Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 75 (2015) 704 – 715

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Economic Viability of Kite-Based Wind Energy Powerships with CAES or Hydrogen Storage

Matthias Schmitz[a], Reinhard Madlener[b]*

[a]RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany
[b]Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Matthieustrasse 10, 52074 Aachen, Germany

Abstract

The rise in the usage of renewable energy technologies in recent years has been remarkable. Still, the growth of these technologies poses formidable problems, mainly concerning the grid integration of intermittent energy sources, such as wind and solar power, by means of advanced storage systems, as well as the land use requirements implied by these low energy density resources. Furthermore, the economic viability of these solutions is in question, which is why to date they are often still heavily subsidized. The Powership concept attempts to tackle some of these shortcomings by harvesting wind energy offshore using an alternative infrastructural approach featuring a special-purpose ship towed by a high-flying kite. The ship's resulting kinetic energy is partially converted by a water repeller and can either be used to compress and store air in steel tubes (Alternative 1) or to drive a generator which in turn delivers electrical energy to produce hydrogen (Alternative 2). In this study, the economic feasibility of each of the two alternatives is investigated and compared with each other using real options analysis, including both R&D and market risks as stochastic variables driving the option value. For determining the strategic value of managerial flexibility under uncertainty, assumptions about changes of the economic environment are made and motivated.

Peer-review under responsibility of Applied Energy Innovation Institute

Keywords: Wind power; Kite; CAES; Hydrogen; Real options analysis; Monte Carlo simulation

1. Introduction

CO_2 emissions arising from the combustion of fossil fuels are widely considered to be the leading cause of anthropogenic climate change [1]. This is why a majority of nations has committed itself to decreasing CO_2 and other greenhouse gas emissions in international treaties like the Kyoto Protocol. In many countries, electrical power supplies to date rely considerably on large-scale, centralized condensing plants. The increased use of renewable energy sources can be a viable measure to cut CO_2 emissions while

---

* Corresponding author. Tel.: +49-241-8049-820; fax: +49-241-8049-829.
E-mail address: RMadlener@eonerc.rwth-aachen.de.

Peer-review under responsibility of Applied Energy Innovation Institute
doi:10.1016/j.egypro.2015.07.497

simultaneously sustaining, or even increasing, power production. Wind power is one of the key renewable energy technologies. Due to its weather-dependent and thus intermittent performance profile and a lack of suitable storage systems, the integration of this technology into the electric grid is problematic. Furthermore, the issue of land use is gaining importance with the construction of an increasing number of onshore wind farms.

Building wind turbines offshore, where wind conditions are more favorable, can ease the effects of both fluctuating power production and increasing land use. On the one hand, the capacity factor is typically higher than for onshore turbines, and noise emissions are considered to be less critical [2]. On the other hand, both construction and maintenance costs of offshore wind farms are significantly higher due to the difficult environmental conditions [3]. Furthermore, negative effects of noise and vibration emissions on marine animals are an issue [4]. By using a mobile wind harvesting platform, the Powership concept described in Section 2 aims at exploiting the potential of offshore wind technology while simultaneously avoiding its major disadvantages.

As emerging technologies often involve operating in an uncertain environment, the calculation of the project's value includes many unknown variables. At the same time, management is given a certain flexibility to react to unfolding risks. The value of that flexibility is not adequately assessed in classical valuation approaches like the net present value (NPV) calculation. To address this issue, real options analysis (ROA) ([5], [6]) is used to calculate the value of an abandonment option in two different technical configurations of the Powership concept.

2. The Powership concept

2.1. Power generation technology

The Powership concept attempts to avoid some of problems mentioned above, while simultaneously benefiting from the advantages of wind energy. The basic idea is derived from the SkySails system, in which a high-flying kite connected to an electronic control unit is installed on conventional freight or fishing ships to reduce the engine load. SkySails has estimated the possible fuel savings to lie between 10 and 35% [7]. With the Powership concept, this idea is transferred to the level of power production: a fully automated special purpose ship is towed by a kite (the so-called "Sky Wing") and its kinetic energy converted by a water repeller. This energy can be stored either as compressed air in steel tubes or as hydrogen (H_2) produced by electrolysis. In altitudes of between 200 and 400 m, the wind blows more strongly and more steadily than closer to the surface. Wind forecasts are also more reliable, making it easier to predict the actual wind power production, which will decrease the need for backup power units. Furthermore, the issues of land use and noise emissions play a secondary role in offshore applications. Powerships are mobile units. In contrast to stationary offshore wind turbines, they do not need foundations in the seabed and can be assembled, maintained, and repaired in harbors, which may result in significant cost benefits. Besides, compared to wind turbines, they can be relocated to follow favorable wind conditions, which can result in a significantly higher capacity factor.

