

Renewable energy investments under different support schemes: A real options approach

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Abstract

This paper adopts a real options approach to analyze investment timing and capacity choice for renewable energy projects under different support schemes. The main purpose is to examine investment behavior under the most extensively employed support schemes, namely, feed-in tariffs and renewable energy certificate trading. We consider both multiple sources of uncertainty under each support scheme and uncertainty with respect to any change of support scheme, and we obtain both analytical (when possible) and numerical solutions. In a Nordic case study based on wind power, we find that the feed-in tariff encourages earlier investment. Comparing renewable certificates with the fixed feed-in tariff, the additional revenue required to trigger investment is 61%. Nevertheless, as investment has been undertaken, renewable energy certificate trading creates incentives for larger projects. Comparing renewable certificates with the fixed feed-in tariff, the capacity is higher by 61%.

Keywords: OR in energy, renewable energy, support schemes, investment under uncertainty, real options

1. Introduction

In order to reduce emissions, to guarantee security of energy supply, and to ensure adequacy of energy resources, many governments set policy targets for the exploitation of renewable energy. Favorable policy instruments to attract investors usually accompany such targets. Typically, investments in renewable energy are either encouraged indirectly through attempts to internalize external costs (of emissions, for example) or by direct renewable energy support schemes [18, 40, 41]. Of these, the most common support schemes are feed-in tariffs, as already implemented in 63 countries and states around the world and under serious consideration by several United States (US) states as a complement to existing energy policy. Yet other widely employed support schemes rely on renewable energy certificates and portfolio standards (as in the US) or tradable green certificates and quota obligations (as in the European Union (EU)), which have been implemented in 49 states and countries globally, including 29 US states. Despite of having already implemented a renewable energy support scheme, governments occasionally alter the choice of support scheme. This can result from a shift in the political environment, the tightening of national or international targets, or a change in technology. An example include the replacement of competitive tendering in the United Kingdom with the tradable certificate trading.

In this paper, we value investments in renewable electricity from the perspective of a private investor. The main purpose is to examine investment behavior under different support schemes, including the most extensively employed support schemes, namely, feed-in tariffs and renewable energy certificate trading. We investigate how the behavior of investors is affected by regulatory uncertainty by including the relevant sources of uncertainty under each support scheme. However, we also consider uncertainty with respect to any change of support scheme. Although we adopt the perspective of a private investor, the appraisal of renewable electricity investments is highly relevant to policymakers, and so the current analysis may also serve to provide recommendations for market design, including how to create appropriate investment incentives.

In the valuation, we account for the special characteristics of renewable energy sources such as wind power, solar power, and run-of-river hydropower. In contrast to conventional power generation, the intermittency of these power sources, notably wind power, renders generation largely uncontrollable and only partly predictable. Moreover, the value of a renewable energy project depends on a number of uncertain factors. Firstly, as such projects often involve higher upfront costs than its conventional energy counterparts, we consider stochastic capital costs. Secondly, another possibly relevant source of uncertainty is the price of electricity. Very importantly, however, the profitability of most renewable electricity investments strongly depends on public incentives, and this is our motivation for considering support scheme uncertainty. For simplicity, we will not account for any possible correlations between the uncertain factors, and as a result we may include uncertainty with respect to generation volumes through expected generation.

The value of a renewable energy project further depends on

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the flexibility of the investment. Here we consider the option to time an investment. Once a license is granted to develop and operate, the investor owns an exclusive right to carry out the project. The option therefore refers to the ability of the investor to postpone investment until the economic environment justifies further commitment of funds. The investor also has the flexibility to decide on the capacity of the project, either before or after applying for the license. Here we consider the ex post capacity choice. We assume that this decision depends on a balance between any economies of scale in capital costs and the property that production increases whereas marginal production decreases with increasing capacity.

The choice of support scheme implemented by the government and any alterations to this choice can have a considerable impact on both the timing of investments and the capacities of projects. The associated regulatory uncertainty creates incentives for investors to wait until the type of support scheme and the corresponding level of support is sufficiently attractive. This has been confirmed in a recent empirical study [20], where the authors investigate small hydropower plants and find that professional investors do actually apply a real options investment rule and that support scheme uncertainty does in fact delay investments.

In our valuation, we use a real options or contingent claims analysis [16]. With the right, but not the obligation, to undertake an irreversible investment at any time, real options analysis accounts for the value of waiting by comparing the immediate and expected ex post payoffs and exploiting the resemblance of deferrable real options with American call options [35, 25]. Although the cash flows are significantly more complex with the ex post capacity choice, as for American call options, investment timing and capacity choice can be valued by so-called risk-neutral valuation, given the absence of arbitrage opportunities in the market [42, 23, 24]. This implies the existence of an equivalent martingale measure, under which the rate of return of a priced asset is the risk-free rate or, equivalently, the discounted asset price is a martingale. In a sufficiently complete market, this equivalent martingale measure is unique. For wind power investors, however, market incompleteness may arise from generation volume risk and the lack of suitable hedging instruments, and from inconsistencies between the electricity spot price process and the dynamics of forward prices (i.e. the cost-and-carry relation does not apply). Furthermore, even when we disregard this, it arises from uncertainty with respect to any change of support scheme. One way to handle market incompleteness is to assume an exogenous discount rate, see for example [46]. Maintaining the resemblance to financial option pricing, another way is to obtain an equivalent martingale measure by pricing the risks. As an example, [1] estimates electricity spot prices from electricity load that cannot be hedged and therefore determines the market price of load risk by minimizing the difference between predicted and actual electricity futures prices. For any change in support scheme, we assume that the market price of risk is zero, or equivalently, that the equivalent martingale measure is the same as the true probability measure. For an overview of alternative approaches to handle market incompleteness, see [47].

We obtain analytical solutions to the investment valuation problems when possible, but at the same time solve these problems numerically. Despite multiple sources of uncertainty, we are able to solve analytically for investment values and project capacities, both when ineligible for renewable energy support and under each support scheme. By using a least squares Monte Carlo approach to solve the dynamic programming problems, we also find investment values and capacities numerically, and include a change of support scheme.

Real option analysis has already been used to value conventional power plants [49, 48]. Similar work with investments in renewable electricity includes [19], who analyze investment timing and a discrete capacity choice between a number of decentralized generation units, such as wind turbines. However, the approach applied there is only feasible for a very limited number of units, which is the reason that we consider a continuous capacity choice. This is also the approach taken in [6], who analyze the option to postpone investments in small hydropower projects and the flexibility to select capacity. We note that both of these studies value investments as contingent claims solely on the market price of electricity whereas we consider various sources of uncertainty, including regulatory uncertainty.

The real options approach to valuing energy investments under climate policy uncertainty can be found in [2, 51]. In both of these papers the uncertainty is represented by carbon price uncertainty, assuming that this price evolves stochastically over time according to a simple diffusion process and may exhibit jumps as a result of a change in policy. The authors find that the presence of such uncertainty creates a risk premium for electricity investments, which we also observe in our paper. As in these papers, we assume that regulatory uncertainty is captured by stochastic prices governed by diffusion processes. We likewise include occasional changes in policy. However, unlike previous papers, we assume that such changes do not only affect the level of prices but also the volatility and thereby the risk exposure for energy investors. Further studies of energy investments under climate policy uncertainty include [30, 43, 21]. It should be remarked though, that none of the above papers compare renewable energy investments under different support schemes.

The comparison of different renewable energy support schemes, in particular the feed-in tariff implemented in Germany and the certificate trading in the United Kingdom, has previously been studied by [36, 5, 29]. This paper could be seen as a quantification of these more qualitative results. [29] provides an overview of support schemes and the associated barriers to investment, with special emphasis on the risk exposure created by market participation. The authors find that the low risk environment that results from a feed-in tariff is more effective in stimulating renewable electricity investments than when facing high market risks under certificate trading. This is confirmed in our analysis. It is also backed up by [36] who consider market price risk, the risk of not being dispatched in the market and the risk of not being able to comply with the market commitments. For simplicity, however, we restrict our attention to price risk, and leave it as future research to include these other sources of risk exposure (This is the same approach as taken in [2, 51]). The effect of differences in risk exposure for

renewable energy investors is further investigated in [5]. It is argued that whereas site selection is the major concern with a feed-in tariff, under other support schemes, financing problems reduce the efforts to invest and license applications becomes a major obstacle. Moreover, the authors identify further barriers for investors, such as grid connection problems. In this paper, however, we confine ourselves to market risks, and show how that uncertainty about future cash flows is a serious barrier to investment.

We illustrate the valuation of renewable electricity investments in a Nordic case study based on wind power. There are several reasons for this. Among renewable energy sources, wind power is the most rapidly growing technology. In 2008, worldwide capacity reached 121 gigawatts (GW) with an annual growth rate of some 29%. Following these developments, global wind power investment was estimated at \$50 billion in 2008 [41, 50], where in addition to public investment incentives, typical sources of investment financing included bank loans, venture capital, and private equity funds. With some of the highest wind speeds in Europe, we restrict attention to the Nordic region, and Norway in particular. As of 2009, Nord Pool, the Nordic electricity exchange (Nord Pool is the electricity market for Norway, Sweden, Finland, Denmark, and Estonia), is Europe's largest and most liquid market for physical and financial power contracts with turnovers in spot and financial markets of 254 terawatt-hours (TWh) and 1,083 TWh, respectively [38], and, thus, an extensive collection of data is available. Furthermore, Norway originally planned to employ a feed-in tariff, but following extensive discussions, in 2010 the government instead decided to work on a tradable green certificate market in cooperation with Sweden, where such a market already exists (until now wind power has been supported by so-called contests for subsidies, in which wind power projects compete for investment support in tenders organized by the authorities).

