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Abstract

We investigate the optimal investment decision in renewables under market demand uncertainty, in the context of the Italian strategy for renewable deployment under the EU policy. Upon investing, the firm has to decide about the time and size of the investment. We find that a higher subsidy level induces the firm to invest earlier with a smaller investment capacity. This implies that a given environmental target cannot be reached by a too high (too low) subsidy level since this will cause the investment level to be low (too late). We show that there exists an optimal (intermediate) subsidy level to reach the environmental target. Furthermore we find that in a more uncertain economic environment the subsidy adjustment to maintain the target level of investment results in the firm investing earlier, which is opposite to the standard real options result.

Keywords: Investment under uncertainty, Renewable energy sources, Public subsidies, Investment timing, Investment size

JEL subject classification: D81, L51

1 Introduction

Deployment of renewable energy source (RES) is a primary concern of the EU 2020 policy, which has been geared to set subsidy levels capable to spur new investment. A recent new target of the European Union (EU) Commission, according to "2030 framework for climate and energy policies", is to achieve 27% of RES in total energy consumption for the entire EU, without detailing individual targets for member countries. At the same time, the EU commission suggests to adopt a feed-in-premium (FIP) and abandon the fixed feed-in-tariff (FIT) instrument, on the ground that more market approach is apt and some risk should be shared between investor and consumers (European Commission, 2014).

The EU policy framework envisions the achievement of a desired RES target with subsidies, and to close the gap between the market price of conventionally sourced energy and the opportunity cost of new RES. In many member countries, the subsidy has been typically implemented as a fixed FIT to provide a clear and certain support to RES policy (European Commission, 2017). However, firms do not necessarily invest more in RES when the subsidy increases (International Energy Agency, 2015). They may react by a lower than expected investment level, if uncertainty characterizes the perception of future market demand. Furthermore, the firm can change the investment time, which can have its own implication for the size of the investment. Therefore, in order to study the policy effectiveness, there is a need to model the firms' decision to account for dynamic uncertainty that impacts the RES investment profitability. In a market with uncertain future demand, the firm is constantly forecasting demand and balancing the value of investing now and delaying investments. For these features, we employ a real options approach to analyze the investment decisions, where we do not only focus on timing as in the traditional real option analysis (see, e.g., Dixit and Pindyck (1994)), but also on the investment size.

This paper sets up and empirically tests a general model to analyze the investment decision in RES using the real option approach under dynamic uncertainty. We model three stochastic components that affect the firm's profitability, namely, demand fluctuations, changes in consumer attitude toward environmental issues, and cost decrease due to innovation and decreasing learning curves. We contribute to the literature in three ways. First, we provide a theoretical model for the firm's decision to invest in RES. Secondly, we calibrate the model with Italian data and study the impact of the government subsidy policy in Italy. Thirdly, we propose an intermediate level of subsidy support to achieve the desired target of the new EU policy.

We show that to reach the target it is not just a matter of setting a high enough subsidy level. This is because the firm reacts to an increased subsidy by investing earlier and less. What the government needs to do is to determine a subsidy level such that the firm invests just enough to reach the target. Hence, the investment is as low as possible in light of the target, which implies that then the firm invests as early as possible with respect to reaching the target in time. In a changing economic environment the subsidy level needs to be adjusted such that the target is still reached. This has the implication that, surprisingly, the firm is expected to invest earlier in a more uncertain environment. The reason is that the direct effect, implying the usual result that the firm invests later when there is more uncertainty, is more than counterbalanced by an indirect effect. This indirect effect is caused by the fact that an increased subsidy level is needed to keep on reaching the target when uncertainty goes up, and this increased subsidy causes a substantial acceleration of investment. If the environmental target cannot be reached, a conditional subsidy rule may help: Only when the demand level is high enough, the subsidy will be issued from that moment on. This is to prevent that the firm invests in a too low capacity level.

This paper is organized as follows. Section 2 reviews the relevant literature of real options modelling of the firm's RES investment decision. Section 3 sets up the theoretical model and derives the firm's optimal investment decision under subsidy support. Section 4 shows the calibration of the model for Italy, using the policy targets for 2020 and a scenario target for 2035, and analyzes the firm's investment decision in light of the target and the corresponding subsidy level. Section 5 discusses the results of some sensitivity analysis of the model parameters. Section 6 shows the conclusions and policy implications.

2   Related Literature

The real options approach proves that investment irreversibility and an uncertain economic environment create a value of waiting with investment. The firm postpones its investment in order to wait for more information about future uncertainty. Applying a real options approach to analyze the firm's investment took off with Dixit and Pindyck (1994). This research mainly determines the timing of the investment. Dangl (1999) is among the first to include the decision of optimal investment size. Recently, more contributions acknowledge that investing is not only about timing but also about determining the optimal size, see e.g., Huisman and Kort (2015); Hagspiel et al. (2016a) and Hagspiel et al. (2016b). A main result of this literature is that increased uncertainty

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not only delays the time of the investment but also increases its size.

