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Repowering of Wind Turbines: Economics and Optimal Timing

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Abstract

For more than 20 years now, wind power has been one of the main renewable energy sources, especially in countries like Denmark, one of the pioneer countries in developing onshore wind turbines. Whereas offshore wind utilization still has a high risk profile the repowering of wind converter offers an interesting alternative to further increase the use of renewable energy. This paper first provides an overview of the historical development of wind utilization in Denmark, with a special focus on incentive systems. Second, we study the economics and optimal timing of repowering for the case of Danish wind farms. We use a two-factor real options modeling framework following the Mc Donald and Siegel (1986) approach, which allows consideration of the investment costs as well as revenues, both following a continuous time, stochastic process. In a next step, a Monte Carlo Simulation is applied to determine the probability of success of repowering for each year. Finally, we discuss the results and highlight the effects necessary to increase repowering activities. We find that until now, the high uncertainty in terms of revenues hinders the further development of repowering in Denmark and lowers the probability of success significantly, while the selling price of the used turbine has only a minor effect on the optimal timing of repowering. Therefore, wind developers should argue for a larger stake of secured parts in revenues, achievable via higher governmental guaranteed incentives.

Keywords: Repowering, Wind power, Real options, Denmark

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List of Abbreviations

a, a_I, a_R	required rate of return (investment, revenue)
b	market price of risk
C	capital expenditure
D	decommissioning costs
dt,	time step
dz_I, dz_R	Wiener process (investment, revenue)
E	expectation value
FLH	full-load hours
h	degree of homogeneity
I	investment cost
NPV	net present value
OV, ov	option value
P	electricity price
PV	present value
r	discount rate
R	revenues
s	time index
S	salvage value
V	subsidy rate granted by the government

Greek symbols

β	beta factor (CAPM)
σ_I, σ_R	volatility (investment, revenue)
δ_I, δ_R	part of the required return on I (R) foregone by receiving the price increases in I (R)
θ	threshold value
Θ	region to exercise
ϑ	correlation between return on the asset the return on market portfolio
τ	future point in time (where process begins)
μ_I, μ_R	drift parameter (investment, revenue)

1 Introduction

In February 2007, the EU summit agreed to endorse a binding energy policy target, namely that 20% of the Union's energy needs have to come from renewable energy sources by 2020 (Fondation EurActiv, 2011). Further development in wind energy is necessary to achieve this ambitious target.

In most European countries wind power, as the least costly renewable energy source, plays a significant role in the energy mix of today, but the best wind sites are often engaged by small-scale wind generators with a size below 1 MW. Hence, repowering – i.e. the rebuilding and the replacement of major parts of an onshore wind turbine instead of doing a greenfield project – seems to be the only possibility for further growth in onshore wind generation. .

The focus of this paper is on Denmark, as the Danish onshore wind power industry has started as early as in the late 1970s (Danish Energy Agency, 2009), so that repowering is an important issue already today, and where wind power already in 2010 contributed a remarkable 6.1 TWh or about 20% of energy demand (National Renewable Action Plan, 2010). Due to the fact that the onshore development started so early, the best sites for onshore wind are already engaged and repowering as well as the expansion of offshore wind energy use are the only opportunities for further growth in wind power generation. As offshore wind energy is risky and expensive, further repowering seems to be an important option for Denmark. Hence, section 2 outlines the historical development of wind energy in Denmark, with a description of major technical and economic milestones and a special focus on the historical incentive systems provided. In section 2, we explain the purpose and effects of repowering, providing an overview about the repowering development until today and a summary of current regulatory trends.

In section 3, the real options approach (ROA) is introduced, which is used to determine the optimal timing of repowering existing wind farms. Although most real options models applied in the energy economics and energy finance literature only account for a single stochastic variable, in this paper, following the basic approach of McDonald & Siegel (MS) (1986), we consider both the revenue stream and the investment stream as stochastic. First, an analytical solution for only one stochastic variable is developed, which is then extended to a two-factor model. After that, we demonstrate how to estimate the model parameters based on historical data and how to apply the model to the case of repowering, given increasing power prices and decreasing investment costs.

Classifying the real options literature according to the type of uncertainty, most papers fall into the category of revenue uncertainty. An example of applying ROA to technological uncertainty is Grenadier & Weiss (1997). There are a few articles similar to the ones written by McDonald & Siegel (1986) and Murto (2006) that cover both technological (investment) and revenue (operational) uncertainty. The main difference between the articles mentioned is that McDonald & Siegel (1986) (hereafter MS) derived an analytical solution for the value of the option to invest in an irreversible project and the optimal investment time in case the value of the project and the cost of investing both follow stochastic processes. Murto (2006) adds technological uncertainty to the basic MS model, represented through a stochastic Poisson arrival process. Unfortunately, his model cannot be solved analytically.

In recent years, research on the optimal timing of investment in the energy sector has been intensified as, for example, evidenced in Zambujal-Oliveira and Duque (2010) or Dobbs (2004), which state that operation costs define the optimal replacement timing Rohlfs & Madlener (2011) develop a multi-factor real options model to evaluate carbon capture-ready coal plants. To this end, the authors used an extension of the MS model developed by Hu & Øksendal (1998).

Regarding onshore wind in Denmark, Munsgaard & Morthorst (2008) and Agnolucci provide a useful overview of historical and current problems. Furthermore, Sperling et al. (2010) present an overview of the historical incentive mechanism and its success in Denmark. In terms of repowering, Madlener and Schumacher (2011) and Goyal (2010) examine the potential and risks of repowering in Germany and India, respectively. Rio et al. (2011) analyze the different incentive schemes for repowering and its effectiveness.

The remainder of this paper is structured as follows: Section 2 provides a brief review of wind power use in Denmark and repowering. Section 3 presents the real options model used. Section 4 reports on the results, while section 5 concludes.

2 Wind power and repowering of wind turbines in Denmark

2.1 Relevance of repowering

In order to meet the ambitious renewable energy targets set by the EU and announced in the National Renewable Energy Action Plan each member country is required to present, Denmark will need 6.4 Terawatt hours (TWh) of onshore wind power by 2020. This means that Denmark will have to reduce CO_2 emissions by 20% and at the same time increase the share of renewable energy in primary energy consumption to 20%. Already today, wind energy is the major renewable technology employed in the Danish market, with a total installed capacity of 2923 Megawatt (MW) (European Comission Energy, 2010), which generates 6.1 TWh in 2010. Hence, wind power is responsible for approximately 20% of the total Danish electricity demand. Due to the fact that the best sites for onshore wind are already used by small-scale wind generators, the potential for repowering in Denmark is large. Lund and Mathiesen (2006) estimate that it is possible to replace the currently installed 5200 turbines with only around 1000 larger ones. It is conceivable that some of the planned offshore capacity in Denmark today will be shifted to the repowering of onshore wind, as the latter is the more riskless alternative, especially since the technology is proven and the investment costs are lower. Nevertheless, there are some hurdles for repowering in Denmark, e.g. lower financial incentives and local opposition against larger wind farms (Meyer, 2004; Agnolucci, 2007).

2.1 History of wind power in Denmark

2.1.1 Development and targets

Since the oil crisis in 1973, Denmark started to develop its own production of energy, focusing mostly on renewable energy. From the beginning, the main focus has been on wind power, as the Danish climate conditions make wind power one of the most obvious sources (Danish Energy Agency, 2009).

The first Danish wind turbine was installed in the late 1970s and had a capacity of 22 kW. From then onwards, wind power showed a strong development and peaked in 2000, with more than 6200 installed turbines, of which more than half had an electrical capacity of less than 500 kW. After that, the number of installed turbines decreased steadily by around 1000 until 2009, while the installed capacity grew by around 1000 MW in the same period. The Danish Energy Agency (2009) believes that this development will continue in the next years (Danish Energy Agency, 2009). Table 1 shows the breakdown of existing turbines by output and installation year and illustrates a clear trend towards more efficient and larger turbines over time.

