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Optimal Expansion of a Hydrogen Storage System for Wind Power: A Real Options Analysis

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Abstract

This paper presents a real options-based techno-economic analysis of a hydrogen-based wind energy storage system (H2-WESS) deployed adjacent to a nearshore wind farm in northern Germany. The H2-WESS can be used to produce and store hydrogen when feed-in management takes place, in order to avoid the shutdown of wind turbines during times of excess electricity supply, or when the spot market electricity price falls below the estimated (efficiency-adjusted) market price of hydrogen. Moreover, an H2-WESS can provide negative minute reserve capacity. The modular design of the H2-WESS gives an investor the option to expand the capacity and gradually adapt to changing market conditions. The comprehensive and novel simulation model considers all relevant volatile inputs, such as stochastic wind conditions, feed-in management events, prices, and minute reserve calls. By means of a Monte Carlo simulation, annual revenues and their volatility are computed with a view on projected technology improvements until 2030. Based on the simulation results, a binomial real options pricing model is used to design four interdependent binominal trees and to evaluate a Bermuda-type compound expansion option. The decision trees, in which the investor can choose the maximum of the option to either upgrade the H2-WESS to the next expansion stage or to keep the real option alive, feature 390 time steps and 76,050 decision nodes each. Each compound decision takes the option of a smaller expansion stage explicitly into account. The compound expansion option to invest in a 5, 10, 15, or 20 MW H2-WESS has a 15-year expiration time and is found to have a value of about €2 million, compared to the net present value of a 5 MW H-WESS of about €2.45 million. We conclude from the real options analysis that for a realistic valuation of modular energy projects subject to various uncertainties it is crucial to incorporate the value of managerial flexibility that is influenced. Due to the modular design, and in contrast to conventional power plants, the flexibility of the H2-WESS comprises many specific options.

Keywords: Wind power, Hydrogen, Storage system, Compound expansion option, Monte Carlo simulation, Germany

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Abbreviations used

BNetzA German Federal Grid Agency (Bundesnetzagentur)
B-S-M Black - Scholes - Merton model (for option pricing)
CAPEX Capital expenditures
CAPM Capital asset pricing model
ComExp Compound expansion (option type)
DWD German National Meteorological Service (Deutscher Wetterdienst)
EEG German Renewable Energies Act (Erneuerbare Energien Gesetz)
EEX European Energy Exchange
EnWG German Energy Act
Eins-Man Feed-in management (Einspeisemanagement) regime in Germany (based on EEG, EnWG)
GBM Geometric Brownian motion
H2-WESS Hydrogen-based wind energy storage system
MC Monte Carlo simulation
NPV Net present value
OPEX Operational expenditures
PEM Proton exchange membrane
PVCF Present value of future cash flows
RES Renewable energy sources
R&D Research and development
ROA Real options analysis
TSO Transmission system operator
vRES Variable renewable energy sources
WACC Weighted average cost of capital

1. Introduction

High shares of variable renewable energy sources (vRES) in electricity supply is a great challenge for the transmission and distribution grid operators who have to ensure grid stability. For easing the balancing of intermittent electricity supply with demand, hydrogen energy storage technology is seen by many experts as potentially important future remedy of the problem.

Wind energy has the potential to make the largest and most efficient contribution to Germany's renewable energy supply, both in both the short and the long term. However, wind as a vRES confronts the current grid feed-in and the electricity markets with a major challenge in terms of predictability and electricity prices. In November 2015, wind power capacity in Germany reached a new all-time high of 32.3 GW, and in 2016 4.625 GW of wind power capacity was newly installed [1]. At the Franco-German power exchange, EPEX, 97 hours with
negative electricity prices occurred between December 2012 and December 2013, with the result that electricity consumers had to pay around €90 million more for the promotion of renewable energies. In 2015, there were already 126 hours with negative electricity prices [2].

An important objective for the sustainable energy transition is to ensure a secure supply of electricity from an increasing share of vRES. Network congestion and bottlenecks due to excessive wind power supply are no longer negligible or marginal phenomena. Despite all the efforts towards an adequate network expansion which can keep up with the growth of the installed capacity of renewable energy, the problem of electricity supply and demand imbalances has not been definitively solved, which is why the potentials and demand for renewable energy storage are currently being discussed.

The aim of our study is the economic analysis of an investment in a technical system for producing, storing, and selling hydrogen from wind power (H2 Wind Energy Storage System, or – in short – H2-WESS; cf. Fig. 1). Moreover, the economic evaluation is scrutinized further by using a real options approach [3]-[6]. The H2-WESS is located in close proximity to a wind farm. The wind farm is fictitious, serving merely as a reference example of a representative nearshore northern German wind farm comprising a total of eight onshore wind turbines of the type Vestas V112 with 3 MW of installed capacity each. The H2-WESS consists of an electrolyzer and a cavern-based H2 storage system. For the electrolyzer, four different capacities of 5, 10, 15, and 20 MW are considered; the cavern storage is assumed to have a capacity of up to 4000 t of H2. This H2-WESS enables the generation and storage of H2 when the possibility of the direct feed-in of wind power is limited in quantity or when the feed-in is uneconomical. Additionally, the H2-WESS can be used to avoid the shut-down of wind turbines. To this end, our study considers four revenue streams: (1) Revenues due to the presence of feed-in management measures, enabling the storage of excess wind power that cannot be fed into the grid and selling of the stored hydrogen; (2) Revenues from providing negative minute reserves (based on the power price); (3) Revenues from providing negative minute reserve (based on working price), additional sale of the H2 stored; and (4) Revenues from exploiting price fluctuations when the (effective) electricity price is lower than the specific price of hydrogen. Other possible applications of the H2-WESS, for example, the coupling with other systems, are not considered and left for future research.
In this study, we pose three research questions:

Q1: What additional revenues and costs are expected in the implementation of different stages of development of a system for storing wind energy in the form of hydrogen?

Q2: What stage or performance class of the H2-WESS is economically optimal?

Q3: How can the option to expand this system be evaluated from an investor’s perspective?

In addition, we aim at answering also the question of what model assumptions should be made when applying real options analysis (ROA) and how do these affect the results, and what recommendations can be derived from the results and how can the findings help to support decision making.

2. Related literature

In recent years, interest in hydrogen storage for renewable energy has risen considerably. Venetsanos et al. [7] identify a framework for the appraisal of power projects under uncertainty within a competitive market environment, focusing on the electricity from renewables in Greece. The framework enables to quantify the option value inherent in an investment opportunity for both enhancing the upside potential as well as for reducing downside risk. Loisel et al. [8] evaluate the H2 power-to-x concept in France in 2030. They find that providing an H2 mix-usage increases the cost in too many infrastructure components and thus significantly decreases profits. H2 production costs of selected projects are found to range between 4–13 € kg⁻¹ in 2030. Marchenko and Solomin [9] examine a green power supply system consisting of photovoltaic converters, wind turbines, batteries for electric energy storage and a system for H2 production, storage and energy use. A mathematical optimization model demonstrates the efficiency of the combined use of wind and solar energy as well as the simultaneous storage of electric energy and hydrogen. The electric energy storage is most efficient for short-term time intervals, whereas an increase in the duration of continuous energy “standstills” up to several...
days makes the storage of hydrogen more cost-effective. Vivas et al. [10] present a simulator for H₂ hybridization with renewables-based systems aiming at providing the best solutions for different energy management strategies. Its main feature is calculating technical and economic parameters for the analysis of influences on energy management strategies. Eypasch et al. [11] conduct a techno-economic evaluation and feasibility study of a stationary electricity storage system with re-electrification for an application in an industrial plant. The system stores the produced hydrogen using Liquid Organic Hydrogen Carriers (LOHC). Results show that, at present, converting excess energy into heat is a more economical option than electricity storage using LOHC. However, if the goal is to provide a major part (> 75%) of the electricity needed by means of on-site renewable energy, an energy storage system becomes economical already today. Based on assumptions for the year 2030 a completely self-sufficient energy supply system built in 2030 is cost-competitive in comparison with electricity purchased from the grid. Finally, Harzendorf et al. [12] analyze the profitability and the demand-adjusted characteristics of a wind farm that is combined with an H₂ storage system. A two-step approach allows to identify a detailed operating strategy that enables to find the minimum requirements for the H₂ price and electrolyzer capacity in order to come up with an economically viable investment. The analysis shows that dimensioning from an economic point of view will always result in a smaller dimension than when taking a demand-adjusted perspective. A real options analysis is applied to incorporate the inherent uncertainty in the investment. The results show that the system’s economic performance is very sensitive to the H₂ price.

