The impact of Norwegian-Swedish green certificate scheme on investment behavior: A wind energy case study

Fredrik Finjord[1], Verena Hagspiel[1], Maria Lavrutich[1] and Marius Tangen[1]
Department of Industrial Economics and Technology Management,
Norwegian University of Science and Technology, 7491 Trondheim, Norway

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Abstract

In order to encourage investments in the most cost-effective renewable energy projects, Norway and Sweden have implemented a joint green certificate subsidy system, where the certificates are traded on a common market. The policies applied in the two countries, however, are not identical and differ most notably by the deadlines for receiving the subsidy. From the policy perspective, the important question is how these differences affect investment behavior in the renewable sector. This paper investigates the impact of the green certificate subsidy scheme on the value of renewable energy investments from the perspective of both Norwegian and Swedish investors based on a wind energy case study. We find that the impact of the policy is greatest when the distinctive Norwegian investment deadline is approaching, making investment optimal for the Norwegian investor for a larger range of prices. The Swedish investor, having no deadline to meet, will be more reluctant to investing. Furthermore, we find that the possibility of a collapse in the green certificate price reduces the values of the investment options. Being able to learn about the likelihood of such a price collapse leads to a small increase in the values of the options.

Key words: Green certificates, subsidy, real options, policy, regulation.

1 Introduction

Investments in renewable energy are an essential part of a sustainable energy future. At least 179 countries had targets for an increased share of renewable energy by the end of 2017 (REN21, 2016). The European Union has a goal of covering 27% of the energy demand from renewable sources by 2030 (European Commission, 2017). Furthermore, on 14 June 2018 the European Commission, the European Parliament and the Council agreed upon a new ambitious renewable energy target for 2030 of 32% with a clause for an upwards revision by 2023. In order to attract sufficient investments in renewable energy to meet these goals, various incentive schemes are implemented by individual governments. These policy schemes can have vastly different characteristics, depending on what the governments deem suitable. The goal of this paper is to assess how the differences in regulations in Norway and Sweden impact the investors' decisions.

The green certificate market is an example of a renewable energy incentive scheme, which entails that qualified renewable energy producers receive certificates from the government per MWh produced. Energy consumers, often in the form of utility companies, are obliged by law to purchase certificates corresponding to a certain percentage of total energy consumed over a year. Norway and Sweden, who are committed to the EU goal to increase renewable production, have both implemented a green certificate scheme where the certificates from both countries are traded on a common market. However, the regulations associated with the green certificates are different in the two countries. Most notably, projects must be operating before the end of 2021 in order to receive green certificates in Norway, while there is no such deadline in Sweden.

This paper presents a case study of a wind energy project eligible to receive green certificates, which is used to analyze the investments opportunities in Norway and Sweden. With uncertainty in both future electricity and green certificate prices, the investor must decide the optimal time to invest in the project. We analyze the investment decision from the perspective of both a Norwegian and Swedish investor, and investigate how the regulatory differences in the green certificate schemes affect the investment opportunities. Furthermore, we examine the effect of a possible collapse in the green certificate price, and how learning about the likelihood of the price collapse affects the investors.

In this paper, we apply the real options theory to analyze investment behaviour in renewable energy projects. Such investments typically entail large and irreversible up-front costs. Additionally, the revenues generated are highly dependent on the electricity and green certificate prices over the lifetime of the project. The investment is thus exposed to considerable market risk (Fernandes et al., 2011). Being able to delay the investment enables the investor to wait for more information before undertaking the investment. This creates an additional value of managerial flexibility.

The net present value (NPV) approach, which treats the investment as a now-or-never decision, is commonly applied in capital budgeting. However, this approach fails to capture the dynamic nature of the investment problem and thus disregards the value of flexibility. Managerial flexibility implies that the investment can be undertaken at any time, where an irreversible cost is paid to receive the profit streams generated by the project. As a result, the characteristics of this investment opportunity resemble those of a time-dependent American call option. Therefore, it is more appropriate to value investments under uncertainty as financial options by applying real options methodology (Dixit and Pindyck, 1994).

The contribution of this paper is threefold. First, we analyze the implication of different subsidy policies in Norway and Sweden by explicitly accounting for the limited time of the policy scheme and country specific regulations. Second, we consider a perpetual option with a complex time-dependent value function, where changes occur at given dates. We find that neglecting the time-dependent features of the model, can have a large impact on investment behaviour and option values. Third, we develop an algorithm to solve the real options model, using least-squares Monte Carlo simulation.

The following section presents the overview of the relevant literature. Section 3 provides background on the electricity and the green certificate market. Section 4 formulates our real options model. Section 5 quantifies the parameters used in the case study. Section 5 discusses the results of the case study and compares the Norwegian and Swedish investment opportunities. Section 7 concludes.

2 Literature

An increasing number of recent contributions study the effect of various support schemes on investment behavior. Real options analysis has been demonstrated as a useful tool in the attempt to quantify the impacts of different policy schemes on power investment. When making policy recommendations it is important to understand the effect of firms expectations about future framework conditions on their investment behavior. The strength of the real options approach compared to larger system analysis models, which consider energy systems from a society point of view, lies in the ability to address the actual decision makers' perspective. Focusing on central mechanisms and ignoring many of the secondary factors allows to develop smaller, more business relevant and transparent models. In the following we mention publications studying the effect of various support schemes taking a real options approach, that are most relevant to our study.

Adkins and Paxson (2016) use a real options approach to derive the optimal investment timing for a renewable energy project with a subsidy. Different subsidy schemes are evaluated, where the subsidy is proportional to a stochastic price and/or a stochastic quantity. The occurrences of a sudden introduction or retraction of a subsidy are modeled by a Poisson process. Adkins and Paxson (2016) find that the type of subsidy scheme has a large impact on the optimal time of investment, where a retractable subsidy gives the strongest incentive for early investments.

Boomsma and Linnerud (2015) analyze how investors respond to market and policy risk, and consider several different support schemes. Market risk refers to the uncertainty in electricity and green certificate prices, while policy risk is defined as a possible change of the subsidy scheme, modeled as a Poisson process. Correlation between electricity and green certificate prices results in risk diversification, which speeds up investments. They find that the possibility of a retroactive termination of the subsidy scheme encourages later investments, while a non-retroactive termination encourages earlier investments.

Kitzing et al. (2017) evaluate a wind energy project under different support schemes using a real options model. They include different correlated factors in one stochastic process to model the gross margin. The investment threshold and optimal capacity is then found for a offshore wind energy case study in the Baltic sea. They find that there is a difference in profit margins and project size when evaluating the various subsidy schemes, where green certificates may lead to a higher profit margin and capacity.

Fleten et al. (2016) consider perpetual investment opportunities in hydropower projects before green certificates were introduced in Norway. They use a real options model to find the implied level of subsidies in each project, and investigate whether the investors base their decisions on the traditional net present value approach or the real options approach by conducting interviews. Even though the investors claimed to use the NPV criterion, their decisions were consistent with the real options approach. Their analysis shows that investors follow real options thinking, but the option values are not explicitly quantified.

Closest to our work here is Boomsma et al. (2012), who examine investment behavior under different policy schemes using a case study of a wind energy project in Norway. They employ a real options approach to analyze the optimal investment timing and capacity choice, with steel price, electricity price and subsidy price as the sources of uncertainty. The policy schemes they examine are feed-in tariffs and green certificates. In addition, they analyze the case where the support scheme employed can change with time, using Markov switching. Boomsma et al. (2012) find that both the timing and capacity choice differ with the various support schemes. Implementing a feed-in tariff encourages an earlier investment, while certificate trading encourages a larger project capacity.

This paper models investments in renewable energy in Norway and Sweden as an American option with a time-dependent value function. This is because the duration for which subsidies will be received depends on the time of investment. In addition, we consider a project with a finite lifetime. Close to this issue is Gryglewicz et al. (2008), who study the effects of uncertainty on finite-life projects. They find that uncertainty in some cases accelerates investments for finite-life projects. Testing the robustness of this finding, they also consider the case with a finite option life similar to our model. They conclude that their result proves robust to the finite life option case.

In most cases, there is no closed form solution to options with time-dependent values, therefore numerical methods must be applied (Moreno and Navas, 2003). There is extensive literature on numerical methods to value of American options. Examples of well recognized approaches are among others Schwartz (1977), Cox et al. (1979), and Boyle (1977). Schwartz (1977) evaluates American options for discrete times and discrete stock prices, by approximating the partial derivatives in the Black-Scholes equation using finite differences. The boundary conditions at the investment deadline of the option are known, and the option value is calculated for a range of stock prices by backwards iterations. Cox et al. (1979) introduce a model where the underlying stochastic process starts at a given value, and follows a binomial process. The value of the option is then derived by iterating backwards using arbitrage arguments, i.e. risk neutral valuation. Boyle (1977) uses Monte Carlo simulation to estimate the value of an European option. This is done by simulating a series of stock price trajectories, which is used to determine the distribution of terminal option values. He finds that this is a simple and flexible method. The underlying variables can, for example, follow different types of stochastic processes. Also a jump process can easily be incorporated into the model.

This paper follows the approach of Longstaff and Schwartz (2001) to estimate the value of the time-dependent option. Longstaff and Schwartz (2001) propose the least-squares Monte Carlo method to approximate the value of an American option numerically. The advantage of using this method is its flexibility. The Monte Carlo model captures the complexity caused by the regulations of the policy scheme, and allows to incorporate different features, such as, for example, learning effects in the investment cost and correlation in the underlying stochastic variables.

3 Background

Power in the Nordic region is traded on Nord Pool, a deregulated and free market where prices are determined by supply and demand. Spot power prices are highly volatile. There are several factors that impact the electricity price, e.g. oil and gas prices, politics and economic growth (Fantoft, 2014). One of the most important factors is weather, as Sweden depends on wind for power production while Norway is largely dependent on rain for hydropower production. There are also seasonal variations in the prices, where demand and supply vary throughout the year. The demand for heating, for example, is higher in the winter.

In addition to selling the electricity, an important source of income for renewable energy projects are green certificates. One certificate is issued for each MWh produced by eligible producers. The common Swedish and Norwegian green certificate market was established in 2012 with the objective to increase renewable production and contribute to the countries' renewable energy goals. This common market is based on the Swedish green certificate market, established in 2003. The purpose of introducing a joint market was to increase renewable energy production in a more cost-effective way by directing investments to the best projects (NVE, 2016).

The price of green certificates is decided by supply and demand. The total supply of green certificates in a given year amounts to the issued certificates for that year in addition to a possible accumulated surplus of certificates from previous years. The demand for green certificates is implicitly decided by the Norwegian and Swedish governments through each country's green certificate quota curve, which is given as a percentage of total consumption. Energy consumers with a quota obligation, e.g. energy retailers, must purchase an amount of green certificates which corresponds to the electricity consumption multiplied by the quota for a given year. Every year on April 1st, the green certificates needed to fulfill the quota obligation are cancelled from the certificate accounts of the energy retailers (Elsertifikatloven, 2011). The quota curves are illustrated in Figure 1.

Of a total increase in renewable energy production of 28.4 TWh by 2020, Norway will contribute 13.2 TWh, and Sweden the remaining 15.2 TWh. Following the recent revision of the Swedish policy, Sweden will contribute another 18 TWh by 2030. Projects in both countries that started production in a specified period before January 1st 2012 are a part of a transition scheme, where the production is not a part of the goal of 28.4 TWh (Elsertifikatloven, 2011). Projects in the transition scheme are eligible to receive green certificates for a reduced period of time. Certificates can be transferred and used in both Norway and Sweden, irrespective of where they were originally issued.

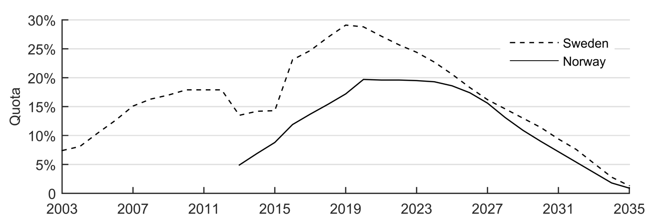


Figure 1: Quota curve for Norway and Sweden (NVE, 2017a; Olje- og energidepartementet, 2017; Energimyndigheten, 2017).

The Swedish quota is higher than the Norwegian quota, which is a consequence of Sweden contributing a larger share of the new production, in addition to having more certificates issued as part of the transition scheme. The future production and consumption of electricity are uncertain, as well as the supply and demand of green certificates. If the forecasted estimates used as basis for the quota curve differ from the realized values, there will be a change in the surplus of certificates. If more are issued than canceled in a year, the total surplus of green certificates will increase. Figure 2 shows the issued and canceled green certificates in the Norwegian-Swedish market, in addition to the accumulated surplus since 2003, whereas Figure 3 shows the prices in the joint market.