Table 1: Number of installed wind turbines in Denmark, 1978-2009, by size class and year of installation

Period	0-225 kW	226-499 kW	500-999 kW	1000+ kW	Total
1978-84	91	1	0	0	92
1985-89	425	43	6	0	474
1990-94	616	169	65	0	850
1995-99	218	91	1687	73	2069
2000-04	44	2	812	526	1384
2005-09	33	0	26	150	209
Total	1427	306	2596	749	5078

Source: Own compilation, based on Agnolucci (2007, p.953)

The development of wind power utilization in Denmark has been characterized by strong public involvement. The first target can be found in Decree Energy 81: the installation of 60,000 windmills to supply 10% of the electricity demand by 2000, a target that had already been reached in 1998 with fewer than 5000 turbines (Agnolucci, 2007). In the early 1990s, a second target was announced by the government, namely to build 100 MW of wind power capacity, while in 1996 the utilities and the government signed a target agreement to install 1500 MW by 2005. Indeed, at the end of 2000, 2300 MW had already been installed (Agnolucci, 2007). The current target for Denmark is fixed in the National Renewable Energy Action Plan (European Commission Energy, 2010) and describes the growth path for each renewable energy technology until 2020. For onshore wind power, the official plan shows a reduction in installed capacity but an increase in generation. This perfectly fits with the idea of repowering, i.e. to cope with less capacity but higher efficiency due to newer turbines. Since the time when the first turbine was installed, the output of the wind generators was gradually scaled up to 55-75 kW in the 1980s and more than 3.6 MW in 2007 (Danish Energy Agency, 2009). Today, turbines with a capacity of up to 6 MW are already available in the market.

The strong historical growth in the Danish wind power industry was only possible because the government started to incentivize onshore wind power from the early beginning. The next sections provide an overview of the historical feed-in tariff structure. In doing so, we distinguish between incentives for investment and such for generation. Compared to investment incentives, generation incentives are linked to the output of the turbine, the incentive is only paid if the turbine produces electricity.

2.1.2 Investment incentives from 1970 until today

In Denmark, investment incentives have been important, both for promoting research and in increasing the development. Since 1979, citizens who built wind turbines received a reimbursement of 30% of the investment costs. During the 1980s, the incentive was reduced to 10% and then altogether abolished in 1989 due to a change in the political climate, and when more than 37.6 million Euros had been spent (Meyer, 2004). As of 1992, a new support scheme for renewable energy was in place, the “Development and Diffusion Program”. This program provided investment grants from 20% up to 40% of the costs for demonstration projects, pre-commercial and commercial technologies. Although the investment schemes were successful, they were replaced by the growth in generation incentives.

2.1.3 Generation incentives from 1970 until today

Early subsidies back in 1979 stimulated interest in wind turbines of cooperatives and private investors alike. From 1984 onwards, wind generators received feed-in rates amounting to 70-85% of the retail electricity price, a contribution to the grid connection costs, and a substantial incentive in the form of a tax refund. After trouble with the utilities regarding the grid connection costs, the Danish parliament passed a feed-in law in 1992, which resulted in a feed-in tariff and the fact that utilities had to accept renewable electricity feed-in, pay a tariff, and sustain grid reinforcement costs. Wind generators received a feed-in tariff that consisted of three different incentives: the tariff (33-52 €/MWh), the remuneration of the CO_2 tax (13 €/MWh), and a production subsidy (23 €/MWh), the latter of which was not given to utilities (Agnolucci, 2007). According to Munksgaard and Morthorst (2008), the tariff (33-52 €/MWh) was partly related to the price of electricity, which was fairly stable. Therefore, the total feed-in tariff was fixed at approximately 81 €/MWh. These high incentives were cut radically after the liberalization of the Danish electricity market in 1999 and changed to different tariffs for old and new wind installations. The reduction of the tariff had a strong impact on the development of new onshore wind power capacity in Denmark, which is shown in Fig. 1.

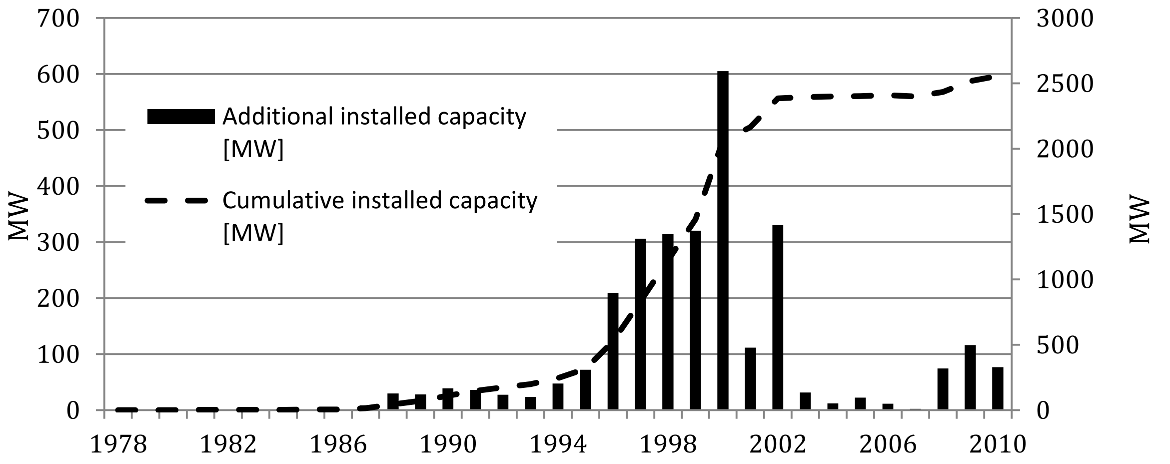


Fig. 1: New onshore wind power capacity in Denmark, additional capacity (left axis) and cumulative capacity (right axis)

Source: Own illustration, based on Danish Energy Agency (2009)

The installation peak in 2000 could be explained by a rush in wind projects to maintain the high feed-in tariff for investment under the 1999 scheme. Wind turbines were simply bought under the old scheme in 1999 and installed during 2000 (Munksgaard and Morthorst, 2008). This had the same effect as could be observed in Germany when the feed-in tariff for photovoltaics was reduced. In Denmark, from 2000 onwards, tariffs were only applied for a restricted period of time. The reform distinguished between three onshore categories, presented in the following:

- *Old wind turbines connected to the grid before 2000.* Developers of old wind power installations benefitted from the transition program, which aimed at softening the transfer to market liberalization by implementing a high feed-in tariff for a transition period of 10 years. Turbines that fell into this category received a general price guarantee of 80 €/MWh for a 10-year production period. Part of this subsidy was restricted to a maximum production limit in full-load hours. Hereby, the maximum production limit differed in relation to the installed turbine size.
- *Wind turbines connected between 2000 and 2002.* Turbines connected to the grid in the period between 2000 and 2002 were covered by a feed-in tariff of 58 €/MWh up to a production limit of 22,000 full-load hours. Thereafter, the owner received a premium of 16 €/MWh on top of the electricity price until the wind farm reached the end of its lifetime of 20 years.
- *New wind installations connected to the grid after January 1, 2003.* Owners of wind

turbines who got connected to the grid after January 2003 had to sell electricity at the market price. On top of that they received a subsidy of 16 €/MWh for the duration of 20 years (Munksgaard and Morthorst, 2008).

The cutback in tariffs resulted in the stagnation of wind power installations from 2003 until 2007 (see Fig. 1) and even in a slight decrease in total capacity in 2007. Taking the ambitious target for renewable energy sources into consideration and the desire to reduce the dependency on fossil fuels, the Danish government published the Energy Agreement in 2008 (Danish Energy Agency, 2009), which formed the basis for the new renewable legislation and also included the aim to reach a renewable share of 20% in gross energy consumption in 2011. Furthermore, it contained four new schemes aimed at promoting the local population's acceptance of onshore turbines; a "loss-of-value" scheme through which the investor must pay for any property losses in the neighborhood of the turbine which is caused by the turbine, an "option-to-purchase" scheme through which local people would be able to buy shares in the wind park; a "green scheme" that allowed municipalities to improve the landscape in areas where turbines are built; and a "guarantee scheme" to support local initiative groups with preliminary investments (Danish Energy Agency, 2009). At the beginning of 2009, the Renewable Energy Act (REA) entered into force, and as part of that, the feed-in tariff for wind power was doubled, compared to the one for turbines installed between 2002 and 2008. In addition, it also provided for compensation of balancing energy costs and a green fund payment. Current incentive structures that are valid for municipalities and project developers but not for energy utilities are summarized in Table 2.

An additional tariff structure was created by the government to support wind investments from energy utilities. Onshore wind turbines receive a subsidy of 10 €/MWh in addition to the electricity price. Both together may not exceed 40 €/MWh and are granted for a period of up to 10 years. Furthermore, energy utilities get an incentive of 13 €/MWh over the whole lifetime of the project (cf. www.res-legal.de, 2010). Due to this new governmental support, the number of installations has risen since.

