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

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Abstract

The rise in the usage of sustainable energy conversion technologies has been remarkable. However, the growth of these technologies poses several problems, mainly concerning the net integration of intermittent energy sources, like wind and solar power, by means of advanced storage systems and the land consumption the use of these energy sources implies. Furthermore, the economic viability of these solutions is in question, as they are to date still often heavily supported by financial subsidies. The Powership concept attempts to tackle these shortcomings by harvesting wind energy offshore using an alternative infrastructural approach which features 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 the other using real options analysis, including both R&D and market risks as stochastic variables driving the option's value. In order to determine the strategic value of managerial flexibility in the face of uncertainty, assumptions concerning the change of the economic environment are made and motivated.

Keywords: Wind power, kite, CAES, hydrogen, real options analysis, Monte Carlo simulation

1 Introduction

The emission of CO_2 from the combustion of fossil fuels is widely considered to be the leading cause of anthropogenic climate change [1]. This is why the majority of countries in the world have committed themselves to decreasing their CO_2 emissions significantly in international agreements, such as the Kyoto Protocol.

In many countries, including Germany, electrical power supplies to date largely rely on big, centralized condensing plants. The increased use of renewable energy sources can be a viable measure to cut CO_2 emissions while simultaneously sustaining or even increasing power production. One of the

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key technologies in the field of renewable power production is that of wind power. Due to its characteristic intermittent, weather-dependent performance profile, and the lack of suitable storage systems, the integration of this technology into the electricity grid is problematic. Furthermore, the issue of land use is gaining importance with the construction of more onshore wind turbines.

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 can be detected [4]. By using a mobile wind-harvesting platform, the Powership concept aims at exploiting the potential of offshore wind technology while simultaneously avoiding its major disadvantages. A more detailed description of the technological background is given in section 2.3.

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, Mun [5] as well as Copeland and Antikarov [6] suggest real options analysis (ROA) as a tool for determining the value of flexibility.

In this paper, we use real options theory to calculate the value of an abandonment option in two different technical configurations of the Powership concept. Starting with a discussion of the technological and economic background in section 2, the analytical framework is introduced in section 3. A conventional NPV calculation for the case of the operation of a Powership in Germany is carried out in section 4, after which the risks driving the option value are identified and included in a Monte Carlo simulation (section 5). In section 6, the robustness of the results is checked by means of a sensitivity analysis. Section 7 concludes.

2 Technical and economic background

2.1 Trends in wind energy use

To fulfill international climate treaties, it is necessary for industrialized countries like Germany to cut back their CO_2 emissions. While several approaches, including smart load management and the use of energy-saving devices, try to solve the problem at the consumer end, the field of power generation needs to evolve towards the use of renewable primary energy carriers instead of fossil fuels in order to meet both power demand and the CO_2 mitigation targets.

The exact way to a more sustainable power supply is not known to date. However, there is a broad consensus that a single technology will not be sufficient to fill the resulting gap. This will result in a significant diversification and decentralization of power generation, in which intermittent energy sources like solar and wind energy will play a key role. Moreover, the extensive use of feed-in tariffs distinctly above market price levels in Germany has led to a remarkable rise in the installed electric capacity (Fig. 1).

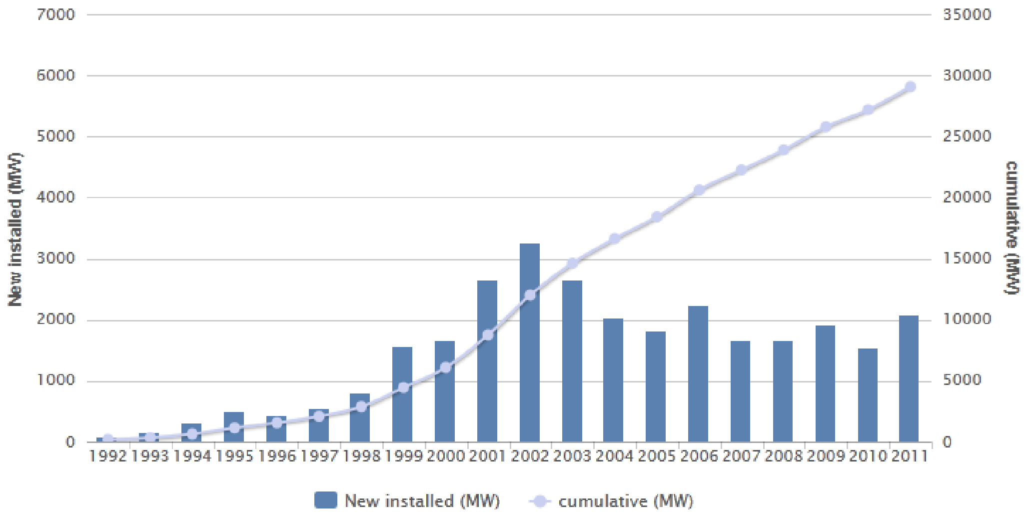


Fig. 1. Installed wind power capacity in Germany, 1992-2011

Source: [7]

Against the backdrop of this development, governments have begun to define the necessary legal framework for a massive increase of renewable power production. As an example, the German government recently passed a law on spatial planning in the country's exclusive economic zone (EEZ), which extends 200 miles into the open sea (Fig. 2).

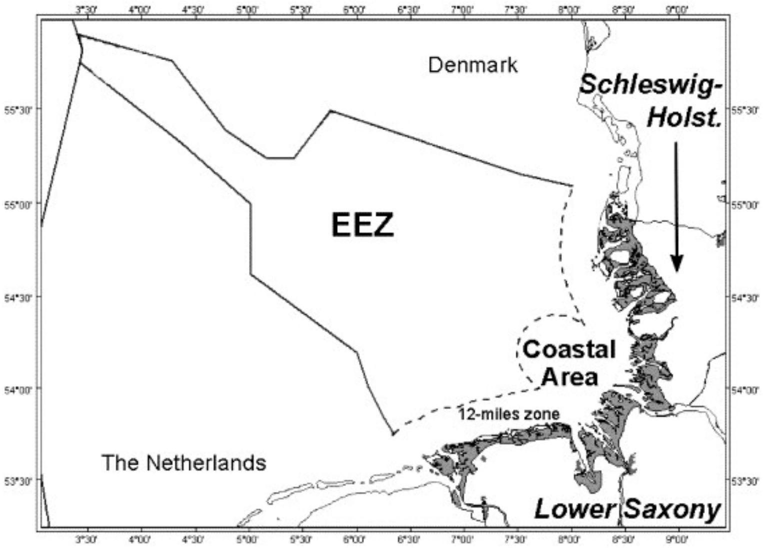


Fig. 2. Germany's exclusive economic zone (EEZ) in the North Sea

Source: [8]

The law allows for 12,000 MW of additional installed wind power capacity until the year 2020 and aims at a total of 25,000 MW offshore-based wind power installations in 2030, mainly in the North Sea. The increased use of wind as an energy source will consequently lead to a replacement of inflexible baseload units, which to date are predominantly coal, lignite, or nuclear power plants [9].

2.2 Shortcomings of existing wind energy technologies

In an electric power grid without considerable storage capacity, as it is the case in Germany and many other countries today, the production and consumption of power have to be balanced at all times to maintain a constant net frequency.