The real options approach has been widely used to analyze the firm's investment decision in renewable energy projects under uncertainty while taking into account different policy instruments. It is a suitable descriptor of the observed investment behavior compared to the net present value rule (Fleten et al., 2016) and has been used to analyze regulatory uncertainty impact on investment decisions (Pawlina and Kort, 2005; Boomsma et al., 2012; Boomsma and Linnerud, 2015; Chronopoulos et al., 2016). Some literature focuses on policy measures like subsidies. This is because energy production from green technologies is usually more costly, and only public subsidies can make the market entry attractive to investors (Nesta et al., 2014). For instance, Ritzenhofen and Spinler (2016) conclude that a fixed subsidy level leads to an immediate decision to invest now or never, and Boomsma et al. (2012) show that FIT encourages earlier investment. Some other contributions emphasize on different policy instruments such as a price cap, and their influence on private firms' investments to achieve the first-best outcome. This stream of literature is represented by Evans and Guthrie (2012), Broer and Zwart (2013), Gatzert and Vogl (2016), and Willems and Zwart (2017).

Several research papers have looked into the influence of policy instruments from an empirical perspective. Fleten et al. (2007) consider the problem of investing in a generator. In a case study, Fleten et al. (2007) focus on the situation at the Nord pool, and show that it is worthwhile to wait for higher prices under price uncertainty. Boomsma et al. (2012) also study the Nordic case and argue that upon investment, renewable energy certificate trading creates incentives for larger projects. Zhang et al. (2016) investigate the dynamics of investment value and the optimal timing for renewable energy investment in China. They find that a subsidy increase would stimulate investment. Detert and Kotani (2013) analyze the switch option from coal to renewables in Mongolia under coal price uncertainty. They assume negative externalities from coal-based operations, and suggest the government should increase electricity prices or switch to renewable energy earlier to reduce the welfare loss, when people are willing to pay more to remove the negative externalities. However, to the best of our knowledge, there is little research on how to reach the RES deployment target by optimally determining the policy instrument level. This paper intends to fill the void and presents a theoretical analysis of the public policy with an empirical application to the Italian RES deployment target.

Several features characterize the RES in Italy. In order to attain 26.4% of green electricity production from RES by 2020, the government policy has promoted subsidies through a feed-in

tariff mechanism for investors. The burden of the subsidy is paid by all consumers with a surcharge on the electricity bill (Bigerna et al., 2015). The Italian consumer's willingness to pay for RES is higher than before. This is because of the positive consumer attitudes towards RES, such as the willingness to pay as a result of increasing environmental awareness (Bigerna and Polinori, 2014). In Section 3, a theoretical model is set up that includes such characteristics.

3 Model

3.1 Model Setup

The unit price of green electricity payments, P, which is measured in euro/MWh (or euro/MW), satisfies a linear inverse demand function with premium s, reflecting the "willingness to pay for green energy", i.e.

$$P_t = \gamma_t + s_t - \eta K.$$

In this formulation η is a positive constant, whereas K stands for green electricity capacity. We impose that the firm always produces up to capacity.

The time function γ_t is stochastic to cover unexpected demand fluctuations. It is expected to increase over time to capture the expected increase of demand for renewable energy over time. The latter is due to the expected price increase of fossil fuels.

The premium s_t is subject to uncertainty, because, as argued by Bigerna and Polinori (2014), uncertainty plays a crucial role in the willingness to pay (WTP) for renewable energy. The WTP, and thus s_t, is expected to increase over time, because as time passes consumers get more aware of environmental problems.

We define c_t to be the unit costs for the green energy firm. Due to innovation and a decreasing learning curve, these costs are expected to decrease over time. Since the future development of innovation is hard to predict, the development of c_t over time will be stochastic, but with decreasing trend.

Summarizing the above, we can define

$$X_t = \gamma_t + s_t - c_t,$$

as the sum of the stochastic components, which affect the firm's profitability. The renewable energy price for the producer is augmented by a fixed feed-in-premium S_F. With this instrument the government can positively influence renewable energy output. Combining the above expression

with the inverse demand function, we can define the net price p_t received by the firm as the difference between the unit price P_t augmented by the feed in premium S_F and the unit costs, c_t:

$$p_t = P_t + S_F - c_t = S_F + X_t - \eta K.$$

To cover the fact that both γ_t and s_t are expected to increase over time, that c_t is expected to decrease over time, and that all are subject to uncertainty, we impose that X_t is a stochastic process satisfying a geometric Brownian motion process, i.e.

$$\mathrm{d}X = \alpha X \mathrm{d}t + \sigma X \mathrm{d}z,$$

with α and σ being positive constants, whereas dz is the increment of a Wiener process.

Investment costs equal θI, where I is the acquired capacity measured in MW, and θ is a positive constant. The production function that converts capacity into electricity is linear and given by

$$K = hI,$$

where K is the MWh produced and h is the specific productivity coefficient (number of hours). The value of h takes into account that a solar park has a lower capacity utilization in one year (1200 hours on average), a wind plant can go up to 4000 hours, and a biomass plant to 6000 hours. This linear relationship makes that for the investment costs we can write

$$\theta I = \delta K \text{ with } \delta = \frac{\theta}{h}.$$

Given that the firm discounts with rate r, the value the representative firm obtains when undertaking an investment in capacity K equals

$$V(X) = \max_K E\left(\int_0^\infty e^{-rt} K (X_t + S_F - \eta K)\, dt - \delta K \mid X_0 = X \right).$$

The green electricity firm thus faces an investment problem where it has to find the optimal time and the optimal size of investment. The optimal time is in fact the point in time that the stochastic process X_t hits the threshold level X^*, provided $X_0 < X^*$. Otherwise, it is optimal for the firm to invest immediately.