Table 2: Overview of the current subsidy scheme in Denmark for new and existing onshore wind turbines without using repowering certificates

	Type of subsidy [€/MWh]	Subsidy period
After Feb 20, 2008	33.6 €/MWh + 3.1 €/MWh + 0.5 €/MWh (price subsidy + balancing fee + green fund)	First 22,000 full-load hours
Between Jan 1, 2005 and Feb 20, 2008	1.34 €/MWh + 0.31 €/MWh (price subsidy + balancing fee)	20 years
Between Dec 31, 2002 and Jan 1, 2005	1.34 €/MWh + 0.31 €/MWh (price subsidy + balancing fee, fixed maximum sum of market price and price subsidy: 4.83 €/MWh)	20 years
Before Dec 31, 2002	Price subsidy adjusted according to fixed maximum sum of market price and price subsidy: 8.05 €/MWh	10 years (until Dec. 31, 2012) During 25,000 full-load hours for turbines below 201 kW
		During 15,000 full-load hours for turbines below 600 kW
		During 12,000 full-load hours for turbines above 600 kW

Source: Own compilation, based on Sperling et al. (2010)

3 Timing of repowering: A real options approach

In this section, we use real options theory to develop a model that enables us to calculate the optimal timing of repowering a fictional wind park in Denmark.

3.1 Real options framework

An option is a security that gives its owner the right to trade a fixed number of shares of a stock at a fixed price at any time on or before a given date. It is important to mention that the owner has the right to exercise the option but not the obligation to do so. In the financial world, options have been traded for a long time and options pricing theory has a long history (Cox, Ross and Rubinstein 1979). Over the last decades, numerous studies have presented ways to transfer the financial option method to real investment decisions. This so-called real options theory is a promising technique of valuing investments in real assets under uncertainty. It has been regarded among researchers and economists as a way of better assessing investment proposals under uncertain market conditions. As explained by Trigeorgis (1993), the real options valuation performs better than conventional discounted cash flow methods, such as the net present value (NPV) and the internal rate of return (IRR). The main reason is that real options theory takes the value of flexibility to change a decision with time into account. Specifically, it explicitly accounts for the value of deferring an investment project, the value of waiting.

If we now consider a rational manager who always wants to maximize project returns, we can calculate for each point in time the trade-off between exercising the option or wait and see. In particular, this means that the manager has an American option on the project return. She can exercise the option, meaning the start of the investment, at each point in time until the investment period ends.

3.2 The optimal timing problem

In the following subsection, we explain the general timing problem with one uncertain variable, namely the revenues, and show how this problem could be considered as an optimal stopping problem. In section 3.2.2, the problem is extended and investment uncertainty is added.

3.2.1 General problem – one uncertain factor

The problem at hand is one of finding the optimal time to invest in an irreversible investment under uncertainty. The question in this case is whether the investor should make the investment or not, and if so, at what time. In other words, the investor has an American option to realize a project during the investment period or not.

Denote by $NPV\,(\mathcal{R}_t, \mathcal{I}_t)$ the net present value of the project if undertaken at time t, which depends on $\mathcal{R}_t$ as well as on $\mathcal{I}_t$. For the moment, $\mathcal{I}_t$ is considered as deterministic. The problem is to choose the timing of investment so that the expected discounted value of the investment is maximized. An investment at the optimal time τ results in a value of the investment opportunity $\mathcal{OV}$, given the current time t:

$$OV(R_t I_t) = E\left[e^{r(\tau-t)} NPV(R_\tau I_\tau)\right] \tag{1}$$

which is simply the net present value if the investment is undertaken at the optimal point in time discounted at time *t*. Hence, the optimal timing problem can be seen as an optimal stopping problem; the investor should examine for each state $\mathcal{R}_t$ if

$$OV(R_t) \geq NPV(R_t) \tag{2}$$

is valid for all states.

Following Murto (2006), the following assumptions are made. The processes $\mathcal{R}_t$ and $\mathcal{I}_t$ are Markov processes, which means that the future state of the process only depends on the current state of the process but not on the past. Both processes are time-homogenous, which means that the calendar time does not affect the evolution of the process. Moreover, we assume that the *NPV* ($\mathcal{R}_t$, $\mathcal{I}_t$) is continuous in all arguments. Through these assumptions it can be understood that, for all states in the future, the decision to invest or to wait and see depends only on the current value of the state $\mathcal{R}_t$, not on the calendar time or the history of the process (Murto, 2006). This means that it is possible to divide the state-space into two different regions, divided by a threshold: the region to exercise where it is optimal to invest and the continue region where it is optimal to keep the option. For a one-dimensional framework, such as the one described above, where the investment is deterministic, this simply means that the optimal investment time is reached when $\mathcal{R}_t$ enters the region to exercise the option the first time. Hence, denote $\Theta \subset \mathbb{R}^n$ as the region to exercise and θ as the border of the region to exercise the option; then, the optimal timing problem is solved when the optimal threshold θ is found.

Following Dixit and Pindyck (1994), this optimal stopping problem in a continuous time frame can be solved by using the Bellman equation:

$$r \cdot OV(R_t) = \frac{1}{dt} E\left[dPV(R_t)\right], \tag{3}$$

where $d\mathcal{PV}$ ($\mathcal{R}_t$) is the derivative in *t*, which simply is the change in $\mathcal{PV}$ ($\mathcal{R}_t$) caused by $\mathcal{R}_t$ in a small time step *dt*. The left-hand side of (3) is the normal return per unit time that the manager, using the discount rate r, would require to hold the asset. On the right-hand side of (3), the term is the expected gain of holding the asset. This results in a no-arbitrage condition, expressing the willingness of the investor to hold the asset (Dixit and Pindyck, 1994).

Now let us imagine what will happen in the region to exercise the option, i.e. where it is optimal to invest. If the investor behaves rationally, he will invest immediately, which implies that in this region the option value must be equal to the net present value of the project, which implies that

$$OV(R_t^*) = NPV(R_t^*) \quad (4)$$

This is the so-called "value-matching condition", because it matches the values of the unknown function $\mathcal{OV}$ ($\mathcal{R}_t^*$) to those of the known payoff function *NPV* ($\mathcal{R}_t^*$). Now there are two boundary conditions to find the optimal threshold θ. Most real options literature considers one additional boundary, the so-called "smooth-pasting condition," which requires that the functions not only match but also meet tangentially at the boundary (Dixit and Pindyck, 1994 p.209)

$$OV_R(R_t^*) = NPV_R(R_t^*) \quad (5)$$

With these conditions we are able to solve the differential equation, which results from the Bellman equation (3). The exact solution is shown in section 3.3 for the case of revenue and investment uncertainty.

3.2.2 Extension – adding investment uncertainty

In the previous section, the general problem of finding the optimal investment timing using the real options theory with one uncertain state variable was considered, keeping the exercise price of the option (i.e. the cost of undertaking the investment) constant. In the following, the exercise threshold price is also considered as an uncertain investment. In this case the value of the option *OV* (R_t,I_t) and the net present value *NPV* ($\mathcal{R}_t$, $\mathcal{I}_t$) depend not only on the uncertain revenues but also on the uncertain investment. Then it is necessary to find the whole region of values ($\mathcal{P}$, $\mathcal{I}$) where the investment will occur and the critical boundary or threshold curve (Dixit and Pindyck, 1994, p.207).

As in the case before the optimal timing problem is now an optimal stopping problem and the main issue is to find the threshold of the border between the region to exercise and the region to wait and see. As this is mathematically difficult, we only consider a special case where the option value ($\mathcal{R}_t$, $\mathcal{I}_t$) is homogenous of degree *h* = 1 in ($\mathcal{R}_t$, $\mathcal{I}_t$), which means that

$$OV(hR_t, hI_t) = h \cdot OV(R_t, I_t) \quad (6)$$

In this case, the problem can be solved by reducing the problem to one state variable (Dixit and Pindyck, 1994, p.210):

$$\Theta = \left\{ (R, I) \mid \frac{R}{I} \geq \theta \right\} \quad (7)$$

This means that the optimal region to exercise is in the ($\mathcal{R}_t, \mathcal{I}_t$) space which can be easily proved by using the fact that the option value is homogenous (Murto, 2006). For more details see McDonald & Siegel (1986) or Murto (2006).

3.3 Model with uncertainty in revenues and investment costs

The aim of this section is to create a model to solve the optimal stopping problem that was introduced in the preceding chapters. First, we obtain an analytical solution for a case with two stochastic variables and identify the important parameters that influence the solution. In a second step, we calculate a numerical model.