3. Investment decision-making under uncertainty

When making a decision in favor of or against an investment, the investor, to be able to act rationally, strives to gain as much information as possible about uncertainties and risks, but also chances associated with the project. The quality of such a valuation, consequently, depends both on the availability of reliable data and a valuation method which accurately reflects the economic environment.

3.1. Real options analysis

ROA has its origin in corporate finance, where an option in general describes the right – but not the obligation – to buy (call option) or sell (put option) an asset in the future by paying or receiving a certain pre-defined price [8]. ROA assumes an analogy between real options and financial options, because managerial flexibilities often follow the pattern described above, which means that the exercising of a real option at a certain time bears a financial value.

The option value is influenced by six variables (cf. [6]): (1) The *value of the underlying*: in corporate finance, the underlying of an option is the actual asset which may be bought or sold by exercising the option. Transferred to real options, the underlying is represented by an investment, an acquisition, or similar. If the value of the underlying changes, so does the option value. (2) The *exercise price*: represents the amount of money needed to exercise the option, i.e., to buy or sell the asset (financial options) or the flexibility (real options) bound to the option. The higher the exercise price of the option gets, the less attractive is its actual exercising, which is why its value decreases in that case. (3) *Time to expiration*: the longer it is possible to exercise the option, the more valuable it gets. (4) The *standard deviation of the underlying's value*: the standard deviation describes the expected volatility of the underlying's value. A rise in uncertainty concerning the development of the underlying's value increases the option value, as it becomes more likely that the underlying's value crosses the border at which an exercising is profitable. (5) The *risk-free interest rate*: a rising interest rate increases the option value. (6) *Dividends*: The distribution of dividends over the lifetime of the option, if available.

The value of options can be determined in many ways, of which closed-form solutions, partial-differential equations, and binomial lattices are the most common [5]. For closed-form solutions, such as the Black-Scholes model, a system of equations based on a set of assumptions is created. While the calculation of the option value can be executed in a quite simple way by inserting variables into the established formulas, the use of the Black-Scholes model is mathematically more demanding and suffers from limited modeling flexibility. A more intuitive and easily explained way of option valuation is the binomial lattice approach used in this study. The basic idea of the concept is that uncertainty at each stage of a project can be described by two alternative states, which are reached with the probability p or $1 - p$, respectively [9]. This is performed by multiplication of the value of the underlying with an upward ($u > 1$) or downward factor ($d < 1$) at each step. The factors u and d are calculated as:

$$u = e^{\sigma\sqrt{T/n})}; \quad d = 1/u = e^{-\sigma\sqrt{T/n}} \tag{1}$$

where σ denotes the volatility of the rate of return, T the lifetime of the option, and n the number of time intervals. The volatility parameter σ combines all the uncertainties in the development of the project's rate of return in one single variable. In a risk-free world, the volatility would be zero and hence the binomial lattice would be a straight line. If the volatility is not zero but can be calculated, a complete lattice showing the possible bandwidth of developments within a certain confidence interval can be created. Due to the vast number of possible combinations if multiple, different uncertainties are assumed, the determination of σ is not trivial. Although it is possible to base the calculation on stakeholders' estimates or historical values, these approaches cannot sufficiently incorporate the interdependencies between the different uncertainties [10]. Therefore, modeling and Monte Carlo simulation, can be used instead to meet the requirements of an adequate forecast. Mathematically, the volatility is represented by the standard deviation of the percentage variation in the project value from one time period to the next, denoted by z (see [6]), $z = \ln\left[\left(PV_1 - FCF_1\right) / PV_0\right]$, where PV_t is the project value at time $t = \{0, 1\}$, respectively, and FCF_1 the free cash flow at time $t = 1$. It is important to note that the denominator of the formula remains constant and only the numerator is simulated. The simulation finally yields the standard deviation and thereby the volatility of the rate of return, σ, which can be used to build up the binomial lattice in accordance with eq. (1). To do so, the option's lifetime is divided into equal time intervals Δt.

Each value at each time step can be reached by multiplying the base value of the underlying at t_0, denoted S_0, with the corresponding number of upward and downward movements. Thus, at the end of the first period, the value of the project can either be S_0u or S_0d, and so forth. The fact that u and d are each other's reciprocals leads to a so-called recombining lattice. This means that at time step 2, for example, both the lower branch of S_0u and the upper branch of S_0d lead to the middle node $S_0u^1d^1$. Furthermore, u and d are required to follow the inequality $u > 1 + r > d$. Otherwise, there would be a profitable possibility of a riskless investment.