From the Nordic case study, we derive the following results. When comparing the analytical solutions with the numerical approximations under identical assumptions, we obtain convergence. The analytical solutions easily facilitate sensitivity analysis, but whereas the analytical approach is based on assumptions standard in real options analysis, the numerical solutions also allow us to find the real options values with more realistic specification of costs and profits, project and option lifetimes, etc. Now, using both the analytical and numerical solutions, we compare the real options approach to the net present value approach and find significant values of waiting. Most importantly, we compare investment behavior under different support schemes. Irrespective of the approach chosen, the results show that the feed-in tariff encourages earlier investment. However, as investment has been undertaken, renewable energy certificate trading creates incentives for larger projects.

The paper is organized as follows. In Section 2, we discuss the economics of renewable electricity investments and the relevant uncertainties. We investigate the options of investment timing and capacity choice in Section 3. The most important renewable energy support schemes are analyzed in Section 4 while a change of support scheme is considered in Section 4.4.

In Section 5, we discuss the results from the Nordic case study. Finally, in Section 6, we provide the conclusion and some directions for further work.

2. The economics of renewable electricity investments

Most renewable energy projects are more capital intensive than conventional energy technologies. For example, capital costs of wind power projects typically account for 75% of total costs [18] (this lies contrary to the capital costs of a natural gas turbine that comprise 30–60% of total costs). These are dominated by the costs of the turbines, whereas other main cost components are associated with grid connection, foundations, and land rent.

Capital costs constitute an important source of uncertainty for a renewable energy investor. In contrast to electricity prices, the uncertainty in capital costs can be locked in by undertaking the investment, which has a crucial impact on the investment timing (Investment should be undertaken when capital costs are low and electricity prices are high. However, capital costs are paid at once, whereas profits are earned over a time horizon, during which electricity prices remain uncertain). We assume that the prices of raw materials drive this uncertainty (In reality, uncertainty may further include technical risk, i.e. exposure to loss in the construction process. Moreover, capital costs may also reflect microeconomic effects such as the supply and sub-supply surpluses and deficits of the raw materials). For wind power, several parts of the turbines and the foundations are often made of steel, making this the most important raw material. We therefore confine ourselves to steel spot prices and assume that such prices are determined in a competitive market.

The capacity choice of a renewable energy investor may be viewed as either discrete or continuous. For example, wind power turbines may be dimensioned by the manufacturers to a given climate class, also known as type-certification, which makes the capacity choice discrete. However, the complexity of a discrete capacity choice [15, 14] and, more importantly, the capacity of most renewable energy projects justifies a continuous approximation and allows us to proceed along the lines in [13].

Based on the above discussion, we assume that capital costs are a function of the capacity installed x and the price of raw materials, here the steel spot price, $S_1(t)$ at time t . We denote these by $I(S_1(t); x)$. When further specifications are necessary, we impose

Assumption 1 $I(S_1(t); x) = (A + Bx)S_1(t)$,

and assume that capital costs are proportional to the price. With this specification, capital costs display economies of scale.

The variable costs of renewable electricity generation are generally small, and comprise the costs of operation and maintenance. For wind power projects, these represent the remaining 25% of total costs and include the costs of repairs, spare parts, administration, and insurance. As customary in the literature, it is often convenient to assume that the variable costs are negligible.

With sale of renewable electricity production, a power purchasing agreement usually specifies the terms of delivery. Depending on the market design, the power purchasing agreement may be a fixed- or indexed-price over-the-counter contract with power purchasers, including retailers, industrial and institutional users, or the transmission system operator. Alternatively, it may simply allow for access to the electricity spot market, although in practice, participation is often facilitated by trading cooperatives, larger traders, or larger power producers (who may typically be the owners of the project). Here we assume production is sold on the spot market, so that the sales price is completely determined by the electricity spot price, and the project fully bears the spot price risk.

Despite electricity sales revenues, the profitability of many renewable electricity investments relies heavily on the renewable energy support schemes employed. For projects eligible for support, the revenues include subsidy payments, e.g. under renewable energy certificate trading revenues are partly determined by certificate prices. As indicated, such subsidy payments involve different degrees of risk exposure to the wind power investor under different support schemes.

Unlike conventional power production, renewable electricity generation is intermittent and hence largely uncontrollable, since the weather conditions directly determine production. This makes production only partly predictable at short time scales and highly variable at both short and medium time scales, such as hourly, daily, and seasonally. However, production is more predictable and less variable in the long-term, e.g. on yearly time scales, and so intermittency does not itself affect the investment timing apart through correlations with the electricity and certificate prices. Here we assume independence between production and price, and therefore without loss of generality, we use a constant expected yearly production for the investment analysis². We consider a production function that is increasing and concave in capacity. Concavity may arise when the larger the capacity, the harder it is to select a good site in terms of both weather conditions and grid connection. For wind power projects, production can be derived from wind speed using the power curve (a power curve describes the relationship between electricity production and wind speed) and by taking into account grid losses, turbine maintenance and failure, and wake effects. Wake effects result from turbulence caused by closely located wind turbines or complex terrain in some locations, and imply that marginal production decreases when capacity increases. Whereas grid losses are typically low and the availability of wind power is generally very high, wake effects can account for losses of 5–10%. Estimates of such effects are often derived from advanced simulation or optimization models. However, for illustration purposes, we simply assume a production function with the appropriate properties. For further references on the site selection for wind turbines, see for

example [37, 22].

With no variable production costs, the profit from electricity production depends only on the electricity price and subsidy payment (if any). We denote profit from total production by $\Pi(S_2(t), S_3(t); x)$, where x is the capacity installed, and $S_2(t)$ and $S_3(t)$, respectively, denote the yearly average electricity price and subsidy payment at time t . We assume that the project is sufficiently small not to affect long-term electricity and certificate prices. Thus, the producer is a price-taker, and profit is given by

Assumption 2 $\Pi(S_2(t), S_3(t); x) = Q(x)(S_2(t) + S_3(t))$.

In the above, $Q(x)$ denotes total annual production as a function of the capacity installed x , where this function is increasing and concave. When further assumptions are necessary, we specify the production function using

Assumption 3 $Q(x) = ax^b$ with $a > 0$ and $0 < b < 1$.

We will disregard any depreciation on renewable electricity investments. As for instance wind turbines are manufactured to withstand the vagaries of a given climate class for a number of years, we can assume limited physical depreciation within a known lifetime. Although depreciation may also apply for taxation purposes, many governments strive towards a neutral tax system in which investment decisions are the same with or without taxes.

2.1. Uncertainty

We wish to account for uncertainty in both capital costs, electricity prices and subsidy payments and value renewable electricity investments as contingent claims on the underlying assets.

We consider a market model based on a filtered probability space equipped with the true probability measure. As shown by [23] and [24], given the absence of arbitrage opportunities in the market, there exists an equivalent martingale measure which allows for risk-neutral valuation. In a sufficiently complete market, this measure is unique.

The valuation of contingent claims on raw materials, here steel, closely resembles the pricing of commodity contingent claims, considered by [44] and [45] for securities and [4] and [9] for real assets. Valuation by spot prices usually involves a so-called convenience yield that represents any excess return required for holding the spot commodity [3] and is comparable to a dividend payment.

In contrast, we value contingent claims on electricity along the lines in [10] and [7] and use forward and futures prices to estimate the spot price process. This has the following advantages. As electricity is nonstorable, we cannot value contingent claims on the spot commodity using no-arbitrage arguments that are based on holding the underlying asset. Nevertheless, it is possible to hold forward and futures contracts. Along the same lines, the notion of a convenience yield does not apply to electricity spot prices, and so the usual cost-and-carry relation breaks down. However, the convenience yield is not directly included in the dynamics of the forward and futures prices.

²By assuming a constant yearly production, we disregard any correlation between wind power production and the electricity price. One way to adjust for this is to multiply $Q(x)S_2$ by the constant $\int_0^H Q(h, x)S_2(h)dh / (Q(x)S_2)$, where $Q(h, x)$ denotes production at time h , $Q(x)$ is production during the year $[0, H]$, $S_2(h)$ is the price at time h , and S_2 is the average price over the year $[0, H]$.

Now, assuming a constant risk-free rate of return, we can handle forward and futures prices in the same way. We assume that contracts with all maturities are continuously traded in a frictionless market, and that at maturity, forward/futures price equals the spot price of the underlying asset. From [12], forward/futures prices are martingales under the equivalent martingale measure, which means that the drift is zero and it is sufficient to specify the volatility.

For subsidy payments, we assume that the uncertainty is spanned by one or more traded assets (such as, for example, renewable energy certificates). We further assume that there is a difference between the expected change in subsidy payments and the expected rate of return required by the holders of such certificates. As above, this difference is comparable to a dividend yield.

For simplicity, we will not account for any possible correlations between capital costs/steel spot prices, electricity forward/futures prices, and subsidy payments. The available data confirms that these processes can indeed be assumed independent on shorter time scales (using data from [32] and [38], all correlations are found to be below 0.02). Likewise, as already mentioned, we assume independence between prices and production volumes (Considering the Nordic region, this is most likely the case in Norway but does not apply to Denmark), and without loss of generality, we include uncertainty with respect to production volumes through expected volumes. On long time scales, however, correlations between prices, subsidies and production may be observed, as indicated by [27, 31].