When the surplus is increasing (decreasing), a negative (positive) pressure is put on the prices of green certificates (NVE, 2016). This can be observed from 2006 to 2008, where the surplus of green certificates was decreasing, and as illustrated in Figure 3, the prices increased by about 100% in the

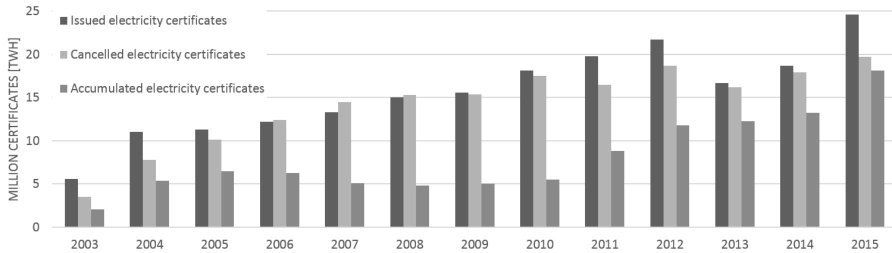


Figure 2: Historical demand and supply of green certificates (NVE, 2016).

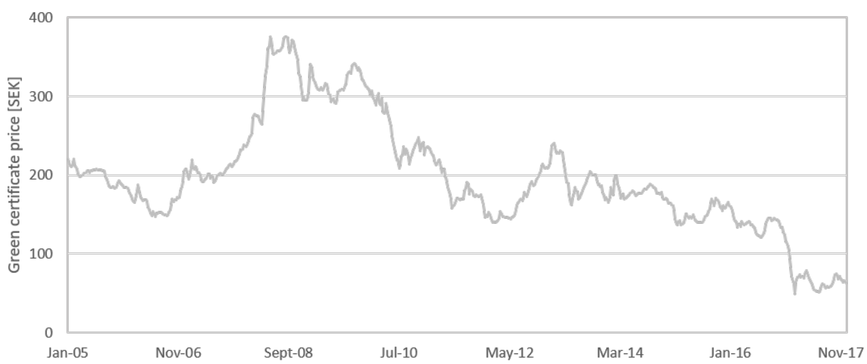


Figure 3: Historical prices of green certificates per MWh in the period 2005 to 2017 (SKM, 2017).

corresponding period. In the period 2010 to 2015, more green certificates were issued than canceled, and the surplus was increasing. In the corresponding period, the prices had a negative trend.

Energy producers that are eligible for green certificates will receive these from the start of production, for a maximum of 15 years. The regulations of the policy scheme differ in the two countries, as there are different constraints on when production must have started in order to receive green certificates. The Norwegian investor has an explicit deadline, and must be in operation by December 31st 2021 to receive green certificates (Elsertifikatloven, 2011) until December 31st 2035. In contrast, the Swedish investor will receive green certificates regardless of the time of investment, but at most until December 31st 2045 (Elsertifikatloven, 2011). This is illustrated in Figure 4, which shows the duration certificates will be received when investing before and after the Norwegian deadline.

The green certificate market is regulated in close cooperation between Norway and Sweden. The first progress review was conducted in 2015, and the renewable energy goal was increased by 2 TWh. The quota curve was adjusted based on previous estimation errors and updated forecasts for electricity consumption (NVE, 2016). Additionally, the Norwegian deadline was extended by one year, from the end of 2020 to the end of 2021, in order to prevent projects from losing the right to receive certificates if they were delayed (Prop. 97L, (2014-2015), 2015).

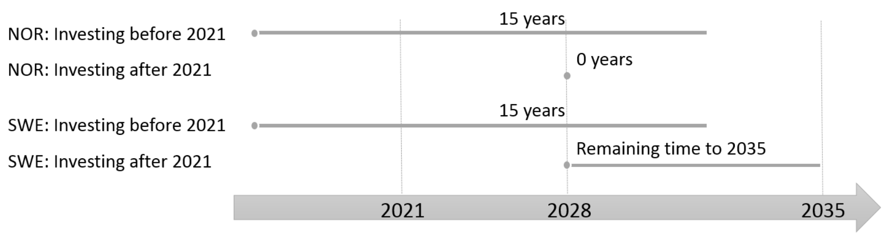


Figure 4: The duration certificates will be received if investing before and after 2021.

4 Model

In this section, a model to evaluate the opportunity to invest in a renewable energy project in Norway and Sweden is presented. The optimal investment strategy from the perspective of a risk-neutral and profit maximizing investor is analyzed. In particular, the value of the option to invest and its optimal exercise timing is determined.

The optimal investment strategy is expected to differ between the Norwegian and Swedish investor when considering a renewable energy project due to different national regulations. As the Norwegian investor has a deadline for the project in order to be eligible to receive green certificates, the intrinsic value is time-dependent. The intrinsic value is also time-dependent for the Swedish investor, since the investor will receive certificates for a shorter duration when investing closer to the end of the policy scheme. In what follows, we present a baseline model where time-dependency of the policy scheme is incorporated. Further, the model is extended, allowing for the possibility of jumps in the prices, both with and without Bayesian learning.

4.1 Baseline model

The revenues of a renewable energy project are dependent on the electricity price, denoted E_t, and green certificate price, denoted S_t. As outlined in Section 3, the future electricity and certificate prices are uncertain. Therefore, the prices are represented using stochastic modeling, utilizing the Geometric Brownian motion model [1],

$$dS = \mu_S S dt + \sigma_S S dW_S, \tag{1}$$

$$dE = \mu_E E dt + \sigma_E E dW_E, \tag{2}$$

[1] Geometric Brownian motions capture the long term development of the prices, which is reasonable in our case, since we consider a long-term investment. In addition, the historical prices in Norway and Sweden have been positive, and geometric Brownian motions, unlike several other processes, does not allow for negative realizations. Both the green certificate and electricity prices have been modeled as geometric Brownian motions by, among others, Fleten et al. (2016), Boomsma et al. (2012) and Boomsma and Linnerud (2015).

where μ_S and μ_E denote the drifts, and σ_S and σ_E denote the volatilities of the green certificate price and electricity price, respectively. The two processes are assumed to be correlated with the correlation coefficient denoted by ρ_{SE}.

The profit flow is dependent on the electricity and green certificate prices, the fixed and variable costs, denoted C_F and C_V, and the quantity produced, q. It is assumed that the electricity from a project is produced in the period from the moment of investment, denoted τ, and for the expected lifetime of the project, denoted T_L. Green certificates will be issued to a production facility for a maximum number of years, denoted T_S, after production has begun. The subsidy scheme and the green certificate market is set to end at a given date, denoted T_E. Green certificates will not be issued after this date, and the revenues from certificates are thus zero after T_E for both Norwegian and Swedish projects. Renewable energy projects in Norway will only be eligible to receive green certificates if the electricity production has started before a deadline, denoted by T_{DN}.

Thus, the instantaneous profit function for the Norwegian investor is equal to

$$\pi_N(S_t, E_t, t) = \begin{cases} (E_t + S_t - C_v)q - C_F, \\ (E_t - C_v)q - C_F, \end{cases} \tag{3}$$

where the first expression is valid for $\{t \leq T_E \quad \wedge \quad \tau \leq T_{DN} \quad \wedge \quad t < \tau + T_S\}$ and the second for $\{t > T_E \quad \vee \quad \tau > T_{DN} \quad \vee \quad t > \tau + T_S\}$.

The Norwegian investor receives certificates if investing before T_{DN}, and if the investor has received certificates for less than T_S years. The investor will not receive certificates after the policy scheme has ended, $t \geq T_E$. The only difference between the Norwegian and Swedish investors is that $T_{DN} = T_E$ for the Swedish investor, whose instantaneous profit function is given by

$$\pi_S(S_t, E_t, t) = \begin{cases} (E_t + S_t - C_v)q - C_F, \\ (E_t - C_v)q - C_F. \end{cases} \tag{4}$$

where the first expression is valid for $\{t \leq T_E \quad \wedge \quad t < \tau + T_S\}$ and the second for $\{t > T_E \quad \vee \quad t > \tau + T_S\}$. The Swedish investor receives certificates if investing before T_E and if the investor has received certificates for less than T_S years.

Using these profit functions, we can find the intrinsic values of the Norwegian and Swedish projects can, i.e. the expected discounted revenues of the projects. The intrinsic value of the Norwegian investment project is given by

$$V_N(S_t, E_t, \tau) = \begin{cases} q(r_S(\tau)S_\tau + r_E E_\tau) - C, & \tau \leq T_{DN}, \\ r_E q E_\tau - C, & \tau > T_{DN}, \end{cases} \tag{5}$$

where $r_S(\tau) = \frac{1}{\rho - \mu_S}(1 - e^{min\{T_E - \tau, T_S\}(\mu_S - \rho)})$, $r_E = \frac{1}{\rho - \mu_E}(1 - e^{(\mu_E - \rho)T_L})$, $C = \frac{qC_V + C_F}{\rho}(1 - e^{-\rho T_L})$ and ρ denotes the discount rate.

If investing for $t \leq T_E - T_S$, the intrinsic value is the same as in the case where the subsidy scheme is perpetual. For investments in the period $T_E - T_S < t < T_{DN}$, certificates will be received for a reduced duration. When $\tau > T_{DN}$, the project does not receive any certificates, and $r_S = 0$. For the Swedish investment project, we have the following intrinsic value,

$$V_S(S_t, E_t, \tau) = \begin{cases} q(r_S(\tau)S_\tau + r_E E_\tau) - C, & \tau \leq T_E, \\ r_E q E_\tau - C, & \tau > T_E, \end{cases} \tag{6}$$

where $r_S(\tau) = \frac{1}{\rho - \mu_S}(1 - e^{min\{T_E - \tau, T_S\}(\mu_S - \rho)})$, $r_E = \frac{1}{\rho - \mu_E}(1 - e^{(\mu_E - \rho)T_L})$, $C = \frac{qC_V + C_F}{\rho}(1 - e^{-\rho T_L})$.

The present value of the revenues from certificates depends on the time of investment. As the time until T_E decreases, r_S goes to 0. If the investment is undertaken before T_{DN}, the intrinsic values of both investors are equal. This is also the case when $t > T_E$, as neither of the investors will receive certificates. See Appendix A for derivations.

Furthermore, the investment cost, I_t, is assumed to decrease in the time-dependent model due to learning effects. There has been a steady decline in wind turbine costs over the last decades, a trend that is expected to continue (NREL, 2012). The learning rate, λ, is a measure of how much the investment cost decreases as the cumulative capacity doubles. The yearly learning rate, λ_Y, is calculated based on forecasted values of production. The investment cost can, therefore, be expressed by $I_t = I_0 e^{-\lambda_Y t}$. Let $F_N(S_t, E_t, t)$ and $F_S(S_t, E_t, t)$ denote the value of the option to invest in Norway and Sweden, respectively. The investors solve the following optimal stopping problems,

$$F_N(S_t, E_t, T) = \max_T \ \mathbf{E}[e^{-\rho T}(V_N(S_t, E_t, T) - I_t)], \tag{7}$$

$$F_S(S_t, E_t, T) = \max_T \ \mathbf{E}[e^{-\rho T}(V_S(S_t, E_t, T) - I_t)], \tag{8}$$

where T represents the optimal time of investment. The solution of these optimal stopping problems is of a threshold type. That means that the investment is optimal when the state variable (S_t, E_t, t) reach a certain threshold value. The option value in this case is then the value of undertaking an investment at the optimal investment threshold properly discounted. The problems (4.1) and (8) can not be solved analytically. We apply the least-squares Monte Carlo simulation approach to value the options. The Monte Carlo algorithm used is outlined in Appendix B.

4.2 Model extension: Possible price collapse

In 2014, the head of Statkraft[2] warned about the possibility of a collapse in the certificate prices. At the same time, both BKK[3] and DNB[4] feared a price drop [5]. The uncertainty about possible price drops is a topic of great interest for investors, as many are relying on green certificates from projects to remain profitable. This section incorporates the possibility of discrete jumps in the green certificate

[2]Statkraft is Norway's largest energy producer, fully owned by the Norwegian state.
[3]BKK is a major Norwegian power company
[4]DNB is Norway's laregst financial services group
[5]https://www.tu.no/artikler/bkk-frykter-elsertifikatene-naermest-blir-verdilose-etter-2020/231025

price into the model in order to account for sudden price collapses. Jumps are assumed to occur at random times following a Poisson process, given by

$$dq = \begin{cases} 0, & \text{with probability } 1 - \Lambda dt, \\ 1, & \text{with probability } \Lambda dt, \end{cases} \tag{9}$$

where Λ represents the mean arrival rate of the jumps.

The green certificate price then follows a geometric Brownian motion combined with a Poisson jump process,

$$dS = \mu_S E dt + \sigma_S E dW_S - \phi S dq, \tag{10}$$

where ϕS is the size of the jump. The process for the electricity price remains as in equation (2). The jumps are assumed uncorrelated to the returns of the prices.