3.2 Optimal Investment Decision

The optimal investment decision can be found in two steps. First, for a given level of the geometric Brownian motion, denoted by X, the corresponding optimal capacity level of K is found by solving

$$\max_K E\left(\int_0^\infty e^{-rt} K (S_F - \eta K + X_t)\, dt - \delta K \mid X_0 = X \right)$$

$$= \max_K \left(\frac{K\left(S_F - \eta K\right)}{r} + \frac{KX}{r - \alpha} - \delta K \right).$$

This gives

$$K = \frac{1}{2\eta}\left(S_F + \frac{r}{r-\alpha}X - r\delta\right). \tag{1}$$

We conclude that the optimal capacity level is increasing in X. Furthermore, at a higher premium level it is optimal for the firm to invest in a larger capacity so that the total profit flow increases.

Inserting (1) in the profit flow $K\left(S_F - \eta K + X_t\right)$ learns that the profit flow becomes quadratic in X. Define $Y = X^2$. Then Ito's lemma gives

$$\mathrm{d}Y = \left(2\alpha + \sigma^2\right)X^2\mathrm{d}t + 2\sigma X^2\mathrm{d}z.$$

Hence X^2 is a geometric Brownian motion process with trend $2\alpha + \sigma^2$. This implies that for the problem to converge we need to impose

$$r > 2\alpha + \sigma^2. \tag{2}$$

Second, we have to derive the optimal investment timing, reflected by the threshold level X^*, so that the firm stops waiting and invests with capacity $K(X^*)$ at the moment X^* is reached. Standard real options analysis (e.g., Dixit and Pindyck (1994)) learns that the value of the option to invest, denoted by F, is equal to

$$F\left(X\right) = AX^\beta,$$

where A is a positive constant and β is the positive root of the quadratic polynomial

$$\frac{1}{2}\sigma^2\beta^2 + \left(\alpha - \frac{1}{2}\sigma^2\right)\beta - r = 0, \tag{3}$$

so that

$$\beta = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} > 2. \tag{4}$$

The inequality follows from the fact that (3) implies that the positive root equals $\beta = 2$ for $r = 2\alpha + \sigma^2$. However, due to (2) we know that r is larger. This implies that $\beta > 2$, since we conclude from (4) that β is increasing in r.

To determine the threshold level X^*, we employ the value matching and smooth pasting conditions

$$
\begin{aligned}
F\left(X^*\right) &= V\left(X^*, K\right), \\
\frac{\partial F\left(X\right)}{\partial X}\Big|_{X=X^*} &= \frac{\partial V\left(X, K\right)}{\partial X}\Big|_{X=X^*}.
\end{aligned}
$$

This gives

$$X^* = \frac{\beta}{\beta - 1} \frac{r - \alpha}{r} \left(r\delta - (S_F - \eta K) \right). \tag{5}$$

Combining and solving (1) and (5) leads to the following proposition.

Proposition 1 *The optimal investment threshold X^* and the corresponding optimal capacity level K^* are given by*

$$X^* = \frac{\beta}{\beta - 2} \frac{r - \alpha}{r} \left(r\delta - S_F \right), \tag{6}$$

$$K^* = K \left(X^* \right) = \frac{r\delta - S_F}{\eta \left(\beta - 2 \right)}. \tag{7}$$

3.3 Evaluation

We could confront the resulting investment decision with the fact that, according to some environmental treaty, the investment should take place before a certain time and should be sufficiently large. For instance, "The goal of Italy is to attain 26.4% green electricity (GE) production from renewable energy sources (RES) by 2020", where the 26.4% is the share in the total annual production of electricity (in MWh). Other big European countries, like Germany and Spain, have similar objectives that can be analyzed as well.

In this sense it is important to note that the effect of the fixed feed-in premium S_F is tricky: on the one hand we obtain from (6) that it accelerates investment, but on the other hand we get that, according to (7), the firm invests in less capacity. The latter seems counterintuitive, since X^* and thus the output price at the moment of investment is lower, but is caused by the fact that earlier investment by the firm implies lower profits per unit capacity at the moment of investment, so that the firm will reduce the investment size. Note that by considering (1) we can conclude that, in case timing is fixed, capacity goes up with S_F.

To reach a specific environmental target like "26.4% green electricity (GE) production in 2020", the government first determines the required capacity level K^*. Then by equation (7) we obtain the corresponding premium level S_F, which gives, via (6), the threshold level X^*. In case the firm is expected to invest too late, we adjust S_F to influence the investment decision such that the goal of this 26.4% in 2020 will be reached. Here a conditional subsidy policy may help: Only when X has reached a high enough value, the firm can receive the subsidy. This is to prevent that the firm invests too early in a too low capacity level.

4 Derivation of the Optimal Subsidy Level

We take Italy as an example by data from AEEG (2016) and conduct an empirical analysis to study the renewable subsidy policy. Because Italy has been performing well and realized the 2020 RES target assigned by the EU earlier in 2015, it is easier to calibrate the parameter values from the historical data. Given the EU policy, we can predict the RES target for Italy. According to the calibrated parameter values and the analytical results of the theoretical model, we can calculate the optimal subsidy level to achieve this target.

4.1 Data

In Italy, the total electricity consumption in 2010 was 320 TWh and decreased to 311 TWh in 2015 due to the sluggish economy. In the same period, RES increased from 23% (71 TWh) to about 35% (109 TWh). This means Italy had already reached the 2020 target of 35% by the EU in 2015. This achievement is largely due to the generous Italian RES policy stance (AEEG, 2016). Note that the 2020 target for total energy consumption assigned to Italy is 17%, which is smaller than 35% because it includes heating and transportation etc.. In terms of electricity, the target is 35% of RES.