Having the advantage of flexibility by utilizing real options means that each node where a real option is applicable now features two values: the first will be taken on by the project if the option is not exercised; the second one if it is. This leads to a situation in which low values in the lattice can be avoided (e.g. with an option to abandon, which limits the negative development for the respective node to the strike price) and that high values can possibly be increased even more (e.g. with an option to expand, which shifts the limit for the positive development upwards). The manager can thus analyze the lattice node by node and decide where the exercising of an option is suitable by simply choosing to exercise it if its value at that point in time is higher than the original one. This process has to be executed replicatively from the right-hand side of the lattice to the left, as eq. (1) still needs to be fulfilled when the value of a node changes. Consequently, the change of a value on the lattice's right-hand side can lead to the variation of other nodes' values, resulting in another starting value S_0. If an option exists and can be executed, each node is calculated again individually, as

$$S_{u^i d^j} = [p \cdot S_{u^{i+1} d^j} + (1-p) \cdot S_{u^i d^{j+1}}] / (1+r) \tag{2}$$

where p is the risk-neutral probability, defined as $p = \left(\left(1+r\right)-d\right)/\left(u-d\right)$. A detailed derivation of these equations can be found, e.g., in [6]. In order to keep track of the changes made and to be able to compare the different developments with and without option exercising, the creation of a second lattice using the above-mentioned equations is recommended. Finally, the option value can be calculated as the difference between the first entries of the two resulting lattices.

4. Application of ROA to the powership concept

4.1. Assumptions and limitations

The economic groundwork for the execution of a ROA is laid next. To this end, data from the firm providing the Powership technology concept (Fischer & Partner, Bonn) and literature is used to calculate the project's NPV. Note that the Powership concept is currently still in an early development stage, making it hard to estimate all relevant data correctly. Hence, to be able to execute on ROA anyway, some assumptions concerning the economic environment must be made, which cannot be backed up completely with measured or derived scientific data. This fact limits the validity of the present analysis.

Offshore operation subsidies: the German subsidy system is based on fixed feed-in tariffs for renewable energies that are combined with a purchase guarantee: the network operators must prioritize electricity from renewable sources before that from conventional sources. Thus, the assumption will be made that all the electric power produced in the Powership can be marketed at a fixed price. The price depends on the type, size, and implementation time of the energy source. In the case of offshore wind power, 0.15 € kWh^{-1} are granted if the site's startup is before the year 2015. The duration of this price guarantee is dependent on the distance to the shore and the water depth. In the base case, it is granted for twelve years; every nautical mile shore distance exceeding 12 miles extends that period by 0.5 months and every meter exceeding 20 m water depth by 1.7 months. After the grant has been phased out, the guaranteed tariff is cut back to 0.035 € kWh^{-1}. These rulings are stipulated in the German Renewable Energy Act [11]. As the legal text does not specify that only stationary wind turbines can be eligible for subsidy grants, it will be assumed that the subsidy is open to other technologies as well. As a result, the full subsidy of 0.15 € kWh^{-1} is assumed for the whole project lifetime because the Powership concept easily allows for wind harvesting in deep and far offshore regions of the sea. Note that fluctuations in the energy price at the European Energy Exchange (EEX) are not taken into account. However, the literature provides numerous analyses of the pricing mechanisms at the EEX ([12]-[15]).

Tax considerations: the calculation will be carried out under the assumption that apart from the German VAT of 19%, no more energy-related taxes are levied. That assumption holds for electricity which has been produced from renewable sources to date. However, as the share of renewables rises, the possibility of an additional tax on electricity and H_2 cannot be excluded.

Permission and insurance: the Powership is supposed to operate automatedly without a crew controlling it. Therefore, it must be assumed that permission to run unmanned ships offshore has been given. The fact that the German government as recently as 2011 passed a law allowing and regulating the traffic of unmanned air vehicles [16] lets this grating of permission seem likely. In comparison, the risk caused by relatively slow vessels at sea seems manageable. Based on this, it is also assumed that insurance companies will agree to cover the operation of the ships.

Number of Powerships: as mentioned above, it is assumed that all produced electricity can be sold under the Renewable Energy Act. The demand, however, is finite. Apart from that, the actual demand and therefore the number of Powerships to be built are difficult to foresee because of the early-stage development process. The presented model thus focuses on the operation of a single unit over its expected lifetime. Further research is needed to include economies of scale to form a more complete forecast. In order to reflect the non-manufacturing cost realistically, first-year operational cost, as estimated by Fischer & Partner, is included as a one-time lump sum payable at the beginning of the project. As those costs would not occur again for each additional unit, further R&D costs are not included in turn.

4.2. Data used

4.2.1. Investment and operating costs

Although a comparable technology does not exist to date, some of the experience from other renewable energy sources, especially offshore wind energy, can be taken into account for an estimation of the required data. This applies, for example, to the expected lifetime of components like repeller, drive unit, or generator. Those are utilized in wind turbines in a more or less similar form, which is why the lifetime of the Powership is estimated to be 20 years, the same as an average wind turbine [17].

