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Authors’ addresses:

Sebastian Weibel
RWTH Aachen University
Templergraben 55
52056 Aachen, Germany
E-mail: sebastian.weibel@rwth-aachen.de

Reinhard Madlener
Institute for Future Energy Consumer Needs and Behavior (FCN)
School of Business and Economics / E.ON Energy Research Center
RWTH Aachen University
Mathieustrasse 10
52074 Aachen, Germany
E-mail: RMadlener@eonerc.rwth-aachen.de

Publisher: Prof. Dr. Reinhard Madlener
Chair of Energy Economics and Management
Director, Institute for Future Energy Consumer Needs and Behavior (FCN)
E.ON Energy Research Center (E.ON ERC)
RWTH Aachen University
Mathieustrasse 10, 52074 Aachen, Germany
Phone: +49 (0) 241-80 49820
Fax: +49 (0) 241-80 49829
Web: www.eonerc.rwth-aachen.de/fcn
E-mail: post_fcn@eonerc.rwth-aachen.de
Cost-Effective Design of Ringwall Storage Hybrid Power Plants: A Real Options Analysis

Sebastian Weibel\textsuperscript{a} and Reinhard Madlener\textsuperscript{b,c,*}

\textsuperscript{a} RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany
\textsuperscript{b} Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, RWTH Aachen University, Mathieustrasse 10, 52074 Aachen, Germany
\textsuperscript{c} JARA-ENERGY, Templergraben 55, 52056 Aachen, Germany

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Abstract
We study the economic viability and optimal sizing and siting of a hybrid plant that combines a ringwall hydro storage system with wind and solar power plants (ringwall storage hybrid power plant, RSHPP). A real options model is introduced to analyze the economics of an onshore RSHPP, and in particular of the varying storage volume in light of the stochastic character of wind and solar power, as well as the optimal investment timing under uncertainty. In fact, many uncertainties arise in such a project. Energy production is determined by the stochastic character of wind and solar power, and affects the optimal size of the storage device. Monte Carlo simulation is performed to analyze the following sources of uncertainty: (i) wind intensity and solar irradiation; (ii) future electricity price; and (iii) investment costs. The results yield the optimal size of the storage device; the energy market on which the operator should sell the electricity generated; numerical examples for two different RSHPP scenarios; and a real options model for analyzing the opportunity to defer the project investment and thus to exploit the value of waiting.

Keywords: Pumped storage hydro power; Hybrid power plant; Real option; Irreversible investment; Risk and uncertainty.

\textsuperscript{*} Corresponding author. Tel. +49 241 80 49 820, Fax: +49 241 80 49 829, E-mail: RMadlener@eonerc.rwth-aachen.de (R. Madlener).
1. Introduction

Due to the ongoing significant changes in the energy markets, shifting away from fossil and nuclear sources towards renewable energy systems, the contribution of wind and solar photovoltaics (PV) in particular has increased a lot over the last few years. Since this development can be expected to continue, fluctuations in power supply from wind and solar PV are rising as well. To tackle this problem effectively and to balance the load fluctuation, energy storage concepts, especially for the longer-term storage (several weeks instead of just minutes or several hours), are an essential element of energy systems. In recent years, the scientific literature on combining volatile renewables with pumped storage hydro power systems has grown rapidly (e.g. [1]-[10]). Circular, so-called Ringwall Storage Hybrid Power Plants (RSHPP), which are based on the principle of pumped storage power plants and either constructed as sealed mounds or as mass concrete artificial structures, are an innovative storage concept [11]. A combination of such a storage plant with wind turbines and PV systems can be referred to as an RSHPP (cf. Fig. 1). This paper presents a real options-based...
model to analyze the economic viability of and the optimal investment timing for an RSHPP in dependence of its stochastically varying energy production and the future evolution of the electricity price.

Fig. 1. Illustration of the RSHPP concept [11].

1.1. Favorable development causing problems

In recent years, the expansion of renewable energies in Europe, and especially in Germany, has progressed rapidly and still does. In 2002, only about 2.7% of the electricity consumed in Germany came from wind and solar power, whereas the contribution of solar power was negligible. By 2012, the share had risen to 12.4%, of which 7.7% came from wind power and 4.7% were generated by PV systems [12]. The energy concept of the German government foresees that the share of renewable energies shall reach 50% by 2030. A similar development and projection can be found for the European Union (EU-27) as a whole.

Two key problems accompany the increasing contribution of wind and solar PV. In the foreseeable future, the majority of wind power will be generated near the coast or on offshore farms, which are usually far away from major metropolitan areas and industrial centers, where the power is consumed. New high voltage transmission lines must be built to transport the electricity from the generation sites to the densely populated areas. The second and more important problem is the fluctuating energy supply from wind turbines and PV systems, due to the stochastic nature of the wind intensity and the solar irradiation. These fluctuations, which can vary considerably daily, weekly, seasonally and annually, lead to inaccuracies in
the prediction of electricity supply. This is the reason why today only 5-10% of the installed capacity of wind power can be considered as secured generation capacity; for a PV system, the share is only about 1% [13] (cf. Table 1).