It lies in the nature of wind turbines that their power output depends on the weather conditions and can only be delivered intermittently. Therefore, for successful grid integration, the difference between generated wind power and the consumption profile has to be compensated by additional reserve power generation units with easily adjustable output or cost-efficient storage facilities. Fig. 3 shows an example for the actual load, wind power forecast, and actual wind power production. As can be seen, apart from the mentioned fluctuations, the difference between forecast and reality (i.e. the forecast error) is a further challenge for successful net integration.

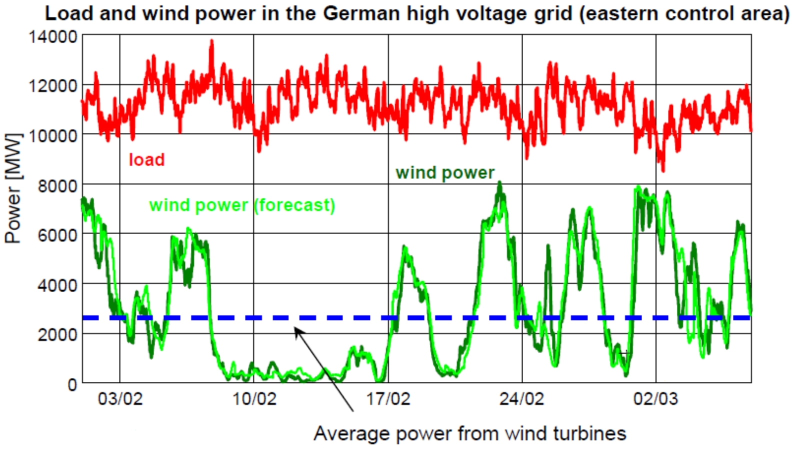


Fig. 3. Load curve and actual vs. predicted wind power utilization

Source: [10]

Different studies have analyzed the potential and economic feasibility of alternative storage technologies, such as compressed air energy storage (CAES; [11], [12], [13]) or “wind gas” (also referred to as “power-to-gas”), i.e., the use of surplus electric energy for the electrolysis of water to produce hydrogen [14], [15]. Although these technologies will most likely contribute significantly to the grid integration of renewable energies in the longer term, it is doubtful that their extended use will be sufficient to keep pace with the rapid development in the short term. Thus, the balancing of fluctuations in the power grid must at least partially be handled by additional power units, resulting in potential redundancy, a lower average utilization factor, and eventually higher electricity prices for the final consumer. Also, the planned development of offshore wind turbines poses other specific problems, since the construction and maintenance of the actual wind farm and the grid connection are more complicated and expensive than on-shore due to more demanding logistics. Additionally, corrosive environmental conditions enforce the use of more sophisticated materials and engineering solutions.

2.3 The Powership concept

2.3.1 Power generation technology

The Powership concept attempts to avoid some of the above-mentioned problems, 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 engine load (Fig. 4). The company producing the system has estimated the possible fuel savings to lie between 10 and 35% [16].

Fig. 4. SkySails system installed on freight vessel “MV Michael A.”

Source: SkySails GmbH

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 (Fig. 5). This energy can be stored either as compressed air in steel tubes or as hydrogen which is produced by electrolysis. A more thorough description of the different storage systems investigated is given later in this section.

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 cost benefits. Besides, they can be relocated to follow favorable wind conditions, which can result in a higher capacity factor compared to wind turbines.

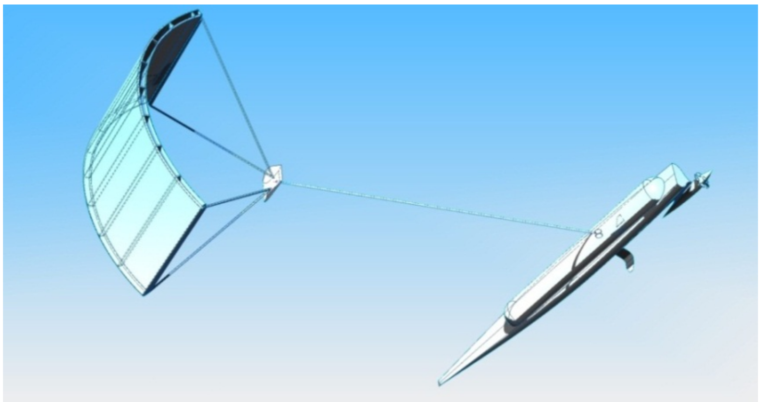


Fig. 5. Concept drawing of a kite-driven Powership

Source: Fischer & Partner

Additionally, the use of Powerships might make it possible to harvest wind energy in sea areas where wind turbines are not applicable due to geological (e.g. the Norwegian continental shelf) or legal (e.g. offshore wind farm Riffgat, see [17]) constraints. At the same time, underwater cables could become unnecessary due to the characteristics of the energy storage technology concerned (compressed air or hydrogen).

2.3.2 Compressed air energy storage (CAES) system

Compressed air has been used as an energy carrier for a long time, for example in the mining industry. The technology is established and safe in operation. Its use as a buffer for fluctuations in the power grid is well-documented ([11], [12], [13]) and technically implemented in two CAES power plants in MacIntosh/USA and Huntorf/Germany, where underground caverns are used as storage spaces.

A major drawback is the thermodynamic feature of gases to become warmer upon compression and colder upon expansion. If the expansion is not executed immediately after the compression, the compressed air will cool down to ambient temperature, especially if the air storage is realized by steel tubes or bottles with a high heat conductance. The energy heat flow through the storage walls is thereby lost and extra energy has to be used to warm up the gas upon expansion again.

A solution to this problem is the innovative A-CAES (Adiabatic compressed air energy storage) technology, which features an additional long-term heat storage [18]. This storage facility, which is implemented by means of a pressure vessel filled with a sand bed or brick stones, cools down the hot compressed air, conserves most of the gained heat, and releases it again upon expansion. The energy flow is depicted in Fig. 6.

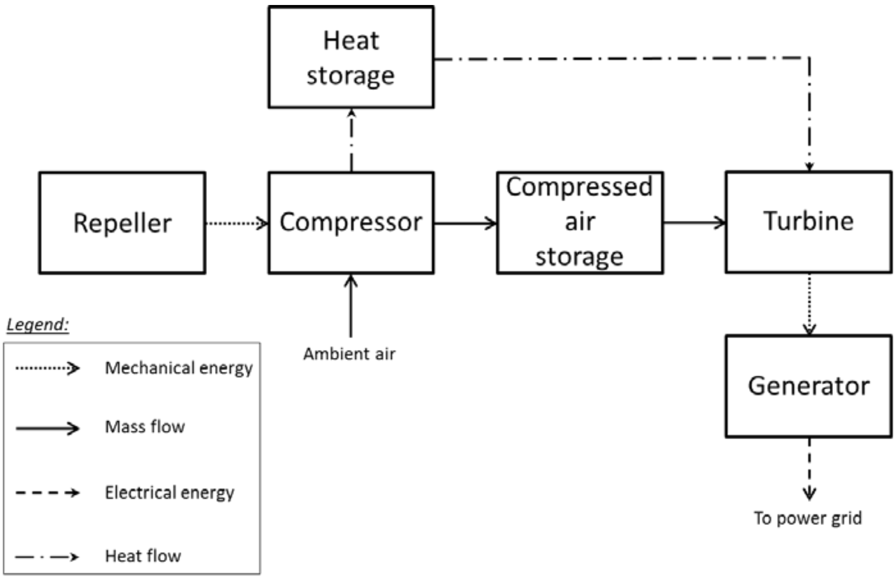


Fig. 6. Simplified energy and mass flow diagram of the CAES system

Through the use of the heat storage, energy losses to the environment can be minimized in order to increase overall efficiency.