The expected cost for the Powership itself including a steel hull, the complete Sky Wing system, an electric maneuvering control and propulsion system, but not energy storage, is supplied by Fischer & Partner. As that number does not include costs for traffic control, onshore logistics, and supply ships, it is multiplied by an estimated factor of 1.25, resulting in a total cost of €898,125 per unit. The cost of first-year operation, as discussed in section 4.1, sums up to an estimated €616,200. Since different storage solutions are analyzed, the cost for the storage system is assessed separately.

Compressed air tanks: having a low energy density, the main cost of that technical solution is caused by the steel bottles storing the air. Cyphelly et. al. [18] estimate those at 71 € kWh^{-1} and the cost of the energy conversion system at 284 € kW^{-1}, resulting in a total storage cost of €4,612,160 if a storage capacity corresponding to 24 hours of full-load operation at 2,320 kW electric power output is assumed.

Hydrogen storage: Concerning the actual H_2 production, an electrolyzer is needed, the cost of which is assumed at 600-800 € kW^{-1}. Based on this estimate, an average cost of 700 € kW^{-1} is chosen. Additionally, tanks, water filters and demineralizers, a generator, and pumps have to be supplied.

Carbazole: For the analysis, the utilization of N-ethylcarbazole will also be assessed. Its future cost is hard to foresee, since production to date has only taken place on the laboratory scale. Chemically, N-ethylcarbazole is a hydrocarbon compound and can be found in crude oil and coal tar. Therefore, its cost is estimated at 2 € kg^{-1}, which is in the vicinity of the sales price of other hydrocarbons like petrol. The total storage system cost adds up to €1,176,000 if a 1,500 kW electrolyzer is chosen.

In a recent study, VDE [19] predicts that the cost of H_2 production and storage will decrease from around 0.25 € kWh^{-1} today to 0.1 € kWh^{-1} (corresponding to 3.33 € kg^{-1}) in ten years. Without further assessment of the technology considered and assumptions made by the VDE, this additional option is also taken into account as an alternative approach because the Powership technology is still in a very early stage of development, still leaving ample room for variety, technological competition, and the evolvement of different trajectories.

4.2.2. Power generation efficiency, electricity and hydrogen prices

Fischer & Partner estimate the power available at the repeller shaft at full load at 2,320 kW. Following the different storage approaches mentioned above, that power can either be used to compress air or to produce H_2 from electrolysis. For the adiabatic storage of compressed air, an overall efficiency of the complete compressing and expanding process of 60% is assumed [19]. In the H_2 production and storage chain, each step involves efficiency losses. A typical generator reaches 90% efficiency, water electrolysis ca. 72%. The final storage and discharge losses in carbazole are around 32%, leaving an effective power for H_2 production of 1,020 kW, which equals ca. 30.6 kg of H_2 per hour at a lower heating value of 33.33 kWh kg^{-1}. As mentioned in section 2.3, H_2 allows for the use of different distribution channels, of which the direct sale will be analyzed here. Thereby, no additional investment cost for a fuel cell on land has to be taken into account. The sales price of H_2 is set to 5 € kg^{-1} [20]. When evaluating the performance of a wind power plant, the net capacity factor, i.e., the ratio of the actual and the nameplate capacity energy output over a certain time period, is a key number. In the present case, offshore wind parks can serve as evidence for estimating the capacity factor. Alpha ventus, the first large offshore wind park in Germany, reached a capacity factor of around 50% in 2011 [21]. As described above, Powerships are mobile and can be relocated easily to spots with more favorable wind conditions. This possibility does not exist for conventional wind turbines, which suggests a modest increase of the estimated capacity factor. It is therefore estimated at 66% by Fischer & Partner. The Powership concept represents a new technology which is not yet available commercially. To account for unplanned outages stemming from technological immaturities, a non-availability of 20% is assumed as a safety factor. Following general experience with wind turbines, operation and maintenance costs are set to 2% of the initial investment cost [22].

4.3. Calculation of the project's NPV

Using the numbers defined above for the three different storage solutions, their NPVs can be calculated (cf. Table 1). The discount rate is set to 8%, VAT to 19%, unplanned outages at 20%, lifetime at 20 years, the capacity factor at 66%, operating & maintenance costs at 2%, and annual payments are assumed. As can be seen, the resulting NPV is positive for all three systems, meaning that an investment should be made according to conventional investment valuation. The calculation yields the highest NPV for the use of the carbazole-based storage solution, whereas the system based on compressed air delivers the highest annual cash flows but is thrown back by its high initial investment. Using the numbers suggested by VDE returns the lowest cash flows and the lowest NPV, because at an initial sales price of 5 € kg^{-1}, 2/3 of the revenues are used to finance the storage.

