E dW^E(t); \\ \frac{dF_t}{F_t} &= \mu^F dt + \sigma^F dW^F(t), \end{aligned} \tag{1}$$

where $\mu^E, \mu^F$ and $\sigma^E, \sigma^F$ are the corresponding instantaneous rates of return and volatilities, respectively. $W^E(t)$ and $W^F(t)$ are two standard correlated Brownian motions, with correlation coefficient $\rho^{EF}$.

## 2.1 Decarbonization schemes

We denote by $G_t$ the instantaneous value of a generic subsidy and use two different stochastic representations to distinguish between FiTs and GCs. The stochastic process that models a FiT is indeed a piecewise constant process, reflecting the fact that a FiT is subject to changes only in response to a change in the support policy. We follow the relevant real options literature and specify the model for a FiT under policy risk by means of a continuous-time Markov chain with two states, $\{G_{Good}, G_{Bad}\}$, of which $G_{Bad}$ is absorbing

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[1] For the sake of brevity, we later suppress the subscript $t$ for both the price of electricity ($E_t$) and the price of fuel ($F_t$) whenever suitable.

and transition rate $\lambda_G$. For additional details about the computation of the relevant quantities, we refer to the Appendix B. Conversely, given that GCs are freely traded, their value changes continuously over time according to the prevalent market conditions. Thus, we use a GBM to model the firm's income due to green certificates, that is

$$dG_t = \mu_G G_t dt + \sigma_G G_t dW_t^G,$$

with $\mu_G, \sigma_G$ being the instantaneous rate of return and the volatility, respectively. The Brownian motion governing the dynamics is correlated to $W^E, W^F$, with correlation coefficients $\rho^{GE}, \rho^{GF}$, respectively.

In the same way, we denote by $C_t$ the cost of a generic carbon price and use two different probabilistic models to differentiate between CTs and CPs. Carbon taxes are subject to policy risk only: they change values only due to a policy change. We use a continuous-time Markov chain again with state-space $\{C_{Good}, C_{Bad}\}$, starting in $C_{Good}$, with $C_{Bad}$ as an absorbing state and transition rate $\lambda_C$ from $C_{Good}$ to $C_{Bad}$. Finally, the value of carbon permits fluctuates according to market conditions. Thus, we model CPs by means of a different GBM:

$$dC_t = \mu_C C_t dt + \sigma_C C_t dW_t^C,$$

with the usual interpretation of parameters $\mu_C, \sigma_C$ and driving Brownian motion $W^C$ correlated to $W^E, W^F$, with correlation coefficients $\rho^{CE}, \rho^{CF}$, respectively.

## 2.2 The decision problems

Let us define the instantaneous profits as usual, by:

$$\pi(E, F, G, C; x_G, x_D) = Q_G(x_G)(E + G) + Q_D(x_D)(E - F - C). \quad (2)$$

The decision problem of the investor consists of choosing the optimal capacities, $x_G, x_D$, and the optimal to invest, $\tau$, so as to maximize the net present value of the future profits. The optimal capacities must lie in the admissible set $\mathcal{I} = \{x_G, x_D \geq 0, I_G x_G + x_D I_D = B\}$, which describes the budget constraint. Different types of decarbonization schemes imply a different decision problem to be solved. In particular, we have:

1. The first case, which we refer to as the Baseline case, is the one in which no decarbonization scheme is active in the country. In this case, we set $G_t = 0$ and $C_t = 0$ and the decision problem is:[2]

   $$\begin{aligned}
   &V^B(E,F) = \\
   &\max_{\tau \geq 0} \max_{x_G, x_D \in \mathcal{I}} \mathbb{E}_{E,F}\left[\int_{\tau}^{\tau+T} e^{-rs}\left(\pi(E_s, F_s, 0, 0; x_G, x_D) - B)\right)ds\right] = \\
   &\max_{\tau \geq 0} \max_{x_G, x_D \in \mathcal{I}} \mathbb{E}_{E,F}\left[e^{-r\tau}\right]\left(L^B(E,F;x_G,x_D) - B\right),
   \end{aligned}$$

   where the net present value of future profits is given by:

   $$L^B(E,F;x_G,x_D) = \left(Q_G(x_G) + Q_D(x_D)\right) E\bar{r}_T(\mu_E, 0) - Q_D(x_D) F \bar{r}_T(\mu_F, 0),$$

   and $\bar{r}_T(\mu, \lambda) = \frac{1 - e^{-(r-\mu+\lambda)T}}{r - \mu + \lambda}$.