2.3.3 *Hydrogen-based energy storage*

An alternative to CAES is the offshore production of hydrogen. In this concept, the mechanical energy from the repeller is first converted to electric energy in a generator, which in turn is used to produce hydrogen from demineralized water in an electrolyzer (Fig. 7). For the sake of system simplicity, the surplus oxygen from the electrolysis is blown off into the atmosphere. From a technical perspective, capturing the produced oxygen would also be a possibility.

Mobile storage technologies for hydrogen are still in an early development stage. Possible solutions are, among others, high-pressure or low-temperature tanks or the storage of hydrogen in metal hydrides. Another promising alternative is the use of an organic substance (N-ethylcarbazole), which can bind hydrogen chemically without prior compression.

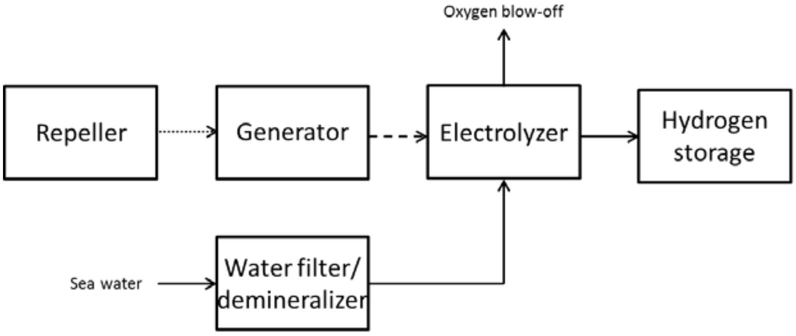


Fig. 7. Simplified energy and mass flow diagram of the hydrogen-based system (legend as in Fig. 6)

The tanks needed to store N-ethylcarbazole can be designed and constructed like common gasoline storage tanks, making them considerably cheaper than conventional hydrogen tanks. Moreover, the handling of the tanks is easier, which allows for an exchange of the tanks to supply ships at sea. Consequently, the Powership itself does not need to interrupt the production of hydrogen for unloading in a harbor.

The produced hydrogen can be marketed in several ways: one possibility is to invest in tanks and a fuel cell on land which can reconvert the hydrogen to electricity. As fuel cells can react to load changes with sufficient speed, this solution has the advantage of being suitable for peak-load utilization, which means that electricity can be produced and sold at high prices during periods of high demand. On the other hand, the stored hydrogen can be sold to both private and business customers directly. Studies [19], [20] foresee a significant rise in the utilization of renewables-based hydrogen as a sustainable energy carrier, e.g. in the transport sector, which will most likely ensure a demand on a high and stable level [9].

3 Investing under uncertain environmental conditions

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 Classical approaches

Classical valuation approaches like the NPV method are usually based on the analysis of predicted net cash flows. The NPV is then calculated by discounting the expected cash flows over T time periods at the interest rate r to account for the time value of money and by comparing them with the investment cost I_0 at $t = 0$, cf. eq. (1):

$$NPV = -I_0 + \sum_{t=1}^{T} \frac{FCF_t}{(1+r)^t} \,. \tag{1}$$

The free cash flows (FCF_t) in eq. (1) are calculated as the expected differences of revenues and costs. An investor using the NPV method to valuate a project will take the decision to invest if the NPV is positive.

The interest rate r is a key variable in the calculation. Depending on what scenario the investor wants to investigate, it can take on different values. If the aim, for example, is to compare two possibilities for investing savings, of which one is considered risk-free (e.g. AAA government bonds), *r* will be the risk-free interest rate, which can, for example, be derived from state obligations. In contrast, if a company wants to take a decision on whether to invest in a new technology or not, *r* should reflect the company's weighted average cost of capital. Finally, the interest rate may also be used for a risk assessment within the NPV method, by calculating and adding a risk premium on top of the risk-free interest rate that reflects the project-specific risks.

If both the interest rate and the future cash flows are known, the NPV reflects the project's value in a clear and easy-to-implement way and provides clear decision guidelines. However, knowing those variables in advance with sufficient precision is anything but easy, especially in long-term investments.

Thus, the NPV method suffers from two major drawbacks: the uncertain estimate of important variables and, maybe more importantly, the assumption that an investment is final and irreversible. This means that future risks, but also opportunities and the managerial flexibilities to react to them, are not covered by the calculation and hence do not represent any value. However, even intuitively, it is clear that, for example, the flexibility to react to changes in interest rates or cash flows by either liquidating or expanding an investment must have a value when compared to a situation where this flexibility does not exist. Real options analysis (ROA) attempts to define just that value.

3.2 Real options analysis

3.2.1 Origin and some basics

Real options have their 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 [21]. 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, as stated in Copeland and Antikarov [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.

3.2.2 Different types of real options

The classification of real options can be done in different ways. Trigeorgis [22] suggests a division into various types of options: options to defer, staged investment options, options to alter the operating scale, options to abandon, switching options, and growth options.

Option to defer: this kind of option provides flexibility regarding the question of whether an investment should be done now or later. It gives the investor the possibility to wait until uncertainties dissolve or to gather more information. Typical examples are options in oil exploration, where the optimal point in time for the beginning of exploitation strongly depends on the world market price of oil.

Staged investment option: in R&D-intensive industries, like the one for pharmaceuticals, or in start-up ventures, investments are usually made consecutively at certain points of time. By not making any further investments which are vital to the project continuation, the project can be abandoned midstream, thereby adding flexibility.

Options to alter the operating scale: in order to be able to react to market fluctuations on the consumer side, a company can use the options to expand, contract, shut down or restart the production scale. These options are frequently used in consumer goods or natural resource industries and the real estate business.

Option to abandon: if market situations turn out to be less favorable than expected, the abandonment option may be valuable to release project-bound capital, which can then be used otherwise. This possibility makes the abandonment attractive in situations such as the launch of completely new products, where consumer needs and wishes are not known for certain.

Switching option: a company may have the possibility to change its input and output by diversification. For example, the production of steam for the chemical industry could both be done by using electricity or natural gas as an energy carrier, depending on the price. Likewise, a chocolate company could choose to produce either Easter bunnies or Santa Clauses, depending on the season, both times using the same raw material and production line. In both examples, the value of the option lies in the flexibility gained by the ability to react to changes in the economic framework.

Growth option: this term describes the option to expand business operations permanently by acquiring the capability to benefit from future growth opportunities. A possible field of application exists for companies that produce multiple product generations or want to expand to international markets.

As one can imagine from the description provided above, a combination of the different options is possible and the boundaries between them are flexible.