For the period of 2016-2035, we use the Italian transmission system operator (TSO) forecast of 0.3% annual growth rate for electricity consumption. This results in about 315.7 TWh in 2020 and 330.2 TWh in 2035. We assume that the target of RES in 2020 remains unchanged at 35%. Therefore, the targeted RES total value in 2020 is about 110.4 TWh. For the time beyond 2020, we take into account that the European Commission (2014) has formulated a new challenging target of RES share in 2030, with about 27% of total energy consumption for the EU. We assume this percentage target remains the same in 2035. Then for Italy, 27% of total energy consumption implies a RES share of 51% in total electricity consumption. This suggests a RES target value of 168.4 TWh in 2035. Obviously, this value is under the assumption that the RES policy target is unchanged and run under the business as usual (BAU) behavior (International Energy Agency, 2016). Nonetheless, as this new EU target is still under discussion, we provide a simulation scenario, which is useful for the policy formulation.

4.2 Calibration

In order to simulate the model, we calibrate the relevant parameters for Italy, using historical data for the most recent period 2010-2015. We have fitted the demand function to recover the values for parameters η, γ, and s. We have calibrated the unit cost component c using the computation of the levelized cost of electricity from Elshurafa et al. (2017). The resulting calibration values for the initial year 2010 are reported in Table 1. As initial values in the year 2010:1 we fixed: $\gamma_0 + s_0 = 185.7$; $c_0 = 175.7$; $X_0 = \gamma_0 + s_0 - c_0 = 11.4$. In this preliminary calibration context, we assume that the parameters α, r, σ, δ are in a plausible range.

[Table 1]

The simulation of the theoretical model is performed for two separate periods. First, we simulate the 2010-2015 period to check the validity of the model and whether the model can simulate the generous Italian subsidy support, which has facilitated to reach the EU 2020 target already in 2015. Second, we conduct a simulation until the year 2035 to investigate the possible policy framework to reach the 2035 target.

For both periods, we simulate the geometric Brownian motion according to

$$X_t = X_0 \exp\left(\left(\alpha - \frac{\sigma^2}{2} \right) t + \sigma W_t \right),$$

with 100 random drawings of the Wiener process $dW_t \sim N(0, 1)$. We compute the average of these 100 simulations and check the attainability of the target RES.

4.3 Historical Simulation

We first simulate for the historical period 2010-2015. We have constructed two scenarios with different levels of S_F, labeled A (high subsidy) and C (low subsidy). In Scenario A we set $S_F = 101$ and in Scenario C we set $S_F = 99$. The purpose of these simulations is to check the validity of the calibrated parameter values and to check the effectiveness of the subsidy policy implemented during this period. For the given parameter values and the capacity target of 2015, $K^* = 109$ TWh, the optimal subsidy rate to reach this target is equal to $S_F = 101$. Thus, in Scenario A the subsidy policy is more suitable to reach the target than in Scenario C. We show detailed simulation results of these scenarios for the investment timing in period 2010-2015, which are reported in Figure 1 and analyzed in Figure 2.

[Figures 1 and Figure 2]

For the convenience of graphic illustration, only 10 out of 100 simulated evolution paths of X_t are demonstrated in Figure 1. Comparing the optimal investment threshold in 1a and 1b, we notice that X^* is larger in Scenario C, implying a larger optimal threshold for a lower subsidy rate. This is coherent with our theoretical results in equation (6), where X^* decreases with S_F. Figure 2 shows for each period the empirical percentage of realizations that reach the optimal threshold. The high subsidy scenario (A) allows to reach the target in about 20% of the cases already in the year 2011. This percentage is steadily increasing until 100% of success in 2015. In the low subsidy scenario (C), the percentage of success in reaching the target remains below 20% up until the year 2015. As these values are close to the historical values, we can conclude that Scenario A represents the subsidy policy in Italy well and that the subsidy level $S_F = 101$ is close to the historical level. Thus, the model can explain the boom of RES investment in 2015 that reaches the EU 2020 target.

4.4 Optimal Subsidy Policy to 2035

We now turn to the simulation of the subsidy policy in the period 2016-2035. According to Proposition 1, for the given parameter values in Table 1 and $K^*_{2035} = 168.4$ TWh, which is the investment level needed to reach the environmental target in 2035, we obtain $S_{F2035} = 98.9$ and $X^*_{2035} = 19.86$. Given that $X_0 = 11.4$ in 2010, this implies that it would take 23.3 years from 2010 on to realize the optimal investment size 168.4TWh. In other words, the required capacity K^* is expected to be acquired in April 2033. In the following analysis, we check by simulation what happens if the subsidy rate deviates from the optimal subsidy level S_{F2035}.

[Figure 3]

Figure 3 reports five scenarios for different values of S_F and the corresponding fractions of empirical realization that hit the target value of X^* in each period until 2035. For instance, for the subsidy rate $S_F = 97$, scenario E in the figure, the corresponding investment threshold is $X^*(S_F = 97) = 25.6$, and $K^*(S_F = 97) = 216.8$ TWh. From the simulation, we get that only 8% of the evolvement paths for X_t can reach 25.6 by 2035, implying that the 2035 target is reached with 8% probability. A higher level of $S_F = 101$, scenario D in the figure, makes the firm invest at $X^*(S_F = 101) = 12.8$ with capacity $K^*(S_F = 101) = 108.4$ TWh. This implies that the environmental target will never be reached because it requires an investment level of 168.4 TWh. These two scenarios support the theoretical implication of the model: a larger S_F makes the firm invest earlier and less. A small threshold X^* means it is more likely for X_t to reach X^* and to realize the corresponding K^*, but this K^* can be too low to reach the required investment level.