Table 1. Calculation of the net present values

Specific variables:	Compressed air	Carbazole	H_2 storage (according to VDE)
Powership cost	898,125	898,125	898,125
1st-year operation cost	616,200	616,200	616,200
Storage cost	4,612,160	1,176,000	-
Storage cost H_2 according to VDE [€ kWh^{-1}]	-		0.1
Net H_2 production power [kW]	-	1,020	1,020
Lower heating value H_2 [kWh kg^{-1}]	-	33.33	33.33
→ H_2 production [kg a^{-1}]	-	141,548	141,548
H_2 selling price [€ kg^{-1}]	-	5.00	1.67
Net compression power [kW]	2,320	-	-
Efficiency of compression/expansion [%]	60	-	-
→Produced electrical energy [kWh a^{-1}]	6,438,390	-	-
Fixed sales price electricity [€ kWh^{-1}]	0.15	-	-
→Yearly cash flow [€]	672,059	531,786	173,165
→ Project value discounted to $t = 0$ [€]	6,598,371	5,221,151	1,700,161
→NPV [€]	2,135,040	3,541,110	972,680

5. Results

The net present value calculated in the preceding chapter does not reflect the uncertainties in the assumption which were made before. However, as the uncertainties bound to innovative R&D projects are not negligible, they will be identified and bundled into a single number – the volatility of the project's value return – by means of Monte Carlo simulation before the calculation of the actual value of an abandonment option is performed.

5.1. Identification of risks and managerial options

Some assumptions from section 4.1 need to be made for actually realizing the project (e.g., that an operating permit is granted). Others deliver a numerical estimate of a value, probability, or price rather than just the options "yes" or "no", which makes them more interesting candidates for a closer analysis. As both the cost of the Powership technology, its field performance, expressed by the capacity factor, and the sales and storage price of H_2 are unknown, they will be investigated.

5.2. Monte Carlo simulation of the volatility

In order to merge all the project's uncertainties into a single factor, Monte Carlo simulation is used. The simulation software applied is Oracle's Crystal Ball®, which allows defining a probability distribution for each variable. Three of the four uncertainties (investment cost for the compressed air storage, H_2 price, and H_2 storage cost) are prices which can be assumed to be non-negative. As the log-normal distribution complies with this and, in addition, is common in the evaluation of the change of stock market and price indices [23], it will be used for the modeling of those uncertainties. In Crystal Ball®, both the mean value and the standard deviation of the log-normal distribution can be chosen by the user. Hydrogen is regarded by many experts as a potential alternative to liquid fossil fuels. Therefore, the future standard deviation of the H_2 price is assumed to correlate approximately with the historical volatility of gasoline, which can be derived from historical data [24], and is set to 30% of the mean value. The same applies for the H_2 storage costs. Note that the log-normal distribution cannot be used to model the capacity factor, because values > 100% could occur, which is physically impossible. Hence the distribution is assumed to take on a triangular shape with a maximum at the mean value of 66% and linear slopes of the chosen min. of 50% and max. of 80%, where the probability approaches zero.

Once all assumptions have been made, the standard deviation of z can be simulated. For this purpose, the software combines random pairs of values within the borders and probabilities given by the distributions defined previously. The number of simulation runs is set to 100,000. Figure A.1 shows the frequency plots of the return distributions for the three different chosen systems. The resulting standard deviations are σ_{Air}=0.11, σ_{Carb}=0.34, and σ_{VDE}=1.01.

5.3. Creation of binomial lattices

With the standard deviations determined, the binomial lattices can be created (for the complete lattices for the whole systems' lifetimes see [25]). The first entry of the lattice is the project value at $t = 0$, i.e., the sum of the foreseen cash flow discounted to that point in time. Starting from there, the recombining lattice is established using the factors u and d from eq. (1). Those are calculated by dividing the lifetime of the option into $n = 20$ intervals of one year each. The equations for u and d can thereby be reduced to:

$$u = e^{\sigma\sqrt{T/n}} = e^{\sigma\sqrt{20/20}} = e^{\sigma}; \;\; d = 1/u = e^{-\sigma}. \tag{3}$$

The final upward and downward multiplication factors for the different storage alternatives considered are: u_{Air} = 1.1198, u_{Carb} = 1.3986, u_{VDE} = 2.7480; d_{Air} = 0.8929, d_{Carb} = 0.7150, d_{VDE} = 0.3639. Note that, due to the high standard deviation, u and d differ markedly for the VDE solution compared to the two other systems and thus return a very broad final distribution with exceptional extreme values. Using the upward and downward factors determined above, the two entries in period 1 of the example can now be calculated as 6,598,731·1.1198=7,389,074 and 6,598,731·0.8930=5,892,281, respectively. This step is executed for each following node. The resulting binomial lattice has not yet taken managerial flexibilities into account. However, it does show the uncertainty associated with the development of the project value.