2. Next, we consider the case in which a Feed-in tariff is active. In this case, we impose $G_t$ to follow the continuous-time Markov chain described in the previous subsection and set $C_t = 0$:

   $$\begin{aligned}
   &V^{FiT}(E,F) = \\
   &\max_{\tau \geq 0} \max_{x_G, x_D \in \mathcal{I}} \mathbb{E}_{E,F,G_{Good}}\left[\int_{\tau}^{\tau+T} e^{-rs}\left(\pi(E_s, F_s, G_s, 0; x_G, x_D) - B\right)ds\right] = \\
   &\max_{\tau \geq 0} \max_{x_G, x_D \in \mathcal{I}} \mathbb{E}_{E,F,G_{Good}}\left[e^{-r\tau}\right]\left(L^{FiT}(E,F;x_G,x_D) - B\right),
   \end{aligned}$$

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[2] We use $\mathbb{E}_y(\cdot)$ to denote the conditional expectation of a stochastic process starting at $y$.

where

$$\begin{aligned}&L^{FiT}(E,F;x_G,x_D) = \\ &\quad \left(Q_G(x_G)+Q_D(x_D)\right)E\bar{r}_T(\mu_E,0) - Q_D(x_D)F\bar{r}_T(\mu_F,0) + \\ &\quad Q_G(x_G)\left(G_{Good}\bar{r}(0,\lambda_G) + G_{Bad}\left(\bar{r}(0,0)-\bar{r}(0,\lambda_G)\right)\right).\end{aligned}$$

3. Next, we consider Green certificates, by setting $dG_t = \mu^G G_t dt + \sigma^G G_t dW^G(t)$ and $C_t = 0$:

$$\begin{aligned}&V^{GC}(E,F,G) = \\ &\max_{\tau\geq 0}\max_{x_G,x_D\in\mathcal{I}} \mathbb{E}_{E,F,G}\left[\int_\tau^{\tau+T} e^{-rs}ds\left(\pi(E_s,F_s,G_s,0;x_G,x_D)-B\right)\right] = \\ &\max_{\tau\geq 0}\max_{x_G,x_D\in\mathcal{I}} \mathbb{E}_{E,F,G}\left[e^{-r\tau}\right]\left(L^{CG}(E,F,G;x_G,x_D)-B\right),\end{aligned}$$

where

$$\begin{aligned}&L^{GC}(E,F,G;x_G,x_D) = \\ &\quad \left(Q_G(x_G)+Q_D(x_D)\right)E\bar{r}_T(\mu_E,0) - Q_D(x_D)F\bar{r}_T(\mu_F,0) + \\ &\quad Q_G(x_G)G\bar{r}_T(\mu_G,0).\end{aligned}$$

4. Next, we consider the case in which a Carbon Tax. In this case, we impose $C_t$ to follow the continuous-time Markov chain described in the previous subsection and set $G_t = 0$:

$$\begin{aligned}&V^{CT}(E,F) = \\ &\max_{\tau\geq 0}\max_{x_G,x_D\in\mathcal{I}} \mathbb{E}_{E,F,C_{Good}}\left[\int_\tau^{\tau+T} e^{-rs}\left(\pi(E_s,F_s,0,C_s;x_G,x_D)-B\right)ds\right] = \\ &\max_{\tau\geq 0}\max_{x_G,x_D\in\mathcal{I}} \mathbb{E}_{E,F,C_{Good}}\left[e^{-r\tau}\right]\left(L^{CT}(E,F;x_G,x_D)-B\right),\end{aligned}$$

where

$$L^{CT}(E,F;x_G,x_D) =$$
$$(Q_G(x_G)+Q_D(x_D))\,E\bar{r}_T(\mu_E,0) - Q_D(x_D)F\bar{r}_T(\mu_F,0) -$$
$$Q_D(x_D)\left(C_{Good}\bar{r}(0,\lambda_G) + C_{Bad}\left(\bar{r}(0,0)-\bar{r}(0,\lambda_G)\right)\right).$$

5. Finally, we consider Carbon Permits for the last case, thus setting $dC_t = \mu^C C_t dt + \sigma^C C_t dW^C(t)$ and $G_t = 0$:

$$V^{CP}(E,F,C) =$$
$$\max_{\tau\geq 0}\max_{x_G,x_D\in\mathcal{I}} \mathbb{E}_{E,F,C}\left[\int_{\tau}^{\tau+T} e^{-rs}ds\left(\pi(E_s,F_s,0,C_s;x_G,x_D)-B\right)\right] =$$
$$\max_{\tau\geq 0}\max_{x_G,x_D\in\mathcal{I}} \mathbb{E}_{E,F,C}\left[e^{-r\tau}\right]\left(L^{CP}(E,F,C;x_G,x_D)-B\right),$$

where

$$L^{GC}(E,F,C;x_G,x_D) =$$
$$(Q_G(x_G)+Q_D(x_D))\,E\bar{r}_T(\mu_E,0) - Q_D(x_D)F\bar{r}_T(\mu_F,0) -$$
$$Q_D(x_D)G\bar{r}_T(\mu_C,0).$$

# 3 Numerical study

In this section, we perform a series of numerical comparisons between the two philosophically different ways of boosting investments in green energy sources: RES subsidies and carbon pricing. To do so, we focus on an energy producer's the point of view, who observes the market conditions and makes investment decisions.