3.3.1 Analytical solution

Consider the optimal time to build a new wind farm that produces a certain expected amount of energy for 25 years and creates revenues that are uncertain and could change from year to year. Please note that it is assumed that the revenues for the whole lifetime of the project are known at the time of investment but the revenues change depending on the optimal investment time. That simply means that the investor knows the whole revenues of his project if he invests now but he does not know whether the revenues are higher or lower if he invests in the future. The only sunk cost of the investor are the investment cost, which include in this special repowering case the capital expenditure for the new project, the salvage value of the used turbine, and the decommissioning costs of the old wind farm. In the following, all these costs are summarized under the term “investment costs” and considered uncertain. This model refers to the model of McDonald and Siegel (1986).

Often investment costs are assumed as decreasing over time due to learning effects, but in the case of repowering the investment could also increase due to the loss in salvage value. Therefore, it is useful to describe the investment cost development as a geometric Brownian motion. Details about the development of investment cost can be found in section 3.4.

$$\frac{dI}{I} = \mu_I dt + \sigma_I dz_I \tag{8}$$

In eq. (8) μ_I represents the drift of the investment cost, σ_I the volatility and dz_I is a Wiener process. The expectation of this geometric Brownian motion is

$$E[I_t] = I_0 e^{\mu_I t}, \tag{9}$$

where $\mathcal{I}_0$ is the investment cost at time $t = 0$. Likewise, the revenues, denoted at time t by $\mathcal{R}_t$, are assumed to follow a geometric Brownian motion

$$\frac{dR}{R} = \mu_R dt + \sigma_R dz_R \quad , \tag{10}$$

where μ_R represents the drift of the revenues, σ_R the volatility, and dz_R is the Wiener process. This seems to be reasonable due to the fact that the revenues are mainly driven by the power price. As the power price shows a clear upwards drift in the long-term view, it seems to be reasonable to model the revenues with a geometric Brownian motion. In section 3.4 this will be shown in more detail. The expectation of this motion is of course

$$E[R_t] = R_0 e^{\mu t} , \tag{11}$$

where $\mathcal{R}_0$ is the revenue at time $t = 0$. It is worth noting that σ changes the uncertainty but has no influence on the expected price path. When repowering has been completed successfully, which means that the new wind park has been built, it produces the revenue stream $\mathcal{R}_t$ forever. Without loss of generality, we can even allow the uncertainty of $\mathcal{R}$ and $\mathcal{I}$ to be correlated due to macroeconomic shocks (Dixit and Pindyck, 1994, p.207).

$$E[dz_R dz_I] = \rho dt \, . \tag{12}$$

Moreover, once the investment is made, further investment uncertainty in investment costs is irrelevant, and the value of the future revenues at time t is simply the expected discounted sum of future revenues:

$$\kappa(P_t) = E\left[\int_{s=t}^{\infty} R_s e^{-r(s-t)} ds\right] = \int R_t e^{\mu(s-t)} e^{-r(s-t)} ds = \frac{R_t}{r - \mu_R} \, . \tag{13}$$

In (13) r is the discount rate for the revenue stream. The net present value at the moment of investment is thus

$$NPV(R_t, I_t) = \frac{R_t}{r - \mu_R} - I_t \tag{14}$$

and the option value the same as in (1). Applying (14), (1) results in

$$OV(R, I) = E\left[e^{-r\tau} \left(\frac{R_\tau}{r - \mu_R} - I_\tau\right)\right], \tag{15}$$

where τ refers to some future time when the process starts. As already mentioned in section 3.2.2, the solution of the problem must be a region to exercise in the ($\mathcal{R}_t, \mathcal{I}_t$) space. We assume that (15) is homogenous in such a way that (6) is valid for this equation. In this case, as shown in section 3.2.2, the optimal region to exercise Θ is of the form:

$$\Theta = \left\{ (R,I) \mid \frac{R}{I} \geq \theta \right\}, \tag{16}$$

where the threshold parameter θ is a constant. If (6) holds, it is possible to write

$$OV(R,I)/I = OV(R/I,1) = Iov(\frac{R}{I}) = Iov(\theta). \tag{17}$$

Equation (16) means that the optimal solution is to invest at the first moment when R/I rises above some threshold level θ. The problem is to find this threshold. With this in mind, let us now return to the general problem in section 3.2.1, and use the Bellman equation (3). By using Itô's Lemma for two dimensions and the fact that both the investment costs and the revenues follow a geometric Brownian motion (GBM), we obtain

$$dOV(R,I)] = \left(\frac{1}{2} OV_{RR}\sigma_R^2 R^2 + OV_{RI}\sigma_R\sigma_I\rho RI + \frac{1}{2} OV_{II}\sigma_I^2 I^2 \right) dt + OV_R\mu_R R dt + OV_I\mu_I I dt\,, \tag{18}$$

where OV_{RR} and OV_{II} refer to the second derivatives of OV with respect to R or I. Dividing eq. (3) by dt,it takes the following differential form (McDonald & Siegel, 1986):

$$\ldots^2 + OV_{RI}\sigma_R\sigma_I\rho RI + \frac{1}{2} OV_{II}\sigma_I^2 I^2 \Big) - rOV(R,I) + OV_R\mu_R R + OV_I\mu_I I = 0 \tag{19}$$

To solve the differential equation, differentiation of OV is necessary. Using the fact that OV is homogenous, successive differentiation gives:

$$\begin{aligned} OV_R(R,I) &= I * \frac{\partial ov(\theta)}{\partial \theta}\frac{\partial \theta}{\partial R} = Iov^{'}(\theta)\frac{1}{I} = ov'(\theta) \\ OV_I(R,I) &= I\,\frac{\partial ov(\theta)}{\partial I}\frac{\partial \theta}{\partial I} = ov(\theta) - \theta ov^{'}(\theta) \\ OV_{RR}(R,I) &= \frac{ov^{''}(\theta)}{I} \\ OV_{II}(R,I) &= \theta^2 ov^{''}(\theta)/I \\ OV_{RI}(R,I) &= -\theta ov^{''}(\theta)/I \end{aligned} \tag{20}$$

This enables us to solve the differential equation (19) and we can write

$$\ldots_R^2 - 2\rho\sigma_R\sigma_I + \sigma_I^2 \Big)\theta^2 ov^{''}(\theta) + (\mu_R - \mu_I)\theta ov^{'}(\theta) - r - \mu_I ov(\theta) = 0. \tag{21}$$

This is an ordinary differential equation for the unknown function $ov\ (\theta)$, which can be solved by using the known boundary condition as presented in section 3.2.1. The value-matching condition becomes

$$ov(\theta) = \frac{\theta}{r - \mu_R} - 1 \quad (22)$$

and the two smooth pasting conditions become

$$\begin{aligned} ov'(\theta) &= \frac{1}{r - \mu_R} \\ ov(\theta) - \theta ov'(\theta) &= -1. \end{aligned} \quad (23)$$

It is worth noting that only two of these three boundaries are necessary to solve (21), as one can be derived by the other two. Introducing a solution in the form of

$$\mathrm{ov}(\theta) = d\theta^{\beta} \quad (24)$$

where d is a constant and β can be derived by the differential equation (21), we find the optimal threshold as

$$\theta = \frac{\beta}{\beta - 1} \quad (25)$$

and (21) in the form of

$$(\sigma_R^2 - 2\rho\sigma_R\sigma_I + \sigma_I^2)\beta(\beta - 1) + (\mu_R - \mu_I)\beta + \mu_I - r = 0. \quad (26)$$

By using (26), it is possible to calculate β. As long as $\mu_r < r$, (26) will have both a positive and a negative root, but only the positive root makes economic sense. Moreover, if

$$-\frac{\mu_R - \mu_I}{\sigma_R^2 - 2\sigma_R\sigma_I + \sigma_I^2} + \sqrt{\left(\frac{\mu_R - \mu_I}{\sigma_R^2 - 2\sigma_R\sigma_I + \sigma_I^2} - \frac{1}{2}\right)^2 + \frac{2(r - \mu_I)}{\sigma_R^2 - 2\sigma_R\sigma_I + \sigma_I^2}} \quad (27)$$

$\mu_r < r$ ensures that $\beta > 1$ and the simple NPV rule is grossly in error (Dixit and Pindyck, 1994). If $\mu_r > r$, then the growth rate of the project's value is expected to exceed the discount rate. Consequently, the value of the investment opportunity would be infinite, and it will never pay to invest (McDonald and Siegel, 1986). As can be seen in (27), β depends on six parameters: (1) volatility of revenues σ_R, (2) volatility of investment σ_I; (3) correlation of investment and revenue volatility ρ; (4) drift rate of revenues μ_R; (5) drift rate of investment μ_I; and (6) discount rate r.