3.2.3 Valuation of real options

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.

Although 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, which is the one 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 q or $1-q$, respectively [23]. 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 follows:

$$u = e^{\sigma\sqrt{\frac{T}{n}}} \tag{2a}$$

$$d = \frac{1}{u} = e^{-\sigma\sqrt{\frac{T}{n}}}\ , \tag{2b}$$

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 [24]. Therefore, modeling and Monte Carlo simulation, the latter of which is based on numerical random sampling, 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 [6]:

$$z = \ln\left(\frac{PV_1+FCF_1}{PV_0}\right)\ , \tag{3}$$

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 ratio depicted in Eq. (3) 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. (2). To do so, the option's lifetime is divided into equal time intervals Δt. The binomial lattice shown in Fig. 8 depicts three such time intervals.

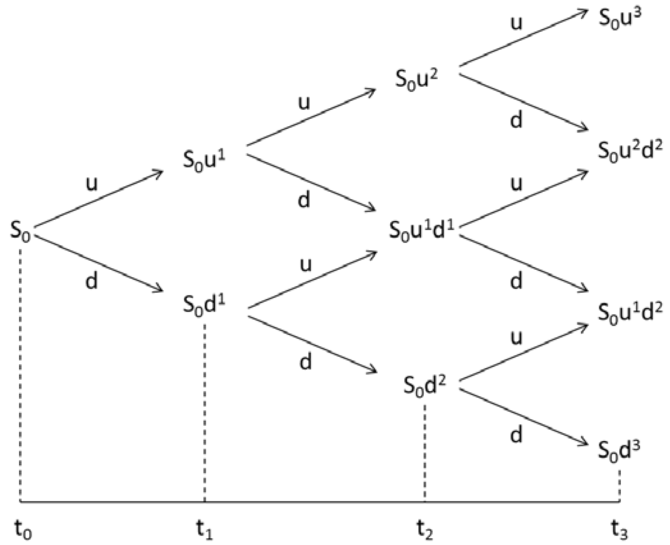


Fig. 8. Recombining binomial lattice for three time steps

Each value at each time step can be reached by multiplying the base value of the underlying at t_0, which will be named 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 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. (2) 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, using the following equation (4):

$$S_{u^i d^j} = \frac{\left[p \cdot S_{u^{i+1} d^j} + (1-p) \cdot S_{u^i d^{j+1}}\right]}{(1+r)}, \tag{4}$$

where p is the risk-neutral probability, defined as

$$p = \frac{(1+r)-d}{u-d}. \tag{5}$$

A detailed derivation of these equations can be found, e.g., in Copeland and Antikarov [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 Economic analysis of the Powership concept

In this section, the economic groundwork for the execution of a ROA is laid. To do so, data both from the company providing the concept for the Powership technology (Fischer & Partner, Bonn) and the literature will be used to calculate the project's NPV in a first step.

4.1 Assumptions and limitations

The Powership concept is currently still in an early development stage, making it hard to estimate all relevant data correctly. 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 [25].

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.

Fluctuations in the energy price at the European Energy Exchange (EEX) are not taken into account in this thesis. However, the literature provides numerous analyses of the pricing mechanisms at the EEX ([26], [27], [28], [29]).

Tax: 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 hydrogen 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 [30] 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, cannot go to infinity. 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 will have to be done 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, will be 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 will not be included in turn.

4.2 Data acquisition

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 [31].

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. [32] 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 production of hydrogen, an electrolyzer is needed, the cost of which is estimated by Nitsch et al. [9] 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.

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.

An alternative approach suggested by the VDE (the German Association for Electrical, Electronic & Information Technologies) will also be included in out analysis for the purpose of comparison. In a recent study [10], the VDE predicts that the cost of hydrogen 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 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 hydrogen from electrolysis.

For the adiabatic storage of compressed air, an overall efficiency of the complete compressing and expanding process of 60% is assumed [10].

In the hydrogen 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 hydrogen production of 1,020 kW, which equals ca. 30.6 kg of hydrogen per hour at a lower heating value of 33.33 kWh kg^{-1}.

As mentioned in section 2.3.3, hydrogen 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 hydrogen is set to 5 € kg^{-1} [33].

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 offshore wind park in the German EEZ (cf. section 2), reached a capacity factor of around 50% in 2011 [34]. 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, until now, has not been tested commercially. To account for unplanned outages stemming from technological immaturities, a non-availability of 20% is assumed as safety factor. Following general experience with wind turbines, operation and maintenance costs are set to 2% of the initial investment sum [35].

4.3 Calculation of the project’s NPV

Using the numbers defined above for the three different storage solutions, their net present values can be calculated as explained in section 3.1 and reported in Table 1. Note that the discount rate is set to 8% 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 the VDE returns both the lowest cash flows and the lowest NPV, because at an initial sales price of 5 € kg^{-1}, two thirds of the revenue are used to finance the storage.

Table 1. Calculation of the net present values

Global variables:			
VAT [%]	19		
Unplanned outages [%]	20		
Lifetime [a]	20		
Discount rate [%]	8.0		
Capacity factor [%]	66%		
Operating & maintenance cost [% of invest.]	2.0		
Specific variables:	*Compressed air*	*Carbazole*	*H_2 storage (accord. to VDE)*
Powership cost	898,125	898,125	898,125
1^{st}-year operation cost	616,200	616,200	616,200
Storage cost	4,612,160	1,176,000	-
Storage cost H_2 accord. 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
Sales price H_2 [€ kg^{-1}]	-	5.00	1.67
Net compression power [kW]	2,320	-	-
Efficiency 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 Real options valuation of the Powership concept

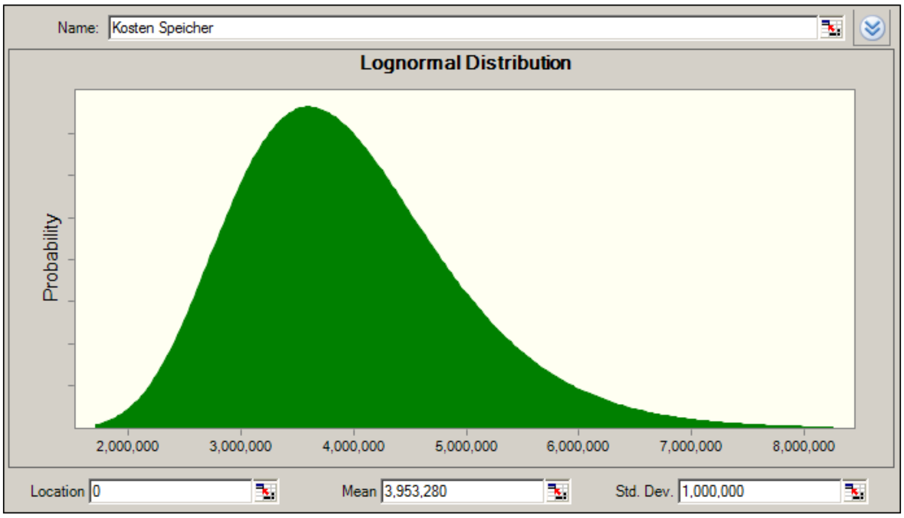
The net present value calculated in the preceding chapter does not reflect the uncertainties in the assumption which were made before. However, as the uncertainties bound to innovative R&D projects are not negligible, they will be identified and bundled into a single number – the volatility of the project's 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 of the assumptions from section 4.1 need to be made in order to actually realize the project: for example, the assumption 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 hydrogen 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 Crystal Ball® by Oracle, which allows defining a probability distribution for each variable. Three of the four uncertainties (investment cost for the compressed air storage, hydrogen price, and hydrogen 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 [36], it will be used for the modeling of those uncertainties. In Crystal Ball®, both the mean value and the standard deviation of the probability distribution can be chosen by the user. Fig. 9 shows an example of the assumed probability distribution for the price of the compressed air storage. The standard deviation was set to ca. 25% of the mean value in order to compensate for possible changes, both in the price per stored energy unit and the physically required storage capacity.