We consider an investment in two types of energy where the project life is 20 years. The investment costs of wind power plants installation are set equal to $I_G = 1600$ T euros/MW years and $I_C = 900$ T euros/MW. These numbers are the median cost for Europe. The risk-adjusted real discount rate is set to $r = 5.0$ %, reflecting an inflation rate of $2,5\%$. We use $\mu_E$=$\mu_F$=0 in the price processes, which implies that these prices likewise grow with the general price level. The electricity price volatility and the fuel price volatility equal 0.06; the corresponding correlation coefficient is estimated to 0.7. The values of the remaining parameters are presented in Appendix A.

We first study the base case, that is a situation in which investors have not incentives. We then examine how investors change their decision if some support scheme is present. As far as the numerical techniques are concerned, we use Monte Carlo simulation in conjunction with Least-Square regression to obtain investment values. Besides, for all two-dimensional problems we use a finite difference scheme to visualize investment regions.

## 3.1 Baseline

Our base case assumes no regulation, such as subsidy payments or carbon pricing. Figure 1 shows the investment decision of an energy producer for all possible combinations of electricity and fuel prices. We restrict attention to the cases in which energy prices are higher than fuel costs. This means that the part of the graphs where $E > F$ is not taken into consideration.[3] Figure 1 is divided into three sub-regions. The white area represents the no-investment region. The colored area a of the graphs indicates combinations of energy prices and fuel costs in which the producer invests. The color of the sector responsible for investment answers the question of how much green energy needs to be invested. Green color indicates investments in green energy only, while the saturation of the shade of blue speaks of the predominance of investments in dirty energy.

We emphasize that we get a graph relative to electricity and fuel prices, each point of which corresponds to the optimal value of $x_G$. To better explain Figure 1, we take two extreme points into consideration. We will consider the investor's decisions when electricity prices equal to 40 and 80 euros. At a low price of electricity, if the fuel cost is sufficiently high, the investor does not invest. Upon reaching a sufficiently low fuel price, the producer invests

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[3] In our setup, this assumption seems to be reasonable. However, we acknowledge that in a real energy market, energy price can be lower than fuel costs. This is due to the so called *marginal pricing*, for which the energy price is the maximum cost for producing a given amount of power. Handling such situations requires a setup in which energy price is endogenous as in Aid et al. (2013) and goes far beyond the scope of the present paper.

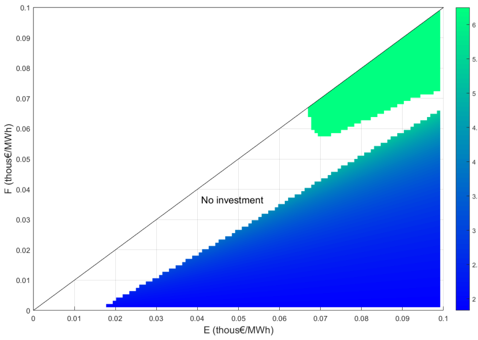


Figure 1: The base case.

most of the budget in dirty energy. When electricity price is high (in our case, 80 euros), the investment decision. If the fuel cost is high enough, the entire budget is invested exclusively in RES.

Table 1: Investment values of base case for different levels of prices, T euros

| E<br>F | 0.05 | 0.06 | 0.07 |
|---|---|---|---|
| 0.01 | 21110.60 | 29331.12 | 37559.98 |
| 0.02 | 11404.14 | 19485.98 | 27632.68 |
| 0.03 | 3115.89 | 10223.31 | 18104.92 |
| 0.04 | 815.05 | 3129.99 | 9358.30 |
| 0.05 | 449.30 | 1339.24 | 3485.56 |

We observe a region where the investor finds optimal not to invest at all. The colorless part of the graph represents that. Given the level of energy price, the fuel cost is not low enough; in this area, the producer does not make any investment but wait for more favorable market conditions. Such regions are typical of a real option framework. It is also worth to note that there is a gap between the zones of investment in both types of energy and only green. In such area, energy prices are very high. However, fuel cost is neither sufficiently low to justify a huge investment in dirty energy, nor high enough to boost investments in green energy sources.

In Table 1, we present the value of the investments in some representative cases. The table shows that the investment values decrease with increasing fuel prices and increase with increasing electricity prices.