3.3.2 The correct discount rate

In the previous section, r, the rate at which future payoffs are discounted, was taken as given. According to McDonald and Siegel (1986), the discount rate r, 'which is the equilibrium expected rate of return on the investment opportunity, must be a weighted average of the equilibrium expected rates of return on assets with the same risk as $\mathcal{R}$ and $\mathcal{I}$' (McDonald and Siegel, 1986 p.715). Let us assume that the option to invest is held by well-diversified investors who only need to compensate for the systematic risks of the investment. Using the Capital Asset Pricing Model (CAPM) (Sharpe, 1964, Lintner, 1965), the risk premium on a project is equivalent to the riskiness of an asset, calculated as

$$a = rf + b\vartheta_{IM}\sigma \tag{28}$$

where a is the required rate of return, rf is the risk-free rate, b is the market price of risk, ϑ_{IM} is the correlation between the return on the asset and the return of the market portfolio and σ is the volatility, i.e. a measure of the risk of the project. The second term on the right-hand side of (28) represents a premium, required by the investor due to the systematic risk of the investment. Comparing (28) with the unanticipated component of the return on the investment opportunity, which can be obtained by taking an Itô derivative of the option value, it can be found that r is given by

$$r = \beta a_R + (1-\beta)a_I \tag{29}$$

where a_R and a_I are determined by (28). Applying (29) in (27) and rearranging the terms leads to the following solution:

$$-\frac{\delta_R-\delta_I}{\sigma_R^2-2\rho\sigma_R\sigma_I+\sigma_I^2}+\sqrt{\left(\frac{\delta_R-\delta_I}{\sigma_R^2-2\rho\sigma_R\sigma_I+\sigma_I^2}-\frac{1}{2}\right)^2+\frac{2\delta_I}{\sigma_R^2-2\rho\sigma_R\sigma_I+\sigma_I^2}} \tag{30}$$

where $\delta_R = a_R - \mu_R$ and $\delta_I = a_I - \mu_I$.

Equation (30) shows that the drift does not influence the optimal investment trigger directly, but that the investment rule is affected by the difference between the drift and the required rates of return. The greater δ_R, the greater is the cost of holding the option and thus the investment will optimally occur at a lower threshold, while an increase in δ_I has the opposite effect (McDonald & Siegel, 1986, p.717).

3.3.3 Forecasting the optimal investment time

With the ROA shown above, the optimal threshold value θ is determined by the parameters of the GBM for the revenues and the investment. However, one assumption for the analytical solution in section 3.3.1 was the independency of time. Hence, it is reasonable that our model remains silent about the optimal timing of repowering. It is, however, essential for rational investors to know after which lifetime repowering is economically feasible (Madlener and

Schumacher, 2011). Following Rohlfs and Madlener (2011), the revenue and the investment cost development is used to determine the optimal time for the investment.

Forecasting the date when θ is reached can be done by tracking the revenue and the investment cost vector, as both follow geometric Brownian motions. Due to the volatility in the Brownian motion, no exact date can be determined but only a distribution for the optimal timing. The distribution of the revenue and the investment vector is given by the expected value of the covariance between the investment and the revenue streams and the probability density function (Rohlfs and Madlener, 2010, p.16). To obtain an analytical solution, the joint probability density function of revenues and investment has to be deducted and integrated. Because of the complexity of this analytical approach, a Monte Carlo simulation is used to determine the optimal timing. Therefore, the stochastic revenue and investment processes are simulated, starting with a known value and checking at each discrete time whether the threshold value has been exceeded. In this case the actual time is used to find the distribution in time (Rohlfs and Madlener, 2011, p.250).

It is worth noting that this approach leads to an important inaccuracy. Once the irreversible decision is made, a future decline in prices will not reverse the investment decision, but in the calculation of the probability distribution, this price decline is considered, which has the effect that the investment will be made earlier than proposed by the simple model.

3.4 Estimating the model coefficients

The ROA described in the previous sections requires a set of variables and parameters in terms of the revenue and investment streams. In this section, we describe the methods and calculate the growth rate of the revenues, the learning curve of the investments, the volatility and the correlation coefficients.

3.4.1 Electricity price as geometric Brownian motion

Keeping the model as simple as possible, we assume that the electricity price (here: the NordPool spot market price) follows a GBM, which has the clear advantage that it is possible to obtain an analytical solution. Note that this can lead to inconsistencies, as the true process might be a multivariate Ornstein-Uhlenbeck or even some other process. According to Lo and Wang (1995), who have compared option values calculated with an Ornstein-Uhlenbeck process and a geometric Brownian motion, the error is on the order of 5%, which seems to be acceptable in real options applications. Moreover, Pindyck and Rotemberg (1999) showed that, in the case of energy prices, the rate of mean reversion is slow, which can be suggested for the NordPool market, so that the GBM assumptions may be a good approximation.

Assuming a GBM, it is necessary to estimate the growth rate and the volatility of the motion. A common way to do this is the use of the maximum likelihood function to estimate both parameters at the same time. The method estimates a growth rate for the daily NordPool electricity price between January 2000 and March 2011, which seems fairly high. It appears that the maximum likelihood method fails, as the underlying distribution of the process is not the one assumed. Rohlfs and Madlener (2011) describe the same observation when estimating a parameter value for the CO_2 prices.

Following Rohlfs and Madlener (2011), we use a least-squares approximation to compute the growth rate. Although the least-squares approximation gives a reasonable growth rate of 7.14% p.a. for the daily power price between January 2000 and March 2011, it must be noted that this growth rate could be imprecise. The reason for that is the fact that the least-squares approximation does not consider the interaction between the growth rate and the volatility of the process.

The annualized volatility of the geometric Brownian process is defined as the standard deviation of the yearly logarithmic returns (cf. Rohlfs and Madlener, 2011)

$$\sigma_P = \frac{(P_{t+1} - P_t) - \mu_P P_t (t+1) - \mu P_t t}{P_t}. \tag{31}$$

Using this method, the yearly volatility of the daily NordPool power price between January 2000 and March 2011 turns out to be 23.2% p.a., which is higher than other estimates, such as that described by Simonsen (2004), who calculated a volatility of 16% p.a. for the period from 1992 until 2004.

Note that the volatility above is the volatility of the power prices, not the one of the revenue stream. The revenues can be calculated as follows:

$$R = C \cdot FLH \cdot (P + V). \tag{32}$$

Here $\mathcal{C}$ represents the capacity of the installed turbine, $\mathcal{FLH}$ are the full-load hours per year, $\mathcal{P}$ is the power price, and $\mathcal{V}$ is the subsidy rate granted by the government. In addition to the power prices, the Danish government pays an incentive of 10 €/MWh for 10 years, but both together may not exceed 40 €/MWh. This incentive has the positive effect that a reduction in power prices does not influence the revenue stream in the same range. Some small adjustments on the volatility of the revenues are therefore made.

The uncertainty in full-load hours, caused by different wind levels, increases the total volatility, but the certainty in a part of the revenue stream has the opposite effect. Due to the fact that the investment is a repowering project, there are excellent wind data available, and the volatility in full-load hours is minor. However, the fact that parts of the revenue stream are secured decreases the volatility significantly.

Hence, we used a volatility of 12% p.a., which is roughly in line with financial models from project developers for the Base Case (E.ON, 2011).

3.4.2 Investment cost as geometric Brownian motion

Similar to the revenue stream, we assume that the investment cost stream follows a GBM with a specific drift and volatility. The investment cost drift is influenced by three main cost drivers; the capital expenditure (*C*), which includes the turbine, foundation, infrastructure, electrical package, and workforce; the decommissioning costs (*D*) of the old turbine; and the salvage value (*S*) of the used turbine.

$$I = C + D - S \,. \tag{33}$$

While the decommissioning cost could be assumed to be stable, the capital expenditure for onshore wind parks shows a constant learning curve, due to newer equipment and more experience in the erection of the parks and economies of scale. Nevertheless, this learning rate is expected to decrease in the future, as meanwhile onshore wind is a proven technology. Furthermore, it is obvious that the salvage value of the used turbines decreases over the lifetime of the project. As discussions with a number of wind experts across the whole of Europe have shown, most project developers do not consider the salvage value in detail (E.ON 2011, Zephyr Windkraft Nusbaum GmbH & Co. KG., 2011) It is common to assume that the salvage value and the decommissioning costs are equal.

In the Base Case we assume that the investment costs will show a slight downwards trend and use a drift rate of -0.5% p.a., which is in line with conservative estimates in the onshore market. Regarding the volatility of the investment cost, we assume a relatively low one, as most players in the market have secured equipment via long-term contracts. Hence, a volatility of 10% seems to be reasonable, especially because the estimation of the salvage value is uncertain.