Name: Kosten Speicher

Location 0

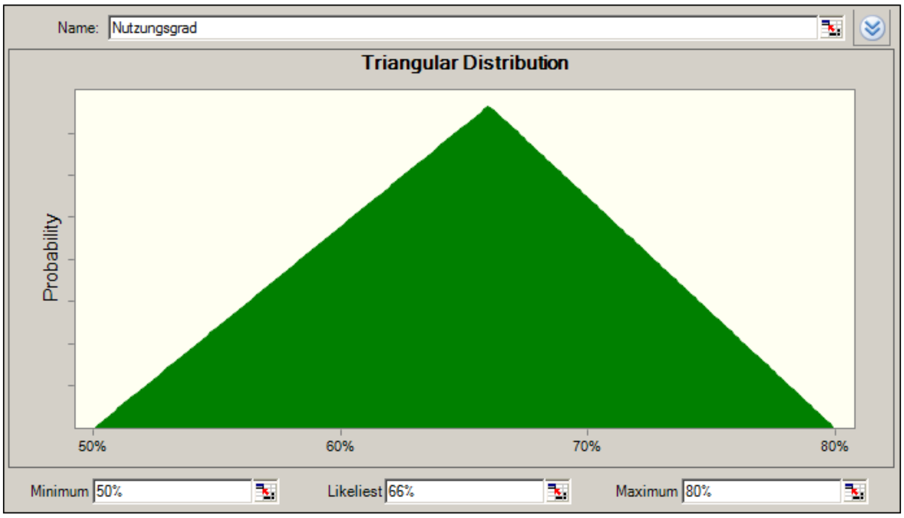
Mean 3,953,280

Std. Dev. 1,000,000

Fig. 9. Log-normal distribution expressing the price of the compressed air storage

As described in section 2, hydrogen is widely regarded as a potential alternative to crude oil-based fuel. Therefore, the future standard deviation of the hydrogen price is assumed to correlate approximately with the historical volatility of petrol, which can be derived from historic data [37], and is set to 30% of the mean value. The same applies for the storage cost of hydrogen. Note that the log-normal distribution cannot be used to model the capacity factor, because values above 100%, which are physically impossible, could occur. The distribution is therefore assumed to take on a triangular shape with a maximum at the mean value of 66% and linear slopes of the chosen minimum of 50% and maximum of 80%, where the probability approaches zero (Fig. 10).

Once all assumptions have been made, the standard deviation of z according to Eq. (3) 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. Fig. A.1 shows the frequency plots of the return distributions for the three different chosen systems. The resulting standard deviations are $\sigma_{Air} = 0.11$, $\sigma_{Carbazole} = 0.34$ and $\sigma_{VDE} = 1.01$.


Name: Nutzungsgrad

Minimum 50%

Likeliest 66%

Maximum 80%

Fig. 10. Triangular distribution for the capacity factor

5.3 Creation of binomial lattices

With the standard deviations determined, the binomial lattices can be created. The excerpt of the binomial lattice for the compressed air storage system shown in Table 2 serves as an example; the complete lattices for the whole systems' lifetimes can be found in the appendix (Tables A.1 to A.3).

Table 2. Excerpt from the binomial lattice for compressed air storage without options

T	0	1	2	3	4	5
0	6,598,371	7,389,074	8,274,528	9,266,090	10,376,473	11,619,917
1		5,892,281	6,598,371	7,389,074	8,274,528	9,266,090
2			5,261,750	5,892,281	6,598,371	7,389,074
3				4,698,692	5,261,750	5,892,281
4					4,195,886	4,698,692
5						3,746,885

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. (2). 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:

$$u = e^{\sigma\sqrt{\frac{T}{n}}} = e^{\sigma\sqrt{\frac{20}{20}}} = e^{\sigma} \tag{6a}$$

$$d = \frac{1}{u} = e^{-\sigma}. \tag{6b}$$

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. It should be noted that, due to the high standard deviation, u and d for the VDE solution differ markedly in comparison with 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 be now calculated as $6{,}598{,}731 \cdot 1.1198 = 7{,}389{,}074$ and $6{,}598{,}731 \cdot 0.8930 = 5{,}892{,}281$, 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 Insertion 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 development of energy markets, discussed in section 2, it is assumed 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.

As mentioned in section 4.1, the produced number of Powerships is not addressed in the present work, which is why no expanding options are analyzed. However, further research might aim in that direction, for example, to investigate economies of scale.

5.5 Determination of the real option values

The value of the real option is calculated starting at the right side of the binomial lattice as described in section 3.2.3. 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. (4) until the last node at $t = 0$ is reached. The risk-neutral probabilities in this equation are calculated by using Eq. (5), which returns 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, an excerpt is depicted in Table 3 (the full binomial lattice is reported in Table A.1 in the Appendix).

Table 3. Excerpt from the binomial lattice for compressed air storage with real option values [in €]

t	0	1	2	3	4	5	…	20
0	6,747,057	7,469,402	8,316,040	9,286,266	10,385,495	11,623,520	…	63,460,278
1		6,156,487	6,743,987	7,466,271	8,313,244	9,284,060	…	50,605,235
2			5,726,839	6,153,279	6,740,106	7,462,364	…	40,354,217
3				5,510,285	5,724,414	6,149,144	…	32,179,730
4					5,510,285	5,510,285	…	25,661,136
5						5,510,285	…	20,463,002
6							…	16,317,846
7							…	13,012,367
8							…	10,376,473
9							…	8,274,528
10							…	6,598,371
11							…	5,510,285
12							…	5,510,285
13							…	5,510,285
14							…	5,510,285
15							…	5,510,285
16							…	5,510,285
17							…	5,510,285
18							…	5,510,285
19							…	5,510,285
20							…	5,510,285

Note: The nodes in which the option is exercised are shaded in grey.

The last step consequently modifies Eq. (4) to:

$$S_{u^0 d^0} = \frac{[p \cdot S_{u^1 d^0} + (1-p) \cdot S_{u^0 d^1}]}{(1+r)} = \frac{[0.6040 \cdot €7\ 469\ 402 + (1-0.6040) \cdot €6\ 156\ 487]}{(1+0.03)}$$

$$\underline{\underline{= €6\ 747\ 057\ ,}} \qquad (7)$$

which is the calculation of the project value at $\boldsymbol{t = 0}$.