## 3.2 Feed-in Tariff versus Carbon Taxes

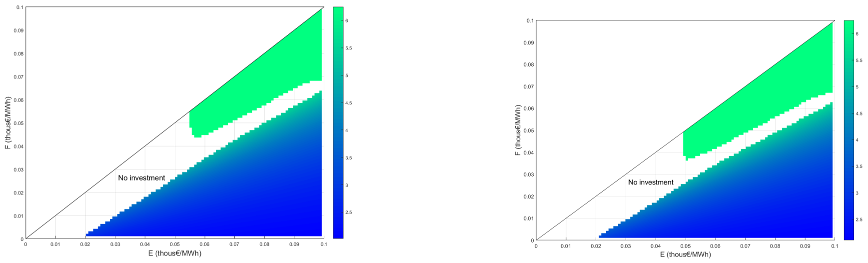
**Capacity choice**. We define

$$\begin{aligned} W(x_G, x_D) = & E\tilde{r}_E^T(Q_D(x_D) + Q_G(x_G)) - F\tilde{r}_F^T Q_D(x_D) + \\ & G\tilde{r}Q_G(x_G) - C\tilde{r}Q_D(x_D) - B. \end{aligned}$$

The problem of maximizing $W(x_G, x_D)$ under the budget and the non-negativity constraint posses a unique solution given by $(x_G^*, \frac{B - I_G x_G}{I_D})$, where

$$x_G^* = \begin{cases} \min\left(\left(\frac{A_G \gamma I_D (E\tilde{r}_E^T + G\tilde{r})}{A_D I_G (E\tilde{r}_E^T - F\tilde{r}_F^T - C\tilde{r})}\right)^{\frac{1}{1-\gamma}}, \frac{B}{I_G}\right) & E > \frac{C\tilde{r} + F\tilde{r}_F^T}{\tilde{r}_E^T} \\ \frac{B}{I_G} & E \leq \frac{C\tilde{r} + F r_F^T}{r_E^T} \end{cases} \tag{3}$$

We investigate how each support scheme or carbon pricing affects the behavior of an energy producer. The similarity between FiT and CT is noted because both are price-based instruments. We take Feed-in Tariff and carbon tax equal to either 10 or 15 euros/MW Hour.

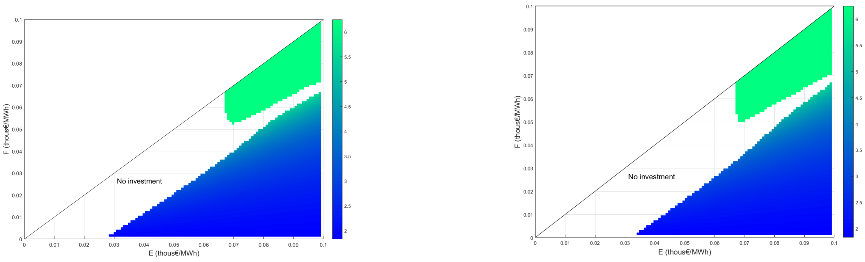


(a)

(b)

Figure 2: Feed-in tariff equal to: (a) 10 euros/MW Hour; (b) 15 euros/MW Hour.

We first analyze the effects of FiT and CT on the investment region, via a visual comparison with the baseline investment region in Figure 1.



(a)

(b)

Figure 3: Carbon Tax equal to: (a) 10 euros/MW Hour; (b) 15 euros/MW Hour.

Figures 2(a) and 2(b) depict the investment region when a FiT of 10 and 15 euro, respectively, is active. When compared with the baseline case, in both panels, we observe an enlargement of the green area. In such cases, the firm invests in green energy only at lower energy prices, provided that the fuel cost is low enough. On the other hand, the remaining part of the colored area of the graph remains basically unchanged. Figures 3(a) and 3(b) depict the investment region when a CT of 10 and 15 euro, respectively, is active. In this case, we observe a restriction of the area in which the firm invests predominantly in dirty energy. Carbon taxes discourages investments in dirty technology but does not boost investments in green energy.

Table 2: Investment values under Feed-in Tariff, percentage change of investment value

| Feed-in Tariff | 10 euros/MW Hour | | | 15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -7.69 | -5.79 | -4.65 | -11.11 | -8.43 | -6.82 |
| 0.02 | -10.36 | -7.09 | -5.44 | -14.50 | -10.17 | -7.89 |
| 0.03 | -10.23 | -8.47 | -6.30 | -11.27 | -11.56 | -8.97 |
| 0.04 | 34.41 | 1.75 | -5.93 | 113.62 | 15.94 | -7.66 |
| 0.05 | 124.56 | 97.45 | 27.75 | 287.53 | 164.89 | 53.60 |

Table 3: Investment values under Carbon Tax, percentage change of investment value

| Carbon Tax | 10 euros/MW Hour | | | 15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E / F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -32.55 | -23.96 | -18.99 | -48.82 | -35.94 | -28.48 |
| 0.02 | -48.83 | -31.25 | -23.17 | -70.41 | -46.88 | -34.76 |
| 0.03 | -54.71 | -44.27 | -29.32 | -69.85 | -63.78 | -43.99 |
| 0.04 | -33.94 | -40.04 | -37.23 | -44.22 | -53.83 | -54.53 |
| 0.05 | -9.72 | -12.66 | -21.14 | -12.35 | -15.55 | -24.14 |