3.4.3 Correlation of revenue and investment correlation

The two-factor real options model accounts for the correlation between the volatility of the investment and the revenue cash flows. As the volatility of the streams is already known, we can compute the correlation as follows (cf. Rohlfs and Madlener, 2010, p.21):

$$\rho = \frac{\sum_k^n [dz_R dz_I]}{\sqrt{\sum_k^n [dz_R(t)]^2} \cdot \sqrt{\sum_k^n [dz_I(t)]^2}} \tag{34}$$

Using (34), the underlying data set leads to a correlation of 0.10, which is used in the Base Case.

3.4.4 Discount rates for revenues and investment

As can be seen in eq. (30), the drift does not influence the optimal threshold directly, but the difference between the drift and the discount rate is important. According to McDonald and Siegel (1986, p.717), the parameter $\delta_R = a_R - \mu_R$ 'represents the portion of the required return on $\mathcal{R}$ that is forgone by merely receiving the price increases in $\mathcal{R}$. The greater δ_R the greater is the cost of holding the option which amounts to holding $\mathcal{R}$ directly.' However, as it is difficult to obtain a realistic value for a_R itself, the earnings-price ratio of an installed project is used, with earnings measured net of depreciation as an estimate of δ_R. This approach is explained by McDonald and Siegel (1986, p.710) as follows.

> *'For an installed and producing project, equilibrium requires that capital gains plus cash flow less depreciation equals the required rate of return on the project. The uninstalled project is not depreciating, so its expected price appreciation is less than the required rate of return by the cash flow net of depreciation which the project would have earned if it were installed. The earnings-to-price ratio, therefore, measures the extent to which μ_R is less than the required rate of return.'*

$$a_R - \frac{earnings}{price} = \mu_R \Leftrightarrow a_R - \mu_R = \delta_R = \frac{earnings}{price} \tag{35}$$

Taking this into account, we assume a_R to be 10% in the Base Case.

Regarding a_I, the discount rate would be equal to the risk-free rate if the investment cash flow is considered as deterministic. As this is not the case, we assume a discount rate of 3%, which is slightly above the risk-free rate.

3.5 Model application

In this section, we apply the model presented in section 3.3 above to determine the optimal investment threshold at which it becomes preferable to repower the project. Furthermore, we use a Monte Carlo simulation analysis for determining the time at which the optimal threshold will be exceeded for the first time.

However, before applying the model to a real case, more information is needed. As already mentioned in a previous section, the optimal threshold has the form:

$$\Theta = \left\{ (R,I) \mid \frac{R}{I} \geq \theta \right\}. \tag{36}$$

As the aim is to evaluate a fictitious wind park, the assumption is made that the wind park that should be replaced and the replacement are installed in the same year, but with different technical data and a different size, which leads to a specific revenue to investment ratio used as a starting point. To obtain this, in the following we summarize the key components of the investment cost cash flow as well as the components of the revenue stream.

3.5.1 Revenue stream of a repowering project

The revenue stream, which in our study is equal to the operational net revenue cash flow, includes all cash flows that are generated during the operation of the project. Cash flows that are related to the initial investment are not part of the revenue stream. Payment flows that are included are the earnings of the repowered project. These are the earnings for the supply of electricity to the grid, the compensation costs for lost earnings from the old project, and the operation and maintenance (O&M) costs of the new project, which are assumed to be stable.

Since the aim of our study is to simulate a fictional wind project, some assumptions have to be made. In the following, it is assumed that the original wind park consists of 4 x 450 kW turbines and that the three new turbines will be Vestas V90/2.0/125 with a capacity of 2 MW each. This leads to an expansion factor of 3.3. To calculate the power earnings, we use the current Danish incentives summarized in section 3.1: Specifically, we assume that both wind parks are owned by utilities and receive an incentive of 10 €/MWh for 10 years and additionally13 €/MWh for the whole lifetime of the project. In addition to that the new turbines receive a repowering bonus of 10.7 €/MWh for 12,000 full-load hours for twice the dismantling capacity. Note that all these incentives are additional to the NordPool power price. Furthermore, we assume that even today the availability of the used turbine is 2% lower than the availability of the new turbine. Referring to project developers, the project will be calculated over a 25-year lifetime. The detailed revenue structure can be reviewed in Table A.2 in the Appendix.

3.5.2. Investment stream of the repowered project

The investment cash flow consists of the acquisition costs of the turbine and additional expenses, like the development, civil works and grid connection costs. The cost structure for repowering differs from the investment cash flow for a greenfield project. Especially the decommissioning costs but also the salvage value of the used turbine has to be taken into account. Furthermore, a repowering project requires less development and infrastructure costs, as often a part of the existing infrastructure can be obtained.

Without loss of generality, it can be assumed that repowering projects do not require any expenses for meteorological analysis and require fewer expenses for infrastructure. In the Base Case assumptions, it is assumed that the salvage value of the used turbine is equal to the decommissioning cost of the old wind park. We will ease this restriction later to determine how much the salvage value will influence the optimal time to exercise the option. The detailed investment cost stream can be seen in Table A.4 in the Appendix.

4 Results

In this section, first the basic assumptions are summarized and then the model results presented. This is followed by sensitivity analyses for the quotient threshold at which it becomes economical to invest. The parameters varied are the real discount rate of the revenue stream δ_R, the volatility of the revenue stream σ_R, the real discount rate of the investment stream $\delta_{I,}$ and the volatility of the investment stream σ_I. Then, the correlation between investment and revenues is presented. The Base Case assumptions summarized in section 4.1 are used for the computations.

4.1 Base Case results

In this section, the Base Case results calculated with the values obtained in section 3.4 are presented. According to eq. (25) and eq. (27), the input factors reported in Table 3 are needed to calculate the threshold value at which an investment in repowering is optimal.

Table 3: Model parameterization for the Base Case

Parameter	μ_R	σ_R	$\mu_{I,I}$	σ_I	P	α_R	α_I
Parameter value	7.14%	12%	-0.5%	10%	9.14%	10%	3%

Applying these values to (28) and (26) results in a threshold value of 1.99514, which means investment is optimal at the time when revenue cash flows are twice the investment costs. Note that this is in stark contrast with regard to the standard discounted cash flow (DCF) method, where investment should be done when the discounted revenues exceed the costs. The quotient (*R*/*I*) adopted for the production year of the repowered turbine is 0.88, a value calculated based on practitioners' cost assumptions (E.ON, 2011) and the NordPool electricity spot market price in March 2011. To compute the optimal timing as described in section 3.3.3, Monte Carlo simulation is used. Therefore, the quotient of the correlated GBM, with the parameters above and a starting threshold value of 0.88, is modeled. Results of this can be seen in Fig. 2, where the cumulative probability is shown for each year that the threshold has been exceeded and repowering should be done. The solid line shows the probability for the Base Case, whereas the dotted line shows the probability for the case with certain revenues. A strongly increasing probability after year 8 can be seen in this case. At the end of the observed time interval the total probability is 98%. In case of uncertainty (σ_R=0.12) the probability increases much slowlier, although it is higher in the earlier years, and does not exceed 50%.

The period between 10 and 15 years is the time frame in which most repowering activities can be observed; the probability that repowering is feasible increases from 17.2% to 27.5%. This low probability of success could be one reason why developers are currently complaining about the minor repowering incentives (see section 2.2). According to Fig. 2, higher secured revenues that result in a less risky revenue stream could raise the probability of success significantly. The high uncertainty of the revenue stream is a nature of the Danish incentive system (see section 2.1.3) where utilities receive a premium on top of the fluctuating NordPool power prices. In contrast to that the case with certain revenues reflects a German system where investors receive a fixed tariff over the entire lifetime of the project. In the next section, the results of the threshold sensitivities are presented.