3. Methodology

3.1 Real options analysis (ROA)

To evaluate the H₂-WESS option, an approach is adopted that is based on the option pricing model of Black, Scholes, and Merton (BSM) [3-6]. The assumptions of the BSM are applied, except that in our case a dividend payment is possible, and instead of a European option (“exercise only at the maturity date”) a Bermuda option (“exercise at defined points in time within the period under consideration”) is used. In the approach adopted, the volatilities of the cash flows are assumed to be constant, whereas for the expansion stage of the H₂-WESS additional volatilities are taken into account simultaneously when computing the option value.

The binomial type of real options model used was developed by Cox, Ross, and Rubinstein (CRR) [13]. It uses as a starting point a so-called ‘underlying asset’ (in short: the ‘underlying’), such as the present value of the expected future cash flows, which undergoes a specific development. Based on the model, initially the cash flows and other project-specific quantities
are calculated using Monte Carlo simulation. These quantities are then used in the ROA. Real options are an analogy from financial derivatives and are characterized by the fact that they are based on an investment that is not or only partially reversible. As in the case of financial options, real options can be classified on the basis of the exercise date: (A) European option – the option can only be exercised at the expiry date; (B) American option – the option can be exercised any time prior to expiry; and (C) Bermuda option – the option can be exercised at one of several previously determined times. The latter is generally less well known but is the one used in our study.

Real options are generally not subject to these restrictions, as investments can be made at any time. In order to take this particular fact into account, the aim of our study is to present a scenario which is as realistic as possible. A maturity date for an investment decision is not useful for many projects, because investments can be made at any time, which assumes continuous access to capital. Weber [14], for instance, questioned whether real option values indeed follow the same development as stock prices, and whether the returns from real assets can actually be expected to be normally distributed.

An option evaluates the possibility to increase revenues or reduce costs through future transactions. ROA has increasingly become popular for evaluating irreversible investment projects also in the energy domain ([15]-[22]). All of the projects comprise three characteristic properties which are relevant to the successful application of the ROA, namely irreversibility, uncertainty, and managerial flexibility to postpone the investment ([7]-[9]).

Financial options are subject to uncertainty and timing as well as to real investments. Only the fact that a large part of the investment is irreversible and considered to be sunk costs is the decisive difference. The ROA method for assessing investment projects is particularly preferred when there are pronounced uncertainties in future payment flows, and thus is predestined also for a great many of the often capital-intensive and long-lived energy projects. In the present context, energy projects – in addition to the exploration of raw materials such as coal, oil / natural gas, etc. – also include the generation of energy through conventional power plants and renewable energies, as well as the transportation, distribution, and storage of electrical energy and heat. In addition to natural uncertainties, such as ignorance of raw material incidents or unpredictable weather conditions, there is also a lack of information on the existence and development of sales markets ([4]). ROA enables to account for the value of managerial flexibility and thus helps to obtain a more realistic valuation of the capital goods, such as power plants and energy storage units. In this context, flexibility means that in addition to timing, it is often possible to influence project design. This means that the type, size, quality etc. of a project
can be adapted to the respective circumstances, depending on the state of development ([4]).

The flexibility that is available to project management over the whole or part of the project duration can be combined into various (types of) options. In our analysis, the real options are developed and the option values calculated by means of a cascaded binomial tree (e.g. [21]-[22]); a schematic representation of the approach adopted is shown in Fig. 2.

**Fig. 2.** Approach adopted to evaluate the H2-WESS by means of Monte Carlo simulation and a binomial real options model.

### 3.2 Model description for calculation of the annual cash flows

Based on the technical specifications, a model is developed for calculating the annual cash flows resulting from the revenue streams and the resulting operating costs through the use of various H2-WESS expansion stages. The model is largely based on random variables that emulate the volatile nature of the input variables with stochastic processes. Subsequently, the model is used to simulate the stochastically distributed present values of the cash flows. There are two types of input variables. The variables that are subject to managerial influence and assumed to have an impact on the results are: (1) the number and (2) the nominal power of the electrolyzer modules used (see Table 1). All other input variables of the model are treated as exogenous, and can be subdivided into constant and time-dependent parameters. The period of analysis is 2015-2030 (i.e. a 15-year modeling horizon).

**Table 1** Overview of model input parameters

<table>
<thead>
<tr>
<th>Parameter (by category)</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management decisions (options):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of electrolyzer</td>
<td>$n_{Ely}$</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

PVCF: Present value of cash flows
OPEX: Operational expenditures
CAPEX: Capital expenditures
* 26 years of lifetime
Nominal power of electrolyzer \( P_{\text{ely}} \) 5 [MW]

**Wind farm:**

Weibull scale factor \( \lambda \) 9.8 [m s\(^{-1}\)]
Weibull shape factor \( k \) 2.32
No. of wind turbines at wind farm \( n_{\text{WTG}} \) 8

**Technical specifications:**

Efficiency electrolyzer \( \eta_{\text{ely}} \) 63 \((t=2015)\), 71 \((t=2030)\) [%]
Efficiency storage system \( \eta_{\text{sto}} \) 97.8 [%]
\( \text{H}_2 \) conversion factor (mass-energy) - 53 [kWh kg\(^{-1}\)]

**Negative minute reserve:**

Probability of demand \( p(W_{\text{demand}}) \) 4.8515 [%]
Log mean power if called \( \mu(\ln) \) 5.3058 [-]
Log standard deviation \( \sigma(\ln) \) 0.8663 [-]

**Feed-in management:**

Energy losses \( W_{\text{loss}} \) See [14], Table 8

**Prices:**

Onshore wind subsidy \( EEG \) 46.5 \((t=2015)\), 37 \((t=2030)\) [€ MWh\(^{-1}\)]
Electricity spot market price \( p_{\text{spot}} \) See [14], Table 6 [€ MWh\(^{-1}\)]
\( \text{H}_2\)-WESS-specific \( \text{H}_2 \) price \( p_{\text{H}_2 \text{ spec}} \) 36.04 [€ MWh\(^{-1}\)]
Capacity price bid \( p_{\text{cap bid}} \) See [14], Table 9 [€ MWh\(^{-1}\)]

**Specific op. costs (OPEX):**

Electrolyzer \( c_{\text{ely}} \) 34,000 \((t=2015)\), 26,500 \((t=2030)\) [€ (MW·a)\(^{-1}\)]

Cavern storage \( c_{\text{sto}} \) 3.73 [€ (kg·a)\(^{-1}\)]

**Specific capital costs (CAPEX):**

Electrolyzer \( C_{\text{ely}}(t=2015) \) 930 [€ kW\(^{-1}\)]
\( C_{\text{ely}}(t=2030) \) 580 [€ kW\(^{-1}\)]

Cavern storage \( C_{\text{sto}} \) 232 [€ kg\(^{-1}\)]

3.3 Revenues

The total annual revenues are determined by the total hourly revenues gained from the feed-in management measures, the provision of negative minute reserve, the retrieving of negative minute reserve, and low electricity prices.

To ensure a stable grid operation, the transmission system operators (TSOs) are forced to shut down wind energy plants if the electricity feed-in exceeds the available transmission capacity. In most cases, the operator of the wind park is compensated by the EEG if its wind energy plants cannot feed into the grid due to feed-in measures by the TSOs. These additional costs of the TSOs are passed on to the end-consumer in the form of an increased EEG surcharge. These external costs are internalized in this calculation by considering the excess energy as lost...
profits and assuming that the wind park operator and the TSOs share the burden of the lost
profits.