Feed-in-Tariffs and Carbon Taxes impact differently also in terms of the value of the investment. In Table 2, we report the percentage changes - with respect to the base case- of the investment values when a FiT is present in the market. We note that for the FiT to have a positive impact on the value of the investment it is necessary to have a sufficiently high marginal profit, that is the difference between energy prices and fuel cost. However, the percentage change of the investment values decreases as the marginal profit increase. In Table 3, we report the percentage change of the investment value in the presence of a Carbon Tax. The introduction of a CT reduces the value of the investment in all the cases considered.

## 3.3 Green certificates versus Carbon permits

**Capacity choice**. We define

$$\begin{aligned} W(x_G, x_D) =& E\tilde{r}_E^T(Q_D(x_D) + Q_G(x_G)) - F\tilde{r}_F^T Q_D(x_D) + \\ & G\tilde{r}_G^T Q_G(x_G) - C\tilde{r}_C^T Q_D(x_D) - B. \end{aligned}$$

The problem of maximizing $W(x_G, x_D)$ under the budget and the non-negativity constraint posses a unique solution given by $(x_G^*, \frac{B-I_G x_G}{I_D})$, where

$$x_G^* = \begin{cases} \min\left(\left(\frac{A_G \gamma I_D (E\tilde{r}_E^T + G\tilde{r}_G^T)}{A_D I_G (E\tilde{r}_E^T - F\tilde{r}_F^T - C\tilde{r}_C^T)}\right)^{\frac{1}{1-\gamma}}, \frac{B}{I_G}\right) & E > \frac{C\tilde{r}_C^T + F\tilde{r}_F^T}{\tilde{r}_E^T} \\ \frac{B}{I_G} & E \leq \frac{C\tilde{r}_C^T + Fr_F^T}{r_E^T} \end{cases} \tag{4}$$

Here we compare the investment value in the presence of green certificates and carbon permits. For GC, we use starting values of the certificate equal to either $G_0 = 10$ or $G_0 = 15$. For CP, we use $C_0$ either equal to 10 or 15. In Tables 4 and 5, we report percentage changes of investment values with respect to the baseline case.

Table 4: Investment values under Green certificates, percentage change of investment value

| Green certificates | $G_0$ =10 euros/MW Hour | | | $G_0$ = 15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E / F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -7.84 | -6.01 | -4.82 | -11.25 | -8.65 | -6.98 |
| 0.02 | -10.51 | -7.28 | -5.60 | -14.64 | -10.35 | -8.05 |
| 0.03 | 18.45 | -8.42 | -6.44 | 14.81 | -11.34 | -9.10 |
| 0.04 | 112.65 | 31.12 | -5.56 | 141.90 | 35.80 | -7.22 |
| 0.05 | 181.89 | 99.39 | 42.67 | 310.52 | 164.51 | 57.66 |

The main difference between green certificates and carbon permits is what they offset. Where CP help reduce greenhouse gas emissions, GC offset electricity use from renewable sources. Carbon permits provide certainty of abatement quantity but render the price per unit of abatement uncertain. Green certificates significantly increase investment values at low electricity prices and high fuel prices, while in the opposite situation (high electricity prices and low fuel prices), the investment values are lower than in the baseline. Carbon permits, on the other hand, reduce the investment value of the firm. This seems in line with the results of the previous subsection about the Carbon Tax.

Table 5: Investment values under Carbon permits, percentage change of investment value

| Carbon permits | $C_0 = 10$ euros/MW Hour | | | $C_0 = 15$ euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -46.03 | -33.71 | -26.56 | -67.24 | -49.73 | -39.40 |
| 0.02 | -65.35 | -47.56 | -34.60 | -78.07 | -67.35 | -50.83 |
| 0.03 | -52.93 | -60.35 | -48.30 | -66.24 | -73.33 | -65.32 |
| 0.04 | -13.64 | -41.34 | -55.00 | -28.33 | -52.04 | -65.88 |
| 0.05 | 21.32 | 1.22 | -21.61 | 29.06 | -0.43 | -23.75 |

# 4 Sensitivity analysis

In this section, we verify the robustness of the previous results with respect to change in some crucial parameters. More specifically, we are interested in two main factors: policy risk and the budget available to the firm. We proceed as usual, by looking at the differences between Feed-in Tariffs versus Carbon Taxes and Green Certificates versus Carbon Permits.