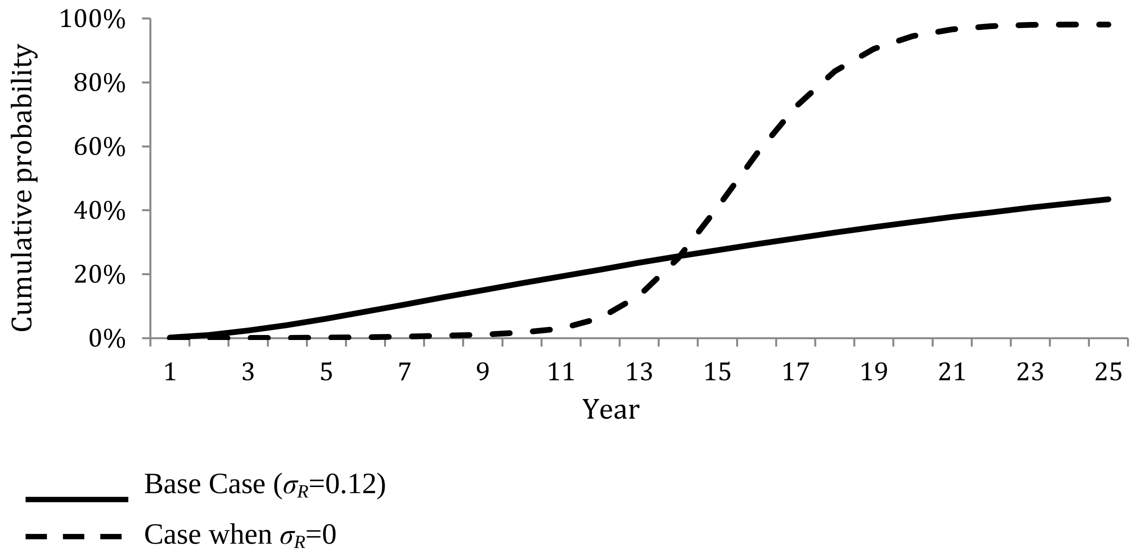


Fig. 2: Cumulative probability for repowering to reach the threshold value in each year, Base Case and case when σ_R=0

4.2 Threshold sensitivity

Following our Base Case assumptions, a risk-adjusted discount rate of 10% for the revenues and a 3% discount for the investment cash flows are used. Fig. 3 summarizes the parameter variations with respect to the threshold value. The greater δ_R, the greater are the costs of holding the option, as the discounted future cash flows are low (McDonald and Siegel, 1986). As can be seen in Fig. 3(a), a high real discount rate in revenues leads to a lower threshold and therefore to an earlier investment.

The sensitivity in δ_I shows the opposite effect; a higher discount rate results in a higher threshold value, as the discounted future costs are lower than today's cost. Recalling that $\delta_I = \alpha_I - \mu_I$, the real discount rates increase if the drift μ_I is zero or negative. This leads to a descriptive way of explaining the rising threshold in rising δ_I, as a negative investment drift means that in the future less investment costs are required than today.

The sensitivity of the threshold, in terms of revenue and investment uncertainty, is demonstrated by altering the values of the volatility of the revenues σ_R and the investments σ_I. (see Fig. 3 plots (c) and (d)). It can be seen that increasing volatility, no matter whether the volatility of the revenues or of the investments is taken, results in a higher threshold value. Uncertainty about future cash flows leads to a deferral in investment decision. A change in volatility level from σ_R=0 to 0.5 causes more than a threefold increase in the threshold value.

Figure 3(e) shows the variation of the correlation coefficient between investment and revenue. Here an increase in correlation causes a decrease in the threshold value. According to Rohlfs and Madlener (2011), the explanation for this is the value of waiting. Imagine that an increase in revenues, which makes the project economically more attractive, is connected to an increase in investment cost. In this case the overall benefit of the project is lower, and therefore the value of waiting is lower. Another possible explanation is the reduction of uncertainty due to the correlation between the cash flows. As mentioned above, less uncertainty leads to a decrease of the threshold value.

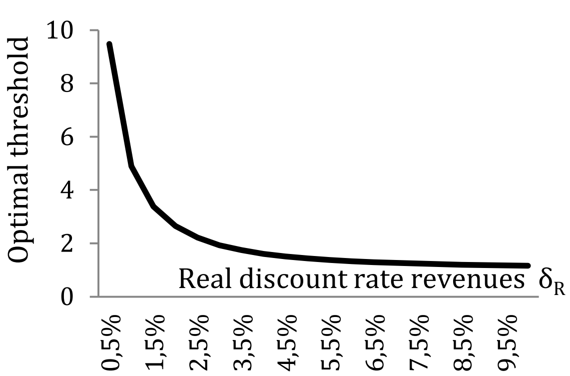
Table 4 shows the qualitative behavior of the threshold value as a function of a variation of the revenue growth rate δ_R, the volatility of the revenue stream σ_R, the growth rate of the investment δ_I, the volatility σ_I, and the correlation between the cash flows ρ.

Apart from the direct effect on the optimal threshold, the factors above also influence the cumulative probability to exceed the revenue to investment ratio in a particular year. Especially lower volatilities in revenues and investments have a decreasing effect on the threshold as well as an increasing effect on the probability of success (Fig. 2 and Fig. 3). Regarding the probability of success, it is worth noting that the effect of the revenue volatility is much higher than the volatility of the investment stream, which can be explained by the different drift rates for both streams. A higher drift rate in revenues leads to a larger effect of the revenue volatility.

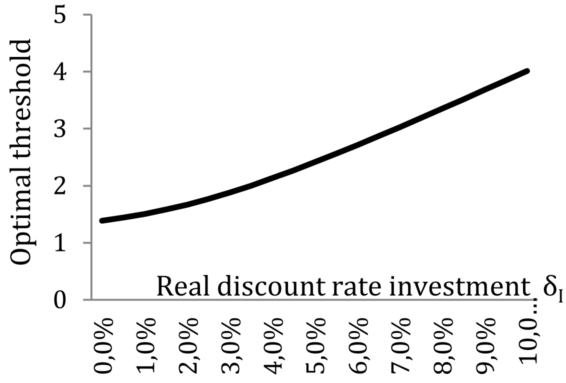
Table 4: Change of threshold value with regard to parameter variation

Parameter	μ_R	σ_R	μ_I,	σ_I	P
Sign of threshold change	-	+	+	+	-

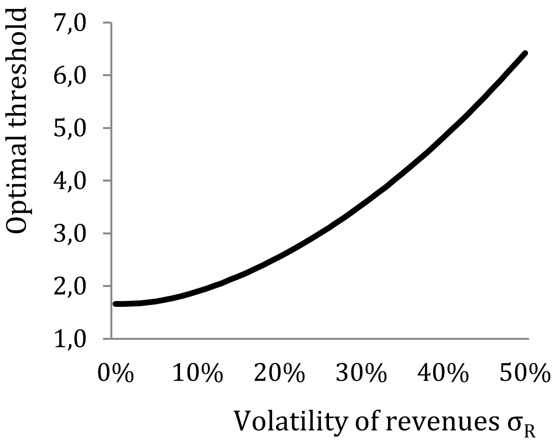
In the following, the influence of a higher incentive and an upper salvage value is evaluated. The Base Case assumptions presented in section 4.1 are again used. Figure 4 shows the difference in probability if the repowering bonus is paid for four times instead of only two times the dismantled capacity. This leads to a current quotient of 0.93 up from 0.88 in the Base Case. As can be seen, the difference between these cases in terms of the cumulative probability is minor (about 1-2%). Even if the current repowering incentive is abolished, the ratio between revenue and investment stream will only fall from 0.88 to 0.83 and there will be a minor change in the cumulative probability. A similar result can be observed if the Base Case and a case with a salvage value, as calculated in section 3.4.2, are compared with each other. As a result of the salvage value of €134,373, the current quotient raises to 0.95 and the cumulative probability is slightly above the one in the Base Case (Fig. 5).