Just by looking at the revised binomial lattice, the purpose of the abandonment option as a tool which helps hedging against downside risks already becomes clear, if only 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. As shown in Table 4, the insertion of an abandonment option significantly increases the NPV of all storage alternatives.

Table 4. Comparison of the option values for the different storage solutions [in €]

	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 Results and sensitivity analysis

The ROA yields a number of interesting results, which are discussed in the following.

NPV: even without the utilization of real options analysis, the returned NPVs for all three storage systems considered are positive, thus suggesting that the Powership concept can be economically feasible. It is found that the carbazole-based storage's NPV 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 sales price of hydrogen might change that result.

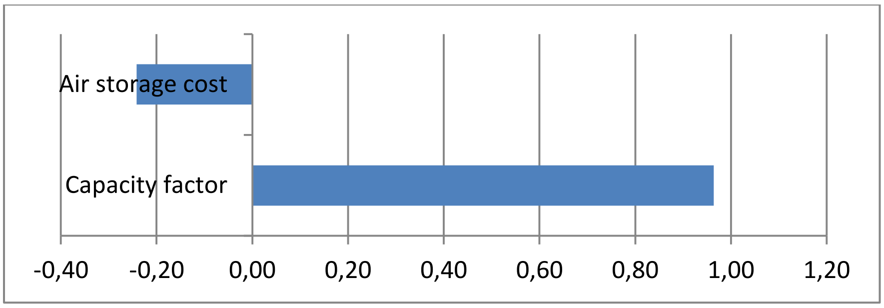
The solution based on the VDE's assumptions concerning hydrogen storage cost in the future returns the lowest NPV due to the high share of storage cost in the end-user price. Consequently, the yearly cash flows are lower compared to the other systems, which cannot be compensated by the lower initial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

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.

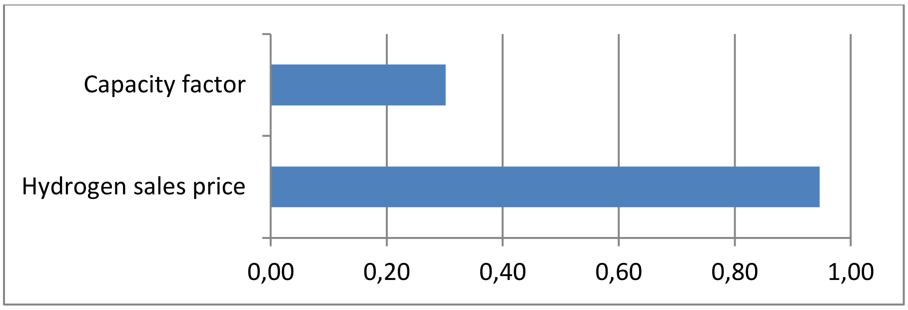
The reason behind this that can be found by analyzing the influence of the individual uncertainties on the different storage systems. Crystal Ball® features a built-in sensitivity analysis, which displays the rank correlation coefficients between the assumptions and the forecasts. A high correlation 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. 11). 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.

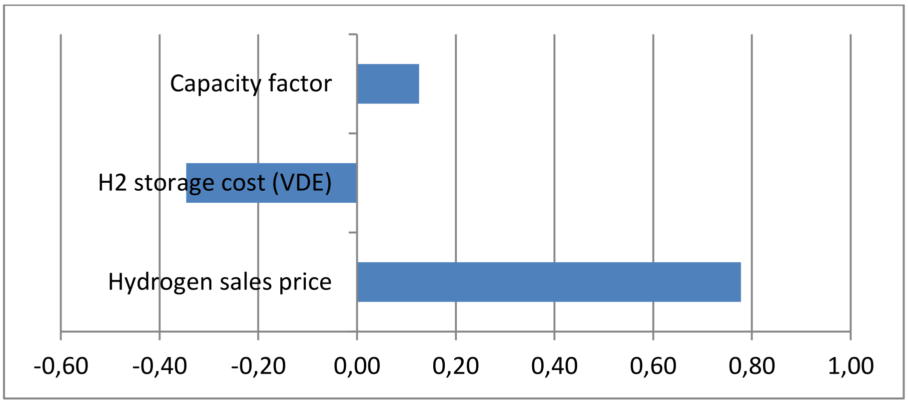
The system based on the VDE's numbers uses the hydrogen storage cost as an additional assumption which finally explains that solution's extraordinarily high standard deviation and the resulting upward and downward factors: the average hydrogen sales price in the analysis was set to 5 € kg^{-1} with a 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 would turn 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.



(a) Compressed air storage system



(b) Carbazole storage system



(c) System based on VDE assumptions

Fig. 11. Sensitivity analysis (rank correlations) for the various storage systems considered

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 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 paper, 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.

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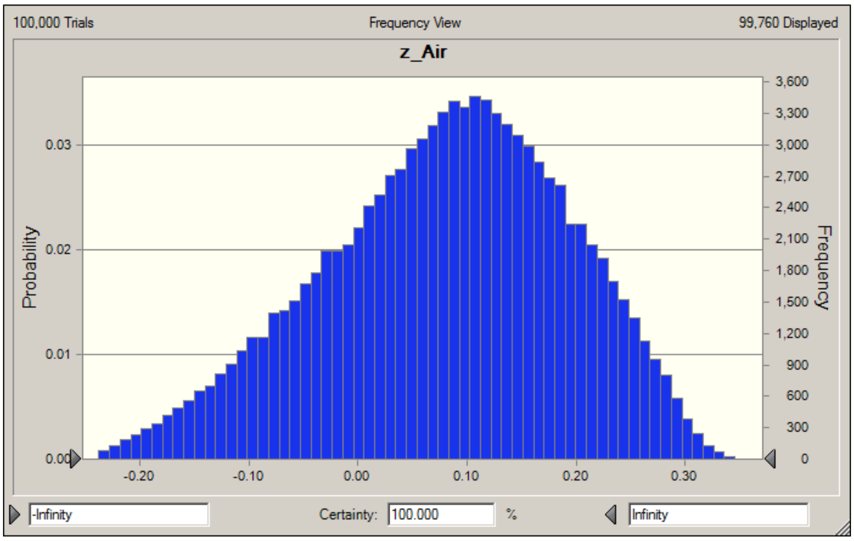
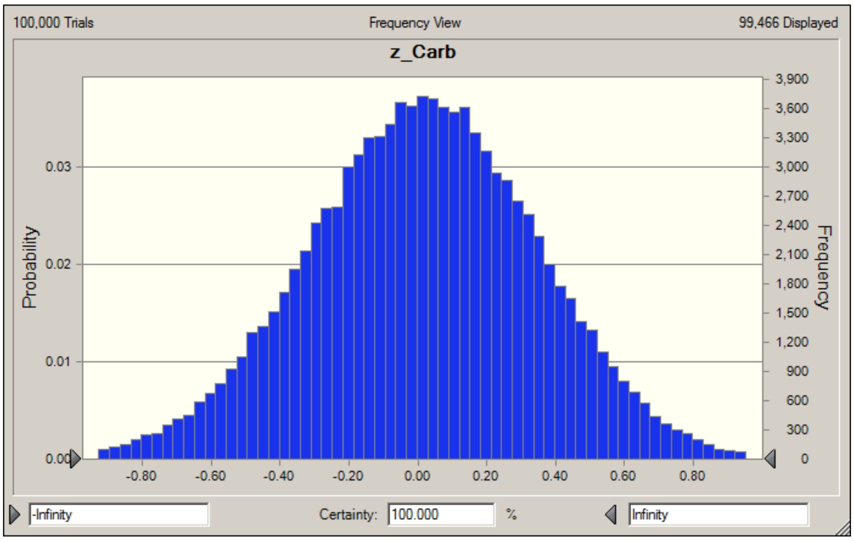
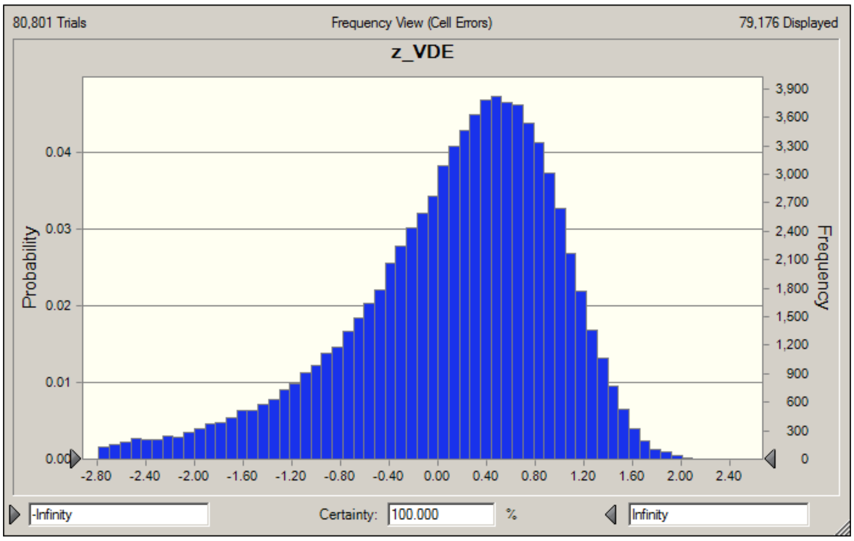
Appendix