In the market model, we assume that geometric Brownian motions govern capital costs/steel spot prices, electricity forward/futures prices and subsidy payments. Under the true probability measure, the processes are therefore

$$dS_i(t) = S_i(t)\mu_i^{\mathbb{P}}dt + S_i(t)\sigma_i dz_i^{\mathbb{P}}(t), i = 1, 3, \quad (1)$$

$$dF_2(t, T) = F_2(t, T)\mu_2^{\mathbb{P}}dt + F_2(t, T)\sigma_2 dz_2^{\mathbb{P}}, \quad (2)$$

where $S_1(t)$ and $S_3(t)$ respectively denote the steel spot price and the subsidy payment at time t and $F_2(t, T)$ denotes the price of electricity forward/futures contracts of maturity T at time t . Moreover, $\mu_i^{\mathbb{P}}, i = 1, 2, 3$ and $\sigma_i, i = 1, 2, 3$ are the corresponding drifts and volatilities and $dz_i^{\mathbb{P}}(t), i = 1, 2, 3$ are increments of independent standard Brownian motions.

For risk-neutral valuation, we let the market prices of risk $\theta_j, j = 1, 2, 3$ be defined by

$$\theta_i = \frac{\mu_i^{\mathbb{P}} + \delta_i - r}{\sigma_i}, i = 1, 3, \quad \theta_2 = \frac{\mu_2^{\mathbb{P}}}{\sigma_2},$$

where r is the risk-free rate of return and $\delta_i > 0, i = 1, 3$ denote the dividend yields. Moreover, when letting $dz_i^{\mathbb{Q}}(t) = dz_i^{\mathbb{P}}(t) + \theta_i dt, i = 1, 2, 3$, we obtain from (1)–(2)

$$dS_i(t) = S_i(t)(r - \delta_i)dt + S_i(t)\sigma_i dz_i^{\mathbb{Q}}(t), i = 1, 3, \quad (3)$$

$$dF_2(t, T) = F_2(t, T)\sigma_2 dz_2^{\mathbb{Q}}(t). \quad (4)$$

Finally, by defining the measure $\mathbb{Q}$ by $L = d\mathbb{P}/d\mathbb{Q}$ and

$$dL(t) = L(t) \sum_{i=1}^3 \theta_i dz_i^{\mathbb{P}}(t),$$

we have that $dz_i^{\mathbb{Q}}(t), i = 1, 2, 3$ are increments of independent standard Brownian motions under $\mathbb{Q}$. Hence, the risk-adjusted processes (3)–(4) remain independent geometric Brownian motions. Moreover, the rate of return is zero for electricity forward/futures prices and is given by the difference between the risk-free rate of return and any dividend payments for steel spot prices and subsidy payments. It should be clear that $\mathbb{Q}$ is the equivalent martingale measure of $\mathbb{P}$.

To estimate the electricity spot price process, we consider the forward/futures price process in (4). By the application of Ito's lemma to both forward/futures prices and spot prices, we obtain

$$dS_2(t) = S_2(t)\mu_2^{\mathbb{Q}}dt + S_2(t)\sigma_2 dz_2^{\mathbb{Q}}(t), \quad (5)$$

where the drift $\mu_2^{\mathbb{Q}} = \partial \ln F_2(0, t)/\partial t$ is assumed constant and less than the risk-free rate of return (see Appendix A).

For ease of exposition, we let $\mu_i^{\mathbb{Q}} = r - \delta_i, i = 1, 3$ for steel spot prices and subsidy payments.

3. Investment timing and capacity choice

When public authorities grant a licence to develop and operate a renewable energy project, and negotiations with the municipality, the transmission company and private landowners has finalized, the investor has an exclusive right to carry out the project. However, because of the comparatively short construction times for such projects (i.e. a number of months compared with a number of years for conventional power plants), the investor may defer this irreversible investment until the development in prices justifies commitment of funds. We value the ability to postpone investment as an option and thereby account for the value of waiting. Although the granting of the licence is for a fixed number of years, extension is often possible, and for now we assume the option to defer is perpetual.

In addition to this flexibility in investment timing, many wind power projects offer a choice of scale. With the possibility of an ex post capacity choice, the investor gains additional value by waiting since different scales may be optimal when prices evolve over time. We assume that once investment is undertaken, capacity is installed instantly. This lies contrary to the incremental capacity choice in [39] but is similar to that in [13]. For simplicity, we assume an unrestricted capacity choice, although in practice, geographical and capital restrictions may apply.

We value the option of investment timing and capacity choice, taking into account the uncertainties in both capital costs, electricity prices, and subsidy payments.

We first value the project given that investment has already been undertaken and capacity chosen. By assuming the project has infinite life (for example, for type-certified wind turbines, the intended lifetime is 20–25 years. However, if capital costs

are substantial, life extension can be profitable), its value is independent of time. Thus, we denote by $V(S_2, S_3; x)$ the value of having installed capacity x when electricity spot prices and subsidy payments are S_2, S_3 . Now, using risk-neutral valuation, the expected rate of return on the project equals the risk-free rate. The return is based on the appreciation in project value and the instantaneous profit incurred during dt , and so

$$\mathbb{E}[dV] + \Pi(S_2, S_3; x)dt = rVdt.$$

By expanding the appreciation in project value and deleting all terms that tend to zero faster than dt , we obtain

$$\begin{aligned} dV &= \frac{1}{2} \sum_{i=2}^3 \frac{\partial^2 V}{\partial S_i^2} dS_i^2 + \sum_{i=2}^3 \frac{\partial V}{\partial S_i} dS_i \\ &= \frac{1}{2} \sum_{i=2}^3 \frac{\partial^2 V}{\partial S_i^2} S_i^2 \sigma_i^2 dt + \sum_{i=2}^3 \frac{\partial V}{\partial S_i} (S_i \mu_i^Q dt + S_i \sigma_i dz_i^Q), \end{aligned}$$

where all derivatives are evaluated at S_2, S_3 . Taking expectations and substituting, the project value is therefore the solution to the following partial differential equation (PDE)

$$\frac{1}{2} \sum_{i=2}^3 \frac{\partial^2 V}{\partial S_i^2} S_i^2 \sigma_i^2 + \sum_{i=2}^3 \frac{\partial V}{\partial S_i} S_i \mu_i^Q - rV + \Pi(S_2, S_3; x) = 0,$$

Under Assumption 2, the solution to this PDE is

$$V(S_2, S_3; x) = Q(x)(\rho_2 S_2 + \rho_3 S_3),$$

where $\rho_i = 1/(r - \mu_i^Q)$, $i = 2, 3$ (see Appendix B).

We next value the option to undertake investment and select capacity. As above, the option value can be assumed independent of time, and we denote it by $C(S_1, S_2, S_3)$ when steel spot prices, electricity spot prices and subsidy payments are S_1, S_2, S_3 . When holding the option, no profits are incurred, and so the return is based only on the expected appreciation in option value. As above, using risk-neutral valuation, the rate of return equals the risk-free rate, and we obtain

$$\mathbb{E}[dC] = rCdt.$$

By arguments similar to the above, the value of holding the option is therefore the solution to the PDE

$$\frac{1}{2} \sum_{i=1}^3 \frac{\partial^2 C}{\partial S_i^2} S_i^2 \sigma_i^2 + \sum_{i=1}^3 \frac{\partial C}{\partial S_i} S_i \mu_i^Q - rC = 0,$$

where all derivatives are evaluated at S_1, S_2, S_3 . In addition, the following boundary conditions apply, i.e.

$$C(S_1^*, S_2^*, S_3^*) = V(S_2^*, S_3^*; x^*) - I(S_1^*; x^*), \quad (6)$$

$$\frac{\partial C}{\partial S_i}(S_1^*, S_2^*, S_3^*) = \frac{\partial V}{\partial S_i}(S_2^*, S_3^*; x^*) - \frac{\partial I}{\partial S_i}(S_1^*; x^*), \quad (7)$$

$$i = 1, 2, 3,$$

$$\frac{\partial V}{\partial x}(S_2^*, S_3^*; x^*) - \frac{\partial I}{\partial x}(S_1^*; x^*) = 0, \quad (8)$$

$$\lim_{S_1 \rightarrow \infty} C(S_1, S_2, S_3) < \infty, \quad \lim_{S_i \rightarrow 0} C(S_1, S_2, S_3) < \infty, \quad (9)$$

$$i = 2, 3,$$

where x^* depends on S_1^*, S_2^*, S_3^* . Moreover, we note that S_1^*, S_2^*, S_3^* are dependent at the boundary. The boundary conditions determine the values of capital costs, electricity prices, and subsidy payments that trigger investment. The conditions (6) and (7) are the usual value-matching and smooth-pasting conditions applied in real options analysis [16]. Value-matching implies that investment is undertaken when the value of the project equals the option value, or equivalently, when the value of waiting is zero. The condition (8) is the necessary condition for optimal capacity choice. Finally, conditions (9) prevent the option value from tending to infinity when capital costs tend to infinity or electricity prices or subsidy payments are zero.

4. Renewable energy support schemes

The profitability of most renewable electricity investments heavily relies on public incentives and in particular the support scheme employed. Hence, we value investment timing and capacity choice of renewable energy projects under different support schemes.

Either prices or quantities drive the most important renewable energy support schemes. With price-driven support schemes, the fixing of prices is at the federal or state level, whereas generators determine quantities. Previously, investment subsidies were widely used, but are now partially replaced by generation-based payments, such as tax credit schemes, and especially, feed-in tariffs. With quantity-driven support schemes, quantity targets apply at the federal or state level (known in the US as renewable portfolio standards and in the EU as quota obligations), whereas competition between generators determine prices. This is typically through tendering systems, or notably, the trading of so-called renewable energy certificates (as in the US) or tradable green certificates (as in the EU). The choice of an appropriate policy instrument is subject to ongoing debate and may alter considerably because of shifts in the political environment, the tightening of national or international targets, a change in technology, or as governments may no longer be able to finance support schemes under the financial crisis.