## 4.1 Feed-in tariff versus carbon taxes

**Introducing policy risk** In section 3, we examined the case where neither the support scheme nor the carbon pricing could be altered during the life of the facilities installed. Here, we introduce policy uncertainty by allowing for a random revision of the support schemes. This seems to be reasonable, given the high speed of technological development in renewable energy sources. We assume that such revisions arrive at intensity $\lambda = 0.1$, implying on average a shift in the scheme every 10 years. We take the initial value of the FiT equal to 15 euros/MW Hour (the good state) and assume that this value can be lowered to 10 euros/MW Hour (the bad state) at some random point in time. For Carbon Taxes, we take the initial value to 10 euros/MW Hour (the good state). Such value is subject to a change to 15 euros/MW Hour at a random point in time.

Table 6 presents the investment values obtained in this new setup. The results are qualitatively similar to the case without policy uncertainty, providing robustness of our analysis with respect to policy uncertainty. However, we see that policy uncertainty prejudices investors' readiness to invest in RES and consequently reduces the effect of decarbonization schemes. At the same time, the penalizing effects of a Carbon Tax in terms of appeal of the investment are slightly reduced.

Table 6: Investment values under FiT and Carbon Tax with policy uncertainty ($\lambda = 0.1$), percentage change of investment value

| Support schemes | FiT | | | Carbon Tax | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -9.44 | -7.14 | -5.75 | -40.67 | -29.94 | -23.73 |
| 0.02 | -12.52 | -8.67 | -6.69 | -60.78 | -39.05 | -28.95 |
| 0.03 | -11.23 | -10.11 | -7.68 | -63.11 | -54.89 | -36.64 |
| 0.04 | 64.47 | 6.99 | -6.90 | -39.67 | -47.56 | -46.34 |
| 0.05 | 193.23 | 131.24 | 40.67 | -11.22 | -14.38 | -23.84 |

**Increasing the budget** Here, we are interested in considering an increase in investment up to 100 million to analyze changes in the optimal patterns. Tables 8 and 9 present percentage changes of investment values in such cases, with respect to the base case, whose investment values are in Table 7. We consider no policy uncertainty ($\lambda = 0$).

Once again, the results are qualitatively consistent with those presented in Section 3. However, the effects of FiT -both positive and negative- are dramatically reduced. This highlights the fact that the smaller the firm, the less pronounced the effect of Feed-in-Tariffs, at least in terms of investment values. On the other hand, the loss of investment value in the presence o a Carbon Tax is much more pronounced.

Table 7: Investment values of base case for different levels of prices, $B = 100$ million

| | Investment values, T euros | | |
|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 |
| 0.01 | 319091.03 | 424306.66 | 529530.62 |
| 0.02 | 212389.46 | 317466.41 | 422608.22 |
| 0.03 | 106685.80 | 211208.63 | 316085.35 |
| 0.04 | 27204.38 | 106364.16 | 210343.62 |
| 0.05 | 7904.62 | 32639.31 | 106487.02 |

Table 8: Investment values under Feed-in Tariff, percentage change of investment value, $B = 100$ million

| Feed-in Tariff | 10 euros/MW Hour | | | 15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -0.51 | -0.40 | -0.33 | -0.73 | -0.58 | -0.48 |
| 0.02 | -0.56 | -0.44 | -0.36 | -0.78 | -0.62 | -0.52 |
| 0.03 | -0.30 | -0.41 | -0.36 | -0.30 | -0.56 | -0.51 |
| 0.04 | 0.80 | 0.12 | -0.26 | 1.63 | 0.34 | -0.34 |
| 0.05 | 4.54 | 1.57 | 0.54 | 9.17 | 2.98 | 0.97 |

## 4.2 Green certificates versus carbon permits

**Increasing the budget** We set the budget available equal to 100 million. The effects of a higher budget when Green Certificates are active on the markets is highlighted in Table 10. As in the case of Section 3, we note that GCs are particularly able to stimulate investment in RES. In fact, the results are qualitatively similar. In addition, Table 10 shows that a higher budget increases the incentive of the firm to invest in RES, as the loss in investment value in the cases observed in Section 3 is much less pronounced than the case of a lower budget. On the other hand, the negative effects of Carbon Permits already observed in the previous section are more pronounced when the firm is willing to invest more, as shown in Table 11.

Table 9: Investment values under Carbon Tax, percentage change of investment value, $B = 100$ million

| Carbon Tax | 10 euros/MW Hour | | | 15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -32.55 | -24.52 | -19.66 | -48.83 | -36.77 | -29.50 |
| 0.02 | -48.29 | -32.47 | -24.47 | -72.44 | -48.71 | -36.70 |
| 0.03 | -89.43 | -48.07 | -32.37 | -121.98 | -72.10 | -48.55 |
| 0.04 | -201.68 | -88.98 | -47.77 | -151.72 | -116.43 | -71.65 |
| 0.05 | -193.52 | -146.53 | -85.86 | -162.72 | -119.05 | -108.58 |