In addition to compensating the feed-in management, H2-WEES is also suitable for
providing control energy. The TSOs have three types of control energy available for the purpose
of regulating the voltage and frequency stability and the imbalance due to fluctuating
consumption, prediction inaccuracies, or stochastically fluctuating generation. The three kinds
of control energy are: (1) The primary control system, which can be provided exclusively by
certain large power plants with special control devices; (2) The secondary control (activation
time < 5 min), which at present is also provided practically only by large power plants with
special control devices; and (3) The minute reserve (activation time < 15 min), which can also
be provided by decentralized generation plants and consumers. Primary and secondary reserves
are controlled automatically, and the minutes are maintained by an automatic retrieval by the
responsible TSO ([21]).

For a storage system with no re-electrification, the negative minute reserve becomes relevant.
The provider is obligated to provide the entire offered minute reserve at the request of the TSO
within 15 minutes. A call is made on a per MW basis ([22]). In 2011, the BNetzA reduced the
minimum bid size from 15 MW to 5 MW, reasoning that "The new framework conditions will
facilitate the provision of services for new and small suppliers and enable the development of
flexible potentials and technologies such as power-controllable consumers, electricity storage,
and renewable energy systems for the control energy market" ([23]). For the H2-WEES
considered in our analysis, the requirements for prequalification for the control energy market
are fulfilled.

In order to participate in the control energy market, the required energy quantities have to be
tendered one day ahead. A bid consists of four items: (1) Time slots \( t_{\text{timeslot}} \) \{00-04; 04-08; 08-
12; 12-16; 16-20; 20-24\}; (2) Tendered capacity \( P_{\text{Ely}} \) (at least 5 MW, increment of 1 MW); (3)
Capacity price \( p_{\text{cap}} \text{ bid} \) [€ MW\(^{-1}\)]; and (4) Energy price in \( p_{\text{energy}} \text{ bid} \) [€ MWh\(^{-1}\)].

The time slots and tendered capacities depend on the provider. In this study, tenders are
submitted at all times and always with the maximum available power of the electrolyzer system.
The level of tendered capacity and energy prices is subject to an individual offer strategy.
According to this, the prices have to be chosen so low that they are “still” accepted and high
enough that they gain the highest possible revenues. For many providers, the price offer is based
on the individual marginal costs. The auction is two-stage. All offers for the tendered capacity
are accepted according to merit order. Accepted offers receive the capacity surcharge. The
marginal price level is not based on the current supply and the requirement for control energy. The marginal rates vary greatly depending on the time frame.

In order to model the revenues by providing control power, a simulation of both the demand and the supply strategy is necessary, also to determine the volatility of the revenues and to take account of the ROA. On the basis of the historical data from Regelleistung.net for the year 2015, it can be deduced that the limit price is almost exponentially distributed ([24]).

In the present case, the revenues from the control energy are maximized. A Monte Carlo simulation has shown that the optimal offer price is exactly the average limit price (see also [25]). An optimal strategy is therefore the case if

\[ p^*_\text{cap bid} = E(p_{\text{cap marginal}}) = \mu(p_{\text{cap marginal}}, t_{\text{timeslot}}). \]

where \( p^*_\text{cap bid} \) [\( \text{€ MW}^{-1} \)] denotes the optimal capacity price bid, \( p_{\text{cap marginal}} \) [\( \text{€ MW}^{-1} \)] the marginal capacity price, and \( \mu \) the mean value of the marginal capacity price per time slot.

In the second stage of the auction, the accepted bidders receive the revenues for the actually retrieved minute reserve. This price also depends on the lowest tendered prices according to merit order. Energy prices for minute reserves can be disproportionately high compared to the spot market price, but the actual performance retrieved or the probability of a call is rather low. According to statistics for 2015, the actual call probability is 1.5%.

The price of hydrogen is chosen in order to extend the sales opportunities: With a price of \( \text{€3.1 per kg of H}_2 \) (equivalent to \( 36.04 \text{ € MWh}^{-1} \)), \( \text{H}_2 \) sales seem possible both to the natural gas grid but also in the electricity sector.

Since the EEG 2014, which entered into force on August 1, 2014, mandatory direct marketing has been applied to all new renewable energy power plants if the installed capacity of the plant exceeds 500 kW. Direct marketing, for example, takes place at the electricity exchange EPEX Spot SE. This marketplace is also used as a reference for determining the market premium, which producers receive as a substitute for the fixed feed-in tariff. The market premium is paid in addition to the spot market revenues, so that at least the average basic rate specified in the EEG can be achieved. In addition, renewable power generators, such as flexible biogas plants, have additional incentives to reduce the feed-in at times of low electricity prices. The \( \text{H}_2\)-WESS project presented here can also make use of this option in that periods of low electricity prices can be used to generate, store, and sell hydrogen. The storage of hydrogen instead of the direct feed-in into the electric grid is only advantageous if the effective price of electricity is below the specific hydrogen price (\( p_{el} < p_{\text{H}_2 \text{ spec}} \)).
Figure 3 shows the development of the effective electricity price, i.e. the spot market price plus the market premium, in Germany in 2015. When the effective electricity price is compared with the determined (constant) hydrogen price, it is noticeable that in 2015 the specific price of hydrogen was in 780 hours below that of the electricity price (including the EEG market premium), which is equivalent to 8.9% of the year. Accordingly, due to the lack of information on the feed-in forecast for onshore wind energy, we assume in our analysis that the hydrogen price is on average undercut during 8.9% of the time of the year.

![Effective electricity price compared to H₂ price 2015](source: own illustration, based on [21])

3.4 Storage strategy

The storage strategy is decisive for the design of the H₂-WESS and the revenues that can be achieved. An optimal strategy is to ensure that the H₂-WESS is always used in a profit-maximizing way. The electrolyte system generates hydrogen in three cases: (I) Feed-in management and/or (II) Recall of negative minutes and/or (III) Low electricity prices. Formally, this can be specified as:

\[
W_{\text{Sto}}(t) = \begin{cases} 
W_{\text{Elý}} \cdot 1\text{h} & W_{\text{MR- call}} + W_{\text{loss}} + W_{\text{low price}} \geq W_{\text{Elý}} \cdot 1\text{h} \\
W_{\text{MR- call}}(t) + W_{\text{loss}}(t) + W_{\text{low price}}(t) & W_{\text{MR- call}} + W_{\text{loss}} + W_{\text{low price}} \leq W_{\text{Elý}} \cdot 1\text{h} \\
0 & W_{\text{MR- call}} = W_{\text{loss}} = W_{\text{low price}} = 0
\end{cases}
\]

\[
W_{\text{low price}}(t) = W_{\text{wind farm}}(t) \quad \text{if } p_{\text{el}} < p_{\text{H₂ spec}}
\]

\[
M_{\text{Sto}}(t) = \begin{cases} 
M_{\text{Sto}}(t-1) + \frac{W_{\text{Sto}}(t)}{53} & t \neq t_{\text{evac}} \\
0 & t = t_{\text{evac}}
\end{cases}
\]

with

\[
W_{\text{Sto}} \quad [\text{MWh}] \quad \text{Energy that is produced by the electrolyzer system and stored in caverns}
\]
Nominal power of electrolyzer system

Actually called negative minute reserve energy

Electrical energy loss due to feed-in management

Electrical energy stored if effective electricity price is lower than H$_2$ price

Energy production of wind farm

Storage level

Time when the storage level resets to 0; the stored H$_2$ is retrieved every 8 weeks

Depending on the overall performance of the electrolyzer system, not all potential energy can be stored. In the case of conflict between feed-in management losses or low electricity prices and simultaneous retrieval of minute reserves, i.e. if the sum of the powers is greater than the overall performance of the electrolyzer system, the minute reserve takes precedence. The prioritization is plausible, since, in contrast to normal wind energy production, the retrieved minute reserve is additionally remunerated via the energy price offered. In the case of negative minute reserve, each megawatt-hour stored is thus remunerated twice: once via the capacity price and once via the hydrogen price. Furthermore, the tendered capacity is contracted and must be provided if required and requested by the regulator.