The possibility of a jump will lower the expected green certificate price, and hence decrease the values of the Norwegian and Swedish projects. Using the same approach as in Appendix A, the intrinsic values of the Norwegian and Swedish projects can be expressed by equation (11) and (12), respectively.

$$V_{JN}(S_t, E_t, \tau) = \begin{cases} q(r_{JS}(\tau) S_\tau + r_E E_\tau) - C, & \tau \leq T_{DN}, \\ r_E q E_\tau - C, & \tau > T_{DN}, \end{cases} \tag{11}$$

$$V_{JS}(S_t, E_t, \tau) = \begin{cases} q(r_{JS}(\tau) S_\tau + r_E E_\tau) - C, & \tau \leq T_E, \\ r_E q E_\tau - C, & \tau > T_E, \end{cases} \tag{12}$$

where $r_{JS}(\tau) = \frac{1}{\rho + \Lambda\phi - \mu_S}(1 - e^{min\{T_E - \tau, T_S\}(\mu_S - \rho - \Lambda\phi)})$, $r_E = \frac{1}{\rho - \mu_E}(1 - e^{(\mu_E - \rho)T_L})$, $C = \frac{qC_V + C_F}{\rho}(1 - e^{-\rho T_L})$.

The solution approach is equivalent to the baseline model, with the difference being the price process of the green certificates. For additional details, see Appendix C.1.

4.3 Model extension: Learning about probability of price collapse

There are speculations about how the price of green certificates will develop, and if a collapse in the price is likely. By observing signals from the government and other institutions, the investors can learn about the likelihood of a price collapse. These signals can, for example, be investment decisions of large projects. Just a few large investments are needed to balance the demand in Norway before the deadline, T_{DN}, and therefore, the prices can drop if investment decisions are taken by large investors (Barstad, 2017).

Following the approach of Thijssen et al. (2004), we implement Bayesian learning into the model, where investors can update their belief about the likelihood of a price drop by receiving signals. The signals arrive at discrete times following a Poisson process. Let n denote the number of signals and

Λ_S the mean arrival rate of the signals. The arrival of the signals is then given by,

$$dn(t) = \begin{cases} 0 & \text{with probability } 1 - \Lambda_S dt, \\ 1 & \text{with probability } \Lambda_S dt, \end{cases} \tag{13}$$

Depending on the state of the world, there is either a high or a low probability of a jump. The jump intensities for the high and low probability cases are denoted Λ_H and Λ_L, respectively. Let P_0 denote the initial likelihood of being in a good state, where the jump intensity is low. By receiving signals, the investors update this probability. The likelihood of a signal indicating a high or low jump intensity depends on the true state of the market. This is illustrated in Table 1, where ω denotes the reliability of the signals.

Table 1: Reliability of signal

	True prob. is low	True prob. is high
Signal indicates low probability	ω	1-ω
Signal indicates high probability	1-ω	ω

Let k denote the number of signals indicating a low jump intensity in excess of signals indicating a high jump intensity. Then the probability of being in a good state is given by

$$p(k) = \frac{\lambda^k}{\lambda^k + \zeta(1-\lambda)^k}, \tag{14}$$

where $\zeta = (1 - p_0)/p_0$. Let V_L and V_H denote the payoff of the project when the jump intensity is Λ_L and Λ_H, respectively. Then the intrinsic value of the project is the conditional expected payoff, given by

$$V(S_t, E_t, \tau) = p(k)V_L(S_t, E_t, \tau) + (1 - p(k))V_H(S_t, E_t, \tau). \tag{15}$$

The value of the project is then solved numerically using Monte Carlo simulation. For details regarding the solution algorithm, see Appendix C.2.

5 Case Study

As there is significant unexploited potential for wind power in both Norway and Sweden, we choose a case study of a wind energy project to analyze the investment problem. In this section, we quantify parameters which will be used as the baseline case in the analysis.[6] The parameters used in the baseline case are summarized in Table 2.

[6]The parameter values are mainly based on estimates from agency reports(see e.g. NVE (2015), IRENA (2014) and IRENA (2016)), scientific contributions (See e.g. Boomsma and Linnerud (2015) and Fleten et al. (2007)), and are

Table 2: Numerical values used in the case study

Parameters	Benchmark value
E_0 - Initial electricity price	250 NOK/MWh
S_0 - Initial certificate price	138 NOK/MWh
μ_E - Drift of electricity price	2.5 %
μ_S - Drift of certificate price	2.5 %
σ_E - Volatility of electricity price	15.5%
σ_S - Volatility of certificate price	16.3%
ρ_{SE} - Correlation	5.1%
I - Investment cost	10,000 NOK/kW
λ_Y - Yearly reduction of investment cost	0.58%
C_V - Variable costs	0.14 NOK/kWh
C_F - Fixed costs	0 NOK/kWh
Q - Capacity	35 MW
ϵ - Capacity factor	40%
q - Production quantity	122,640 MWh/year
ρ - Discount rate	6 %
T_0 - Start year	2017
T_L - Project lifetime	20 years
T_S - Maximum duration of certificates	15 years
T_{DN} - Norwegian deadline	2021
T_E - End of policy scheme	2035

The end of the policy scheme, T_E, is set to 2035 for both countries, which was the case until the recent change in the Swedish scheme. The recent extension of the deadline in Sweden to 2045 does in fact not influence our main conclusions. The effect of this extension is that investors are more inclined to postpone investment as they can wait longer for information and still receive the full 15 years of certificates. In order to isolate the effect of the unique Norwegian deadline, which is arguably the most interesting policy difference, we have chosen to keep using the scenario with a common scheme end. Wind energy investments typically have a long-term planning horizon, where the certified lifetime of most wind turbines are $T_L = 20$ years (DNV, 2016; NVE, 2015).

Because electricity and green certificate prices are assumed to follow geometric Brownian motions, the initial values, drift and long term volatility of the processes need to be estimated. These parameters

chosen in cooperation with Knut-Harald Bakke, Head of Industrial Portfolio and Projects at Hydro Energi AS, one of Norway's largest electricity producers.

are the same for Norwegian and Swedish investors, since they are operating in a joint market and are exposed to the same price process for electricity certificates. The initial prices of electricity and green certificates in the baseline case are set to the average daily price of 2016[7] to focus on long term development, rather than short term fluctuations and seasonal variations in the prices. This gives an initial electricity price of $E_0 = 250$ NOK/MWh, and an initial green certificate price of $S_0 = 138$ NOK/MWh. Similarly to Boomsma and Linnerud (2015), it is assumed that the prices are expected to increase with the general price level, and the drift of both price processes is set to the inflation rate, $\mu_E = \mu_S = 2.5\%$.

Following the approach of Fleten et al. (2007) and Boomsma and Linnerud (2015), we use historical average weekly three-year-forward contracts to estimate the volatility of electricity and green certificate prices[8]. In the period 2007-2016, the annual volatilities of the electricity and green certificate prices are estimated to be $\sigma_E = 15.5\%$ and $\sigma_S = 16.3\%$, respectively. As explained in Section 3, both green certificate and electricity prices are affected by the production from renewable energy projects and the demand for electricity. Therefore, it is likely that the prices are correlated. For the same time period and data as considered for the volatility estimates, a correlation of $\rho_{SE} = 5.1\%$[9] is calculated.

Naturally, individual project characteristics can vary a lot depending on e.g. location and investors' required rate of return. As the goal is to study implications of regulatory differences, a similar project in Norway and Sweden which is based on an average Norwegian wind park is used.

According to NVE (2017b), the average Norwegian wind park has 15 turbines with a capacity of 2.3 MW each. So a project capacity of $Q = 35$ MW is chosen for the case study. The produced electricity is then calculated from the maximum capacity and the capacity factor, denoted by ϵ[10]. The capacity factor is a measure of the relationship between the actual power produced and the maximum possible power produced. ϵ is assumed to be constant throughout the wind turbine lifetime[11]. A capacity factor of 37.5% was achieved by the best wind power projects in Norway in 2014 (NVE, 2015). Assuming a small increase by 2017, we set $\epsilon = 40\%$.

The investment cost for wind power projects is often expressed as a cost per installed capacity, i.e. investment cost increases linearly with the capacity[12]. Vindportalen (2017) finds that a wind power project typically has a total investment cost of 10,000-12,000 NOK/kW. This is consistent with NVE (2015), who finds that the average investment cost of wind turbines in Norway between 2011-2013 was 12,005 NOK/kW, but expects the cost to decrease to approximately 10,000 NOK/kW due to learning

[7] The electricity spot price data was obtained from Nord Pool.

[8] The data for electricity forward prices was obtained from NASDAQ Commodities using Montel, while the data for the green certificate forward prices was obtained from SKM (2017).

[9] Boomsma and Linnerud (2015) find a correlation of 4% in the period 2005-2015, using the same method.

[10] $q = 8760\, Q\, \epsilon$, where 8760 is the number of hours in one year and ϵ is the capacity factor.

[11] Short term and seasonal variations in the capacity factor are neglected since the focus is on a long-term investment decision.

[12] See e.g. NVE (2015) and IRENA (2014)

effects by 2017. Therefore, $I = 10,000$ NOK/kW is assumed. In addition, NVE (2015) forecasts the expected learning rate for the investment cost to be 10% in the period 2014-2020, and 7% in the period 2020-2035. IRENA (2016) analyses the historical average global learning rate, and finds that in the period 1983-2014, it has been 7%. Accordingly, the investment cost is assumed to be decreasing with a learning rate of $\lambda = 7\%$. NVE (2015) estimates the global capacity of wind energy in 2012 to be 282 GW, and forcasts capacity to be 612 GW and 1130 GW in 2020 and 2035, respectively. Using this data, the yearly growth rate of the global capacity of wind energy is estimated to be 5.8%, using exponential regression. Consequently, with the learning rate of 7 %, the investment cost is estimated to decrease with a yearly rate of 0.58%.

The service agreements typically have a long contract period, and constant operational costs throughout the project lifetime are assumed. Vindportalen (2017) estimates a range of 0.10-0.15 NOK/kWh, while NVE (2015) assumes a cost of 0.15 NOK/kWh. Based on these estimates, a total operational cost of $C_V = 0.14$ NOK/kWh is used, which includes all variable and fixed costs.

Based on the assessment of the Norwegian Water Resources and Energy Directorate (NVE) that concluded on a discount rate of 6% in 2017 for a general Norwegian project[13]

Lastly, a summary of the parameters related to the policy scheme is provided, which was discussed in detail in Section 3. The start date of the case study is set to the beginning of 2017. After investing, certificates will be received for a maximum period of $T_S = 15$ years. The parameter values for the deadlines represent the 31st of December that year. In the original agreement between Norway and Sweden, the end of the policy scheme is set to $T_E = 2035$. The Swedish investor will receive green certificates regardless of the time of investment, while the Norwegian investor must invest before the Norwegian deadline at $T_{DN} = 2021$.

6 Results

In this section, we compare the values of the investment opportunities that were obtained using the Monte-Carlo simulation. First, the effect of time-dependency on the option value and investment behavior is analyzed. Further, a comparison between the Norwegian and Swedish investment opportunities is made, and a sensitivity analysis is performed. Finally, the possibility of jumps in the green certificate price with and without learning is assessed.

[13]NVE announced that in an update about adjustments to the original report (NVE (2015)) published in 2015., we set the discount rate to $\rho = 6\%$. This is a rather conservative estimate advised to be used for government projects (NVE (2015)). However, as we focus primarily on insights of the comparison between a Norwegian and Swedish investor, this moderate estimate serves our purpose. In practice, the discount is very dependent on individual characteristics of a project.

6.1 The effect of time-dependency on investment behavior

In what follows, the effect of an investment deadline to receive green certificates is considered. The initial time is set to $t = 2017$, and an option with a perpetual subsidy scheme is compared to the cases where there is a deadline such that investments must be made before $t = 2018$, $t = 2022$, and $t = 2032$. We use the parameter values outlined in Section 5, with the exception of $\rho_{SE} = 0$ and $\lambda_Y = 0$ in order to isolate the effect of the time-dependency on the option values[14].

If we assume a perpetual subsidy scheme, we find that the value of the investment opportunity is equal to 190 MNOK. The impact of a deadline on the option value is illustrated in Figure 5.