We aim to examine investment behavior under different renewable energy support schemes. First, we consider investments that are not eligible for renewable energy support. Next, we consider investments under two of the most extensively employed support schemes, namely, feed-in tariffs and renewable energy certificate trading. To an investor, these two regimes may differ in terms of the level of subsidy payments but also in the degree of risk exposure. With the implementation of feed-in tariffs, electricity market price risk is either completely removed (with a so-called fixed feed-in tariff) or the investor is exposed to electricity market price risk only (with what is known as a price premium). In contrast, the implementation of renewable energy certificate trading allows for a significant risk from market prices of both electricity and the certificates themselves. As already indicated, we disregard any equilibrium considerations, and assume that the investment is sufficiently small not to affect either electricity and certificate prices. We investigate

how the behavior of investors is affected by support scheme uncertainty. In particular, we include the relevant sources of uncertainty under each support scheme. However, we also consider uncertainty with respect to any change of support scheme.

As in previous sections, the investment analysis of the following sections generally applies to many renewable energy sources such as solar, wind and run-of-river hydropower. However, for illustration purposes, we will focus on a wind power project.

4.1. Without renewable energy support

We begin by considering a wind power project that is ineligible for renewable energy support. Under Assumptions 1–3, we obtain the investment value and the investment triggers analytically (see also Appendix D). This analytical solution easily facilitates sensitivity analysis. With two sources of uncertainty, i.e. steel and electricity spot prices, the triggers for undertaking investment define the line

$$S_1^* = \left(\frac{((1-\alpha)(1-b)-1)B}{(1-\alpha)bA} \right)^{1-b} \left(\frac{ab\rho_2}{B} \right) S_2^*,$$

where

$$\alpha = \frac{1}{2} - \frac{\mu_1^Q - \mu_2^Q}{\sigma_1^2 + \sigma_2^2} - \sqrt{\left(\frac{1}{2} - \frac{\mu_1^Q - \mu_2^Q}{\sigma_1^2 + \sigma_2^2} \right)^2 + \frac{2(r - \mu_2^Q)}{\sigma_1^2 + \sigma_2^2}} < 0.$$

It is optimal to postpone investment for price combinations below this line, i.e. when the steel price is high relative to the electricity price. While deferring investment, its value is

$$C(S_1, S_2) = \beta S_1 \left(\frac{S_2}{S_1} \right)^{1-\alpha},$$

with

$$\beta = \left(\frac{A}{(1-\alpha)(1-b)-1} \right) \left(\frac{S_1^*}{S_2^*} \right)^{1-\alpha}.$$

As expected, the investment value is seen to be decreasing in the steel price and increasing in the electricity price. The first time a price combination is above the line, i.e. when the steel price becomes sufficiently low compared to the electricity price, investment should be undertaken. The optimal capacity to install is then

$$x^*(S_1, S_2) = \left(\frac{ab\rho_2 S_2}{BS_1} \right)^{\frac{1}{1-b}},$$

and so, given the investment has been undertaken, the optimal capacity is likewise seen to be decreasing in the steel price and increasing in the electricity price. Upon investment, the value of installing this capacity is

$$C(S_1, S_2) = \left(\frac{1-b}{b} \right) \left(\frac{ab\rho_2 S_2}{BS_1} \right)^{\frac{1}{1-b}} BS_1 - AS_1.$$

4.2. Feed-in tariffs

As the name suggests, a feed-in tariff involves a payment to the renewable electricity producer proportional to the volume fed into the grid. This can be implemented as a fixed tariff for electricity or as an electricity price premium. Under a fixed

feed-in tariff, the wind power producer receives a fixed payment that is independent of the electricity spot price, whereas under a price premium, he/she receives a payment on top of this price. To provide incentives for renewable generation, both types of implementation should account for the external costs of conventional production [18]. In practice, however, the fixed tariff is estimated from the production costs of renewable electricity generation whereas the price premium reflects the difference between the production costs and the electricity spot price. The levy is borne by taxpayers or consumers. In spite of the risk that the tariff will be reduced if consumers object to paying the levy, and when renewable energy projects become cheaper with the development of technology, feed-in tariffs are generally rather rigid. For now, we therefore assume that a constant tariff is guaranteed throughout the life of the wind power project.

As above we impose Assumptions 1–3. With a fixed tariff, we again obtain the investment value and the investment trigger analytically. We denote the fixed tariff by FT . When facing only steel price uncertainty, the trigger for undertaking investment is

$$S_1^* = \left(\frac{((1-\alpha)(1-b)-1)B}{(1-\alpha)bA} \right)^{1-b} \left(\frac{ab\rho FT}{B} \right),$$

where

$$\alpha = \frac{1}{2} - \frac{\mu_1^Q}{\sigma_1^2} - \sqrt{\left(\frac{1}{2} - \frac{\mu_1^Q}{\sigma_1^2} \right)^2 + \frac{2r}{\sigma_1^2}} < 0$$

and $\rho = 1/r$ (this assumes a fixed feed-in tariff that is not adjusted over time. However, in spite of the name, a fixed tariff may be adjusted over time using a fixed percentage). For steel prices above this trigger, it is optimal to postpone investment. Its value is then

$$C(S_1) = \beta S_1^\alpha,$$

with

$$\beta = \left(\frac{A}{(1-\alpha)(1-b)-1} \right) S_1^{*1-\alpha}.$$

It is again confirmed that the value of the investment decreases when steel prices increase. The investment should be undertaken once the steel price is below the trigger. The optimal capacity to install is then

$$x^*(S_1) = \left(\frac{ab\rho FT}{BS_1} \right)^{\frac{1}{1-b}},$$

and so, the higher the price, the lower the optimal capacity. Upon investment, the value of installing this capacity is

$$C(S_1) = \left(\frac{1-b}{b} \right) \left(\frac{ab\rho FT}{BS_1} \right)^{\frac{1}{1-b}} BS_1 - AS_1.$$

For details, see Appendix E. With price premiums, we can only obtain the investment value numerically.

4.3. Renewable energy certificates

Renewable energy certificates are issued to the renewable power producer in proportion to the volume generated and traded when portfolio standards or quotas obligate suppliers or

consumers to produce or use a certain share from renewable energy sources and demonstrate compliance with a required number of certificates. Here we assume that the certificates can always be traded. Now, the profit to the renewable power producer depends on both the electricity spot price and the certificate price. Settlement of these prices is on a regular basis in the electricity spot market and a separate market for certificates. In an efficient market, the certificate price reflects the difference in production costs between renewable energy generation and conventional power production [18].

As above, we obtain the investment value and the investment triggers under Assumptions 1–3. When facing three sources of uncertainty, the triggers for undertaking investment define the plane

$$S_1^* = \left(\frac{((1 - \alpha_1)(1 - b) - 1)B}{(1 - \alpha_1)bA} \right)^{1-b} \left(\frac{ab\rho_2}{B} \right) \left(\frac{1 - \alpha_1}{\alpha_2} \right) S_2^*,$$

$$S_2^* = \frac{\rho_3\alpha_2}{\rho_2(1 - \alpha_1 - \alpha_2)} S_3^*,$$

where α_1 and α_2 are the respective negative and positive roots of

$$\frac{1}{2}(\sigma_1^2 + \sigma_3^2)\alpha_1(\alpha_1 - 1) + \frac{1}{2}(\sigma_2^2 + \sigma_3^2)\alpha_2(\alpha_2 - 1) + \sigma_3^2\alpha_1\alpha_2 + (\mu_1^{\mathbb{Q}} - \mu_3^{\mathbb{Q}})\alpha_1 + (\mu_2^{\mathbb{Q}} - \mu_3^{\mathbb{Q}})\alpha_2 - (r - \mu_3^{\mathbb{Q}}) = 0.$$

It is optimal to postpone investment for price combinations below this plane. While deferring investment, its value is

$$C(S_1, S_2, S_3) = \beta S_1 \left(\frac{S_2}{S_1} \right)^{\alpha_2} \left(\frac{S_3}{S_1} \right)^{1 - \alpha_1 - \alpha_2},$$

with

$$\beta = \left(\frac{A}{(1 - \alpha_1)(1 - b) - 1} \right) \left(\frac{S_1^*}{S_2^*} \right)^{\alpha_2} \left(\frac{S_1^*}{S_3^*} \right)^{1 - \alpha_1 - \alpha_2}.$$

The first time a price combination is above the plane, i.e. when the steel price becomes sufficiently low compared to the electricity and certificate prices, investment should be undertaken. The optimal capacity is then

$$x^*(S_1, S_2, S_3) = \left(\frac{ab(\rho_2 S_2 + \rho_3 S_3)}{BS_1} \right)^{\frac{1}{1-b}},$$

and the corresponding investment value is

$$C(S_1, S_2, S_3; x) = \left(\frac{1 - b}{b} \right) \left(\frac{ab(\rho_2 S_2 + \rho_3 S_3)}{BS_1} \right)^{\frac{1}{1-b}} BS_1 - AS_1.$$

Note that the roots α_1 and α_2 define a space of dimension one. We cannot find these roots until we reach the investment triggers, and thus, we cannot find the investment value until then. When the triggers are reached, the dimension of this space reduces to zero and an analytical solution can be obtained (see Appendix F). We determine numerically when we reach the investment triggers.

4.4. Change of support schemes

The choice of policy instrument is subject to ongoing debate and governments occasionally alter the choice of support scheme over longer periods, affecting both the level and the risk of subsidy payments. Even when a support scheme prevails for a longer period, many countries may revise their feed-in law by changing the tariff level, by adjusting the percentage change of the tariff, or by extending the feed-in period. Others may introduce or remove capacity caps or modify their quotas such that they apply only to specific renewable energy sources or smaller generators. Here we assume that changes of support scheme may occur at random points in time and that this changes the drift and volatility of subsidy payments.