### 3.5 Revenues

The total annual revenues comprise the total of the hourly revenues gained from (I) Feed-in management measures; (II) Provision of negative minute reserve; (III) Retrieval of negative minute reserve; and (IV) Low power prices. They can be calculated by using the following formula:

\[
R_{H2WESS} = R_{\text{cap}} + R_{\text{MR-call}} + R_{\text{feedin}} + R_{\text{low price}}
\]

\[
R_{\text{cap}} = \sum_{t=1}^{8766} \left(p_{\text{cap bid}}(t) \cdot p_{Ely} \mid p_{\text{cap bid}} \leq p_{\text{cap margin}} \right)
\]

\[
R_{\text{MR-call}} = \sum_{t=1}^{8766} \left(p_{\text{energy bid}}(t) + p_{H2\text{ spec}} \cdot \min \left( p_{Ely} \cdot 1h, W_{\text{MR-call}}(t) \right) \right)
\]

\[
R_{\text{feedin}} = \sum_{t=1}^{8766} \left(p_{H2\text{ spec}} \cdot \min \left( p_{Ely} \cdot 1h - W_{\text{MR-call}}(t), W_{\text{loss}}(t) \right) \right)
\]

\[
R_{\text{low price}} = \sum_{t=1}^{8766} \left(p_{H2\text{ spec}} \cdot \min \left( p_{Ely} \cdot 1h - W_{\text{MR-call}}(t), W_{\text{wind farm}}(t) \right) \mid p_{el} < p_{H2\text{ spec}} \right)
\]

Revenues due to minute reserve only if bid is accepted

Revenues due to low electricity price only if effective electricity price is lower than specific H$_2$ price
with

\begin{align*}
R_{\text{H2 WESS}} & \quad [\text{€ a}^{-1}] \quad \text{Sum of annual revenue} \\
R_{\text{cap}} & \quad [\text{€ a}^{-1}] \quad \text{Annual revenue due to negative minute reserve capacity} \\
R_{\text{MR-call}} & \quad [\text{€ a}^{-1}] \quad \text{Annual revenue due to negative minute reserve energy called} \\
R_{\text{feedin}} & \quad [\text{€ a}^{-1}] \quad \text{Annual revenue due to feed-in management} \\
R_{\text{low price}} & \quad [\text{€ a}^{-1}] \quad \text{Annual revenue due to low effective electricity prices} \\
p_{\text{cap bid}} & \quad [\text{€ MW}^{-1}] \quad \text{Capacity price bid, depending on time slot (optimal bidding strategy)} \\
p_{\text{cap margin}} & \quad [\text{€ MW}^{-1}] \quad \text{Marginal capacity price (simulated)} \\
p_{\text{energy bid}} & \quad [\text{€ MWh}^{-1}] \quad \text{Energy price bid depending on time slot (optimal bidding strategy)} \\
p_{\text{H2-spec}} & \quad [\text{€ MWh}^{-1}] \quad \text{H2-WESS specific price of hydrogen} \\
p_{\text{Ely}} & \quad [\text{MW}] \quad \text{Nominal power of electrolyzer system} \\
W_{\text{MR-call}} & \quad [\text{MWh}] \quad \text{Actually called negative minute reserve energy (call probability 1.5\%)} \\
W_{\text{loss}} & \quad [\text{MWh}] \quad \text{Energy losses due to feed-in management} \\
W_{\text{wind farm}} & \quad [\text{MWh}] \quad \text{Energy production of the wind farm}
\end{align*}

3.6 Expenditures (OPEX and CAPEX)

The level of the operating expenditures of the H2-WESS, the capital expenditures and the efficiency all depend on the date of implementation, i.e. are time-dependent. Thus, the predicted technological advancement of electrolyzers over the years 2015 to 2030 is considered. The OPEX of the storage device are assumed to be constant. The total OPEX are based on the sum of the individual systems and depend on the commissioning year, the choice of the expansion class (performance class), and the share of cavern storage. In contrast to the OPEX and the efficiency of the electrolyzer, the investment expenditures of the cavern storage are assumed to decrease in a non-linear, regressive manner (learning curve effect) over the years (see Table 1).

4. Simulation and real-time evaluation of the H2-WESS

Based on the model description, the following section reports on the results of the Monte Carlo simulation and the ROA. The main goal of the simulation is to determine the present value of the respective cash flows. In addition, further relevant statistics of the simulated project are discussed. The ROA is applied to the simulated cash flows. After introducing the method, the present values and the volatilities with regard to the corresponding H2-WESS expansion stage are determined. Then, these quantities are used to generate the binomial tree and to evaluate a compound expansion option (CompExp). Finally, a sensitivity analysis is performed to check the robustness of the results.

4.1 Monte Carlo simulation

In the analysis that follows, the calculation model from the previous section is used to simulate cash flows that are resulting from the implementation of H2-WESS. A distinction is
made here between the individual expansion stages, which can assume a total output of either 5, 10, 15, or 20 MW. A deterministic calculation of secure cash flows is not possible because of their volatile nature, in particular due to the uncertainty arising from intermittency of the wind, the probability of low power prices, failure due to feed-in management measures, and the provision of negative minute reserve (marginal service price).

These variables are determined by random numbers depending on their characteristic distribution functions, whereas the volatilities determine the spread of the revenues.

By means of Monte Carlo simulations the average annual energy production of the wind park is determined. To this end, the hourly energy production is computed on the basis of the randomly, Weibull-distributed wind speed, combined with the stochastic performance curve of the wind turbine generator. A realistic and representative average value as well as the frequency distribution is determined by means of 5000 runs of the annual result. With the optimal supply strategy (average limit price per time slice), an average of 63% (standard deviation 0.01%) of the offered service price is accepted. At the same time, this value corresponds to the optimum, since a higher quota would not necessarily result in multiples. For a given storage utilization strategy, the demand for storage mass is at a maximum of 4 kg MW\(^{-1}\) of power of the H2-WESS, and thus determines the share of the cavern costs.

On average, the H2-WESS is in operation about 31% of the year. This value is the same for all expansion stages. A further statistic shows the capacity utilization of the H2-WESS as a quotient of the annual quantities of actually produced storage energy and the energy that can theoretically be produced by the electrolyzer system. The load factor varies according to the expansion stages; it is 17.12% for a 5 MW H2-WESS and falls regressively to 8.07% in the case of a 20 MW H2-WESS. The decreasing utilization with increasing power is plausible with regard to the storage requirement, which does not increase proportionally to the performance of the H2-WESS. Although a capacity utilization of between 8–18% may give the impression that the system is inefficient, such an assessment needs to take into account the character of freely available resources such as wind with very low marginal cost of power generation in the absence of fuel costs. Maximizing the utilization is therefore not the goal of the optimization, but the maximization of the revenue, the minimization of the production lost (i.e. the potential generation that cannot be fed into the grid) and the provision of reserve energy. Figure 4 shows the development of the CAPEX and OPEX based on the technical improvements expected until 2030.
On the one hand, it is to be expected that the overall efficiency of the H2-WESS, i.e. the electrolyzer system and cavern storage system, including compressors, will improve linearly from 61.6% to 69.4%. On the other hand, the operating expenditures are expected to decrease linearly from 34,000 € (MW · a)⁻¹ to 26,500 € (MW · a)⁻¹, and the investment expenditures from 931,000 € MW⁻¹ to 581,000 € MW⁻¹, until 2030. The latter is not subject to a linearly declining (but an approximately regressive) course, whereby between 2022 and 2028 only a slight cost reduction is expected (Fig. 4). For obvious reasons, all three development projections have a positive effect on the economic viability of H2-WESS. With regard to the option value of the implementation, these developments mean more favorable conditions the longer the waiting period is.