(a) Compressed air storage



(b) Hydrogen storage using carbazole



(c) Hydrogen storage according to VDE

Fig. A.1. Frequency plots of *z* for the alternative storage options considered

Air																					
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	**6 598 371**	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730	36 035 924	40 354 217	45 189 983	50 605 235	56 669 412	63 460 278
1		5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730	36 035 924	40 354 217	45 189 983	50 605 235
2			5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730	36 035 924	40 354 217
3				4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730
4					4 195 886	4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136
5						3 746 885	4 195 886	4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002
6							3 345 932	3 746 885	4 195 886	4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846
7								2 987 885	3 345 932	3 746 885	4 195 886	4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473	11 619 917	13 012 367
8									2 668 152	2 987 885	3 345 932	3 746 885	4 195 886	4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528	9 266 090	10 376 473
9										2 382 634	2 668 152	2 987 885	3 345 932	3 746 885	4 195 886	4 698 692	5 261 750	5 892 281	6 598 371	7 389 074	8 274 528
10											2 127 669	2 382 634	2 668 152	2 987 885	3 345 932	3 746 885	4 195 886	4 698 692	5 261 750	5 892 281	6 598 371
11												1 899 988	2 127 669	2 382 634	2 668 152	2 987 885	3 345 932	3 746 885	4 195 886	4 698 692	5 261 750
12													1 696 671	1 899 988	2 127 669	2 382 634	2 668 152	2 987 885	3 345 932	3 746 885	4 195 886
13														1 515 111	1 696 671	1 899 988	2 127 669	2 382 634	2 668 152	2 987 885	3 345 932
14															1 352 979	1 515 111	1 696 671	1 899 988	2 127 669	2 382 634	2 668 152
15																1 208 197	1 352 979	1 515 111	1 696 671	1 899 988	2 127 669
16																	1 078 908	1 208 197	1 352 979	1 515 111	1 696 671
17																		963 455	1 078 908	1 208 197	1 352 979
18																			860 356	963 455	1 078 908
19																				768 289	860 356
20																					686 075
0	6 747 057	7 469 402	8 316 040	9 286 266	10 385 495	11 623 520	13 013 599	14 572 015	16 317 911	18 273 269	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730	36 035 924	40 354 217	45 189 983	50 605 235	56 669 412	63 460 278
1		6 156 487	6 743 987	7 466 271	8 313 244	9 284 060	10 383 966	11 622 606	13 013 144	14 571 838	16 317 863	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730	36 035 924	40 354 217	45 189 983	50 605 235
2			5 726 839	6 153 279	6 740 106	7 462 364	8 309 839	9 281 476	10 382 282	11 621 694	13 012 757	14 571 723	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730	36 035 924	40 354 217
3				5 510 285	5 724 414	6 149 144	6 735 139	7 457 447	8 305 686	9 278 489	10 380 500	11 620 862	13 012 486	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136	28 736 187	32 179 730
4					5 510 285	5 510 285	5 721 235	6 143 722	6 728 684	7 451 201	8 300 634	9 275 124	10 378 748	11 620 226	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002	22 915 145	25 661 136
5						5 510 285	5 510 285	5 510 285	5 716 977	6 136 460	6 720 145	7 443 194	8 294 555	9 271 536	10 377 276	11 619 917	13 012 367	14 571 678	16 317 846	18 273 262	20 463 002
6							5 510 285	5 510 285	5 510 285	5 510 285	5 711 114	6 126 463	6 708 589	7 432 855	8 287 470	9 268 178	10 376 473	11 619 917	13 012 367	14 571 678	16 317 846
7								5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 702 736	6 112 176	6 692 505	7 419 548	8 279 959	9 266 090	10 376 473	11 619 917	13 012 367
8									5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 690 107	6 090 639	6 669 348	7 403 199	8 274 528	9 266 090	10 376 473
9										5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 669 410	6 055 343	6 635 111	7 389 074	8 274 528
10											5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 629 825	5 987 838	6 598 371
11												5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285
12													5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285
13														5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285
14															5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285
15																5 510 285	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285
16																	5 510 285	5 510 285	5 510 285	5 510 285	5 510 285
17																		5 510 285	5 510 285	5 510 285	5 510 285
18																			5 510 285	5 510 285	5 510 285
19																				5 510 285	5 510 285
20																					5 510 285