We account for such discrete changes of support scheme with Markov switching. In particular, we assume that political regimes switch between a finite number of states, reflecting a change of policy instrument or a revision in the support scheme, and that the drift and volatility of subsidy payments shift accordingly. Shifts occur according to a continuous time Markov process $X(t)$ with a finite state space $\{1, \dots, K\}$ and rate matrix $P = (p_{kl})_{K \times K}$. Hence, the probability of a shift from state k to state l within time period dt is given by $p_{kl}dt$ for $k \neq l$. We assume the Markov process is independent of the geometric Brownian motions. Thus, under the true probability measure, a Markov modulated geometric Brownian motion governs subsidy payments, i.e.

$$dS_3(t) = S_3(t-)\mu_3^{\mathbb{P}}(X(t-))dt + S_3(t-)\sigma_3(X(t-))dz_3^{\mathbb{P}}(t),$$

where $t-$ denotes the left limit of t . The drift and the volatility equal $\mu_3^{\mathbb{P}}(k)$ and $\sigma_3(k)$ when $X(t-)$ is in state k .

With the introduction of Markov switching, the market is no longer complete and the equivalent martingale measure is not unique. We assume that the market price of switching risk is zero, or equivalently, that the market price of risk in regime k is

$$\theta_3(k) = \frac{\mu_3^{\mathbb{P}}(k) + \delta_3(k) - r}{\sigma_3(k)}, k = 1, \dots, K.$$

Using similar arguments to the above, a Markov modulated geometric Brownian motion therefore governs the risk-adjusted subsidy payments

$$dS_3(t) = S_3(t-)(r - \delta_3(k))dt + S_3(t-)\sigma_3(X(t-))dz_j^{\mathbb{Q}}(t), \quad (10)$$

given the equivalent martingale measure $\mathbb{Q}$ is determined by $L = d\mathbb{Q}/d\mathbb{P}$ and

$$dL(t) = L(t) \sum_{j=1}^3 \theta_j(X(t-))dz_j^{\mathbb{P}}(t).$$

Note that under this equivalent martingale measure, the probability of a switch between political regimes is the same as under the true probability measure. As above, we let $\mu_3^{\mathbb{Q}}(k) = r - \delta_3(k)$, $k = 1, \dots, K$.

For ease of exposition we let $K = 2$. For $k = 1, 2$, we denote by $V^k(S_2, S_3; x)$ the project value under regime k of having installed capacity x when electricity spot prices and subsidy payments are S_2, S_3 . This value is the solution to the set of coupled PDE's

$$\frac{1}{2} \sum_{i=2}^3 \frac{\partial^2 V^k}{\partial S_i^2} S_i^2 \sigma_i^2(k) + \sum_{i=2}^3 \frac{\partial V^k}{\partial S_i} S_i \mu_i^Q(k) + p_{kl}(V^l - V^k) - rV^k + \Pi^k(S_2, S_3; x) = 0, k, l = 1, 2, k \neq l,$$

where all derivatives are evaluated at S_2, S_3 and $\mu_2^Q(k) = \mu_2^Q, \sigma_2(k) = \sigma_2, k = 1, 2$. Thus, the value of the project under one of the regimes depends on the probability of a switch to the other regime and its value under this regime. Under Assumption 2, the solutions to these PDE's are

$$V^k(S_2, S_3) = Q(x)(\rho_2 S_2 + \rho_3(k) S_3), k = 1, 2,$$

where $\rho_2 = 1/(r - \mu_2^Q)$ and $\rho_3(k) = (r - \mu_3^Q(k) + p_{lk} + p_{kl})/((r - \mu_3^Q(k))(r - \mu_3^Q(l)) + p_{lk}(r - \mu_3^Q(k)) + p_{kl}(r - \mu_3^Q(l)))$, $k, l = 1, 2, k \neq l$ (see Appendix C).

Similarly, we denote by $C^k(S_1, S_2, S_3)$ the value of the option under regime k when steel and electricity spot prices and subsidy payments are S_1, S_2, S_3 . While holding the option its value is likewise the solution to the set of coupled PDE's

$$\frac{1}{2} \sum_{i=1}^3 \frac{\partial^2 C^k}{\partial S_i^2} S_i^2 \sigma_i^2(k) + \sum_{i=1}^3 \frac{\partial C^k}{\partial S_i} S_i \mu_i^Q(k) + p_{kl}(C^l - C^k) - rC^k = 0, k, l = 1, 2, k \neq l,$$

where all derivatives are evaluated at S_1, S_2, S_3 , and in addition to the above $\mu_1^Q(k) = \mu_1^Q, \sigma_1(k) = \sigma_1, k = 1, 2$. As above, boundary conditions apply. As an extension of the previous notation, we denote by $D^k(S_1, S_2, S_3)$ the value of the option under regime k given investment has been undertaken under regime l . Moreover, $S_1^{k*}, S_2^{k*}, S_3^{k*}$ and $S_1^{k**}, S_2^{k**}, S_3^{k**}$ denote the values of steel and electricity spot prices and subsidy payments that trigger investment under regime k . The conditions (11)–(14) are the value-matching and smooth-pasting conditions at the boundary when investment is undertaken under regime k , cf. (11) and (13), but not regime l , cf. (12) and (14),

$$C^k(S_1^{k*}, S_2^{k*}, S_3^{k*}) = V^k(S_2^{k*}, S_3^{k*}; x^*) - I^k(S_1^{k*}; x^*), \quad (11)$$

$$C^l(S_1^{k*}, S_2^{k*}, S_3^{k*}) = D^l(S_1^{k*}, S_2^{k*}, S_3^{k*}), \quad (12)$$

$$\frac{\partial C^k}{\partial S_i}(S_1^{k*}, S_2^{k*}, S_3^{k*}) = \frac{\partial V^k}{\partial S_i}(S_2^{k*}, S_3^{k*}; x^*) - \frac{\partial I^k}{\partial S_i}(S_1^{k*}; x^*), \quad (13)$$

$$\frac{\partial C^l}{\partial S_i}(S_1^{k*}, S_2^{k*}, S_3^{k*}) = \frac{\partial D^l}{\partial S_i}(S_1^{k*}, S_2^{k*}, S_3^{k*}), i = 1, 2, 3. \quad (14)$$

Similarly, the conditions (15)–(18) are the value-matching and smooth-pasting conditions when investment is undertaken under both regime k , cf. (15) and (17), and regime l , cf. (16) and

(18),

$$D^k(S_1^{k**}, S_2^{k**}, S_3^{k**}) = V^k(S_2^{k**}, S_3^{k**}; x^*) - I^k(S_1^{k**}; x^*), \quad (15)$$

$$D^l(S_1^{l**}, S_2^{l**}, S_3^{l**}) = V^l(S_2^{l**}, S_3^{l**}; x^*) - I^l(S_1^{l**}; x^*), \quad (16)$$

$$\frac{\partial D^k}{\partial S_i}(S_1^{k**}, S_2^{k**}, S_3^{k**}) = \quad (17)$$

$$\frac{\partial V^k}{\partial S_i}(S_2^{k**}, S_3^{k**}; x^*) - \frac{\partial I^k}{\partial S_i}(S_1^{k**}; x^*),$$

$$\frac{\partial D^l}{\partial S_i}(S_1^{l**}, S_2^{l**}, S_3^{l**}) = \quad (18)$$

$$\frac{\partial V^l}{\partial S_i}(S_2^{l**}, S_3^{l**}; x^*) - \frac{\partial I^l}{\partial S_i}(S_1^{l**}; x^*), i = 1, 2, 3.$$

Hence, the value-matching conditions imply that investment should be undertaken under a given regime once the value of the project equals the option value. However, this option value depends on whether investment is undertaken in the other regime. As previously, (19) are necessary conditions for optimal capacity choice and conditions (20) prevent the option values from tending to infinity when steel prices tend to infinity or either electricity prices or subsidy payments are zero

$$\frac{\partial V^k}{\partial x}(S_2^{k*}, S_3^{k*}; x^*) - \frac{\partial I^k}{\partial x}(S_1^{k*}; x^*) = 0, \quad (19)$$

$$\lim_{S_1 \rightarrow \infty} C^k(S_1, S_2, S_3) < \infty, \lim_{S_i \rightarrow 0} C^k(S_1, S_2, S_3) < \infty, \quad (20)$$

$$k = 1, 2.$$

The set of coupled PDE's must be solved numerically.

5. Results and discussion

We approximate the value of investment timing and capacity choice numerically using a least squares Monte Carlo approach to option pricing [33]. This approach allows for both American-style exercise features and multiple state variables and provides a lower bound on the option prices.

When solving numerically, we discretize the risk-adjusted processes (3), (5) and (10). We assume that the options have a finite life and consider a partition $0 = t_1 \leq \dots \leq t_L = T$ of the lifetime $[0, T]$ into equiwidth time intervals $\Delta t = [t_i, t_{i+1}]$. The discretizations of (3) and (5) are

$$S_i(t_{i+1}) = S_i(t_i) + S_i(t_i) \mu_i^Q \Delta t + S_i(t_i) \sigma_i e_i(t_{i+1}) \sqrt{\Delta t}, i = 1, 2, 3, \quad (21)$$

where $\mu_i^Q = r - \delta_i, i = 1, 3, \mu_2^Q = \Delta \ln F_2(0, t)/\Delta t$ and $e_i(t_1), \dots, e_i(t_L), i = 1, 2, 3$ are independent standard normal random variables. Likewise, the discretization of (10) is

$$S_3(t_{i+1}) = S_3(t_i) + S_3(t_i) \mu_3^Q(X(t_i)) \Delta t + S_3(t_i) \sigma_3(X(t_i)) e_3(t_{i+1}) \sqrt{\Delta t}, \quad (22)$$

where $\mu_3^Q(X(t_i)) = r - \delta_3(X(t_i))$ and where we take $X(t_{i+1})$ to be the U_{t_i} -quantile of the distribution of $X(t_{i+1})$ conditional on

$X(t_l)$ and $U(t_1), \dots, U(t_L)$ to be independent uniform random variables on $[0, 1]$.