Figure 5 shows the mean revenues for the various H2-WESS expansion stages. For the 5 MW unit, for instance, we find that the largest revenue portion is generated from the feed-in management measures stipulated in the German Energy Industry Act (EnWG) and the German Renewable Energies Act (EEG), respectively, referred to as feed-in management (in German referred to as Einspeisemanagement, or short Eins-Man) (169 k€ a⁻¹ or 38.2%), followed by the provision of negative minute reserve (148 k€ a⁻¹ or 33.3%) and the exploitation of the lowest price levels (103 k€ a⁻¹ or 23.4%).
4.2 Real options analysis of the H2-WESS

As already explained in the methodology part, the options to be assessed are differentiated according to their nature. The variety of options can be used to combine different types of options in order to make the investor's flexible scope of action as realistic as possible. In the present case, the investor can decide whether the H2-WESS is implemented and then expanded by additional modules, or not. When selecting the expansion stage, it is limited only by three conditions: (1) The minimum capacity of the electrolyzer system is 5 MW for being allowed to participate in the reserve energy market, (2) Each additional module has a capacity of 5 MW, since from a technical point of view this performance class is optimal in terms of the cost-benefit ratio; and (3) The investment is assumed to be totally irreversible or sunk (i.e. no net gain from dismantling and sale in a secondary market are expected).

Considering the maximum wind farm capacity of 8 x 3 MW (V112), i.e. 24 MW, it can be seen that an H2-WESS of more than 24 MW is not suitable for achieving additional revenues with feed-in management and low electricity prices. Therefore, power ratings of 5, 10, 15, and 20 MW are considered in the analysis. Due to the above conditions, the following two option types apply for the valuation of the scope: (1) Option to Expand (old operation scale), i.e. the expansion of the H2-WESS and resulting increase in revenues or (2) Compound Option, i.e. the decisions take into account the option values of other levels.

Fig. 5. Simulated mean revenues for the various H2-WESS modules in 2015 [€ a⁻¹]
We use the term "compound expansion option (ComExp)" to describe the above-mentioned combined option type, thus following [4]. In this context, the compound expansion option means that the decision to expand the H2-WESS depends on the option value of the previous expansion stage. At the same time, this needs to be compared with the option value of future extensions.

A special feature of the ROA is that the exercise price (or so-called strike price) of the option, i.e. the cost of a system expansion, is not constant but decreases over time (see CAPEX). The Bermuda-type ComExp option is evaluated using the binomial tree method. As the following analysis shows, binominal trees enable a flexible adaptation of the node-like calculation; furthermore, various model properties can explicitly be taken into account.

The cash flow used for the reference year is the underlying for the binominal tree, or the present value of the cash flows, PVCF. In the case of the implementation of an H2-WESS, the expected payment flows are determined over the entire lifetime of the electrolyzer system (17):

\[
PVCF_i = \sum_{\tau=1}^{T_{El}} \frac{R_{H2\text{ WESS}}(\tau) - C_{H2\text{ WESS}}(\tau)}{(1+r_{rd})^\tau},
\]

where \(PVCF_i\) denotes the present value of cash flows of module \(i\) [€], \(T_{El}\) the expected lifetime of the electrolyzer system [a], \(R_{H2\text{ WESS}}\) the sum of the annual revenues (that depend on the year of deployment), \(C_{H2\text{ WESS}}\) the sum of the annual operational costs (that also depend on the year of deployment), and \(\tau\) denotes time, starting in the year 2015.

5. Results

5.1 Determination of the present value cash flows

The main objective of the simulation is to determine the present value of the respective cash flows. In addition, other relevant statistics of the simulated project are discussed. Based on the simulated cash flows, the ROA is performed. Subsequently, the net present values and volatilities are determined with regard to the expansion stage of the H2-WESS considered here. These variables are then used to generate the binominal tree and to evaluate a compound expansion option. Figure 6 shows the computed net present values. The slopes of the curves decrease due to the regressive CAPEX assumption. As can be seen, all power levels have negative net present values up to 2030, so that implementation is not reasonable. Technological progress will decrease costs and increase the technical efficiency.
Figure 6. Net present values for each H2-WESS capacity considered [€]

Figure 7 and table 2 give an overview of the simulated PVCF for each H2-WESS option considered in 2015.

<table>
<thead>
<tr>
<th>2015</th>
<th>5 MW</th>
<th>10 MW</th>
<th>15 MW</th>
<th>20 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong> [€]</td>
<td>2,201,276</td>
<td>2,441,456</td>
<td>2,483,750</td>
<td>2,495,011</td>
</tr>
<tr>
<td><strong>Skewness</strong></td>
<td>0.27</td>
<td>0.47</td>
<td>0.35</td>
<td>0.44</td>
</tr>
<tr>
<td><strong>Kurtosis</strong></td>
<td>2.85</td>
<td>3.16</td>
<td>2.94</td>
<td>3.04</td>
</tr>
<tr>
<td><strong>Volatility</strong> [%]</td>
<td>10.73</td>
<td>18.75</td>
<td>27.74</td>
<td>39.87</td>
</tr>
<tr>
<td><strong>Error</strong> [%]</td>
<td>0.24</td>
<td>0.29</td>
<td>0.42</td>
<td>0.56</td>
</tr>
</tbody>
</table>

Fig. 7. Plotted distribution of simulated PVCF for each H2-WESS module (5000 iterations)

Table 2 Simulated present value of cash flows (PVCF) for each H2-WESS option 2015

<table>
<thead>
<tr>
<th>2015</th>
<th>5 MW</th>
<th>10 MW</th>
<th>15 MW</th>
<th>20 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong> [€]</td>
<td>2,201,276</td>
<td>2,441,456</td>
<td>2,483,750</td>
<td>2,495,011</td>
</tr>
<tr>
<td><strong>Standard deviation</strong> [€]</td>
<td>165,870</td>
<td>316,786</td>
<td>463,920</td>
<td>620,439</td>
</tr>
<tr>
<td><strong>Skewness</strong></td>
<td>0.27</td>
<td>0.47</td>
<td>0.35</td>
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</tr>
</tbody>
</table>

*Note: Based on $T_{Ely} = 26$ a (lifetime of electrolyzer), $r_{id} = 6\%$*
As expected, the current value of future cash flows increases with each construction step, *cet. par*. It is striking that the cash flow volatility of a 20 MW H2-WESS compared to a 5 MW H2-WESS is approximately four times higher. This clear difference can be explained by the fact that the H2 WESS revenues are more sensitive to fluctuations in the volatile input variables when the rated output increases.

The maximization of the option value in each node is realized by a comparison with the next smaller capacity level. For example, the option of the same node for a 10 MW H2-WESS is compared in an arbitrary other node by considering the underlying for a 15 MW H2-WESS. If the implementation of the 15 MW expansion stage is not cost-efficient because the underlying is less than the capital expenditure for the expansion, the option for the 10 MW expansion stage remains open. Instead of considering the option entirely or not at all for 15 MW, the option value of the next lower level is taken into account.

In order to be able to intuitively follow the stepwise determination of the option value, the terminal nodes of the 5 MW binominal tree are considered first (backward induction). At the end of the exercise period, the investor is faced with the decision to implement or to reject a 5 MW H2-WESS. The value of the refusal is zero, since no H2-WESS costs are incurred, but no additional revenues can be generated for the wind farm. The value of the option to implement the H2-WESS is derived from the developed underlying minus the investment expenditures.

### 5.2 Value of the Bermuda Compound Expansion Option

The binominal tree describes the development of the underlying (on the basis of the values reported in Table 15). With the help of the PVCF and the volatility of all H2-WESS expansion stages, it is possible to produce four binomial trees in total, all of which are based on the same risk-free interest rate. The value of any node is determined according to eq. (4), shown here for the final nodes of the expansion stage 5 MW, as well as arbitrary nodes of the 5 and 10 MW expansion stages:

\[
V_5(\tau = T, j) = \max \left( \begin{array}{c}
g_5(\tau) \cdot PVCF_5 \cdot u_5^{(\tau-j)} \cdot d_5^j - 5 \cdot C(\tau) \\
0
\end{array} \right)
\]  

\[
V_5(\tau, j) = \max \left( \begin{array}{c}
g_5(\tau) \cdot PVCF_5 \cdot u_5^{(\tau-j)} \cdot d_5^j - 5 \cdot C(\tau) \\
[p_5 \cdot V_5(\tau + 1, j) + (1 - p_5) \cdot V_5(\tau + 1, j + 1)] \cdot e^{-(r_r - \delta) \cdot \Delta \tau}
\end{array} \right)
\]