Table 10: Investment values under Green certificates, percentage change of investment value, $B = 100$ million

| Green certificates | $G_0$ =10 euros/MW Hour | | | $G_0$ =15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -0.69 | -0.57 | -0.51 | -0.96 | -0.75 | -0.70 |
| 0.02 | -0.70 | -0.67 | -0.53 | -0.93 | -0.77 | -0.68 |
| 0.03 | -0.19 | -0.60 | -0.55 | 0.00 | -0.75 | -0.68 |
| 0.04 | 69.16 | 1.83 | -0.47 | 66.76 | 1.10 | -0.50 |
| 0.05 | 173.28 | 66.60 | 7.95 | 157.18 | 63.69 | 7.22 |

# 5 Conclusion

This article presents a real options framework to value investment timing and capacity choice of investments in energy facilities. Our main focus is on contributing to the debate on which renewable energy support scheme does the best job in boosting investment in renewable energy sources.

On the modeling side, our paper differs from the relevant literature in one major aspect: We give the investor the opportunity to invest also in traditional energy sources. We call this opportunity the Dirty Option.

In our analysis, we observe the effectiveness of FiT in driving green en-

Table 11: Investment values under Carbon permits, percentage change of investment value

| Carbon permits | $C_0$ =10 euros/MW Hour | | | $C_0$ =15 euros/MW Hour | | |
|---|---|---|---|---|---|---|
| E<br>F | 0.05 | 0.06 | 0.07 | 0.05 | 0.06 | 0.07 |
| 0.01 | -33.55 | -25.29 | -20.36 | -50.12 | -37.82 | -30.41 |
| 0.02 | -49.81 | -33.52 | -25.29 | -69.21 | -50.15 | -37.85 |
| 0.03 | -61.18 | -49.00 | -33.55 | -73.98 | -67.05 | -49.96 |
| 0.04 | -35.76 | -54.31 | -47.81 | -58.00 | -68.52 | -62.38 |
| 0.05 | -7.43 | -30.37 | -48.60 | -35.89 | -51.38 | -63.01 |

ergy investment. At the same time, CT is holding back investment in RES. Difficulties and complexities in the development of GC and CP may explain why these incentives are not so common. However, the incentive effect of a green certificate is comparable to FiT.

# A Supplementary data

| Symbol | Description | Value | Unit of measure |
|---|---|---|---|
| $r$ | Discount rate | 0.05 | - |
| $\mu_E=\mu_F$ | Trend parameter E e F | 0 | - |
| $\mu_G=\mu_C$ | Trend parameter green certificates e carbon permits | 0 | - |
| $\sigma_E=\sigma_F$ | Volatility parameter E e F | 0.06 | - |
| $\sigma_G=\sigma_C$ | Volatility parameter green certificates e carbon permits | 0.07 | - |
| $\rho_{EF}$ | Correlation coefficient E F | 0.7 | - |
| $\rho_{EG}=\rho_{FC}$ | Correlation coefficient | 0.6 | - |
| $\rho_{FG}=\rho_{EC}$ | Correlation coefficient | 0.5 | - |
| $B$ | Budget | 10000 | Thousands of EUR |
| $I_D$ | Marginal cost of installation of dirty energy | 900 | Thousands of EUR per MW |
| $I_G$ | Marginal cost of installation of green energy | 1600 | Thousands of EUR per MW |
| $A_D * h_D$ | Production coefficient of D | 8076 * 0.95 | MW*h per MW |
| $A_G * h_G$ | Production coefficient of G | 8076 * 0.34 | MW*h per MW |
| $\gamma$ | Diseconomies of scale of G | 0.9 | - |
| $T$ | Project's life | 20 | years |
| $M$ | Time to maturity of option | 30 | years |
| $G_{good}$ | FiT in the good state | 0.015 | Thousands of EUR per MW*h |
| $G_{bad}$ | FiT in the bad state | 0.01 | Thousands of EUR per MW*h |
| $C_{good}$ | Carbon tax in the good state | 0.01 | Thousands of EUR per MW*h |
| $C_{bad}$ | Carbon tax in the bad state | 0.015 | Thousands of EUR per MW*h |
| $\lambda_G$ | Instantaneous transition rate for FiT | 0 or 0.1, 0.2 | 1/years |
| $\lambda_C$ | Instantaneous transition rate for Carbon tax | 0 or 0.1, 0.2 | 1/years |

# B Market and policy uncertainty

Let's fix a two dimensional model[4]:

$$\begin{aligned} \pi_t = Q_G(x_G)(E_t + G_t) + Q_D(x_D)(E_t - F_t - C_t) = \\ E_t(Q_G(x_G) + Q_D(x_D)) - F_t Q_D(x_D) + G_t Q_G(x_G) - C_t Q_D(x_D), \end{aligned} \tag{5}$$

where $E_t$ and $F_t$ are GBMs, $G_t$ and $C_t$ are continuous-time Markov chains.