Based on the risk-neutral processes (21) or (22), we simulate a number of sample paths for the state variables using Monte Carlo sampling. Along each path, we obtain an optimal stopping rule by comparing the immediate payoffs from exercise with the expected value of discounted ex post payoffs from continuation, and exercise the option as soon as the former exceeds the latter. For investment timing and capacity choice, the immediate payoff is given by the net project value provided the option is in-the-money, i.e. that investment is undertaken (for perpetual options, it is possible to postpone investment forever. With a finite life of the options we include the option to abandon investment). Hence, the immediate payoff at time t_l is

$$P(S_1(t_l), S_2(t_l), S_3(t_l); t_l, t_l) = \max_{x \geq 0} \{V(S_2(t_l), S_3(t_l); x) - I(S_1(t_l); x), 0\}.$$

The continuation value at time t_l is

$$C(S_1(t_l), S_2(t_l), S_3(t_l)) = \mathbb{E}_{t_l}^{\mathbb{Q}} \left[\sum_{t=t_l+1}^{t_L} e^{-r(t-t_l)} P(S_1(t), S_2(t), S_3(t); t_l, t_L) \right],$$

where $\mathbb{E}_t^{\mathbb{Q}}[\cdot]$ denotes the conditional expected value under $\mathbb{Q}$ at time t and $P(S_1(t), S_2(t), S_3(t); t_l, t_L)$ denotes the path of ex post payoffs conditional on the option not being exercised prior to time t_l and following the optimal stopping rule at all times $t = t_l + 1, \dots, t_L$. We estimate conditional expected values using least squares regression. In particular, we regress the discounted values of $P(S_1(t), S_2(t), S_3(t); t_l, t_L)$, $t = t_l + 1, \dots, t_L$ on functions of the state variables $S_1(t_l), S_2(t_l), S_3(t_l)$. By using power functions, an estimate of the continuation value is given by

$$\hat{C}(S_1(t_l), S_2(t_l), S_3(t_l)) = \hat{\beta}_0 + \sum_{i=1}^3 \hat{\beta}_{1i} S_i(t_l) + \sum_{i,j=1}^3 \hat{\beta}_{2ij} S_i(t_l) S_j(t_l),$$

where $\beta_0, \beta_{11}, \dots, \beta_{13}, \beta_{211}, \dots, \beta_{233}$ are regression coefficients. To improve efficiency, we include only paths that are in-the-money.

We implemented the least squares Monte Carlo approach in Matlab Version 7.9.0.529 (R2009b) and ran it on a Quad-Core AMD Opteron(tm) Processor 8356, using 10,000 sample paths in the simulation.

5.1. Case study

We illustrate the valuation of renewable electricity investments in a case study based on wind power. With some of the highest wind speeds in Europe, we restrict attention to the Nordic region and Norway in particular. Norway had an installed wind power capacity of only 428 megawatt (MW) by the end of 2008 [17], and thus, has a largely unexploited potential in wind power generation.

The wind power data is mainly based on European estimates from 2006 to 2007 [18]. We consider an investment in a wind park for which the lifetime of the turbines is 20 years. The capital costs of the investment are derived from the average costs of a 2 MW turbine, assuming that 25% of the costs are independent of capacity and 75% are capacity-dependent. Moreover, we assume that steel costs account for 10% of both cost components. For the average cost of steel, this corresponds to approximately 370 tons (T) per MW capacity installed or, equivalently, 740 T of steel for a 2 MW turbine. With these assumptions, the cost components are 44.17 mill. euros plus 0.82 mill. euros/MW capacity installed (excluding steel costs). Steel costs are 4.91 mill. euros plus 0.09 mill. euros/MW capacity. The average variable costs are 14.50 euros/MWh. Finally, with an annual capacity factor of 35% and ignoring wake effects, yearly production is 3066 MWh/MW capacity installed, which corresponds to the function $\hat{Q}(x) = 3066x$. To estimate wake effects, we have assumed the functional form $Q(x) = ax^b$ for fixed b and determined a such that this function is as close as possible to $\hat{Q}(x)$.

For the Nordic region, we assume the risk-free rate of return is 5%. To estimate the stochastic processes for the state variables (21) and (22), we have used steel spot prices from 2008 to 2009 available from [32], electricity forward prices from 2004 to 2009 from the Nordic electricity exchange [38], and tradable green certificate prices from 2004 to 2007 available from the Swedish green market and also traded at [38] (see Table .1). For steel spot prices, the risk-neutral drift is estimated to 2.50%, assuming a convenience yield of 2.50%, and the standard deviation is 62.70%. For electricity, the risk-neutral drift of spot prices is estimated from forward prices to be 2.15% and the standard deviation is 29.29%. Finally, for subsidy payments, the risk-neutral drift is likewise assumed to be 2.50% and the standard deviation is estimated to be 18.12%. The initial level of the fixed feed-in tariff is taken to be 50 euros/MWh with an annual percentage increase of 2%. Similarly, the initial level of the price premium is taken to be 10 euros/MWh with an annual percentage increase of 2% (note that the increases in the tariff and premium are less than the risk-free rate of return, and so the nominal tariff and premium decrease). The levels of the tariff and the premium are based on existing support schemes in the Nordic region [26]. For a change of support schemes, we consider two political regimes, i.e. the feed-in tariff implemented as a price premium (which was originally planned in Norway) and the tradable green certificates (that the Norwegian government instead decided to work on). We assume that the price premium is initially employed. Furthermore, we assume that the probabilities of a shift in regimes are the same for both regimes (we made this assumption because of an otherwise rather small data set. In reality, a regime shift may occur with a larger probability when the subsidy payments are fixed) and is estimated to be 13% (the empirical frequency with which changes of support scheme takes place. Note that the regimes are observable, and so the empirical frequency is the maximum likelihood estimate for the transition probability) based on information on changes of support schemes in Europe from 1997 to 2006 [8].

i) Analytical and numerical solutions

Under each political regime, we solve both analytically (when possible) and numerically. The analytical solutions easily facilitate sensitivity analysis, but are based on assumptions standard in real options analysis, whereas the numerical solutions allow us to find the real options values with more realistic specification of costs and profits, project and option lifetimes, etc. We obtain analytical solutions without renewable energy support and under the fixed feed-in tariff, and semi-analytical solutions with renewable energy certificate trading (for simplicity, in the following, we refer to analytical and semi-analytical solutions simply as analytical solutions). At the same time, we solve numerically under all regimes and with changes of support scheme (we refer to numerical solutions).

We first use the analytical solutions for sensitivity analysis, investigating how the option values vary when the initial values of the underlying assets vary under the different political regimes, see Figs. .1–.3. These figures confirm the expected real options behavior, namely that option values are decreasing in the initial steel price and increasing in the initial electricity price and subsidy payment.

Next, we ensure that the numerical solutions converge to the corresponding analytical solutions under identical assumptions. Table .2 displays the numerical and analytical project and option values for varying initial values of the underlying assets and under the different political regimes. The table confirms convergence without renewable energy support (the absolute difference between the numerical approximations and analytical option values is on average 0.61%) and under the fixed feed-in tariff (the average absolute difference is 2.78%). However, with renewable energy certificate trading, we observe that the semi-analytical solutions underestimate the option values, which is most likely due to the numerical trigger estimates used. Nevertheless, we find the semi-analytical solution to be a reasonable approximation as this underestimation does not affect the conclusions.

We finally obtain numerical solutions with more realistic specification of costs and profits, project and option lifetimes, etc. (In the following, we refer to these as the numerical solutions). The differences in assumptions between the analytical and numerical solutions are listed in Table .3 and discussed below. In the numerical solutions, capital costs consist of both steel price-dependent components and components that are independent of the steel price. In the analytical solutions, all capital costs are assumed proportional to the price of steel (Assumption 1). Here, the cost components are determined such that the capital costs remain the same for the initial steel price. Along the same lines, the numerical approach allows for variable costs whereas variable costs are assumed zero in the analytical solutions (Assumption 2). When solving numerically, the fixed feed-in tariff and price premium may increase over time. In contrast, the tariff and premium are both constant when solving analytically. However, in the analytical solutions, we have adjusted the tariff and premium such that the project values remain the same. The numerical approximations also allow for finite project and option lifetimes under all political

regimes. Nonetheless, the numerical solutions are based on analytical project values, and under changes of support scheme we were only able to derive this by assuming an infinite project life. When possible, we therefore consider a project lifetime of 20 years and an option lifetime of 10 years. In contrast, the analytical solutions apply for infinite project and option lifetimes. Here, we have scaled capital costs according to the difference in profits between a finite and an infinite life. Finally, the numerical approach allows for a discrete capacity choice whereas the analytical solutions use a continuous approximation.