If S_F is too low, K^* is large enough to reach the target, but it is less likely that the geometric Brownian motion process X_t reaches X^* before the year 2035. So the investment is expected to take place too late.

Figure 3 also shows scenarios for $S_F = 98.9$ (B), $S_F = 100$ (C), and $S_F = 103$ (E). Moreover, it demonstrates the increase of the percentage realization for the corresponding X_F^* in period 2016-2035. For instance, the grey line DDC in Figure 3 illustrates the fraction of realizations where the threshold target is reached in time in Scenario C. This fraction increases from zero at the beginning to around 40% in 2016 and over 50% in 2035.

5   Comparative Static Analysis

5.1   Keeping the Policy Instrument S_F Fixed

Changes in the market conditions can result in variations of the parameters, and thus influence the firm's investment decision. We have conducted a sensitivity analysis around the calibrated values of the parameters σ, α, δ, and r, to assess the response of the probability of realization of the target. The results are illustrated in Figure 4 for five different values of each parameter, which are increasing from Scenario A to Scenario E. In each panel of Figure 4 we show the corresponding fractions of realizations that hit the target value of X^* before 2035. We observe that the realization fraction is decreasing with an increase in each parameter.

[Figure 4]

Panel 4a shows that a smaller σ corresponds to a higher probability of realization, demonstrated by DDA, implying a lower threshold level X^*. For a given subsidy rate S_F, in line with the standard real options results, an increase in the uncertainty makes the firm undertake a larger investment and invest later. The intuition is that when there is more uncertainty about the future market, the firm would like to wait for more information and invest more, because at the moment of investment market demand is higher.

In panel 4b, as α increases, the probability of the RES target realization decreases. The intuition is as follows: a larger α implies that the market grows faster, and the firm anticipates a larger future market demand when deciding on the size of investment. This leads to a larger investment capacity K^* and thus more investment costs. So the firm prefers to invest later when market demand is higher in order to defray the investment costs. This implies that X^* increases with α. In our simulations, therefore a negative correlation between α and the fraction of the cases in which the

target is reached, prevails.

Panel 4c shows that a larger δ implies a larger X^* and thus a smaller probability of target realization, illustrated by DDE, implying a larger X^*. This is because for a given subsidy rate S_F, a larger δ means investing is more expensive, which motivates the firm to invest later when the market demand is higher. As for parameter r, note that for the given parameter values, we obtain that the optimal investment capacity K^* increases with r, which leads to a larger threshold X^* and a lower probability of realization of the target as demonstrated by Panel 4d.

5.2 Optimally Adjusting the Policy Instrument S_F

With the subsidy instrument, government can anticipate the changing environment and act proactively by adjusting the level of the feed-in premium S_F. It does so with the aim to keep the probability of realizing the target as high as possible. For the corresponding changes in parameters, say σ for instance, in order to guarantee a certain level of investment, the government needs to adjust S_F such that

$$\frac{\mathrm{d}K^*}{\mathrm{d}\sigma} = \frac{\partial K^*}{\partial \beta}\frac{\partial \beta}{\partial \sigma} + \frac{\partial K^*}{\partial S_F}\frac{\partial S_F}{\partial \sigma} = -\frac{r\delta - S_F}{\eta(\beta - 2)^2}\frac{\partial \beta}{\partial \sigma} - \frac{1}{\eta(\beta - 2)}\frac{\partial S_F}{\partial \sigma} = 0.$$

Because $\partial \beta / \partial \sigma < 0$ according to (Dixit and Pindyck, 1994), it holds that

$$\frac{\partial S_F}{\partial \sigma} = -\frac{r\delta - S_F}{\beta - 2}\frac{\partial \beta}{\partial \sigma} > 0.$$

The changes in uncertainty parameter σ and the corresponding subsidy adjustment also influence the optimal investment timing X^*. According to equation (6), this influence is given by

$$\frac{\mathrm{d}X^*}{\mathrm{d}\sigma} = \frac{\partial X^*}{\partial \beta}\frac{\partial \beta}{\partial \sigma} + \frac{\partial X^*}{\partial S_F}\frac{\partial S_F}{\partial \sigma} = \frac{r\delta - S_F}{\beta - 2}\frac{r - \alpha}{r}\frac{\partial \beta}{\partial \sigma} < 0.$$

Hence, we obtain the surprising result that the firm invests earlier in a more uncertain environment, which contradicts the standard real options result that uncertainty generates a value of waiting with investment (Dixit and Pindyck, 1994). The reason is that when there is more uncertainty (larger σ), the firm would delay investment and invest more. Delaying investment would imply that the probability of reaching the environmental target in time would decrease. Therefore, the government wants to speed up investment by increasing the feed-in premium. It does this in a way that it fixes this premium such that the required investment size is just sufficient for reaching the target. Consequently, there are two effects on the optimal investment timing, resulting from an increase in σ: a direct (positive) effect that delays investment, and an indirect (negative) effect that

accelerates investment. The direct effect reflects the standard real options result, where an increase in the market uncertainty makes the firm invest later and more. The indirect effect reflects the adjustment of the policy instrument to counter the influence of the increased market uncertainty. The indirect effect dominates the direct effect, which leads to the accelerated investment in capacity size K^*, and implies a faster realization of the RES target.