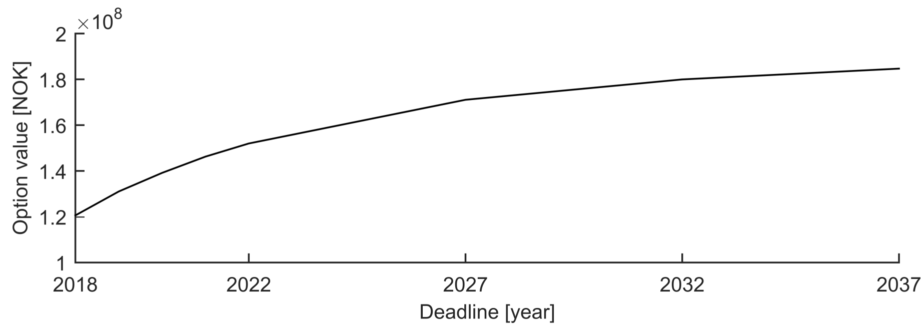


Figure 5: $F(E_0, S_0, t)$ as a function of deadline for the set of parameters, $E_0 = 250$ NOK/MWh, $S_0 = 138$ NOK/MWh, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=0%, λ_Y=0%.

A short time until the deadline has a clear impact on the value of the investment opportunity. With a deadline of 1 year, the option value is reduced by 36% to 121 MNOK. In contrast, the impact of a deadline in 2032 compared to the perpetual subsidy scheme is limited, reducing the option value by just 5% to 180 MNOK. Thus, it is important to incorporate time-dependency when evaluating investment opportunities in renewable energy in Norway and Sweden, especially when the deadline is in the near future.

6.2 Optimal investment strategies: Norwegian versus Swedish perspective

In this section, we analyze the results of the baseline model and conduct a sensitivity analysis.

The intrinsic values of the Norwegian and Swedish projects, $V_N(E_0, S_0, t)$ and $V_S(E_0, S_0, t)$, are illustrated in Figure 6 as a function of time.

[14] We wish to keep the development of the electricity price equal for all deadlines, thus, $\rho_{SE} = 0$.

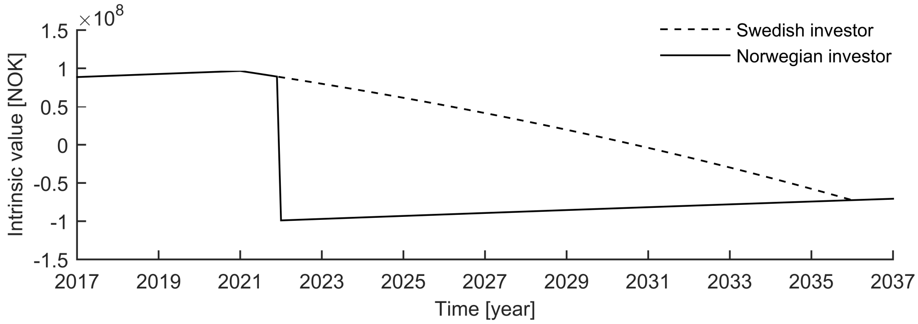


Figure 6: $V_N(E_0, S_0, t)$ and $V_S(E_0, S_0, t)$ as a function of time, t, for the set of parameters, $E_0 = 250$ NOK/MWh, $S_0 = 138$ NOK/MWh, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%.

Initially, the intrinsic values of both projects are 89 MNOK. Two factors influence these values. First is the learning effect which gradually reduces the investment cost over the whole investment period. This increases the intrinsic values of the projects, and is the dominant effect for both investors in the periods $2017 \leq t < 2021$ and $t \geq 2036$. The second factor is the decreasing duration of certificates the investors will receive when investment is postponed, which decreases the intrinsic values of the projects. We find that the second factor has a larger impact on the projects than the first factor in the period $2021 \leq t < 2022$. Hence, the intrinsic values are decreasing. After the end of 2021 until the end of 2035, the intrinsic values differ between the two countries as a consequence of the difference in policy regulations. In this period, the Norwegian project is no longer eligible to receive certificates, and the value drops from 88 MNOK to -99 MNOK when the deadline, T_{DN}, is reached. In contrast, the Swedish intrinsic value has a steady decrease in the corresponding period. After the end of the policy scheme in 2035, the intrinsic values of both investors are equal.

Because the initial intrinsic value is greater than zero, the optimal decision is to invest in the project immediately according to the NPV approach. However, doing so ignores the possibility to delay the investments. Applying the real options approach, the values of the investment opportunities of the Norwegian and Swedish investors at $t = 2017$ are 154 MNOK and 160 MNOK, respectively. By having the possibility to delay the investments, the value of the Norwegian option increases by 73%, or 65 MNOK, while the value of the Swedish option increases by 80%, or 71 MNOK. The primary reason for the additional value from flexibility is the opportunity to wait for higher electricity and green certificate prices. The value of the Norwegian and Swedish investment opportunities, $F_N(E_0, S_0, t)$ and $F_S(E_0, S_0, t)$, change as a function of time, as illustrated in Figure 7.

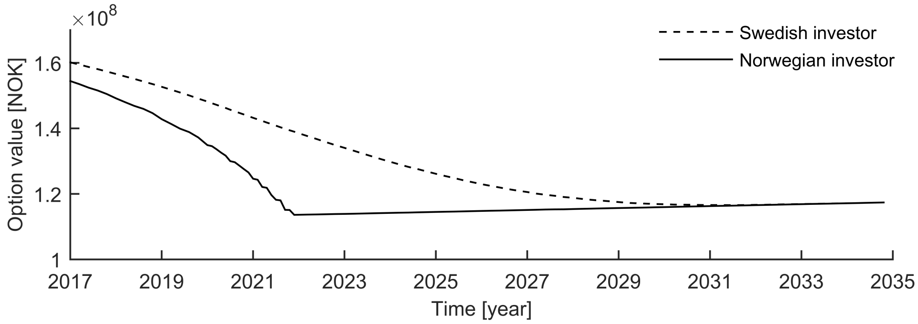
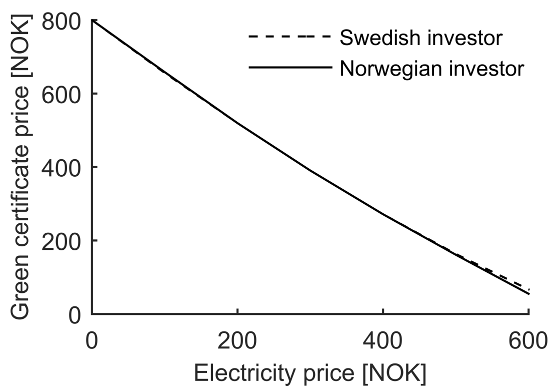


Figure 7: $F_N(E_0, S_0, t)$ and $F_S(E_0, S_0, t)$ as a function of time, t, for the set of parameters, $E_0 = 250$ NOK/MWh, $S_0 = 138$ NOK/MWh, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%.

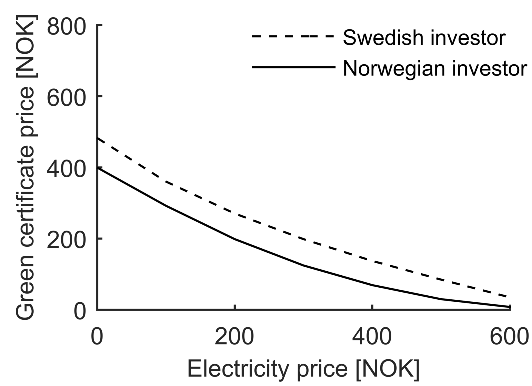
Prior to the Norwegian investment deadline, $t \leq 2021$, the value of the Norwegian option decreases faster with time than the Swedish option. The difference between the Norwegian and Swedish option values reaches a maximum at the investment deadline, T_{DN}. At this point, the investment opportunity in Sweden in considerably more valuable at 139 MNOK compared to 114 MNOK for the investment opportunity in Norway. This discrepancy is a consequence of the different policy regulations as the Swedish investor can delay the investment at T_{DN} and still receive certificates for a project, while the Norwegian investor must invest immediately or lose the right to receive certificates.

In the period after the investment deadline, the Norwegian option value increases steadily due to the decreasing investment costs. The value of the Swedish investment opportunity decreases steadily from 2017 to a minimum of approximately 116 MNOK in the middle of 2031. Waiting longer before investing results in a shorter period of receiving certificates, and consequently a lower option value. Around 2031, this effect becomes smaller than the learning effect, and the option value will increase as a consequence of the decreasing investment cost. Note that since the option value is essentially the discounted value of undertaking the project at the optimal investment threshold net of investment cost, it is affected by I_t both directly and indirectly via the optimal threshold. The smaller is the investment cost the more attractive is the investment opportunity. This implies that the value at the investment threshold is larger and the firm has an incentive to invest sooner. Both effects work in the same direction, resulting in an increase of the option value. The difference in the Norwegian and Swedish option values decreases after T_{DN}, and the option values are relatively similar for $t > 2031$, where the regulatory differences provide close to zero additional value to the Swedish investor.

Next, we analyze the investment behavior of the investors by comparing the investment thresholds, E_t^* and S_t^*, which are illustrated in Figures 8a and 8b, for the initial time, $t = T_0$ and the Norwegian deadline, $t = T_{DN}$.



(a) $t = T_0$.



(b) $t = T_{DN}$

Figure 8: Investment threshold for the following set of parameter values: μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%.

With a high electricity price, a lower green certificate price is required for the investment to be profitable. At the start of 2017, the investment thresholds of the Norwegian and Swedish projects are very close. This implies that both will invest at approximately the same prices, even though the Swedish investor has a more valuable investment opportunity. It can therefore be concluded that the Norwegian deadline has a low effect on the investment behavior at $t = T_0$. However, at $t = T_{DN}$, there is a substantial difference in the investment thresholds. The Norwegian investor has a significantly lower threshold because the opportunity to receive green certificates is about to expire. As a consequence, the Norwegian investor will invest for a larger range of certificate prices.

The investment threshold of the Norwegian investor as a function of time is illustrated in Figure 9, and the difference to the Swedish threshold is illustrated in Figure 10.

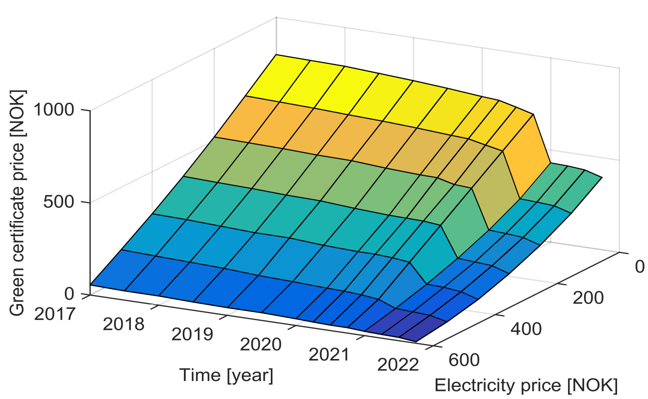


Figure 9: Investment threshold for the Norwegian investor. The parameters used are μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%.

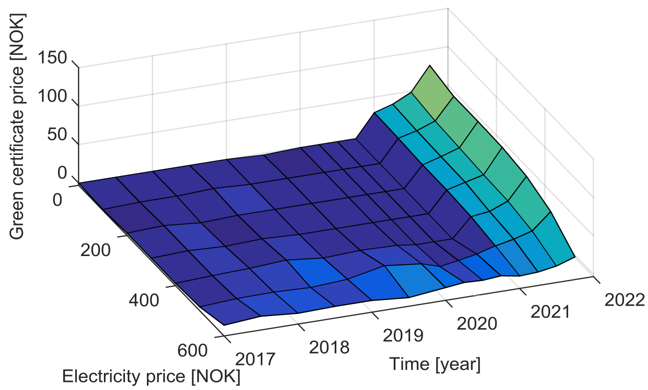


Figure 10: Difference in the investment thresholds of the investors. The parameters used are μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%.

Initially, the thresholds of both investors are similar and decrease relatively slowly by time. At the end of 2020, there is a large drop in both thresholds. E.g. for the Norwegian investor for $E_t^* = 200$, the threshold S_t^* decreases by 48 % in 3 months. The main reason for this drop is that the intrinsic values start declining in 2021 (see Figure 6), which makes the possibility to delay the investments less attractive. The difference in the thresholds starts to increase during this period, since the difference in regulations has a larger effect on the threshold close to the deadline. In the period from 2021 to 2022, the Norwegian threshold stays relatively constant. The two aforementioned factors influence the threshold in this period. The reason for a constant threshold is thus that these two factors have approximately the same impact. In the same period, the difference in threshold between the two projects increases, which is a consequence of the Swedish investor having no deadline. The Swedish investment threshold increases in the period, $2021 \leq t \leq 2035$ as the duration for which certificates will be received decreases, and a higher certificate price is thus required for the project to be profitable. In conclusion, the investment behavior will remain similar before 2021. In 2021, there will be an additional incentive for both investors to exercise their options, as the thresholds drop significantly. In the period 2021-2022, the Norwegian investor will invest for lower prices than the Swedish investor. Given the current prices, investments are not optimal for either of the investors before the Norwegian deadline.

These conclusions have a direct implication for the probability to undertake the investment. Figure 11 illustrates the likelihood of undertaking an investment by a certain year in Norway and Sweden, and, thus, can be interpreted as the accumulated probability of investment.