We assume that $\alpha_t$ be time-homogeneous continuous-time Markov with transition intensities $\lambda_\alpha$ and two states: $\alpha_{Good}$ and $\alpha_{Bad}$. $\alpha_t = G_t, C_t$

$$\alpha_t = \begin{cases} \alpha_{Bad} & \text{if there was any change of policy in } (0,t] \\ \alpha_{Good} & \text{otherwise} \end{cases}$$

One should note here that $\alpha_{Bad}$ is absorbing state (once reached, the system where leaves).
$P(\alpha_{t+dt} = \alpha_{Bad} | \alpha_t = \alpha_{Good}) = \lambda_\alpha dt + o(dt)$
$P(\alpha_{t+dt} = \alpha_{Good} | \alpha_t = \alpha_{Good}) = 1 - \lambda_\alpha dt + o(dt)$
$P(\alpha_{t+dt} = \alpha_{Bad} | \alpha_t = \alpha_{Bad}) = 1$
$P(\alpha_{t+dt} = \alpha_{Good} | \alpha_t = \alpha_{Bad}) = 0$

We have a generator matrix of the Markov chain $A = \begin{pmatrix} -\lambda & \lambda \\ 0 & 0 \end{pmatrix}$.

The Kolmogorov forward equations can be written as the matrix differential equations $P'(t) = P(t)A$. The system can be solved $P(t) = P(0)e^{tA} = e^{tA}$. We can decompose A into $A = QDQ^{-1}$, where $Q$ consists of the eigenvectors of $A$ and $D$ consists of the eigenvalues of $A$. In this case, we get $e^{At} = Qe^{Dt}Q^{-1}$, where $e^{Dt}$ is a diagonal matrix. The transition matrix is $P(t) = \begin{pmatrix} e^{-\lambda t} & 1 - e^{-\lambda t} \\ 0 & 1 \end{pmatrix}$.

$$E_{\alpha_{Good}}\left(\int_0^T e^{-rt} \alpha_t dt\right) = \int_0^T e^{-rt} E_\alpha(\alpha_t) dt, \tag{6}$$

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[4] Do not consider green certificates and carbon permits

where $E_{\alpha_{Good}}(\alpha_t) = (1,0)\begin{pmatrix} e^{-\lambda t} & 1-e^{-\lambda t} \\ 0 & 1 \end{pmatrix}\begin{pmatrix} \alpha_{Good} \\ \alpha_{Bad} \end{pmatrix} =$
$= (e^{-\lambda t}, 1-e^{-\lambda t})\begin{pmatrix} \alpha_{Good} \\ \alpha_{Bad} \end{pmatrix} = \alpha_{Good}e^{-\lambda t} + \alpha_{Bad}(1-e^{-\lambda t})$.
So we have

$$\alpha_{Good}\frac{1-e^{-(r+\lambda)T}}{r+\lambda} + \alpha_{Bad}[\frac{1-e^{-rT}}{r} - \frac{1-e^{-(r+\lambda)T}}{r+\lambda}] \tag{7}$$

We get general pay-off equation for 2D models ($E_0 = E$, $F_0 = F$):

$$\begin{aligned} &E(Q_G(x_G)+Q_D(x_D))\frac{1-e^{-(r+\mu_E)T}}{r-\mu_E} - FQ_D(x_D)\frac{1-e^{-(r+\mu_F)T}}{r-\mu_F} + \\ &Q_G(x_G)[G_{Good}\frac{1-e^{-(r+\lambda_G)T}}{r+\lambda_G} + G_{Bad}[\frac{1-e^{-rT}}{r} - \frac{1-e^{-(r+\lambda_G)T}}{r+\lambda_G}]] + \\ &Q_D(x_D)[C_{Good}\frac{1-e^{-(r+\lambda_C)T}}{r+\lambda_C} + C_{Bad}[\frac{1-e^{-rT}}{r} - \frac{1-e^{-(r+\lambda_C)T}}{r+\lambda_C}]] \end{aligned} \tag{8}$$

To summarize, replace on $\tilde{r_h}(\mu_h, \lambda) = \frac{1-e^{-(r+\lambda-\mu_h)T}}{r+\lambda-\mu_h}$,
$\overline{G} = G_{Good}\overline{r}(0,\lambda_G) + G_{Bad}(\overline{r}(0,0) - \overline{r}(0,\lambda_G))$, and
$\overline{C} = C_{Good}\overline{r}(0,\lambda_C) + C_{Bad}(\overline{r}(0,0) - \overline{r}(0,\lambda_C))$.
In the end, we have general pay-off with policy uncertainty:

$$Q_G(x_G)[E\overline{r}(\mu_E,0) + \overline{G}] + Q_D(x_D)[E\overline{r}(\mu_E,0) - F\overline{r}(\mu_F,0) + \overline{C}] \tag{9}$$

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