Similar results can be obtained for the trend parameter α. If the subsidy rate is adjusted such that the optimal investment capacity stays the same for a changing α, then

$$\frac{\partial S_F}{\partial \alpha} = -\frac{r\delta - S_F}{\beta - 2}\frac{\partial \beta}{\partial \alpha} > 0,$$

provided that $\partial \beta / \partial \alpha < 0$ (Dixit and Pindyck, 1994). The subsidy adjustment has influence on the optimal investment threshold X^* as given by

$$
\begin{aligned}
\frac{\mathrm{d}X^*}{\mathrm{d}\alpha} &= \frac{\partial X^*}{\partial \alpha} + \frac{\partial X^*}{\partial \beta}\frac{\partial \beta}{\partial \alpha} + \frac{\partial X^*}{\partial S_F}\frac{\partial S_F}{\partial \alpha} \\
&= -\frac{r\delta - S_F}{r}\frac{\beta}{\beta - 2} + \frac{r\delta - S_F}{\beta - 2}\frac{r - \alpha}{r}\frac{\partial \beta}{\partial \alpha} < 0.
\end{aligned}
$$

The implication is that for a faster growing market (larger α), the negative indirect effect from the policy instrument dominates the effect from the standard real options[1]. This leads to the accelerated investment and a faster realization of the RES target, contrary to the demonstration in Panel 4b.

The subsidy instrument can also adapt to changes in the unit investment cost δ. In order to maintain the optimal capacity level K^*, $\partial S_F / \partial \delta$ should satisfy that

$$\frac{\mathrm{d}K^*}{\mathrm{d}\delta} = \frac{r - \partial S_F/\partial \delta}{\eta(\beta - 2)} = 0,$$

implying $\partial S_F / \partial \delta = r > 0$. This indicates that a proportional increase of S_F can offset the influence of an increased δ on K^*. Furthermore, it can be derived that

$$\frac{\mathrm{d}X^*}{\mathrm{d}\delta} = \frac{\beta}{\beta - 2}\frac{r - \alpha}{r}\left(r - \frac{\partial S_F}{\partial \delta}\right) = 0.$$

So the effect from the policy instrument adjustment is equal to the effect from the standard real options in Panel 4c.

A similar analysis can be carried out with respect to a change in the firm's discount parameter r. In order to obtain the desired level of investment, the subsidy rate S_F should be adjusted to a

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[1]The effect from standard real options is denoted by $\frac{\partial X^*}{\partial \alpha} + \frac{\partial X^*}{\partial \beta}\frac{\partial \beta}{\partial \alpha}$, and the sign depends on the parameter values (Wen et al., 2017).

change in r such that $\mathrm{d}K^*/\mathrm{d}r = 0$. Therefore, it holds that

$$\frac{\partial S_F}{\partial r} = \delta - \frac{r\delta - S_F}{\beta - 2}\frac{\partial \beta}{\partial r}.$$

Given that $\partial\beta/\partial r > 0$ from (4), the sign for $\partial S_F/\partial r$ is not straightforward. Thus, in order to maintain a certain level of RES investment, the government needs to take the other parameter values into consideration when deciding on S_F. The adjusted S_F affects the optimal investment threshold X^* and

$$\begin{aligned}
\frac{\mathrm{d}X^*}{\mathrm{d}r} &= \frac{\beta}{\beta - 2}\frac{r^2\delta - \alpha S_F}{r^2} + \frac{\partial X^*}{\partial \beta}\frac{\partial \beta}{\partial r} + \frac{\partial X^*}{\partial S_F}\frac{\partial S_F}{\partial r} \\
&= \frac{\beta}{\beta - 2}\frac{\alpha(r\delta - S_F)}{r^2} + \frac{r\delta - S_F}{\beta - 2}\frac{r - \alpha}{r}\frac{\partial \beta}{\partial r}.
\end{aligned}$$

In a market with positive trend parameter α, we can get $\mathrm{d}X^*/\mathrm{d}r > 0$. It indicates that an increase in r results in an increase in X^* after the corresponding adjustment of S_F, implying the positive direct effect from the standard real options result, $\frac{\partial X^*}{\partial r} + \frac{\partial X^*}{\partial \beta}\frac{\partial \beta}{\partial r}$, dominates any possible negative indirect effect from the subsidy instrument. In a market with negative trend parameter α, $\mathrm{d}X^*/\mathrm{d}r$ can be either positive or negative, depending on other parameter values.

We also compute the sensitivity analysis around the calibrated values of the parameters to assess how the subsidy changes to attain the target and give the corresponding investment threshold after adjustment, as reported in Table 2. It is interesting to notice that the required level of optimal subsidy is increasing with all parameters. For σ, α, and δ, this confirms the analysis above, and implies that more subsidy should be provided to the firm in order to achieve the target level of investment. Moreover, Table 2 also shows that the firm invests earlier for larger σ and α, and the investment threshold does not change with δ. This supports the existence of the negative effect on X^* from adjusting the subsidy rate. This negative indirect effect dominates the positive standard real options effect for larger σ and α, and counterbalances the positive standard real options effect for an increasing δ. Table 2 also illustrates that for the given Italian economy parameters demonstrated in Table 1, an increase in discount parameter r results in a larger subsidy rate and investment threshold. This implies that for larger r, though the government subsidizes more to keep the investment size at the desired level, the firm still invests later. However, given the fact that the current interest rate in Italy is much lower than that in 2010, implying a smaller discount rate for the firm and a smaller X^*, there is larger probability for Italy to reach the RES target in 2020 and 2035.