These differences in assumptions affect the results as follows. First, we find that Assumptions 1–2 make a significant difference. By imposing Assumption 1 (all capital costs are assumed proportional to the price of steel), the mean net project value remains the same but the variance increases and therefore the option value is larger in the analytical solution than in the numerical solution. For the same reason, investment is further delayed and capacity is larger. By imposing Assumption 2 (variable costs are assumed zero), the project value increases and therefore the analytical option value further exceeds the numerical option value. The investment timing and capacity choice remain almost the same. We observe only a small difference in the results when allowing the fixed feed-in tariff and price premium to increase over time (numerical solution) as opposed to constant a tariff and premium (analytical solution). By construction, the project value remains the same but the option value is slightly larger as investment can be undertaken at a higher tariff and premium. Finally, with a realistic project lifetime (numerical solution), we find that both the mean and the variance of the project value are considerably lower than with an infinite project life (analytical solution) and therefore the option value is lower. This is also the reason why investment occurs earlier and capacity is smaller in the numerical solution than in the analytical solution. In contrast, with a realistic option lifetime (numerical solution) as opposed to an infinite option life (analytical solution), the option value is only slightly lower as investment occurs early in most cases. The difference in the results between the continuous and discrete capacity choice is likewise small. In conclusion, both the project and option values are substantially smaller with more realistic specification of costs and profits, project and option lifetimes, etc. The differences in investment timing and capacity choice are similar, i.e. investment occurs earlier and capacity is smaller.

In the following, we restrict attention to the numerical solutions based on the assumptions listed in Table .3. Table .4 displays the net present values of the project, the option values as well as corresponding capacities for varying initial values of the underlying assets and under the different political regimes.

ii) Comparing the net present value and real options approaches

To assess the effects of adapting a real options approach, we consider the differences between the net present values and the option values, also referred to as the values of waiting. We note that the numerical approximation provides only lower bounds on the option values and therefore the listed values of waiting may be underestimated. The static net present values suggest

immediate investment, as these values are positive. In contrast, the dynamic real options approach proposes to defer investment with positive values of waiting. Clearly, by waiting for a favorable change in asset values (lower steel prices and higher electricity prices and subsidy payments), the project value will be larger upon investment, and therefore the option value will exceed the net present value. Likewise, by waiting for a favorable change in asset values, the capacity will be larger upon investment. Except with the fixed feed-in tariff, this is strongly confirmed by the differences between investment values and between capacities in the net present value and real options approaches under all regimes. Overall, the average value of waiting is 14.3% with an average time to investment of 5.4 years. Moreover, the average difference in capacities is 29.2%.

iii) Comparing investment behavior under different support schemes

We now investigate how each support scheme and the change of support scheme affect the behavior of a renewable energy investor. For the case study, the initial steel price is 265 euros/T, the initial electricity price is 40 euros/MWh and the initial subsidy payment is 20 euros/MWh. Using these initial asset values, we find as expected, that the option value under renewable energy certificate trading (resp. price premium) is higher than under a feed-in tariff via price premium (resp. fixed feed-in tariff). Comparing renewable certificates with the price premium, the additional revenue (measured in net present values) required to trigger investment is 39%, whereas comparing the price premium with the fixed feed-in tariff, the additional revenue is 16%. These numbers can also be seen as social costs of regulatory policy differences, including the costs of risk exposure (Note that the difference in option values under the three support schemes is not only caused by differences in the risk exposure, but also by the levels of subsidy payments and electricity prices). The differences in risk exposure imply that under a fixed feed-in tariff, an investor may delay investment and wait for lower steel prices, with a price premium he/she may wait for lower steel prices at the same time as higher electricity prices and with renewable certificate trading he/she may wait for lower steel prices at the same time as both higher electricity prices and subsidy payments. This would make investment occur later and at higher project values under the renewable certificates (resp. price premium) than under the price premium (resp. fixed feed-in tariff), and is confirmed when comparing the price premium to the fixed feed-in tariff (The reason this is not the case when comparing renewable certificates to the price premium is the differences in the levels of subsidy payments and electricity prices). We continue by observing that the lower the steel price, and the higher the electricity price and subsidy payment, the higher the capacity upon investment. Therefore, the capacity under renewable certificates is 29% higher than under the feed-in tariff via price premium, whereas the capacity under the price premium is 25% higher than under the fixed feed-in tariff. For the case study, we conclude that a fixed feed-in tariff encourages earlier investment, and an additional revenue is required to trigger investment under renewable energy certificate trading. Nevertheless, as investment has been

undertaken, renewable certificates creates incentives for larger projects. It should be remarked that the conclusions of the case study depends on the levels of the fixed feed-in tariff and the price premium compared to the electricity price and subsidy payment as seen in Figs. .2–.3. If the fixed feed-in tariff is high relative to electricity price and subsidy payment (resp. the price premium is high compared with subsidy payment), the opposite may hold.

When the investor is ineligible for renewable energy support, the option value is lower than under the price premium and renewable certificate trading since the net present value is lower. For the case study, this is also the case when comparing to a fixed feed-in tariff. The additional revenue required to trigger investment under the fixed feed-in tariff, the price premium and certificate trading is 18%, 37% and 91%, respectively. However, depending on the level of the feed-in tariff, the option value may be higher without support than under a fixed feed-in tariff since the risk exposure is higher. This is confirmed in Figs. .2. Hence, contrary to our expectations, without support, the investment value may be higher and the capacity may be larger than with renewable energy support.

As above, under shifts in political regimes, the investor may wait for lower or higher asset values but he/she may at the same time wait for a change of support scheme. Therefore, with switching between a price premium and renewable certificate trading, the option value is likely to be lower than under renewable certificates since a change of support scheme also changes the risk exposure. Note that it is not possible to see this from Table .4 as the numerical solutions under a change of support scheme are based on an infinite project life. However, this is confirmed in Table .2. In contrast, we expect the option value to be higher than under the price premium. Nevertheless, this is not necessarily the case if the project value is lower under shifts in political regimes as also seen in Table .2. Still, although not shown here, our numerical results confirm that the value of waiting is higher under shifts in political regimes than with both a price premium and renewable certificates. Furthermore, with a price premium initially employed, we find that uncertainty with respect to a change of support scheme creates an incentive to defer investment and encourages larger projects. With renewable certificate trading employed, most likely the opposite holds.

6. Conclusion and directions for further work

This paper presented a real options framework to value investment timing and capacity choice for renewable energy projects under different support schemes. In particular, we investigated investment behavior under two of the most extensively employed support schemes, namely, feed-in tariffs and renewable energy certificate trading, and considered both multiple sources of uncertainty under each support scheme and uncertainty with respect to any change of support scheme. In a Nordic case study based on wind power, we found that feed-in tariffs encourage earlier investment. Comparing renewable certificates with the fixed feed-in tariff, the additional revenue

required to trigger investment was found to be 61%. Nevertheless, as investment has been undertaken, renewable energy certificate trading creates incentives for larger projects. Comparing renewable certificates with the fixed feed-in tariff, the capacity was found to be higher by 61%. We also showed that, with a feed-in tariff initially employed, uncertainty about a change of support scheme creates an incentive to defer investment and encourages larger projects. Finally, contrary to our expectations, without renewable energy support, we found that the investment value may be higher and the capacity may be larger than with renewable energy support.

The investment appraisal in our paper may provide decision support for private investors, but no less importantly, may assist policy makers in the design of efficient electricity markets and appropriate investment incentives. As shown, the choice of renewable energy support scheme and any corresponding uncertainty has a crucial impact on both the timing and size of investments in renewable energy. As an example, and in relation to the case study, the extended discussions in Norway about whether to deploy a feed-in tariff or green certificates trading may unintentionally have caused a delay in renewable energy investment. Moreover, the additional revenue required to trigger investment provides an estimate of the social costs of regulatory policy differences.

For further policy recommendations, a relevant idea for future research is to use the framework for simulating renewable energy investment capacity over time. In particular, we may simulate the evolution of investment costs, electricity prices and subsidy payments over time, and use the real options models to predict the timing of investments and the corresponding sizes of the projects. As a result, it would be possible to predict the overall investment level of a given investor under different support schemes or any change of support schemes. This could be extended for a number of investors such as to estimate the overall investment level in the market.

Extensions of the framework are possible in several directions. First, the framework could be used for valuing expansions of existing projects by taking into account an already installed capacity. This would however be at the expense of being able to obtain analytical solutions. Second, we assumed that capacity is installed instantly once investment is undertaken, which lies contrary to an incremental capacity choice. However, a stage-wise investment may be relevant for many renewable energy technologies. For wind power investments in particular, typical real options include the flexibility to stage an investment by considering an exploration phase, a licencing phase and a construction phase. Stage-wise investments should be valued as nested options, and so when modeling this, our real options model would serve as a basis in every stage. As usual, the optimal timing would be determined by comparing the immediate value of the project with the continuation value, which would now include the value of the option to continue with the next stage. In all cases, our framework could be further improved by introducing mean reversion in steel and electricity spot prices (as often observed in commodity prices), and correlations between electricity spot prices and subsidy payments and between electricity spot prices and wind power production.

However, this would likewise be at the expense of being able to obtain an analytical solution. Finally, it would in many cases be straightforward to incorporate other support schemes, such as tax credit schemes, into our framework.

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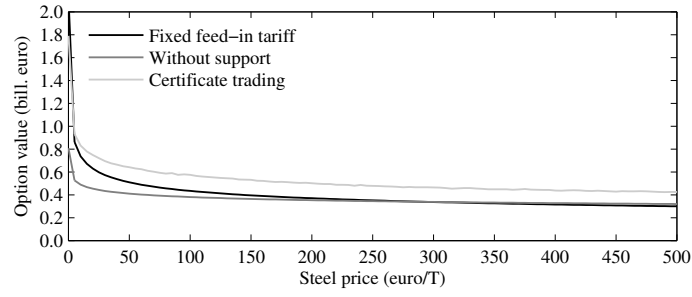


Figure .1: Analytical option values as functions of steel prices.