Table A.1. Binomial lattices for the compressed air storage

Carbazole																					
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	**5 221 151**	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428	799 734 633	1 118 470 532	1 564 239 285	2 187 670 101	3 059 570 563	4 278 968 765
1		3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428	799 734 633	1 118 470 532	1 564 239 285	2 187 670 101
2			2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428	799 734 633	1 118 470 532
3				1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428
4					1 364 746	1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630
5						975 828	1 364 746	1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538
6							697 741	975 828	1 364 746	1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954
7								498 903	697 741	975 828	1 364 746	1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524
8									356 728	498 903	697 741	975 828	1 364 746	1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300	14 282 433	19 974 726
9										255 069	356 728	498 903	697 741	975 828	1 364 746	1 908 668	2 669 371	3 733 255	5 221 151	7 302 052	10 212 300
10											182 381	255 069	356 728	498 903	697 741	975 828	1 364 746	1 908 668	2 669 371	3 733 255	5 221 151
11												130 407	182 381	255 069	356 728	498 903	697 741	975 828	1 364 746	1 908 668	2 669 371
12													93 244	130 407	182 381	255 069	356 728	498 903	697 741	975 828	1 364 746
13														66 672	93 244	130 407	182 381	255 069	356 728	498 903	697 741
14															47 672	66 672	93 244	130 407	182 381	255 069	356 728
15																34 087	47 672	66 672	93 244	130 407	182 381
16																	24 373	34 087	47 672	66 672	93 244
17																		17 427	24 373	34 087	47 672
18																			12 461	17 427	24 373
19																				8 910	12 461
20																					6 371
0	5 542 802	7 525 590	10 357 701	14 369 193	20 020 944	27 956 835	39 077 332	54 642 842	76 418 254	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428	799 734 633	1 118 470 532	1 564 239 285	2 187 670 101	3 059 570 563	4 278 968 765
1		4 156 652	5 523 904	7 505 659	10 338 537	14 352 653	20 008 437	27 948 834	39 073 237	54 641 338	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428	799 734 633	1 118 470 532	1 564 239 285	2 187 670 101
2			3 219 432	4 137 585	5 502 209	7 483 186	10 317 629	14 335 600	19 996 653	27 942 297	39 070 620	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428	799 734 633	1 118 470 532
3				2 613 878	3 201 551	4 115 348	5 477 148	7 457 821	10 295 125	14 318 676	19 986 401	27 937 789	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630	408 873 175	571 830 428
4					2 257 070	2 598 725	3 180 490	4 089 152	5 447 927	7 429 295	10 271 555	14 302 945	19 978 727	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538	209 040 932	292 354 630
5						2 090 663	2 246 122	2 580 881	3 155 421	4 057 711	5 413 579	7 397 716	10 248 065	14 290 075	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954	106 874 488	149 469 538
6							2 074 125	2 084 998	2 233 461	2 559 863	3 124 715	4 019 085	5 373 328	7 363 842	10 226 898	14 282 433	19 974 726	27 935 695	39 069 524	54 640 764	76 417 954
7								2 074 125	2 074 125	2 078 776	2 219 553	2 534 217	3 085 329	3 971 146	5 326 710	7 329 939	10 212 300	14 282 433	19 974 726	27 935 695	39 069 524
8									2 074 125	2 074 125	2 074 125	2 074 125	2 204 222	2 499 950	3 033 593	3 911 067	5 274 424	7 302 052	10 212 300	14 282 433	19 974 726
9										2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 182 978	2 452 465	2 963 513	3 835 019	5 221 151	7 302 052	10 212 300
10											2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 152 162	2 383 586	2 863 769	3 733 255	5 221 151
11												2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 105 828	2 280 019	2 669 371
12													2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125
13														2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125
14															2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125
15																2 074 125	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125
16																	2 074 125	2 074 125	2 074 125	2 074 125	2 074 125
17																		2 074 125	2 074 125	2 074 125	2 074 125
18																			2 074 125	2 074 125	2 074 125
19																				2 074 125	2 074 125
20																					2 074 125

Table A.2. Binomial lattices for the hydrogen storage using carbazole

VDE																					
t	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
0	**1 700 161**	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737	6 542 653 884 408	17 979 248 738 472	49 407 074 088 116	135 770 910 423 259	373 099 206 083 009	1 025 278 663 491 420
1		618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737	6 542 653 884 408	17 979 248 738 472	49 407 074 088 116	135 770 910 423 259
2			225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737	6 542 653 884 408	17 979 248 738 472
3				81 929	225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737
4					29 814	81 929	225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186
5						10 849	29 814	81 929	225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582
6							3 948	10 849	29 814	81 929	225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769
7								1 437	3 948	10 849	29 814	81 929	225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811	266 426 856	732 142 460
8									523	1 437	3 948	10 849	29 814	81 929	225 141	618 689	1 700 161	4 672 051	12 838 823	35 281 156	96 952 811
9										190	523	1 437	3 948	10 849	29 814	81 929	225 141	618 689	1 700 161	4 672 051	12 838 823
10											69	190	523	1 437	3 948	10 849	29 814	81 929	225 141	618 689	1 700 161
11												25	69	190	523	1 437	3 948	10 849	29 814	81 929	225 141
12													9	25	69	190	523	1 437	3 948	10 849	29 814
13														3	9	25	69	190	523	1 437	3 948
14															1	3	9	25	69	190	523
15																0	1	3	9	25	69
16																	0	0	1	3	9
17																		0	0	0	1
18																			0	0	0
19																				0	0
20																					0
0	2 367 527	5 288 468	13 398 824	35 775 330	97 368 433	266 750 832	732 367 031	2 012 061 202	5 528 854 280	15 193 182 550	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737	6 542 653 884 408	17 979 248 738 472	49 407 074 088 116	135 770 910 423 259	373 099 206 083 009	1 025 278 663 491 420
1		1 333 593	2 364 113	5 280 889	13 384 025	35 749 614	97 328 815	266 697 555	732 306 338	2 012 005 709	5 528 817 676	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737	6 542 653 884 408	17 979 248 738 472	49 407 074 088 116	135 770 910 423 259
2			989 562	1 331 651	2 359 018	5 269 706	13 362 629	35 713 643	97 276 196	266 632 320	732 241 210	2 011 958 517	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737	6 542 653 884 408	17 979 248 738 472
3				898 125	988 763	1 328 704	2 351 330	5 253 070	13 331 615	35 663 725	97 208 203	266 557 527	732 181 087	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186	866 400 624 632	2 380 873 665 737
4					898 125	898 125	987 531	1 324 165	2 339 575	5 228 095	13 286 627	35 595 537	97 124 609	266 482 068	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582	114 731 736 635	315 283 441 186
5						898 125	898 125	898 125	985 601	1 317 048	2 321 320	5 190 229	13 221 574	35 505 309	97 031 729	266 426 856	732 142 460	2 011 931 492	5 528 798 769	15 193 169 323	41 750 912 582
6							898 125	898 125	898 125	898 125	982 505	1 305 635	2 292 417	5 132 228	13 128 618	35 393 958	96 952 811	266 426 856	732 142 460	2 011 931 492	5 528 798 769
7								898 125	898 125	898 125	898 125	898 125	977 399	1 286 812	2 245 555	5 042 534	13 000 055	35 281 156	96 952 811	266 426 856	732 142 460
8									898 125	898 125	898 125	898 125	898 125	898 125	968 663	1 254 605	2 167 197	4 902 509	12 838 823	35 281 156	96 952 811
9										898 125	898 125	898 125	898 125	898 125	898 125	898 125	953 009	1 196 895	2 029 565	4 672 051	12 838 823
10											898 125	898 125	898 125	898 125	898 125	898 125	898 125	898 125	923 883	1 089 522	1 700 161
11												898 125	898 125	898 125	898 125	898 125	898 125	898 125	898 125	898 125	898 125
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Table A.3. Binomial lattices for the hydrogen storage according to VDE

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