5.4. Specification of a real option

Copeland and Antikarov [6] regard the abandonment option as significant, especially for risky R&D projects. As the case of a new energy conversion technology fits that definition, this type of real option was chosen to be investigated here. To determine the options value, an assumption towards the expected possible strike price of the option has to be made. In the light of the foreseen rapid development of the renewable energy markets, we assume that each Powership can be sold at its manufacturing cost, i.e., the sum of the individual storage cost and the cost of the ship. This seems reasonable because of the mobile character of the concept and the low expected infrastructure and installing costs in comparison with conventional wind energy technologies. The abandonment option will be applicable at each time step in the project's lifetime. It is executed when the expected income from the sale of the unit exceeds the original project value. Note that the produced number of Powerships is not addressed in the present work, which is why no expanding options are analyzed. Further research could aim in that direction, for example, to investigate economies of scale.

5.5. Determination of the real option value

The value of the real option is calculated starting at the right side of the binomial lattice as described in section 3.3. The option is executed in the case where the strike price of the option is higher than the current value of the considered node in the last column of the binomial lattice. Otherwise, the original value remains. Once the 20 values in the right column have been analyzed and replaced where applicable, the new values of the nodes in the next columns are calculated using eq. (2) until the last node at $t = 0$ is reached. The risk-neutral probabilities in this equation are calculated by using eq. (4), which yields the following values for the different storage concepts: $p_{\mathrm{Air}} = 0.6040$, $p_{\mathrm{Carb}} = 0.4608$, and $p_{\mathrm{VDE}} = 0.2794$. The risk-free interest rate was chosen as 3%. For the exemplary calculation of the binomial lattice for the compressed air storage system see [25], where also the full binomial lattice is reported. The last step consequently modifies eq. (2) to:

$$\begin{aligned} S_{u^0d^0} &= [p\cdot S_{u^1d^0} + (1-p)\cdot S_{u^0d^1}]/(1+r) = [0.6040\cdot \text{€}7{,}469{,}402 + \\ &+(1-0.6040)\cdot \text{€}6{,}156{,}487]/(1+0.03) = \text{€}6{,}747{,}057, \end{aligned} \tag{4}$$

which is the calculation of the project value at $t = 0$. By only looking at the revised binomial lattice, the purpose of the abandonment option as a useful tool for hedging against downside risks already becomes clear, at least qualitatively. As soon as the project value takes a turn which probably will prove to be unfavorable even in the long run, the abandonment option can be executed, thus limiting the project value at the downside to the initial manufacturing cost of the Powership. The quantitative option value can finally simply be calculated as the difference between the nodes at $t = 0$ in the lattices with and without consideration of a real option. Table 2 shows that the insertion of an abandonment option increases the NPV of all storage alternatives significantly.

Table 2. Comparison of the option values for the different storage solutions

	Compressed air	Carbazole	H_2 according to VDE
Investment cost [€]	5,510,285	2,074,125	898,125
NPV w/o option [€]	2,135,040	3,541,110	972,680
NPV with option [€]	2,283,726	3,862,761	1,640,046
Abandonment option value [€]	148,686	321,651	667,366
Percentage increase of NPV	7.0%	9.1%	68.6%

6. Sensitivity analysis

Even without the utilization of real options analysis, the NPVs for all three storage systems considered are positive, thus suggesting that the Powership concept can be economically feasible. It is found that the NPV of the carbazole-based storage system is the highest, followed by the compressed air system. This is especially remarkable because the compressed air system's NPV is calculated using a guaranteed feed-in tariff above the average market price. Despite the disadvantage of being subject to market risks, the expected NPV of the carbazole-based technology is higher, and the project therefore more favorable from an economic point of view. However, the uncertainty in the selling price of H_2 might change that result.

The solution based on VDE's assumptions concerning H_2 storage cost in the future yields the lowest NPV due to the high share of storage cost in the end-user price. Consequently, the yearly cash flows are lower compared to the other systems, which cannot be compensated by the lower initial investment.

6.1. Risk analysis in binomial lattices

The Monte Carlo simulation of the change of the project value through time *z* returns a very high standard deviation for the system on the basis of the VDE's assumptions. The reason behind this that can be found by analyzing the influence of the individual uncertainties on the different storage systems. Crystal Ball® features a built-in sensitivity analysis, which displays the rank correlation coefficients between the assumptions and the forecasts. A high correlation coefficient expresses a strong impact of the assumption on the forecast. If the correlation coefficient is negative, an increase of the assumption value will cause a decrease of the forecast value. As the Powership's concept and purpose, independent of the choice of a certain storage system, is to generate usable energy from wind, it is intuitively clear that the capacity factor has an impact on the project value and thus must correlate with *z*. In fact, that conclusion is true for all three analyzed storage systems (Fig. 1). As can be seen, for the CAES system, the influence of the capacity factor has the higher correlation of the two assumptions connected to the forecast. The main reason is that the sales price of electrical energy was assumed to be fixed due to the feed-in tariffs granted (i.e. a guaranteed price over 20 years) and, therefore, does not represent an uncertainty. The air storage cost plays a less important role. For the two hydrogen-based systems, the sales price is variable and correlates strongly with the variation in the project value. The system based on the VDE's numbers uses the H_2 storage cost as an additional assumption which finally explains that solution's extraordinarily high standard deviation and the resulting upward and downward factors: the average H_2 sales price in the analysis was set to 5 € kg^{-1} with a standard deviation of 30% or 1.5 € kg^{-1}, whereas the average storage cost was assumed to be 3.33 € kg^{-1} with the same relative standard deviation. That combination allows for many value pairs close to zero for the net sales price, which in the static case turns out to be (5 € kg^{-1} – 3.33 € kg^{-1}) = 1.67 € kg^{-1}. The natural logarithm, as used for the calculation of *z*, is numerically sensitive to values close to zero and therefore returns a high standard deviation for data series in that region.