\[
V_{10}(\tau, j) = \max \left( \begin{array}{c}
g_{10}(\tau) \cdot PVCF_{10} \cdot u_{10}^{(\tau-j)} \cdot d_{10}^j - 10 \cdot C(\tau) \\
[p_{10} \cdot V_{10}(\tau + 1, j) + (1 - p_{10}) \cdot V_{10}(\tau + 1, j + 1)] \cdot e^{-(r_r - \delta) \cdot \Delta \tau}
\end{array} \right)
\]

\[
g_i(\tau) = \left( 1 + \frac{(g_{i, base} - 1) \cdot \Delta \tau}{\tau} \right)
\]
where $V_i(\tau,j)$ denotes the value of node $\tau,j$ of module $i = 5, 10, 15,$ or $20$ MW [€], $\tau$ is the time index (year, day, …) starting with 0, $T$ is the expiration date of option (terminal node), $j$ the node index from top to bottom starting with 0, $g_i$ the growth factor considering higher cash flows due to better efficiency, $PVCF_i$ the present value of the cash flows [€] of module $i = 5, 10, 15,$ or $20$ MW, $u_i (d_i)$ the up-factor (down-factor) of module $i$, $p$ the probability of the occurring up-state of module $i$, $C(\tau)$ the CAPEX per MW depending on year of implementation (in € MW$^{-1}$), $r_{rf} – \delta$ the risk-free interest rate minus the dividend, and $\Delta \tau$ the incremental time step. Equation (4) describes the core of the ComExp Option valuation method. Its complexity is grounded in the orientation between the individual underlyings of the respective expansion stages.

5.2.1 Terminal nodes

The option value is determined by means of recursive induction, starting from the terminal node of the 5 MW binominal tree. At the end of the exercise period the investor has to decide whether to invest in a 5 MW H2-WESS or to wait, i.e. to decline from doing so. The value of the rejection is zero, since without building an H2-WESS no costs will occur (by assumption project preparation costs are assumed to be negligible), but obviously also no revenues additionally to the operation of the wind farm. The option value of implementing the H2-WESS thus results from the underlying minus the investment costs, where the underlying is determined as the product of the underlying’s PVCF, the up- and down-factors leading to the terminal node and the technology growth factor $g_i$. This factor is dependent on the investment time and takes, among others, the rising efficiency of the electrolyzer into account. An H2-WESS, say, implemented in 2030, shows a projected efficiency of 71%, compared to 63% in 2015 (cf. Table A.2). For the revenue calculations, the conversion efficiency has a direct impact on the specific H$_2$ prices, and thus raises the sales revenues that can be achieved from the hydrogen stored.

The technology growth factor also takes into account decreasing OPEX. Both efficiency and operating and maintenance (O&M) expenditures are assumed to be linear, representing the technological progress of the electrolyzer system. The growth factor $g_i$ is determined by using the simulated cash flows for the years 2015 until 2030. Due to the linearity assumption of the technological progress, the cash flows also feature a linear development, which is why the base factor $g_i$ corresponds with the $PVCF_i$ growth. When exercising the expansion option, the CAPEX is subtracted from the development of the underlying in the form of the specific CAPEX in € MW$^{-1}$. Here again, the investment expenditures are dependent on the investment time, featuring the typical regressive development (cf. Fig. 4). If the investment expenditures exceed the underlying, the implementation of the 5 MW H2-WESS at the end of the evaluation
period should be forfeited: the investor prefers to let the option expire and thus obtains the value of zero instead of a negative value. This opportunity to choose leads to the situation where the investment only takes place if the underlying develops positively, i.e. as in the upper terminal nodes (see Fig. 8).

Fig. 8. Terminal nodes and option value of 5 MW H2-WESS binomial tree (Note: the blue square dots indicate that the option is actually exercised).

5.2.2 Arbitrary nodes

In a second step, starting from the terminal nodes the predecessor nodes are considered. In any arbitrary node, according to eq. (4) the option value of the expansion is compared with the option value to wait. To this end, the decision-maker chooses the maximum of the resulting underlying, which includes the technology growth factor minus the investment expenditures for the expansion, and the value of the option to wait. The option value of waiting is equal to the discounted expected value in the successive period. The expectation value in turn is additively composed of the probability that an upward price movement will occur, multiplied by the up-value, and the counter-probability, multiplied by the down-value (see [4] or [5] for details). The discounted expectation value corresponds to the present values of the future action alternatives.

5.2.3 Dependence of the option value on another option

An ordinary option to expand is based on the assumption that the output of a project is increased by a predetermined fixed factor, e.g. the doubling of production (cf. [6], p.175). This
assumption requires, however, that at any point in time and independently of the project value, the PVCF can be increased by this constant factor. Moreover, this implies that an expansion is based on the same uncertainty as the underlying. The volatility of the cash flows is thus assumed to be constant. Obviously, this assumption does not fit well with many real-world projects. In light of economies of scale, it is plausible that the volatility will change significantly when the power class of the H2-WESS is varied. As depicted in Fig. 5 and Table 2, the volatility rises with higher power classes of the expansion stage. In order to take the variable volatilities appropriately into account in the ROA, the developments of the underlying of all expansion stages (5, 10, 15, 20 MW) are considered simultaneously. The so-called compound option serves as a basis for doing so. In the case of a simple compound option, the output, i.e. the expected cash flow streams, is constant. Classic examples are R&D projects that can be subdivided into several phases. In the project considered in our analysis, the cash flows are, however, significantly dependent on the expansion. In our ROA, instead of using a constant factor, the option value of the previous expansion stage is used as a direct reference and value for comparison. This option value in turn underlies the own development with the own volatility of the own binomial trees. When taking the above-mentioned aspects into account, the option value of an expansion can be represented in a more realistic way than with a constant factor. In the case of a decision to implement an expansion stage, the option of the next-smaller expansion stage is considered, too, which itself considers the option of the next-smaller expansion stage, and so forth. Note that the cascaded dependence described does not imply that the expansion stages necessarily need to be implemented in a sequential manner. The direct implementation of a 20 MW system comprising 4 x 5 MW modules is also permissive at any time.

5.2.4 Option value and exercise period

Analogously to the above-described procedure, and in line with eq. (4), all values of the nodes of the four binomial trees are determined by means of backward induction until eventually all branches are brought together into a single option value at \( \tau = 0 \). The option values for the 5, 10, 15, or 20 MW H2-WESS can be considered individually, as can the option value of the 20 MW ComExp option, which is based on all realizable expansion stages. Apart from the development of the GBM and the options, also the exercise time period for the ComExp Option has a decisive influence on the respective option values. In Fig. 9 the option values of the H2-WESS compound expansion option; expansion stages 5, 10, 15, und 20 MW are shown in dependence on the exercise time period. We find that the value of the CompExp option is always higher than that of the single options. The 20 MW module shows significantly higher values than the smaller power plants. The maximum option value is less than the (negative)
NPV (i.e. €1.97 million < €2.45 million), so that even after accounting for the option value of waiting, the expanded NPV is still negative (€0.45 million); for further details, see [29,30].

![Fig. 9]( Compound) Option values of modular expansion of the H2-WESS in dependence of the expiration time.

### 5.3 Sensitivity analysis

As already mentioned above, the 20 MW ComExp are dependent on the 15 MW ComExp option and the latter again on the 10 MW ComExp option. As expected, the ComExp option values of higher power classes are always/consistently higher than (in absolute terms) or equal to the lower power classes. This outcome is due to the greater decisional scope. In principle, the larger the flexibility to act (i.e. to control profits and losses) the larger the option value.