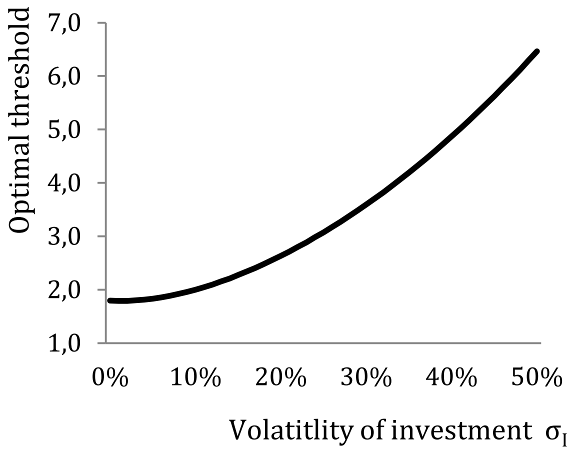
(a) Variation of δ_I



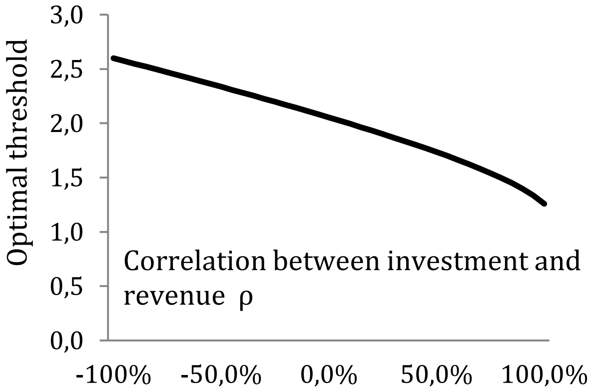
(b) Variation of δ_R



(c) Variation of σ_R

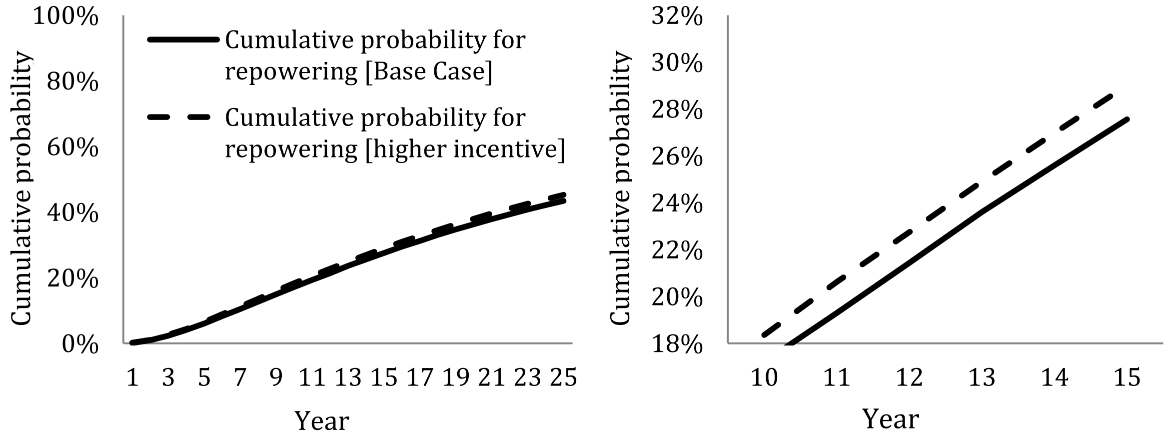


(d) Variation of σ_I



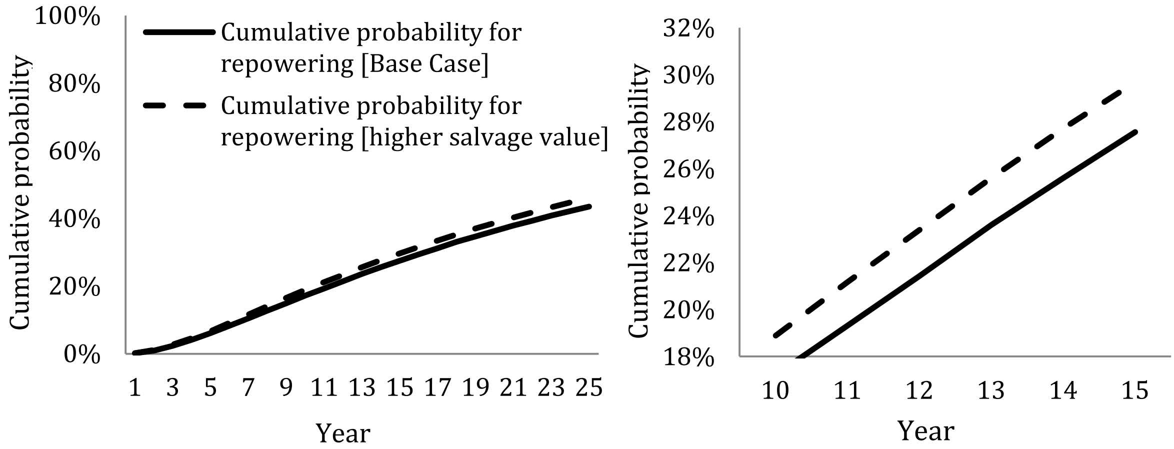
(e) Variation of $\rho_{R,I}$

Fig. 3: Parameter variations using the 2-factor model



(a) Periods 1 -25 (b) Period 10 to 15 years (display detail)

Fig. 4: Cumulative probability of repowering, comparison between Base Case and case with higher incentive



(a) Periods 1 -25 (b) Period 10 to 15 years (display detail)

Fig. 5: Cumulative probability of repowering, comparison between Base Case and case with higher salvage value

To sum up, the influence of the salvage value and changes in the incentive level have only a minor effect on the optimal timing decision. The overall probability to repower remains the same, with the result that investment in repowering is fraught with risk, and the probability of success will not exceed 50%.

5 Conclusions

In this paper we have applied the two-factor real options model of McDonald and Siegel (1986) for determining the optimal investment timing in repowering an onshore wind park. The model allows the consideration of the investment costs as well as revenues, both following a stochastic process. Using Denmark as a potential repowering market, we present a short overview of the historical development of the onshore wind industry and the corresponding incentive schemes.

The study demonstrates that the probability of success for repowering depends mainly on the volatility of the revenue stream and less so on the selling price of the used turbine. Volatility of the revenue stream will decrease the threshold directly as well as increase the cumulative probability for each year that repowering should be done. Therefore, wind developers should argue for a larger stake of secured parts in revenues, achievable via higher governmental guaranteed incentives. As mentioned in section 4.2, the volatility of the revenue stream has a larger influence on the probability of success than the investment-related volatility. In contrast to the volatilities, the salvage value of the used turbines has no effect on the optimal threshold and only a minor impact on the probability of success. Therefore, it is reasonable that wind developers around the world do not focus on selling their used turbines but instead assume that the value of the used turbine and the decommissioning costs are equal.

We assume that repowering should be considered after a lifetime of 11 to 15 years, with a cumulative probability of 21% and 30.5%, respectively. At a first glance, 30.5% seems to be too low to consider repowering, but it should be possible to reduce uncertainty with detailed project-based calculations, especially as most project developers have a well-modeled view of power prices based on different scenarios. Also, it is clear that every investment decision is prone to uncertainty.

To conclude, it can be said that both project developers and scientists should focus on price developments of new turbines and not on the time-consuming evaluation of the second-hand turbine market. Nevertheless, some research has to be conducted to examine what the possibilities for governments are to attract repowering.

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Appendix: Base Case assumptions

Table A.1: General assumptions

Category	Unit	Amount
Size of wind park	[No. of turbines]	6
Interest rate	[%]	6
Type of turbine	-	Vestas V90/2,0/125
New turbines:		
WTG size	[MW]	2
WTG price	[€/WTG]	2,224,348
No. of WTG	-	3
WTG size, new/old	[MW]	3.3
Full-load hours	[h/a]	2850
Repowered turbines:		
Park size, old	[MW]	1.8
Full-load hours	[h/a]	2750

Source: Own compilation, based on E.ON (2011)

Table A.2: Net revenue stream in detail

Revenue category	Unit	Amount
Net revenues	[€]	**8,115,715**
FLH new turbine	[h/a]	2850
FLH old turbine	[h/a]	2750
Power price	[€/MWh]	52
Incentive (feed-in tariff)	[€/MWh]	13
Operational costs:		
Old	[€/MWh]	1,721,879
New	[€/MWh]	4,337,856
Gross revenues, old turbine	[€/MW]	**4,183,768**
Repowering bonus (paid for 5 a)	[€/MWh]	10.7
Gross revenues, new turbine	[€/MW]	**14,915,460**

Source: Own compilation, based on E.ON (2011)

Table A.3: Operational costs in detail

Cost category	Unit	Amount
Maintenance	[€/MWh]	**41,000**
WTG maintenance	[€/MWh]	2
Substation maintenance	[€/a]	6,800
Repairs	[€/MWh]	**6**
Power cost	[€/a]	**10,000**
Land lease	[€/MW/a]	**25,000**
Insurance	[€/a]	**30,000**

Source: Own compilation, based on E.ON (2011)

Table A.4: Investment cost stream in detail

Cost category	Unit	Amount
Total investment cost	[€/MW]	**1,382,531**
Development (acquisition price, project development, meteorological analysis etc.)	[€/MW]	**80,000**
Civil works (foundations etc.)	[€/WTG]	**250,000**
Electrotechnical equipment	[€/WTG]	**45,000**
Wind turbines	[€/MW]	**1,112,174**
Infrastructure (crane, roads on site, site facilities etc.)	[€/WTG]	**25,714**
Grid connection	[€/MW]	**30,000**
Decommissioning costs	[€/MW]	**28,500**
Salvage Value	[€/MW]	**28,500**
Financing costs	[%]	**2**

Source: Own compilation, based on E.ON (2011)

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