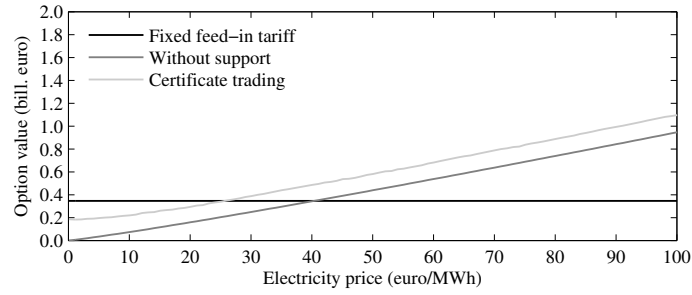


Figure .2: Analytical option values as functions of electricity prices.

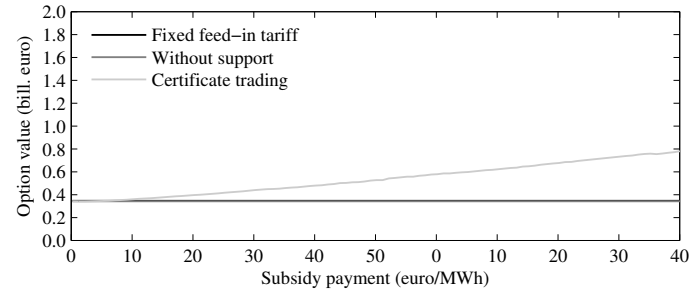


Figure .3: Analytical option values as functions of subsidy payments.

Table .1: Parameter estimates. Yearly estimates in percent.

State variable	Steel price	Electricity price	Certificates price
Drift	-5.73		-4.66
Drift, risk-neutral	2.50	2.15	2.50
Standard deviation	62.70	29.20	18.12

Table .3: Assumptions in the analytical and numerical solutions.

	Capital costs	Variable costs	Fixed feed-in tariff	Price premium
Analytical	Linear ^a	Zero	Constant	Constant
Numerical	Affine	Non-zero	Increasing	Increasing
	Project life	Option life	Capacity choice	
Analytical	Infinite	Infinite	Continuous	
Numerical	20 years	10 years	Discrete	

^a Linearity and affinity refer to the functional dependency of capital costs on steel spot prices.

Table .2: Numerical and analytical results. All numerical results are averages.

	Initial value	Net present value		Option value	
		Mill. euros		Mill. euros	
		Numerical	Analytical	Numerical	Analytical
Steel	euros/T				
Without renewable energy support	200.00	284.14	284.12	355.56	353.08
Fixed feed-in tariff		347.60	360.37	361.32	370.17
Feed-in tariff via price premium		377.30	380.92	425.61	–
Renewable energy certificates		517.20	519.50	575.39	502.07
Markov switching ^b		310.52	314.16	405.83	–
Without renewable energy support	250.00	257.15	255.43	345.50	344.61
Fixed feed-in tariff		318.08	330.02	342.01	351.61
Feed-in tariff via price premium		347.37	350.12	410.72	–
Renewable energy certificates		483.98	485.68	557.19	480.74
Markov switching		282.37	284.82	394.35	–
Without renewable energy support	300.00	232.85	228.34	335.75	337.84
Fixed feed-in tariff		290.98	301.59	326.87	337.14
Feed-in tariff via price premium		320.05	321.33	399.24	–
Renewable energy certificates		453.43	454.47	542.52	465.36
Markov switching		256.92	257.20	384.89	–
Electricity	euros/MWh				
Without renewable energy support	30.00	157.08	150.47	245.73	248.90
Fixed feed-in tariff		309.62	321.33	337.20	346.92
Feed-in tariff via price premium		241.79	242.27	307.18	–
Renewable energy certificates		373.77	374.45	451.30	385.78
Markov switching		199.84	199.84	305.83	–
Without renewable energy support	40.00	249.60	247.17	340.84	342.43
Fixed feed-in tariff		309.62	321.33	337.20	346.92
Feed-in tariff via price premium		338.92	341.31	407.19	–
Renewable energy certificates		474.57	476.09	552.73	475.92
Markov switching		274.47	276.38	390.82	–
Without renewable energy support	50.00	346.73	346.31	441.88	438.56
Fixed feed-in tariff		309.62	321.33	337.20	346.92
Feed-in tariff via price premium		438.92	442.35	509.45	–
Renewable energy certificates		577.10	579.34	655.31	570.05
Markov switching		351.48	354.63	481.17	–
Subsidy	euros/MWh				
Without renewable energy support	10.00	249.60	247.17	340.84	342.43
Fixed feed-in tariff		309.62	321.33	337.20	346.92
Feed-in tariff via price premium		338.92	341.31	407.19	–
Renewable energy certificates		360.02	360.36	442.47	384.12
Markov switching		274.47	276.38	390.82	–
Without renewable energy support	20.00	249.60	247.17	340.84	342.43
Fixed feed-in tariff		309.62	321.33	337.20	346.92
Feed-in tariff via price premium		338.92	341.31	407.19	–
Renewable energy certificates		474.57	476.09	552.73	475.92
Markov switching		274.47	276.38	390.82	–
Without renewable energy support	30.00	249.60	247.17	340.84	342.43
Fixed feed-in tariff		309.62	321.33	337.20	346.92
Feed-in tariff via price premium		338.92	341.31	407.19	–
Renewable energy certificates		591.58	593.92	667.06	578.59
Markov switching		274.47	276.38	390.82	–

^b With Markov switching the numerical solution assumes an infinite project lifetime.

Table .4: Numerical results. All results are averages.

	Initial value	Net present value	Capacity	Option value	Capacity	Time to investment	Value of waiting ^a
		Mill. euros	MW	Mill. euros	MW	Years	%
Steel	euros/T						
Without renewable energy support	200.00	58.95	9.28	80.45	14.56	5.35	36.48
Fixed feed-in tariff		95.43	14.00	95.56	15.45	2.19	0.13
Feed-in tariff via price premium		98.53	14.00	109.78	19.29	6.90	11.41
Renewable energy certificates		143.87	20.00	153.00	24.92	6.24	6.35
Markov switching ^b		257.07	16.00	275.86	20.88	6.31	7.31
Without renewable energy support	250.00	57.89	9.23	79.76	14.27	5.31	37.78
Fixed feed-in tariff		94.22	14.00	94.43	15.16	2.28	0.23
Feed-in tariff via price premium		97.31	14.00	109.10	18.97	6.86	12.12
Renewable energy certificates		142.56	20.00	151.82	24.47	6.27	6.50
Markov switching		254.28	16.00	273.20	20.47	6.32	7.44
Without renewable energy support	300.00	56.85	9.16	78.85	13.99	5.27	38.70
Fixed feed-in tariff		93.01	14.00	93.37	14.95	2.43	0.39
Feed-in tariff via price premium		96.09	14.00	107.84	18.59	6.87	12.23
Renewable energy certificates		141.25	20.00	150.82	24.04	6.27	6.78
Markov switching		251.51	16.00	271.80	20.24	6.42	8.07
Electricity	euros/MWh						
Without renewable energy support	30.00	22.75	3.95	46.28	9.08	4.35	103.44
Fixed feed-in tariff		93.85	14.00	94.10	15.09	2.32	0.26
Feed-in tariff via price premium		56.23	9.98	69.66	13.39	6.47	23.88
Renewable energy certificates		100.31	14.00	110.68	19.42	6.85	10.34
Markov switching		160.64	12.00	181.96	15.33	6.95	13.27
Without renewable energy support	40.00	57.58	9.21	79.48	14.16	5.28	38.04
Fixed feed-in tariff		93.85	14.00	94.10	15.09	2.32	0.26
Feed-in tariff via price premium		96.94	14.00	108.69	18.86	6.88	12.11
Renewable energy certificates		142.16	20.00	151.46	24.32	6.25	6.54
Markov switching		253.45	16.00	272.72	20.35	6.29	7.60
Without renewable energy support	50.00	97.91	14.00	116.48	19.27	5.71	18.96
Fixed feed-in tariff		93.85	14.00	94.10	15.09	2.32	0.26
Feed-in tariff via price premium		138.74	20.00	149.65	23.91	6.39	7.86
Renewable energy certificates		184.88	24.00	194.28	29.53	5.88	5.08
Markov switching		348.51	22.00	368.30	25.72	5.97	5.68
Subsidy	euros/MWh						
Without renewable energy support	10.00	57.58	9.21	79.48	14.16	5.28	38.04
Fixed feed-in tariff		93.85	14.00	94.10	15.09	2.32	0.26
Feed-in tariff via price premium		96.94	14.00	108.69	18.86	6.88	12.11
Renewable energy certificates		99.05	20.00	112.66	19.37	6.66	13.73
Markov switching		253.45	16.00	272.72	20.35	6.29	7.60
Without renewable energy support	20.00	57.58	9.21	79.48	14.16	5.28	38.04
Fixed feed-in tariff		93.85	14.00	94.10	15.09	2.32	0.26
Feed-in tariff via price premium		96.94	14.00	108.69	18.86	6.88	12.11
Renewable energy certificates		142.16	20.00	151.46	24.32	6.25	6.54
Markov switching		253.45	16.00	272.72	20.35	6.29	7.60
Without renewable energy support	30.00	57.58	9.21	79.48	14.16	5.28	38.04
Fixed feed-in tariff		93.85	14.00	94.10	15.09	2.32	0.26
Feed-in tariff via price premium		96.94	14.00	108.69	18.86	6.88	12.11
Renewable energy certificates		186.24	24.00	193.60	29.12	5.44	3.95
Markov switching		253.45	16.00	272.72	20.35	6.29	7.60

^a The value of waiting is the difference between the option value and net present value.^b With Markov switching the numerical solution assumes an infinite project lifetime.