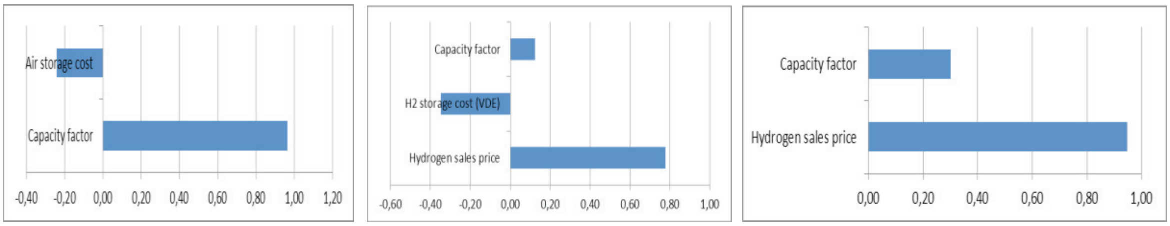

Fig. 1. Sensitivity analysis (rank correlations) for the various storage systems considered: (a) Compressed air; (b) Carbazole; (c) H_2 storage based on VDE assumptions

6.2. Real options value

Since all three investigated NPVs rise through the insertion of a real option, the overall investment is considered to be more valuable. However, this does not mean that the project will definitely be profitable. It merely means that the start of the project implementation is sensible due to the reversibility added by an abandonment option. The magnitude of the NPV's rise due to the insertion of the abandonment option differs significantly depending on the chosen storage solution. Whereas the rise for storage in compressed air and carbazole amounts to 7.0% and 9.1% of the original NPV, respectively, it reaches 68.6% for the calculation based on the VDE numbers. Even in absolute numbers, the option value is highest for that storage system. This is noteworthy because the strike price of its abandonment option, represented by the manufacturing cost price of ship and storage system, is considerably lower than for the other two systems (€898,125 vs. €2,074,125 and €5,510,285, respectively). The reason for the high option value lies in the uncertainty bound to the storage system: the high volatility as explained above results in a wide-spread distribution of the lattice's extreme values, which in the present example makes the execution of the abandonment option more attractive for hedging against downside risks. Thus, it can be stated that the use of real options makes most sense in those projects and economic environments with high uncertainties.

7. Conclusion

The introduction of a completely new technology to the market is always associated with high uncertainties both concerning the R&D and the market risk. This can challenge the validity of conventional valuation methods, such as the net present value approach. Furthermore, these approaches do not take into account that management might have the possibility to react to changes in the economic environment mid-way through the process. Real options analysis attempts to model both the uncertainties associated with an investment and the value of the managerial flexibility. In the case of Powerships, which represent an innovative power generation technology, the manufacturing, operating, and maintenance costs as well as the amount and sales price of the final product are uncertain.

In this study, the use of real options analysis has been investigated as a method of valuing an investment in the Powership concept, which can be implemented in three ways using different types of energy storage. With the individual net present values of the three storage technologies as initial points, the above-mentioned risks have been modeled by means of Monte Carlo simulation. Their influence on the potential project value has been shown by utilizing binomial lattices. Finally, the values of an abandonment option have been calculated. The initial NPV analysis yields positive values for all three storage systems, showing the economic potential of the technology. However, many values regarding the performance and the cost of the Powership and the variations of the economic environment had to be estimated. Those values will have to be investigated and updated in the course of further research and product development. The value of the investigated abandonment option differs for the individual storage systems. In the system based on a forecast from the Association for Electrical, Electronic & Information Technologies (VDE), the option value lifts the net present value by more than two thirds, which shows the considerable value of the possibility to react to new information during the project's lifetime.

Summing up, the real options approach can help to further analyze the results gained by a basic NPV calculation and to quantify the value represented by managerial flexibilities. It converts the gut feeling a manager might have concerning the value of those flexibilities into a measurable number. Once implemented, it provides a detailed investment strategy which can be modified at different points in time and is therefore suitable to evaluate the economic feasibility of innovative technologies. The Powership concept itself looks promising from a techno-economic point of view. According to the results of the executed calculations, the technology could work profitably in the future and thereby help to increase the share of renewables in the energy mix.