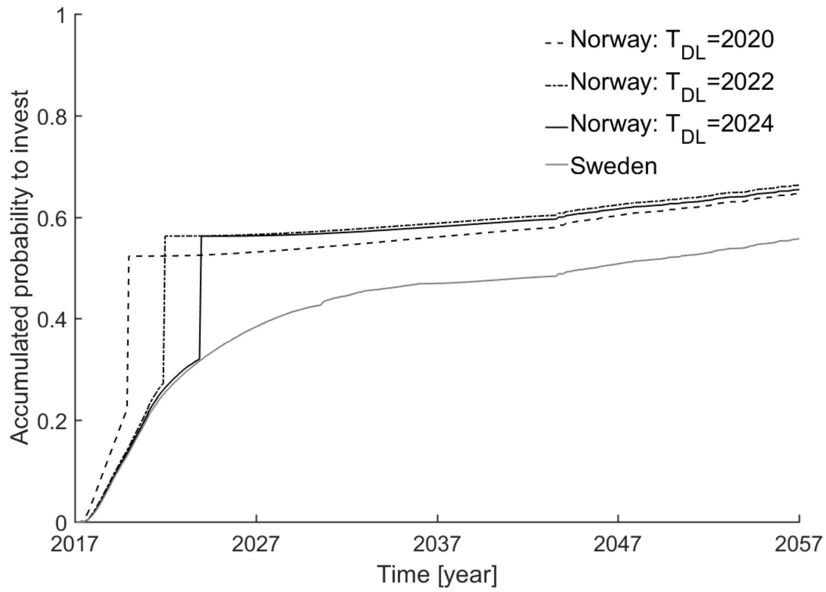


Figure 11: Accumulated probability of undertaking an investment for the set of parameters, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%, t=T_0

As can be seen from Figure 11, the accumulated probability of investment in Sweden gradually increases over time. This is due to the fact that in the absence of the deadline it becomes more likely that the optimal investment threshold is hit as the time goes by. For the Norwegian investor, the presence of the deadline has a positive effect on the investment probability. At the deadline, we observe a jump in the investment probability, caused by a quick drop in the investment threshold. Due to this drop the investment probability increases steeply just before the deadline. Note that this drop is smaller for longer deadlines. Thus, a longer deadline for the Norwegian investor implies that the jump occurs later, as it is more likely that the investment would already be optimal before the deadline. In that case the investment probability before the deadline is closer to the one of the Swedish investor. This is because for a longer deadline, the thresholds of a Norwegian and Swedish investors are more similar. Therefore, we can conclude, that the short-term effect of the deadline is more pronounced if it is set for an earlier date. If the deadline is set further in the future, its short-term effect is more concentrated around the deadline. The long term effect of the investment deadline, however, is non-monotonic. A small increase in the deadline results in a larger increase in the long-term accumulated investment probability. Nevertheless, as the deadline moves farther away, the long-term effect becomes smaller. As we increase the deadline ever farther, the investment probability of a Norwegian investor will eventually approach the probability of the one of the Swedish investor. This analysis has direct implications for policy makers. On the one hand, in order to achieve a more significant short-term effect, the policy makers should set an early deadline. On the other hand, if the goal is to boost the investment activity in the long run, the deadline should be set for the medium term. In our example, the best long-term effect is achieved by setting a deadline to 2022.

We now conduct a sensitivity analysis for both the Norwegian and Swedish projects. Figure 12 illustrates the difference between the option values, $F_S(E_t, S_t, t) - F_N(E_t, S_t, t)$, as a function of electricity and green certificate prices, E_0 and S_0, when $t = T_0$.

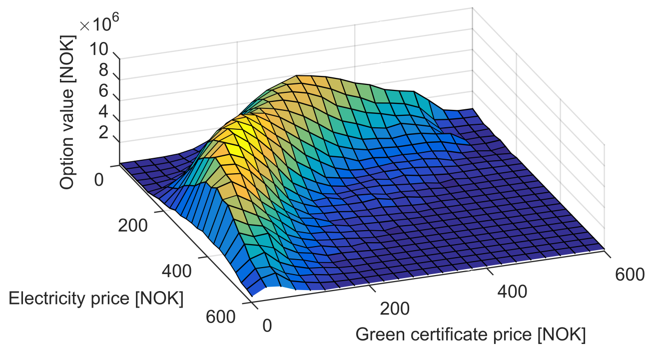


Figure 12: Difference in $F_S(E_t, S_t, t)$ and $F_N(E_t, S_t, t)$ as a function of E_0 and S_0, for the set of parameters, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%, t=T_0

When both prices are close to zero, the options are deep out-of-the-money. As a result, the options have a low value, and the difference between the investment opportunities is small. The option values are also similar when the green certificate price is close to zero, regardless of electricity price. This is because the regulatory differences have a limited effect on the option values when the revenues from certificates are low. When the prices of electricity and green certificates gradually increase from zero to the break-even prices, the values of the options increase, albeit at a higher rate for the Swedish investor. When the prices increase further toward the investment thresholds, the difference between the options decreases. The difference is zero for prices above the investment thresholds of both investors. This is because it is optimal to exercise the options immediately. The option values are thus equal to the intrinsic values.

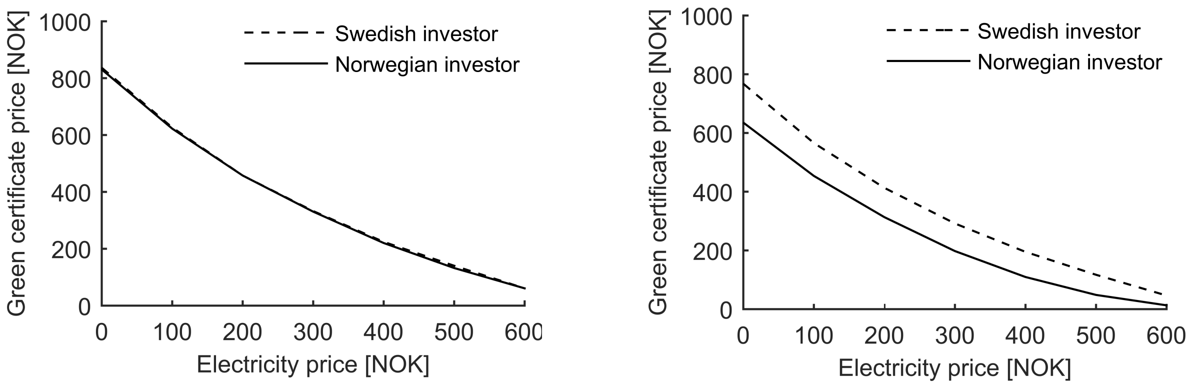
The Norwegian and Swedish investment opportunities are approximately equally sensitive to a change in the drift parameters. The option values are most sensitive to the drift of the electricity price. Decreasing the drift by one percentage point from the baseline case, decreases the option values by 28%. In contrast, decreasing the drift of the green certificate price by one percentage point from the baseline case decreases the option value by 6%. The option values are highly sensitive to both the drifts and the volatilities of the prices. Since both parameters are difficult to predict and investors might have different beliefs about the future drifts and/or volatilities, there will be large variations in their estimated option values.

In the following we summarize the main implications of the presented results for policy makers. When implementing new policies aimed at stimulating investment, policy makers need to correctly take the effect of price uncertainty and the flexibility to wait into account. Our analysis shows that these factors induce firms to postpone investment, which should be anticipated by policy makers. Furthermore, by imposing a deadline at which the right to receive certificates is lost, investments can be stimulated. On the one hand, the short-term effect of the deadline is more pronounced when it is set for the relatively near future. Such an investment deadline could therefore, serve as a policy instrument to boost the investment activity in short run. On the other hand, the long-term effect of the deadline is larger for medium term deadlines.

6.3 Possibility of a price collapse

This section analyses how the possibility of drops in the green certificate price influences the option values and investment behavior. The assumptions from the baseline case are used, where the arrival rate of jumps is assumed to be equal to $\Lambda = 0.156$. Thus, during a time step of $dt = 0.1$, the probability of a jump is 1.56 %. To put this in perspective, the probability of a jump during a year is equal to 15%. The jump magnitude is set to $\phi = 0.5$, which means the price will drop by 50 % in the case of a jump. This is consistent with a drop in prices which occurred from week 2-7 in 2017, see Figure 3. Considering this case, the option values of the Norwegian and Swedish investors are 119 MNOK and 123 MNOK, respectively. Thus, the possibility of jumps decreases the option values by 23 %, for both investors. This is a considerable decrease in the option values, and neglecting the possibility of a price collapse can therefore lead to an misleading valuation of the investment opportunities.

Figures 13a and 13b illustrate investment thresholds, E_t^* and S_t^*, when there is a possibility of a jump. The possibility of a jump causes the investment thresholds of both investors to increase, especially for low electricity prices. For example, at $t = T_0$ for a given electricity price of $E^* = 100$, the required green certificate price for investment, S^*, has increased by 14 NOK for both investors. The effect is, however, much larger at $t = T_{DN}$, where the threshold for the corresponding electricity price has increased by 232 NOK and 278 NOK for the Norwegian and Swedish investors, respectively. Therefore, the possibility of a jump causes the investors to wait longer before investing compared to the baseline case.



(a) $t = T_0$.

(b) $t = T_{DN}$

Figure 13: Investment threshold for the following set of parameter values: μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%, $\Lambda dt = 0.0156$, $\phi = 0.5$.

Figure 14 illustrates how the option values of both investors change as a function of the jump magnitude.

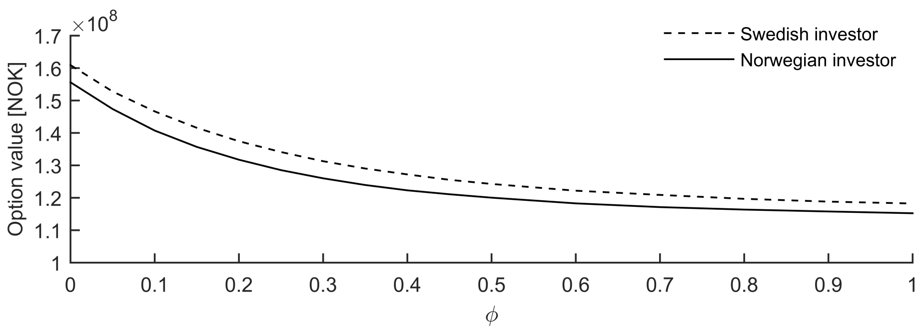


Figure 14: $F_N(E_0, S_0, t)$ and $F_S(E_0, S_0, t)$ as a function of jump magnitude, ϕ, for the set of parameters, E_0 = 250 NOK/MWh, S_0 = 138 NOK/MWh, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%, $\Lambda dt = 0.0156$.

The option values of both investors decrease with ϕ. This is expected, since when ϕ is higher, the expected future green certificate price is lower. When the jump magnitude is low, the sensitivities of the option values are relatively high, however, the sensitivities decrease with ϕ. The Norwegian investor is slightly more affected by the introduction of price jumps for low values of ϕ. However, for larger jumps, the Swedish investor is more affected. Therefore, the difference between the investors increases for low jump magnitudes, and decreases when the jump magnitude is high.

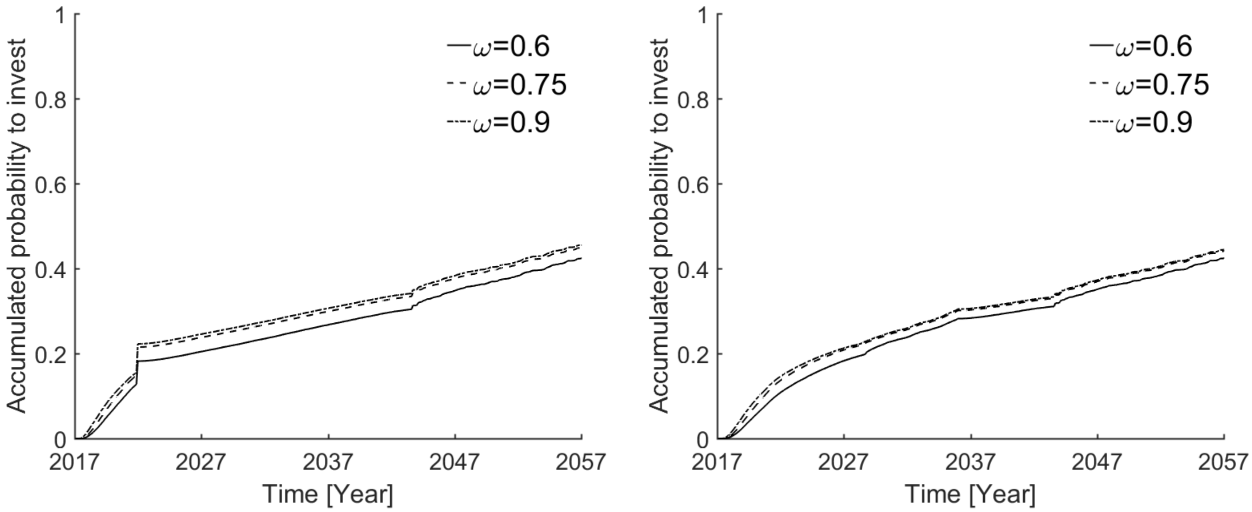
Similarly to the jump magnitude, increasing the jump intensity lowers the expected future green certificate price, and therefore, the option values decrease. This is because the expected revenues from green certificates decrease for both investors. Intuitively, when the green certificate price is low, the impact of the regulatory differences decreases.