When looking at the exercise periods of one and two years, it is noticeable that the option values of the expansion stages 5, 10, and 15 MW are actually identical. Moreover, the option values of the 5 and 10 MW expansion stages for the exercise period of three years are identical, too (cf. Table A.4). The reason for that is the orientation of the expansion stages 15 and 10 MW at the option value of the 5 MW expansion stage, through which these can become better off than without the option on the 5 MW. All expansion stages have an S-shaped curvature, taking off progressively and then continuing on a nearly linear trajectory. The reason for that are the rapidly decreasing CAPEX over the years 2015–2019, which drive up the option value markedly (cf. Fig. 9). It also catches the eye that for the calculated ComExp option values, when considering exercise periods of up to about six years, the differences between the expansion stages 5, 10, and 15 MW are rather minor. With a rising option duration, the upper expansion stages rise disproportionally highly, with the 20 MW ComExp option values taking off in particular.
The standard number of time steps in the binomial tree is $n = 390$, so that when considering 15 years, the smallest time step is $1/26$ year, i.e. approximately two weeks. When considering five years before expiration of the option, the time step is about five days (for the same number of time steps $n$). The binomial trees considered here thus have, independently of the expiration date, always 390 terminal nodes for a total amount of nodes of $n^2/2$, i.e. 76,050 nodes. Since the calculation method is a numerical one, additional intermediate steps lead to a higher precision and converge to the analytical form. However, it turns out that if sufficiently small time steps are chosen, the option value converges. Figure 10 illustrates this for the example of the 20 MW CompExp option: the option value varies considerably less for small than for large (e.g. 1 year) time steps. Notice also that in reality management decisions are also not taken arbitrarily quickly, as a certain reaction time between the receipt of the information and the exercising of the option can be expected.

In our analysis the risk-free interest rate is assumed to be constant at $rrf = 1.01\%$, a value which corresponds with the average return of a German government bond. Figure 11 shows how the option value of the 20 MW ComExp option changes when the interest rate is varied. The solid bar indicates the value of the interest rate used in the previous analysis. Higher interest rates expectedly imply higher option values, since the risk-neutral probability and the up-factor are both positively affected. The example also shows that the dividend payment up to the risk-free interest rate is possible, but in which case the option value would decrease to about €1.8 million.
Apart from deviating interest rates and dividend payments, the development of the option value for varying capital expenditures (CAPEX) per installed MW of power is also of interest. By varying these it can be shown, for example, what additional and unpredictable expenditures can be tolerated. Figure 12 shows the option values in dependence on additional expenditures of between €100,000 and €1 million per MWh of installed H2-WESS capacity.

The assumption of a stochastic distribution of the option value can also be scrutinized. To this end, the so far fixed present values of the cash flows as the underlyings for the binomial tree are varied. The variation corresponds to the original probability distribution reported in Fig. 13 and Table 2. Computationally, the randomly generated underlyings (the PVCFs) can be determined by Monte Carlo simulation. At the same time, the corresponding option value of the ComExp option (on the basis of the four nested binominal trees) are calculated. This results
in a distribution of the option values as shown in Fig. 11. The figure also shows that the skewness of the distribution rises with shorter exercise periods. The mean option values deviate little in comparison to the option values reported in Table 3.

(a)  

Stochastic 20 MW ComExp option value  
\[ T = 15 \text{ a} \]  
Mean: €2,079,834  
St. dev.: €598,059  
Skewness: 0.625  
Kurtosis: 3.36

(b)  

Stochastic 20 MW ComExp option value  
\[ T = 5 \text{ a} \]  
Mean: €657,164  
St. dev.: €280,946  
Skewness: 1.085  
Kurtosis: 4.66

**Fig. 13.** Distribution of the 20 MW ComExp option value. (a) Upper plot: \( T = 15 \text{ a} \), (b) lower plot: \( T = 5 \text{ a} \).

6. Summary and conclusions

In the real options analysis of the hydrogen wind power storage system (H2-WESS) considered here, the superiority of ROA over the static net present value method becomes obvious, as the value of its managerial flexibility and the information obtained over time are explicitly considered in the economic valuation of the project. The H2-WESS consists of an electrolyzer for producing hydrogen from the wind power of a wind farm combined with a cavern storage unit for H\(_2\). Depending on the development of the project, an investor has the option to expand the H2-WESS in various stages. Specifically, he can expand the H2-WESS at any time by a 5 MW module and thus increase the revenues (see Fig. 2).
For answering the main research question, i.e. what revenues and costs can be expected when implementing an H2-WESS, we developed a detailed model for computing the future expected cash flows. The model is based on the technical specifications of the above-mentioned partial H2-WESS systems and considers four revenue opportunities: (I) in the presence of feed-in management measures excess wind power is stored as H2. The hydrogen produced is subsequently sold. The expected future H2 price is determined by using vehicle fuel (diesel, gasoline) prices as a reference. (II) The H2-WESS is suited to providing negative minute reserve power and can provide it cost-effectively. Revenues are generated via the capacity price for the provision of reserve energy. (III) When minute reserve is called, the H2-WESS produces and stores hydrogen, and the working price is remunerated additionally to the revenues gained from the H2 sales. (IV) In the case of low electricity spot market prices, the storage of wind power is more profitable than the feed-in and remuneration of wind power based on the market premium scheme as part of the German Renewable Energies Act (EEG).

The stochastic wind power production, the probabilities for the occurrence and level of feed-in management, the probability of occurrence of low spot market electricity prices, the probability for the call, and the level of negative minute reserves (including an optimized supply strategy and acceptance) are all considered in the model. Based on our model, the average cash flows and the corresponding volatilities are computed by means of a Monte Carlo simulation that also accounts for technological progress of the H2-WESS.

The simulation results show that the present values of the H2-WESS expansion stages 5, 10, 15, and 20 MW are all negative. The net present values of the cash flows of all four expansion stages of the H2-WESS then serve as starting values for the ROA that is based on the CCR model [13]. For each expansion stage, a binominal tree with 76,050 nodes is developed. We consider a Bermuda option, for which the exercising at discrete points in time before maturity is possible. Taking into account that the investor at any discrete time step holds the option to expand the H2-WESS, the option value is determined on the basis of a compound expansion (ComExp) option. This option type implies that in the nodes of the binominal trees, the option values of the lower expansion stages are considered as well. An advantage of interlacing dependent binominal trees is that no simplifications and assumptions regarding constant volatilities have to be made.

Each underlying of the individual expansion stages of the binominal tree considered rests on its specific volatility of the cash flows. This enables the second main research question to be answered concerning the optimal expansion stage. The investor can, at any moment in time, either conduct the expansion to the next stage or keep the option alive. Due to this investment
flexibility, the investor can choose the optimal expansion stage depending on the development of the project value.

For answering the third research question on how to value the options, the model assumptions and the method are critically reflected. Through partner institutions at our university (in the TESA project) we had access to projections on the technological development of the H2-WESS until 2030. Since the modeling horizon is only 15 years, developments beyond cannot be taken into account. The value of the ComExp option amounts to about €2 million and is also based on a time horizon to exercise the option of 15 years at maximum. Compared to that, the net present value of the 5 MW H2-WESS is -2.45 million €. When considering the expanded present value, where one adds the option value to the NPV, one can see that for an exercise period of 15 years, the expanded NPV of -450,000 € is still negative (cf. [5]: p.152 for further details). Under the assumption that no cost reductions or efficiency increases of the electrolyzer technology are expected beyond 2030, the breakeven point of the expected NPV can be determined. When investment expenditures as well as the technology growth factor remain unchanged at 2030 levels, the required exercise period for the ComExp option turns out to be about 20 years.

It is reasonable to assume that the hydrogen price will not remain constant. However, no liquid and transparent market for hydrogen exists today, so that reasonably accurate hydrogen price projections cannot be made. Historical price developments are also not available from which trends, price jumps and the like can be derived. However, the prices of competing fuels can be used as a suitable reference for realistic hydrogen price assumptions. The coupling of the hydrogen price with the volatile development of other fuel prices is an interesting further development of the model that would allow the inclusion of another volatile variable for option valuation.

Finally, we conclude that two important aspects render the use of ROA indispensable for assessing the economic viability of H2-WESS. First, the method accounts for the marked uncertainty in the cash flows based on volatile variables that are typical for energy projects such as the one considered. Second, the method allows the incorporation of all relevant managerial options of the investor to be taken into account when determining the option value. For the example of the H2-WESS, it becomes evident that with the option to realize four expansion stages, the actual project value is significantly higher than the simple NPV.