References

[1] Hansen J, Sato M, Ruedy R, Nazarenko L, Lacis A, Schmidt GA, et al., Efficacy of climate forcings. *J Geophys Res-Atmospheres* 2005;**110**(D18104):1-45.

[2] Leung DYC, Yang Y. Wind energy development and its environmental impact: A review. *Renew Sust Energy Rev* 2012;**16**: 1031-9.

[3] van der Zwaan B, et al. Cost reductions for offshore wind power: Exploring the balance between scaling, learning and R&D. *Renew Energy* 2012; **41**: 389-93.

[4] Thompson PM, et al. Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Marine Pollution Bulletin* 2010;**60**: 1200-8.

[5] Mun J. *Real Options Analysis - Tools and Techniques for Valuing Strategic Investments and Decisions*. Wiley Finance. Vol. 320. Hoboken, NJ: John Wiley & Sons; 2005.

[6] Copeland T, Antikarov V. *Real Options: A Practitioner's Guide*, New York: Texere, 2001.

[7] SkySails GmbH. http://www.skysails.info/fileadmin/user_upload/Presselounge/Dokumente/ deutsch/ DE_Pressemappe_ SkySails.pdf. [accessed July 10, 2012].

[8] Bajeux-Besnainou I, Joshi S, Vonortas N. Uncertainty, networks and real options. *J Econ Beh*, 2010. 75: 523-41.

[9] Cox JC, Ross SA, Rubinstein M. Option pricing: A simplified approach. *J Fin Econ* 1979;**7**: 229-263.

[10] Madlener R, Stoverink S. Power plant investments in the Turkish electricity sector: A real options approach taking into account market liberalization. *Applied Energy* 2012;**97**: 124-34.

[11] Gesetz für den Vorrang Erneuerbarer Energien - (Erneuerbare-Energien-Gesetz – EEG), Bundesministerium für Umwelt, 2011.

[12] Wenzel B. *Beschaffungsmehrkosten für Stromlieferanten durch das Erneuerbare-Energien-Gesetz* 2009, 2010.

[13] Daskalakis G, Markellos RN. Are electricity risk premia affected by emission allowance prices? Evidence from the EEX, Nord Pool and Powernext. *Energy Policy* 2009;**37**: 2594-604.

[14] Bierbrauer M, et al. Spot and derivative pricing in the EEX power market. *J Banking & Fin* 2007;**31**: 3462-85.

[15] von Roon S, Huck M. Merit Order des Kraftwerkparks, 2010, Forschungsstelle für Energiewirtschaft e.V.: Munich.

[16] Plenarprotokoll des deutschen Bundestages 17/149, 2011: Berlin.

[17] Guezuraga B, Zauner R, Pölz W. Life cycle assessment of two different 2 MW class wind turbines. *Renew Energy* 2012;**37**: 37-44.

[18] Cyphelly I, Brückmann AR, Menhardt W, Reller A. *Einsatz von Druckluftspeichersystemen*, Bundesamt für Energie, Bern, 2004.

[19] VDE Verband der Elektrotechnik Elektronik Informationstechnik e.V., VDE-Studie: Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger 2012.

[20] Jørgensen C, Ropenus S. Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration. *Int J Hydrogen Energy* 2008;**33**: 5335-44.

[21] Deutsche Offshore-Testfeld und Infrastruktur GmbH & Co. KG. http://www.alpha-ventus.de/index.php?id=22#c727. [accessed July 12, 2012].

[22] Deutsche Energie-Agentur GmbH (dena). http://www.thema-energie.de/energie-erzeugen/erneuerbare-energien/ windenergie/grundlagen/wirtschaftlichkeit-von-windenergieanlagen.html. [accessed June 18, 2012].

[23] Black F, Scholes M. The Pricing of Options and Corporate Liabilities. *J Pol Econ* 1973;**81**: 637-54.

[24] U.S. Energy Information Administration. http://www.eia.gov/dnav/pet/hist/ LeafHandler.ashx?n=PET&s=EER_EPMRU_ PF4_Y35NY_DPG&f=M. New York Harbor Conventional Gasoline Regular Spot Price FOB [accessed July 12, 2012].

[25] Schmitz M., Madlener R. Economic Feasibility of Kite-Based Wind Energy Powerships with CAES, *FCN Working Paper No. 16/2012*, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, December.

Biography

Dr Reinhard Madlener is full professor of energy economics and management at RWTH Aachen University, Germany, and vice-director of JARA Energy (a Jülich Aachen Research Alliance section; www.jara.org). He teaches energy economics, environmental economics, economics of technical change, and economics of technological diffusion. His main research is on energy economics and policy-making, and the adoption and diffusion of technological (energy) innovation under uncertainty.