6.3.1 Possibility to learn about a price collapse

The possibility to learn about the probability of a price drop is now included by letting the investors receive signals from the government and other institutions. The probability of a price drop is either low or high, based on e.g. surplus of certificates. The low probability is set to 1% during the year, while the high probability is set to 25% during a year.Thus, with a time step of $dt = 0.1$, the jump intensities are $\Lambda_L = 0.01$ and $\Lambda_H = 0.284$, for the low and high probability cases, respectively. Similarly to the previous section, the drop magnitude is set to $\phi = 0.5$, in both cases. The investor has an initial belief when $t = T_0$, about the likelihood of being in a good state with a low probability of a price drop. The initial probability is set to $P_0 = 0.3$. By receiving signals indicating the likelihood of a jump, the investors update this probability. The reliability of a signal, i.e. the likelihood of a signal reflecting the true state of the world, is set to $\omega = 75\%$. The signals are received at discrete times following a Poisson process. The signal intensity is set to Λ_S=2.06, such that the probability of a signal each time-step equals to 0.21%, for $dt = 0.1$. To put this in perspective, the investors have a 90% probability of receiving at least one signal during a year.

If there are no signals, and consequently no learning, the values of the investment opportunities reflect the initial beliefs of the investors, and are 119 MNOK and 123 MNOK for the Norwegian and Swedish investors, respectively. If the possibility to learn is included, the value of the investment opportunities increase to 123 MNOK and 126 MNOK. Thus, the possibility to learn increases the option values by 4 MNOK and 3 MNOK. For the Norwegian investor, the possibility to learn is slightly more beneficial compared to the Swedish investor. In the case of no learning, the probabilities of investing before T_{DN} are 9.5% and 16.5% for the Norwegian and Swedish investors, respectively. These are significantly lower, than in the case without a potential price jump (as evident from Figure 11). When the investors have the possibility to learn, the probabilities of investing before the deadline increase to 14% and 22%.

Figure 15 presents the investment probabilities when the firms can learn about the probability of a price drop in green certificates for different values of signal reliability.



(a) Norwegian investor

(b) Swedish investor

Figure 15: The accumulated probability of investment as a function of time for different values of learning reliability for the set of parameters, $E_0 = 250$ NOK/MWh, $S_0 = 138$ NOK/MWh, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=5.1%, $\Lambda dt = 0.0156$.

As is evident from Figures 15a and 15b, the possibility of a price drop reduces the probability of investment for both countries. The learning reliability slightly increases the investment probabilities, but as signals become more reliable, this effect becomes less pronounced.

To conclude, policy makers should take into account the effect of a potential price drop on investment activity. In particular, that the possibility of a price collapse leads to a decrease in the investment probability. However, we find that this effect can be mitigated by improving transparency in the market, as this increases the confidence of investors in being able to foresee a potential price collapse.

7 Conclusions

This paper develops a real options model to evaluate investments in renewable energy in Norway and Sweden, focusing on how regulatory differences in the green certificate market impact investors. Insights gained from our study are valuable to private investors as they support the decision making in the renewable sector, as well as to official bodies as they can aid in future policy decisions.

A case study of a wind power project is introduced to analyze the investment opportunities from the perspectives of both a Norwegian and Swedish investor. Norwegian investors must invest before an upcoming deadline for projects to be eligible to receive certificates. Swedish investors do not have such a deadline, but certificates are received for a shorter duration for later investments. After the end of the policy scheme, both investors have an equivalent perpetual investment opportunity. The investment opportunities are modeled using a time-dependent real options model, where the electricity and green certificate prices are uncertain. The model also accounts for a finite project lifetime, learning effects in the investment costs and correlation between the prices. In an extension to the model, the possibility of a collapse in the prices is incorporated, and investors are allowed to learn about the likelihood of a price drop by observing the market and policy announcements.

Initially, the effect of an investment deadline to receive green certificates is assessed. Having a deadline lowers the option values and investment thresholds of the investors, where the effect is larger for shorter deadlines. The option values are sensitive to both short and long deadlines, in contrast to the investment thresholds, which are mainly sensitive to deadlines of less than one year. Therefore, a deadline of 5 years, similar to the Norwegian deadline, has a large impact on the option values, but a low impact on the investment thresholds.

Regulatory differences make the Swedish investment opportunity more valuable than the Norwegian. The difference in option values are initially relatively low. However, this difference increases as the Norwegian deadline is approached, to a maximum of 22%. The same effect is evident when considering the investment thresholds. At the initial time, the Norwegian deadline has a low effect on investment behavior, and both investors will invest at approximately the same price levels. An interesting finding is that the deadline is not what mainly affects the thresholds, but rather the declining duration of certificates for later investments. This causes a significant reduction in the investment thresholds of both investors, and, therefore, provides a strong inventive to invest.

Just before the Norwegian deadline, the difference between the investors increases, and the Norwegian investor will invest for a larger range of prices than the Swedish investor. More specifically, investment is optimal for a green certificate price which is approximately 100 NOK lower than the Swedish investor. Given the current price levels, it is not optimal to invest before the Norwegian deadline for either of the investors.

The Swedish investor is more affected by the uncertainty in green certificate prices, as it can receive certificates if investing after the Norwegian deadline. This also explains the observed effect when increasing the correlation between the prices. The option value of the Swedish investor will increase at a higher rate than the Norwegian investor, as the Swedish investor benefits more from the additional uncertainty. The option values are also highly sensitive to the discount rate, which affects the option values of the investors similarly.

Introducing the possibility of a collapse in the green certificate price has a large impact on the investment opportunities, and reduces the option values by 23% for both investors. The possibility of a collapse in the green certificate price increases the investment thresholds for both investors considerably, and the investors are thus less likely to invest. The possibility to learn about the likelihood of a price collapse increases the probability of early investments for both investors.

Our findings bear important implications for policy makers. In particular, our model shows that firms' behavior is strongly affected by market uncertainty and by their possibility to flexibly time investment. Therefore, failing to take into account these effects when making policy decisions could jeopardize the intended effect of a policy scheme. Furthermore, we find that a deadline-type policy can stimulate the investment activity in two different ways. On the one hand, if set for a relatively near future, the deadline induces more investment activity in the short-run. On the other hand, if set for the intermediate term, the deadline maximizes the long-run effect of the policy. We also find that increased market transparency may partially mitigate the negative effect of the possibility of the certificates' price drop on the investment probabilities.

In what follows we point out several possibilities to future research. An interesting extension of our model is to explicitly take into account the decisions about the quota curve in the modeling of the price process for green certificates. Another possible direction for further research is to take a macroeconomic perspective, and focus on how regulatory differences affect the total capacity of renewable energy in both countries. In addition, it is interesting to consider how different project characteristics influence the results.

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A The intrinsic value of the project

A.1 Norwegian investor

The instantaneous profit function of the Norwegian investor can be expressed by,

$$\pi_N(S_t, E_t, t) = \begin{cases} (E_t + S_t - C_v)q - C_F \\ (E_t - C_v)q - C_F \end{cases}, \tag{16}$$

where the upper yields for $\{t \leq T_E \ \wedge \ \tau \leq T_{DN} \ \wedge \ t \leq \tau + T_S\}$ and the lower for $\{t > T_E \ \vee \ \tau > T_{DN} \ \vee \ t > \tau + T_S\}$. The Norwegian investor has two regions where he can invest, either before or after the deadline, T_{DN}. If investing in the period $t \leq T_E - T_S$, the investor receives certificates for a duration of T_S years. However, if investing in the period $T_E - T_S < t \leq T_{DN}$, the investor will receive certificates for a reduced duration of $(T_E - \tau)$ years. Thus, investments in the region before the deadline yield certificates for a duration of $min(T_S, T_E - \tau)$ years. The intrinsic value of the investment is the net present value of the profit stream through the lifetime of the project, and we get the following equation,

$$\begin{aligned} V_N(S_t, E_t, t) &= \mathbf{E}\left[\int_{\tau}^{\tau+T_L} \pi(S_t, E_t, t) e^{-\rho(t-\tau)} \, dt \right], \\ &= \mathbf{E}\left[\int_{\tau}^{min(\tau+T_S, T_E)} ((E_t + S_t - C_V)q - C_F) e^{-\rho(t-\tau)} \, dt + \right. \\ &\quad \left. \int_{min(\tau+T_S, T_E)}^{\tau+T_L} ((E_t - C_V)q - C_F) e^{-\rho(t-\tau)} \, dt \right]. \end{aligned} \tag{17}$$

By combining equation (45) and (17), we get the following equation,

$$\begin{aligned}
&V_N(S_t, E_t, \tau) = \\
&= \int_{\tau}^{min(\tau+T_S,T_E)} ((E_\tau e^{\mu_E(t-\tau)} + S_\tau e^{\mu_S(t-\tau)} - C_V)q - C_F) \\
&\cdot e^{-\rho(t-\tau)} dt + \int_{min(\tau+T_S,T_E)}^{\tau+T_L} ((E_\tau e^{\mu_E(t-\tau)} - C_V)q - C_F) \\
&\cdot e^{-\rho(t-\tau)}\ dt = \int_{\tau}^{min(\tau+T_S,T_E)} ((qS_\tau e^{\mu_S(t-\tau)} e^{-\rho(t-\tau)}\ dt \\
&+ \int_{\tau}^{\tau+T_L} ((E_\tau e^{\mu_E(t-\tau)} - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt \\
&= \int_{\tau}^{min(\tau+T_S,T_E)} ((qS_\tau e^{(\mu_S-\rho)(t-\tau)}\ dt \\
&+ \int_{\tau}^{\tau+T_L} (qE_\tau e^{(\mu_E-\rho)(t-\tau)}\ dt - \int_{\tau}^{\tau+T_L} (qC_V + C_F)e^{-\rho(t-\tau)}\ dt \\
&= \tfrac{qS_\tau}{\mu_S-\rho}(e^{min(T_E-\tau,T_S)(\mu_S-\rho)} - 1)+ \\
&\tfrac{qE_\tau}{\mu_E-\rho}(e^{(\mu_E-\rho)T_L} - 1) - \tfrac{qC_V+C_F}{-\rho}(e^{-\rho T_L} - 1).
\end{aligned} \tag{18}$$

By rearranging, the intrinsic value of the project can be expressed by,

$$V_N(S_t, E_t, \tau) = q(r_S(\tau)S_\tau + r_E E_\tau) - C, \tag{19}$$

where $r_S(\tau) = \frac{1}{\rho-\mu_S}(1 - e^{min\{T_E-\tau,T_S\}(\mu_S-\rho)})$, $r_E = \frac{1}{\rho-\mu_E}(1 - e^{(\mu_E-\rho)T_L})$, $C = \frac{qC_V+C_F}{\rho}(1 - e^{-\rho T_L})$.

If investing after the deadline, $\tau > T_D$, the intrinsic value is given by,

$$\begin{aligned}
&V_N(S_t, E_t) = \mathbf{E}\left[\int_{\tau}^{\tau+T_L} \pi(S_t, E_t)e^{-\rho(t-\tau)}\ dt\right] \\
&= \mathbf{E}\left[\int_{\tau}^{\tau+T_L} ((E_t - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt\right] \\
&= \int_{\tau}^{\tau+T_L} ((E_\tau e^{\mu_E(t-\tau)} - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt \\
&= \int_{\tau}^{\tau+T_L} (qE_\tau e^{(\mu_E-\rho)(t-\tau)}\ dt - \int_{\tau}^{\tau+T_L} (qC_V + C_F)e^{-\rho(t-\tau)}\ dt \\
&= \tfrac{qE_\tau}{\mu_E-\rho}(e^{(\mu_E-\rho)T_L} - 1) - \tfrac{qC_V+C_F}{-\rho}(e^{-\rho T_L} - 1).
\end{aligned} \tag{20}$$

By rearranging, the intrinsic value of the project can be expressed by

$$V_N(S_t, E_t) = q(r_E E_\tau) - C, \tag{21}$$

where $r_E = \frac{1}{\rho-\mu_E}(1 - e^{(\mu_E-\rho)T_L})$, $C = \frac{qC_V+C_F}{\rho}(1 - e^{-\rho T_L})$.
We then get the following intrinsic value for the Norwegian investor,

$$V_N(S_t, E_t, \tau) = \begin{cases} q(r_S(\tau)S_\tau + r_E E_\tau) - C & \tau \leq T_{DN}, \\ q(r_E E_\tau) - C & \tau > T_{DN}, \end{cases} \tag{22}$$

where $r_S(\tau) = \frac{1}{\rho-\mu_S}(1 - e^{min\{T_E-\tau,T_S\}(\mu_S-\rho)})$, $r_E = \frac{1}{\rho-\mu_E}(1 - e^{(\mu_E-\rho)T_L})$, $C = \frac{qC_V+C_F}{\rho}(1 - e^{-\rho T_L})$.