[Table 2]

6   Conclusion

We design a model for a firm investing in capacity for green energy in an uncertain economic situation. The model allows for analyzing the effect of the governmental subsidy in the form of a fixed feed-in-premium on the firm's investment decision. In particular we find that a larger subsidy induces the firm to invest earlier in less capacity.

This analysis allows to find the most suitable subsidy level to reach a certain environmental target level as soon as possible. This goes as follows. First, the environmental target fixes the required investment size. Based on this size, we can find the subsidy level and the investment threshold. From the threshold, we can obtain the expected time to reach the environmental target.

Using the Italian data, we applied this model to determine the most suitable subsidy level to reach the given environmental EU target in 2020 and 2035.

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Table 1: Calibration of parameter values in 2010 for Italy.

Parameter	Value	Range
r	0.06	$0.045 - 0.06$
α	0.02	$0.0185 - 0.0210$
σ	0.07	$0.007 - 0.008$
δ	1750	$1535 - 1770$
η	0.00007	
X_0	11.4	

Table 2: Sensitivity analysis of parameters σ, α, δ, and r, for policy targets 2020 and 2035: Optimal S_F to reach K^* and the corresponding threshold X^*.

	Target 2020	Target 2035
Optimal S_F value	100.9	98.8
Optimal K^* value	110.4	168.4

	2020		2035			2020		2035	
σ	S_F	X^*	S_F	X^*	α	S_F	X^*	S_F	X^*
0.05	99.5	14.0	96.6	21.3	0.018	99.5	14.6	96.7	22.3
0.07	100.9	13.0	98.8	19.9	0.019	100.3	13.8	97.8	21.1
0.09	102.3	12.1	100.8	18.5	0.02	100.9	13.0	98.8	19.9
0.095	102.6	11.9	101.3	18.2	0.021	101.6	12.3	99.8	18.7
0.1	102.9	11.7	101.8	17.9	0.022	102.2	11.6	100.7	17.7
	2020		2035			2020		2035	
δ	S_F	X^*	S_F	X^*	r	S_F	X^*	S_F	X^*
1650	94.9	13.0	92.8	19.9	0.045	78.7	8.6	78.7	13.1
1700	97.9	13.0	95.8	19.9	0.048	83.1	9.5	82.7	14.5
1750	100.9	13.0	98.8	19.8	0.055	93.5	11.6	92.0	17.7
1800	103.9	13.0	101.8	19.9	0.058	97.9	12.5	96.1	19.0
1850	106.9	13.0	104.8	19.9	0.06	100.9	13.0	98.8	19.9

Figure 1: Historical simulation of quarterly values for geometric Brownian motion X_t and X^* in the period 2010-2015 with Scenario (A): S_F=101, and Scenario (C): S_F=99.

(a) XSTARA = X^* in Scenario A; XXA = Average X_t in Scenario A; XXjA = X_t realization j
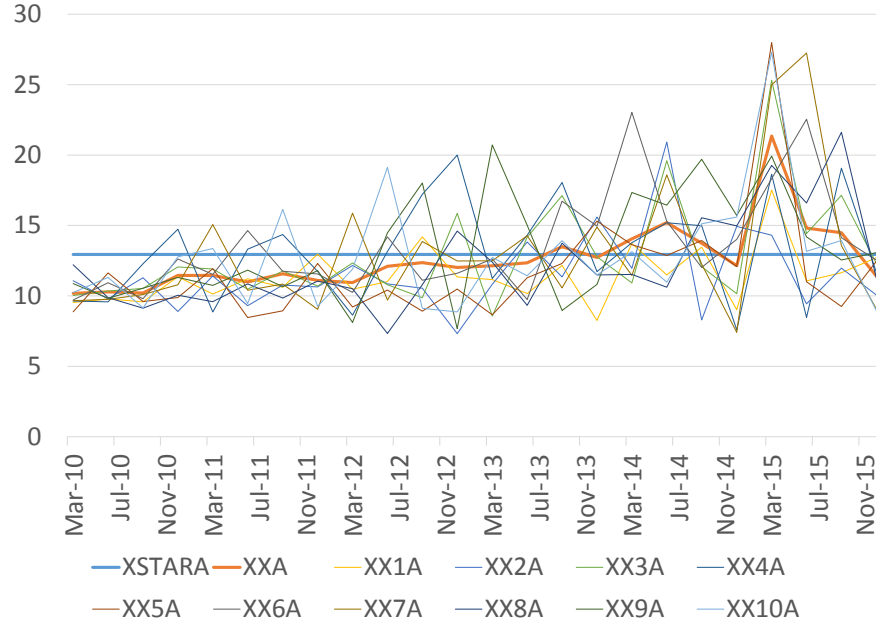
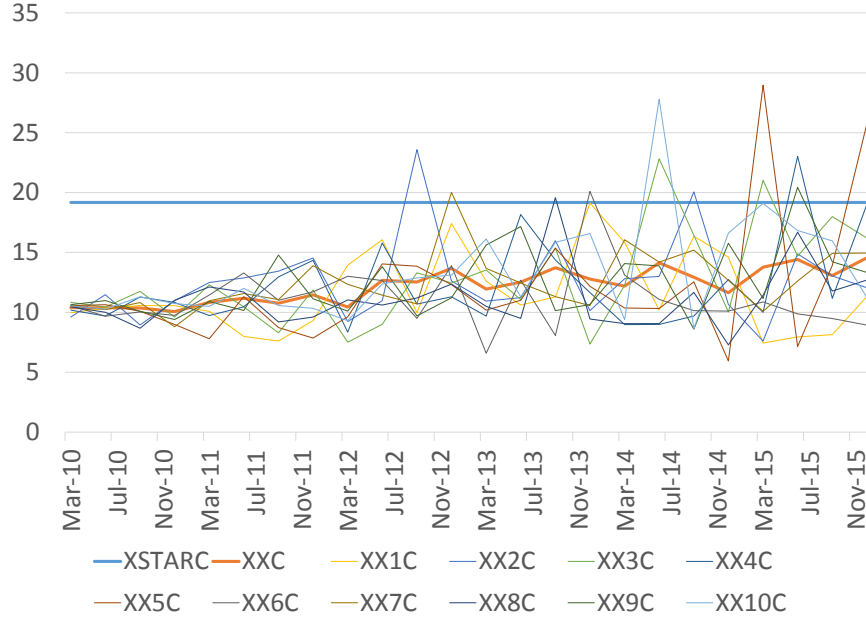(b) XSTARC = X^* in Scenario C; XXC = Average X_t in Scenario C; XXjC = X_t realization j