Acknowledgments
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**References**


**Appendix**

**Table A.1** Hydrogen price assumptions for 2015

<table>
<thead>
<tr>
<th>Input parameter</th>
<th>Unit</th>
<th>Size (min)</th>
<th>Size (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average fuel consumption fuel cell car</td>
<td>[kg (100 km)^{-1}]</td>
<td>0.76</td>
<td>0.988</td>
</tr>
<tr>
<td>Average fuel consumption gasoline car</td>
<td>[l (100 km)^{-1}]</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Average fuel consumption diesel car</td>
<td>[l (100 km)^{-1}]</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Gasoline price (Super)</td>
<td>[€ l^{-1}]</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Diesel price</td>
<td>[€ l^{-1}]</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>H\textsubscript{2} price as a substitute for Super</td>
<td>[€ (100 km)^{-1}] / [€ kg^{-1}]</td>
<td>5.6 / 7.37</td>
<td>9.8 / 9.92</td>
</tr>
<tr>
<td>H\textsubscript{2} price as a substitute for Diesel</td>
<td>[€ (100 km)^{-1}] / [€ kg^{-1}]</td>
<td>4.8 / 6.32</td>
<td>8.4 / 8.5</td>
</tr>
</tbody>
</table>

Source: [31]. Hydrogen prices determined by the formula $p_{H2}(t) = p_{H2 \ max} \cdot 100,053 \ kg MW h \eta_{H2}(t)$

**Table A.2** Parametrization of the electrolyzers investigated

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Alkaline</th>
<th>PEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyzer efficiency 2015 / 2030</td>
<td>[%]</td>
<td>63 / 71</td>
<td>63 / 71</td>
</tr>
</tbody>
</table>

**CAPEX & OPEX:**

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>System costs2015</td>
<td>[€/kW]</td>
<td>930</td>
<td>1570</td>
</tr>
<tr>
<td>System costs2020</td>
<td>[€/kW]</td>
<td>630</td>
<td>1000</td>
</tr>
<tr>
<td>System costs 2025</td>
<td>[€/kW]</td>
<td>610</td>
<td>870</td>
</tr>
<tr>
<td>System costs 2030</td>
<td>[€/kW]</td>
<td>580</td>
<td>760</td>
</tr>
</tbody>
</table>
Operating costs 2015 / 2030 \[\text{€ (kW} \cdot \text{a})^{-1}\] 17-51 / 9-44 32-66 / 12-46

**System characteristics:**
- Availability \[\%\] 95 95
- Operational lifetime \[\text{a}\] 26 22
- Electricity input \[\text{kWh (kg H}_2\text{)}^{-1}\] 53 52
- Min. part-load operation 2015 / 2020 \[\% \text{ of full load}\] 24 / 15 7 / 4
- Min. part-load operation 2025 / 2030 \[\% \text{ of full load}\] 15 / 15 4 / 4
- Ramp-up time from part load to full load \[\% \text{ of full load s}^{-1}\] 17 40
- Power level per module 2015 (range) \[\text{kW}\] 1600-5600 1300-10,000
- Power level per module 2020 (range) \[\text{kW}\] 5000-6000 1600-90,000
- Power level per module 2025 (range) \[\text{kW}\] 5000-7300 1800-90,000
- Power level per module 2030 (range) \[\text{kW}\] 4900-8600 2100-90,000

Source: [31]

**Table A.3 CAPEX and OPEX of the cavern storage**

<table>
<thead>
<tr>
<th>Storage characteristics:</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass capacity</td>
<td>[t H\textsubscript{2}]</td>
<td>4,000</td>
</tr>
<tr>
<td>Geometric volume</td>
<td>[m\textsuperscript{3}]</td>
<td>500,000</td>
</tr>
<tr>
<td>Storage density (depth 1000 m)</td>
<td>[kg H\textsubscript{2} m\textsuperscript{3}]</td>
<td>8</td>
</tr>
<tr>
<td>Energy capacity acc. to calorific value</td>
<td>[GWh]</td>
<td>133</td>
</tr>
<tr>
<td>Charge/discharge speed</td>
<td>[t H\textsubscript{2} h\textsuperscript{-1}]</td>
<td>13.5</td>
</tr>
<tr>
<td>Charge/discharge power</td>
<td>[MW H\textsubscript{2}]</td>
<td>450</td>
</tr>
<tr>
<td>Total effic. of cavern storage system (ignoring start-up losses)</td>
<td>[%]</td>
<td>97.8</td>
</tr>
<tr>
<td>Efficiency of compression (charge)</td>
<td>[%]</td>
<td>98.0</td>
</tr>
<tr>
<td>Efficiency of dehydration (discharge)</td>
<td>[%]</td>
<td>99.8</td>
</tr>
<tr>
<td>Long-term losses</td>
<td>[% a\textsuperscript{-1}]</td>
<td>0.02</td>
</tr>
<tr>
<td>Lifetime</td>
<td>[a]</td>
<td>&gt; 30</td>
</tr>
</tbody>
</table>

**CAPEX:**
- Specific investment costs, cavern preparation \[\text{€ m}^{-3}\] 60
- Total investment costs, cavern \[\text{€}\] 30,000,000
- Specific investment costs, cushion gas \[\text{€ (t} H\textsubscript{2})^{-1}\] 2,381
- Total investment costs, cushion gas \[\text{€}\] 5,594,679
- Total underground investment costs \[\text{€}\] 35,594,679
- Investment costs, monitoring station \[\text{€}\] 300,000
- Investment costs, compressors (2) \[\text{€}\] 30,000,000
- Investment costs, pressure regulator \[\text{€}\] 500,000
- Investment costs, dehydration unit \[\text{€}\] 2,400,000
- Misc. surface infrastructure costs (incl. engineering) \[\text{€}\] 23,000,000
- Total investment costs, surface structures \[\text{€}\] 56,200,000
- Reserve \[\text{€}\] 805,321
**Table A.4** Compound expansion option values of the H2-WESS modules considered

<table>
<thead>
<tr>
<th>Expiration time $T$ [a]</th>
<th>5 MW</th>
<th>10 MW</th>
<th>15 MW</th>
<th>20 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>872</td>
</tr>
<tr>
<td>2</td>
<td>15,945</td>
<td>15,945</td>
<td>15,951</td>
<td>40,487</td>
</tr>
<tr>
<td>3</td>
<td>82,288</td>
<td>82,288</td>
<td>86,230</td>
<td>170,750</td>
</tr>
<tr>
<td>4</td>
<td>179,477</td>
<td>179,477</td>
<td>200,029</td>
<td>361,935</td>
</tr>
<tr>
<td>5</td>
<td>274,607</td>
<td>275,762</td>
<td>324,489</td>
<td>566,305</td>
</tr>
<tr>
<td>6</td>
<td>345,940</td>
<td>352,430</td>
<td>432,254</td>
<td>748,518</td>
</tr>
<tr>
<td>7</td>
<td>388,912</td>
<td>403,407</td>
<td>514,534</td>
<td>899,268</td>
</tr>
<tr>
<td>8</td>
<td>430,179</td>
<td>454,748</td>
<td>597,673</td>
<td>1,044,469</td>
</tr>
<tr>
<td>9</td>
<td>467,808</td>
<td>504,051</td>
<td>678,497</td>
<td>1,183,614</td>
</tr>
<tr>
<td>10</td>
<td>504,062</td>
<td>553,032</td>
<td>757,164</td>
<td>1,315,832</td>
</tr>
<tr>
<td>11</td>
<td>539,114</td>
<td>601,203</td>
<td>836,163</td>
<td>1,445,064</td>
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<tr>
<td>12</td>
<td>589,708</td>
<td>667,351</td>
<td>930,624</td>
<td>1,584,387</td>
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<tr>
<td>13</td>
<td>624,994</td>
<td>716,863</td>
<td>1,009,372</td>
<td>1,704,686</td>
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<tr>
<td>14</td>
<td>669,015</td>
<td>776,969</td>
<td>1,095,954</td>
<td>1,830,947</td>
</tr>
<tr>
<td>15</td>
<td>730,367</td>
<td>855,581</td>
<td>1,201,851</td>
<td>1,969,682</td>
</tr>
</tbody>
</table>

Source: [31]
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2008


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