A.2 Swedish investor

The instantaneous profit function for the Swedish investor is given by

$$\pi_S(S_t, E_t, t) = \begin{cases} (E_t + S_t - C_v)q - C_F \\ (E_t - C_v)q - C_F, \end{cases} \tag{23}$$

where the upper yields for $\{t \leq T_E \quad \wedge \quad t \leq \tau + T_S\}$ and the lower for $\{t > T_E \quad \vee \quad t > \tau + T_S\}$. The Swedish investor has two regions where he can invest, either before or after the end of the policy scheme, T_E. If investing in the period $t \leq T_E$, the Swedish investor will receive certificates for a duration of $min(T_S, T_E - \tau)$ years. In the region $t \leq T_E$, we get the following intrinsic value,

$$\begin{aligned} V(S_t, E_t, t) &= \mathbf{E}\Bigg[\int_{\tau}^{\tau+T_L} \pi(S_t, E_t, t)e^{-\rho(t-\tau)}\ dt\Bigg], \\ &= \mathbf{E}\Bigg[\int_{\tau}^{min(\tau+T_S, T_E)} ((E_t + S_t - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt + \\ &\int_{min(\tau+T_S, T_E)}^{\tau+T_L} ((E_t - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt\Bigg]. \end{aligned} \tag{24}$$

This value function is equal to the Norwegian value function in the period $t \leq T_{DN}$, see equation (18), and can, thus, be expressed by

$$V_S(S_t, E_t, \tau) = q(r_S(\tau)S_\tau + r_E E_\tau) - C, \tag{25}$$

where $r_S(\tau) = \frac{1}{\rho - \mu_S}(1 - e^{min\{T_E - \tau, T_S\}(\mu_S - \rho)})$, $r_E = \frac{1}{\rho - \mu_E}(1 - e^{(\mu_E - \rho)T_L})$, $C = \frac{qC_V + C_F}{\rho}(1 - e^{-\rho T_L})$.

If investing after the end of the policy scheme, $\tau > T_E$, the intrinsic value is equal to the Norwegian value function in the period $t > T_{DN}$, see equation (20), and can, thus, be expressed by

$$V(S_t, E_t) = q(r_E E_\tau) - C, \tag{26}$$

where $r_E = \frac{1}{\rho - \mu_E}(1 - e^{(\mu_E - \rho)T_L})$, $C = \frac{qC_V + C_F}{\rho}(1 - e^{-\rho T_L})$.
We then get the following intrinsic value for the Swedish investor,

$$V_S(S_t, E_t, \tau) = \begin{cases} q(r_S(\tau)S_\tau + r_E E_\tau) - C & \tau \leq T_E, \\ q(r_E E_\tau) - C & \tau > T_E, \end{cases} \tag{27}$$

where $r_S(\tau) = \frac{1}{\rho - \mu_S}(1 - e^{min\{T_E - \tau, T_S\}(\mu_S - \rho)})$, $r_E = \frac{1}{\rho - \mu_E}(1 - e^{(\mu_E - \rho)T_L})$, $C = \frac{qC_V + C_F}{\rho}(1 - e^{-\rho T_L})$.

B Numerical solution of the baseline model

B.1 Price paths

Following the approach by Brandimarte (2014), we transform geometric Brownian motions into discrete price paths. To discretize the price paths, we combine equation (1) and Ito's lemma, given by

$$dF = \frac{\partial F}{\partial S}dS + \frac{1}{2}\frac{\partial^2 F}{\partial S^2}(dS)^2 + \frac{\partial F}{\partial t}dt, \tag{28}$$

which gives

$$dF = \left(\frac{1}{2}\sigma_S^2 S^2 \frac{\partial^2 F}{\partial S^2} + \mu_S S \frac{\partial F}{\partial S} + \frac{\partial F}{\partial t}\right)dt + \sigma_S S \frac{\partial F}{\partial S} dW. \tag{29}$$

We set $F(S,t) = log(S,t)$, and derive the following partial differentials,

$$\frac{\partial F}{\partial S} = \frac{1}{S}, \qquad \frac{\partial^2 F}{\partial S^2} = -\frac{1}{S^2}, \qquad \frac{\partial F}{\partial t} = 0. \tag{30}$$

Combining equation (30) with equation (29), we get

$$dF = \left(-\frac{1}{2}\sigma_S^2 + \mu_S\right)dt + \sigma_S dW. \tag{31}$$

Integrating this equation gives

$$logS(t) = logS(0) + \left(-\frac{1}{2}\sigma_S^2 + \mu_S\right)t + \sigma_S W(t). \tag{32}$$

Expressing $W(t)$ as $\epsilon\sqrt{t}$, where ϵ is a standard normally distributed random variable. We solve for S(t), and get

$$S(t) = S(0)exp\big[(-\frac{1}{2}\sigma_S^2 + \mu_S)t + \sigma_S\epsilon\sqrt{t}\Big]. \tag{33}$$

Considering the discrete case, we estimate the price after a small interval Δt by

$$S_{t+\Delta t} = S_t \cdot exp\Big[(-\frac{1}{2}\sigma_S^2 + \mu_S)\Delta t + \sigma_S\epsilon\sqrt{\Delta t}\Big]. \tag{34}$$

To simulate correlated returns between two geometric Brownian motions, $dW_1 dW_2 = \rho dt$, we let ϵ_2 depend on the realized values of ϵ_1. Let $Z_1, Z_2 \sim N(0,1)$, then, $\epsilon_1 = Z_1$ and $\epsilon_2 = \rho Z_1 + \sqrt{1-\rho^2}Z_2$ (Brandimarte, 2014).

B.2 Monte-Carlo algorithm

To calculate the value of the option using Monte Carlo simulation, the investment problem must be reduced to a finite number of sub-problems. This is achieved using the Bellman equation,

$$F(S,E,t) = max\Big\{V(S,E,t) - I(t), \\ \tfrac{1}{1+\rho dt}\mathbf{E}[dF(S+dS, E+dE, t+dt)|S,E,t]\Big\}, \tag{35}$$

which states that the value of the option is the maximum of the immediate exercise value and the expected value if delaying the investment. To be able to solve the problem numerically, time is discretized in N_{time} steps. The time between each step is $\Delta t = \frac{T_D}{N_{time}}$, such that $t = 0, \Delta t, 2\Delta t, ..., T_D$, where T_D denotes the time at the end of the simulation. Price paths for a large number of scenarios, denoted i, are simulated, where $i = 1, ..., N_{Paths}$. For each scenario, there is a path for both the green certificate price, denoted S_{ti}, and the electricity price, denoted E_{ti}. To simulate the price paths, equation (1) and (2) must be discretized. To avoid discretization errors when simulating the price paths, Ito's Lemma is used to transform these equations, which gives

$$S_{(t+\Delta t)i} = S_{ti} e^{(\mu_S - \frac{1}{2}\sigma_S^2)\Delta t + \epsilon_1 \sigma_S \sqrt{\Delta t}}, \tag{36}$$

$$E_{(t+\Delta t)i} = E_{ti} e^{(\mu_E - \frac{1}{2}\sigma_E^2)\Delta t + \epsilon_2 \sigma_E \sqrt{\Delta t}}, \tag{37}$$

where $\epsilon_1 \sim N(0,1)$ and $\epsilon_2 \sim \rho\epsilon_1 + \sqrt{1-\rho^2}N(0,1)$ (Brandimarte (2014)). At the investment deadline, there is no value of delaying the investment. Hence, the value of the option is the net present value of the investment opportunity,

$$F_i(S_{T_D i}, E_{T_D i}, T_D) = max\{0, V_c(S_{T_D i}, E_{T_D i}, T_D) - I_{T_D}\}, \tag{38}$$

where V_c represents V_N and V_S for the Norwegian and Swedish case, respectively.

Following the least-squares Monte Carlo approach by Longstaff and Schwartz (2001), we estimate the value of the option by iteration from the investment deadline to the first time step. At each time step, the investors will decide to either exercise the option or wait. The optimal strategy is to exercise the option if the immediate expected payoff from exercising the option, is larger than the expected future payoff if delaying the investment (Huynh et al. (2011)). The immediate expected payoff is the profit from exercising the option, i.e. $V_c(S_{ti}, E_{ti}, t) - I_t$. The continuation value is calculated using least squares regression, where it is assumed that the value of the option can be expressed as a linear combination of a set of basis functions, denoted by $\phi_b(S_t, E_t, t)$, where $b = 1, ..., B$ is the number of basis functions. Further, let α_{bt} denote the regression coefficients, then, the value of waiting can be expressed by

$$F(S_t, E_t, t) = \sum_{b=1}^{B} \alpha_{bt} \phi_b(S_{ti}, E_{ti}, t). \tag{39}$$

For each time step, the regression coefficients are calculated based on the future expected cash flows, denoted CF_i, where the option is exercised at $t = \tau_i$. Thus, for a given time step, the present value of the cash flows for a given scenario can be calculated by

$$Y_{ti} = CF_i e^{-\rho(\tau_i - t)dt}. \tag{40}$$

Only paths where the option is in the money are used in the regression, as this increases the efficiency of the approach, and decreases the computations needed (Longstaff and Schwartz (2001)). Let the in-the-money paths be denoted by M_t. Then, for a given t, the regression coefficients can be represented by

$$\begin{aligned} &min \quad \textstyle\sum_i e_{ti}^2, \\ &s.t. \quad Y_{ti} = \textstyle\sum_{b=1}^{B} \alpha_{bt}\phi_b(S_t, E_t, t) + e_{ti}, \qquad rall\ i \in M_t, \end{aligned} \tag{41}$$

where e_{ti} is the residual for path i at time t (Brandimarte (2014)). At each step, if it is optimal to exercise the option for a scenario, the exercise time, τ_i and the cash flows, CF_i, for that scenario are updated. At $t = 0$, the continuation value is calculated by taking the average of the discounted cash flows for all scenarios. The value of the option at $t = 0$ is, therefore,

$$F(S_0, E_0, 0) = max\left\{0, V_c(S_0, E_0, 0) - I_0, \frac{\sum_{i=1}^{N_P} Y_{ti}}{N_P}\right\}. \tag{42}$$

The computational time and results of the Monte Carlo simulation are highly dependent on the model parameters, specifically the number of simulated paths, i, the number of time steps, N_{time}, and the basis functions, ϕ_b. These parameters must, therefore, be carefully calibrated.

As a reference in the calibration we use the semi-analytical solution derived below.

In what follows, we calibrate the parameters of the Monte Carlo simulation, by comparing it to the semi-analytical solution.