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Figure 2: Quarterly percentage realization of X^* in the period 2010-2015 for Scenario (A): S_F=101, and Scenario (C): S_F=99.
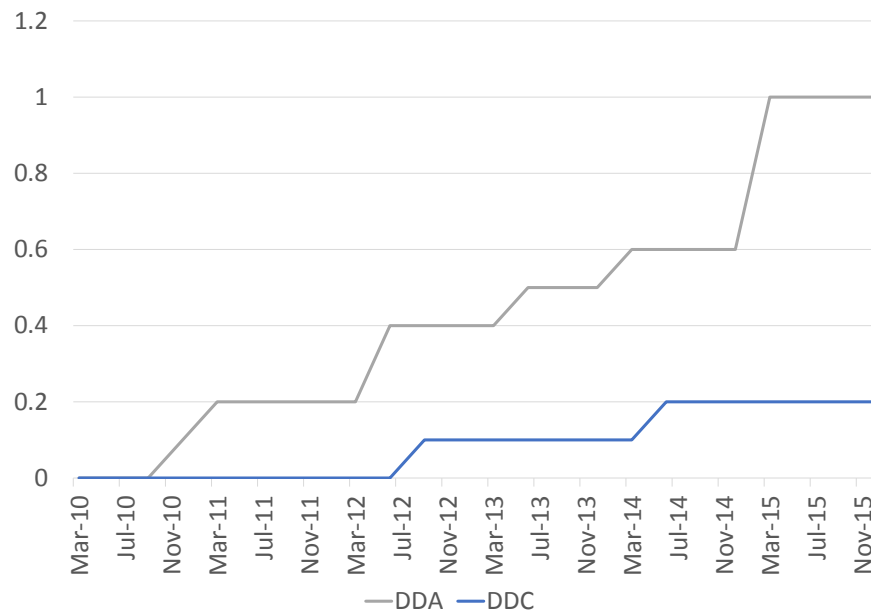

Figure 3: Percentage realization of X^* in the period 2016-2035 under different subsidy rates.
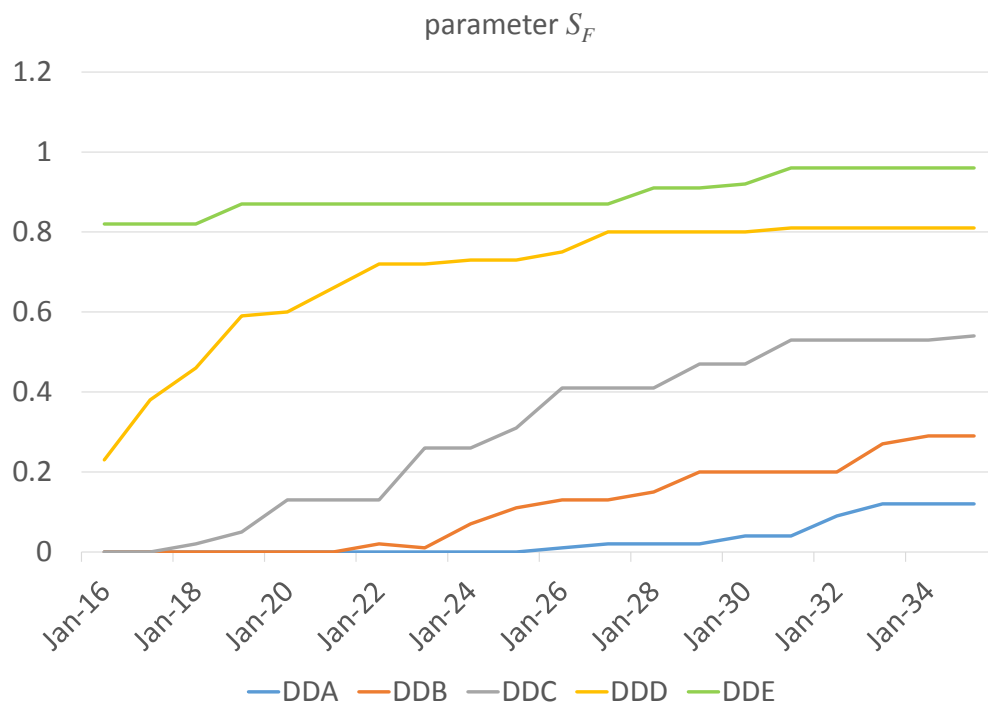
Figure 4: Parameter sensitivity and percentage realization of X^*: Annual values in the period 2016-2035.