B.3 Semi-analytical solution

The profit stream of the project is given by,

$$\pi(S_t, E_t) = \begin{cases} (E_t + S_t - C_V)q - C_F & t \leq \tau + T_S, \\ (E_t - C_V)q - C_F & t > \tau + T_S. \end{cases} \tag{43}$$

The value of the project is the net present value of the profit stream through the lifetime of the project,

$$\begin{aligned} V(S_t, E_t) &= \mathbf{E}\left[\int_{\tau}^{\tau+T_L} \pi(S_t, E_t) e^{-\rho(t-\tau)}\ dt \right], \\ &= \mathbf{E}\left[\int_{\tau}^{\tau+T_S} ((E_t + S_t - C_V)q - C_F) e^{-\rho(t-\tau)}\ dt + \right. \\ &\quad \left. \int_{\tau+T_S}^{\tau+T_L} ((E_t - C_V)q - C_F) e^{-\rho(t-\tau)}\ dt \right]. \end{aligned} \tag{44}$$

The expected values of the stochastic variables, S_t and E_t, which follow geometric Brownian motions, are given by

$$\mathbf{E}[S(t)] = S_\tau e^{\mu_S(t-\tau)}, \quad \mathbf{E}[E(t)] = E_\tau e^{\mu_E(t-\tau)}, \tag{45}$$

where τ is the time of investment (Dixit and Pindyck, 1994). By combining equation (44) and (45), we obtain

$$\begin{aligned}
V(S_t,E_t) = & \int_{\tau}^{\tau+T_S}((E_\tau e^{\mu_E(t-\tau)} + S_\tau e^{\mu_S(t-\tau)} - C_V)q - C_F) \\
&\cdot e^{-\rho(t-\tau)}\ dt + \int_{\tau+T_S}^{\tau+T_L}((E_\tau e^{\mu_E(t-\tau)} - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt \\
&= \int_{\tau}^{\tau+T_S}((qS_\tau e^{\mu_S(t-\tau)}e^{-\rho(t-\tau)}\ dt + \\
&\int_{\tau}^{\tau+T_L}((E_\tau e^{\mu_E(t-\tau)} - C_V)q - C_F)e^{-\rho(t-\tau)}\ dt = \\
&= \int_{\tau}^{\tau+T_S}((qS_\tau e^{(\mu_S-\rho)(t-\tau)}\ dt + \int_{\tau}^{\tau+T_L}(qE_\tau e^{(\mu_E-\rho)(t-\tau)}\ dt \\
&\quad - \int_{\tau}^{\tau+T_L}(qC_V + C_F)e^{-\rho(t-\tau)}\ dt \\
&= \tfrac{qS_\tau}{\mu_S-\rho}(e^{(\mu_S-\rho)T_S} - 1) + \tfrac{qE_\tau}{\mu_E-\rho}(e^{(\mu_E-\rho)T_L} - 1) \\
&- \tfrac{qC_V+C_F}{-\rho}(e^{-\rho T_L} - 1).
\end{aligned} \tag{46}$$

By rearranging, the intrinsic value of the project can be expressed by

$$V(S_t,E_t) = q(r_S S_\tau + r_E E_\tau) - C, \tag{47}$$

where $r_S = \frac{1}{\rho-\mu_S}(1 - e^{(\mu_S-\rho)T_S})$, $r_E = \frac{1}{\rho-\mu_E}(1 - e^{(\mu_E-\rho)T_L})$, $C = \frac{qC_V+C_F}{\rho}(1 - e^{-\rho T_L})$. The constants r_S and r_E represent the discount factors for green certificate and electricity prices, respectively.

We model the investment decision using the dynamic programming approach. This breaks the investment problem into two sub-problems, the immediate decision, and the consequences of all future decisions (Dixit and Pindyck (1994)). This is expressed using the Bellman equation, where the value of the investment option at any time is given by

$$\rho F(S,E) = \pi + \frac{1}{dt}\mathbf{E}[dF(S,E)]. \tag{48}$$

Using Ito's lemma to derive the value of $dF(S,E,t)$, provides the following partial differential equation,

$$\frac{1}{2}\sigma_S^2 S^2 \frac{\partial^2 F}{\partial S^2} + \frac{1}{2}\sigma_E^2 E^2 \frac{\partial^2 F}{\partial E^2} + \mu_S S \frac{\partial F}{\partial S} + \mu_E E \frac{\partial F}{\partial E} - \rho F = 0. \tag{49}$$

We follow the approach by Boomsma and Linnerud (2015), and assume the form $F(S,E) = AS^{\beta_S}E^{\beta_E}$. We then get the following fundamental quadratic,

$$Q(\beta_S,\beta_E) \ = \tfrac{1}{2}\bigg(\sigma_S^2\beta_S(\beta_S - 1) + \sigma_E^2\beta_E(\beta_E - 1)\bigg) \tag{50}$$

$$+\mu_S\sigma_S + \mu_e\sigma_E - \rho. \tag{51}$$

The boundary conditions are expressed by,

$$A(E^*)^{\beta_E}(S^*)^{\beta_S} = r_E E^* + r_S S^* - (I + C), \tag{52}$$

$$A\beta_E(E^*)^{\beta_E-1}(S^*)^{\beta_S} = r_E, \tag{53}$$

$$A\beta_S(E^*)^{\beta_E}(S^*)^{\beta_S-1} = r_S, \tag{54}$$

$$F(V(0,0)) = 0, \tag{55}$$

where equation (52) is the value matching condition, and equation (53) and (54) are the smooth pasting conditions. In addition, if both prices are zero, the option value is also zero, hence, we get the boundary condition in equation (55). By combining the boundary conditions in equation (52), (53) and (54), we obtain the following expressions for the investment threshold,

$$S^* = \frac{\beta_S}{\beta_E + \beta_S - 1}\frac{I + C}{r_S}, \tag{56}$$

$$E^* = \frac{\beta_E}{\beta_E + \beta_S - 1}\frac{I + C}{r_E}. \tag{57}$$

To find the threshold for the subsidy price, we must specify the electricity price, E.
Let

$$\eta(E) = \frac{I + C - r_E E}{r_E E}. \tag{58}$$

Then, β_E can be calculated from equation (50) and (57), which gives,

$$\beta_E = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \tag{59}$$

where,

$$a = \frac{1}{2}\Big(\sigma_E^2 + \sigma_S^2\eta^2(E)\Big),$$

$$b = \frac{1}{2}\Big(-\sigma_E^2 + \sigma_S^2\eta(E)\Big) + \mu_E + \mu_S\eta(E),$$

$$c = \mu_S - \rho.$$

This is used to calculate β_S using equation (57). Further, the threshold, S^*, is calculated using equation (56). The option value at the boundary can then be expressed by,

$$F(S^*, E^*) \quad = r_E E^* + r_S S^* - C - I = \tag{60}$$

$$= \left(\tfrac{\beta_E + \beta_S}{\beta_E + \beta_S - 1}\right)(I + C) - C - I \tag{61}$$

B.4 Calibration

Two parameters which have a large impact on the results and the computational time is the number of time steps and the number of simulated price paths. The number of time steps will increase the value of the option, since there are more possible exercise dates. Ideally, the investor should be able to exercise the option at any time, hence, more exercise dates will be a more realistic approximation, and therefore improve the accuracy of the simulation. Increasing the number of price paths reduces the random error of the simulation, and thus improves the accuracy and the precision of the results. Increasing these model parameters will, however, increase the computational time of the simulation, where we observed a close to linear relationship between the running time and the number of price paths or time steps. Therefore, the parameters must be optimized, such that the error of the results are minimized with an acceptable running time.

We calibrate the Monte Carlo simulation by approximating the investment threshold of the semi-analytical solution. We find that simulating a time period of $T_D = 50$ years, gives a good approximation of a perpetual option. Figure 16 illustrates the investment thresholds of two perpetual options, where one is solved using the semi-analytical approach, and one is approximated using the Monte Carlo simulation approach.

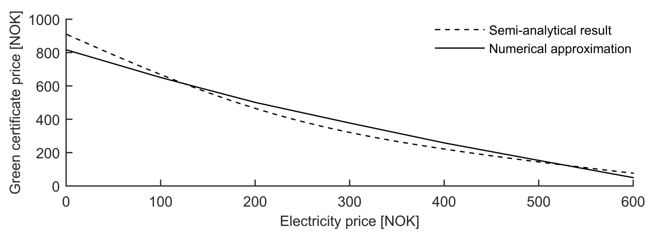

Figure 16: Investment threshold, S^* and E^*, for the set of parameters, μ_E =2.5%, μ_S=2.5 %, σ_E=15.5%, σ_S=16.3%, ρ_{SE}=0%, $\lambda_Y = 0\%$.

The thresholds are highly sensitive to the option values, and since the difference in the thresholds are relatively small, the Monte Carlo simulation provides a sufficient estimation of the option values. The thresholds have the same shape, with a non-linear relationship between the prices. This is a consequence of diversification effects. Since the prices are non-zero and not perfectly correlated, some of the individual risk is diversified in the project. The investment threshold of the semi-analytical solution is lower than the numerical approximation where both prices are high, as the diversification effect is larger for the semi-analytic solution. This is likely a result of the time dependency of the numerical approximation, where the prices will diverge by time, and hence the diversification will decrease by time. Where one of the prices are zero, there is no diversification effect, and it can be observed that the semi-analytical solution has a higher investment threshold than the numerical approximation. This is a consequence of the approximation having a limited number of investment opportunities and a finite-lifetime, which reduces the value of the option, and thus, the investment threshold.

We found that when calculating only one option value, 300,000 paths and 500 time steps provide a sufficient estimation of the option value for an acceptable running time. When performing a simulation where several option values are calculated, e.g. investment threshold and sensitivity analysis, the computational time is significantly longer. Therefore, 100,000 paths and 500 time steps are chosen for these simulations.

There are different types of polynomials that can be used in the regression, and as proposed by Longstaff and Schwartz (2001), we tested weighted Hermite polynomials and weighted Laguerre polynomials. In addition, we have tested simple power functions, e.g. x, x^2, x^3. The polynomials were tested by comparing the numerical results to the semi-analytical solution, where the criteria used were convergence speed, precision and accuracy. There were only minor differences using the various polynomials. This is consistent with the findings by Moreno and Navas (2003), who find that the least-squares method is quite robust to the choice of basis functions. However, we found the Laguerre polynomials to be slightly better across all criteria. We have, therefore, chosen to use the weighted Laguerre polynomials in the regression, which can be calculated by

$$L_n(x) = e^{-x/2}\frac{e^x}{n!}\frac{d^n}{dx^n}(x^n e^{-x}), \tag{62}$$

where the first Laguerre polynomials are

$$\begin{aligned} L_0 &= e^{-x/2}, \\ L_1 &= e^{-x/2}\ (-x+1), \\ L_2 &= e^{-x/2}\ \tfrac{1}{2}(x^2-4x+2), \\ L_3 &= e^{-x/2}\ \tfrac{1}{6}(-x^3+9x^2-18x+6). \end{aligned} \tag{63}$$

Based on the literature, intuition and testing, we found a combination of 33 basis functions, that provide a sufficient accuracy of the calculated option values. These basis functions consist of four expressions used as variables in the Laguerre polynomials up to the 8th degree, in addition to a constant. The chosen variables are the electricity price, E, the green certificate price, S, the sum of the prices weighted by the discount factors, $r_E E + r_S S$, and the product of the prices, $E \times S$. We found that increasing the degrees of polynomials further, did not make improvements to the results.

According to Longstaff and Schwartz (2001), the problem must be renormalized when using weighted Laguerre polynomials. This is because these polynomials can lead to computational issues, since there are exponential terms, e.g. if the price is 1500, $L_n(1500)$ would be rounded to 0 in Matlab. We therefore renormalized the problem by applying a scaling factor to the costs and the initial prices. The scaling is used when making all computations, and the final results are scaled back by the same factor. We got the best results when scaling the problem by the investment cost, which is consistent with Longstaff and Schwartz (2001). The least-squares Monte Carlo model was implemented in Matlab

Version 8.5.0.197613 (R2015a), and was run on a Intel(R) Core(TM) i7-4790S. The programming code is available upon request.

C Solution approach for model extensions

C.1 Possibility of green certificate price collapse

To generate paths for S_t, when there is a possibility of price jumps, we first generate prices. We then adjust for jumps by drawing random numbers, $n_{ti}i$, for each time-step, t, and price path, i, from a Poisson distribution with mean Λdt. $n_{ti}i$ then indicates the number of jumps for a price path and time-step. If a jump occurs, the prices after the jump are adjusted by the factor $(1-\phi)^{n_{ti}}$, where ϕ is the jump magnitude.

C.2 Possibility of green certificate price collapse with learning

When solving the Monte Carlo model with learning, there are two differences to the case where the price can collapse. The first is that price paths have a random jump intensity. The second is that the intrinsic value depend on an additional stochastic process, which represents the good signals in excess of the bad signals. The probability of a price path having a low jump intensity is represented by P_0. Let the jump intensity for the green certificate price in scenario i be denoted by Λ_i. Then, the jump intensities of the price paths are expressed by,

$$\Lambda_i = \begin{cases} \Lambda_L & \text{with probability } P_0, \\ \Lambda_H & \text{with probability } 1-P_0, \end{cases} \qquad \forall\ i \in N_{paths}. \tag{64}$$

In each scenario, signals are received at discrete times, following a Poisson process. The signals can either indicate a low or a high jump intensity. Let k_{ti} denote the number of signals indicating a low jump intensity in excess of signals indicating a high jump intensity, for scenario i at time t. Then the probability of path i having a low jump intensity at time t, is represented by

$$p_{ti}(k_{ti}) = \frac{P_0\lambda^{k_{ti}}}{P_0\lambda^{k_{ti}} + (1-P_0)(1-\lambda)^{k_{ti}}}. \tag{65}$$

Let $V_L(S_{ti}, E_{ti}, t)$ and $V_H(S_{ti}, E_{ti}, t)$ denote the payoff of a project with a low and high jump intensity, respectively. Then the intrinsic value of the project at the time of investment can be expressed by the conditional expected payoff,

$$V(S_{ti}, E_{ti}, t, k_{ti}) = p_{ti}(k_{ti})V_L(S_{ti}, E_{ti}, t) \tag{66}$$

$$+ \ (1-p_{ti}(k_{ti}))V_H(S_{ti}, E_{ti}, t). \tag{67}$$