Table 1. Secured capacity of various types of power plants [13].

<table>
<thead>
<tr>
<th>Power plant</th>
<th>Secured capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine</td>
<td>5 – 10%</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>1%</td>
</tr>
<tr>
<td>Pumped storage</td>
<td>90%</td>
</tr>
<tr>
<td>Coal</td>
<td>86%</td>
</tr>
<tr>
<td>Lignite</td>
<td>92%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>93%</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>42%</td>
</tr>
</tbody>
</table>

To ensure a reliable supply of electricity, especially with a high contribution of renewable energy, large amounts of reserve energy must be available within a short time, both in case of a lack or an oversupply of wind or PV power. Positive reserve energy is often provided by gas-fired power plants, which have a short start-up time, but produce at high costs. Base load power plants, such as lignite-fired, coal or nuclear plants, can provide both, positive and negative balancing power. Therefore, they are usually operated in a throttled-down state to retrieve their full power when demanded. With an oversupply of renewable energies, these units need to be throttled down even further or shut down completely. This will also lead to increased production costs and waste of resources, because a throttled-down power plant no longer works at its optimal operating point. Moreover, such base load power plants are not designed for frequent load changes and especially large-scale steam turbines suffer greatly from such suboptimal operation modes. A fact that further reinforces this problem is the priority feed-in of renewable energy into the grid, as stipulated e.g. in the German Act on Granting Priority to Renewable Energy Sources [14].

Energy storage is a viable solution to counteract the problems of fluctuating supply from wind and solar power. If supply exceeds demand, the storage device is charged, whereas vice versa it is discharged. Storing energy helps to relieve the electrical grid and thus reduce the demand for balancing power. There are several concepts to store electric energy, e.g. compressed air energy storage systems or electrolysis for hydrogen production (Power-to-
Gas, P2G), albeit most of them are not yet technologically mature and/or cost-competitive [15].

Today, conventional pumped storage power plants (PSPPs) are the only well-proven technology for storing large amounts of energy effectively. Due to their high efficiency and low technical effort, such systems have been in use successfully for many years. The average total efficiency of PSPPs in Germany is about 70% [16]. Today, newer systems can reach efficiencies of up to 85%. In 2012, Germany had a total of 30 commercially operated PSPPs, providing a rated power of 6.7 GW in total. In the European electricity supply system, there was an installed capacity of about 43 GW available in 2011.

Conventional PSPPs can only be built in regions where a certain height difference between the upper and lower basins can be ensured. These regions are often far away from coastal areas where most of the onshore and the offshore wind energy will be generated. Furthermore, there are only a few suitable sites left for the construction of new PSPPs. Especially in Germany almost all sites with appropriate natural preconditions are already in use. Thus, installed capacity has remained nearly constant in recent years, both in Germany, and in the EU. Fig. 2 illustrates the development of the capacity of PSPP, wind turbines, and PV systems installed in Germany.

![Fig. 2. Installed Capacity of PSPP, Wind, and PV power in Germany, 2000-2012 [12]](image)

All of these facts show that new energy storage concepts will be essential for the future development of electricity supply with a growing share of renewables. Artificially constructed PSPPs, such as RSHPPs, could help to mitigate at large scale the load imbalances induced by intermittent wind and solar power supply.
1.2. Economic analysis of RSHP

With such a large-scale project, a number of uncertainties arise that need to be taken into account. These include the investment costs, which are risky because of a lack of experience and the fact that an enormous amount of earth moving is necessary to construct the ringwall and the upper and lower basins.

In our study, we investigate a ringwall hydro power plant that is combined with wind turbines and PV cells. The stochastic character of wind and solar power is an important determining factor for energy production. It is also decisive for filling up the storage device, and influences the optimal device size. The required storage volume itself also has a significant influence on the project’s profitability. A further economic uncertainty is the future development of the prevailing electricity prices on the various energy markets. The operator of an RSHP has to choose on which energy market to offer his generated power. He can offer it either on the day-ahead or the intraday spot market, or, alternatively, he can enter into long-term contracts on the futures market. Still another possibility is to offer the large capacity of an RSHP on the balancing energy market.

During the long period of planning and constructing, many issues can arise that may affect the project’s economic viability. At several times, the investor has the opportunity to adapt his project to the changing market conditions. If the investor expects improved economic conditions in the future, he or she could defer the investment to a later period, or cancel the project if the expected deficit exceeds the costs of abandonment.

A classical investment analysis using the net present value (NPV) approach does not adequately address uncertainty and ignores the various options that an investor can exercise, i.e. the value of management flexibility. Hence traditional analyses may underestimate a project’s value [17]. The NPV rule implicitly assumes absence of flexibility in decision making, although the investment may be either (partly) reversible or a now or never decision. This inflexibility assumption violates fundamental characteristics of many real investment decisions [18]. Real options analysis (ROA) helps to more appropriately integrate uncertainties and the flexibility of exercising different kinds of options into the economic examination. This paper introduces an ROA model that allows an investigation of the economic viability of an RSHP, regarding the stochastically varying electricity supply from wind and solar power. It also determines the optimal size of the power plant and the storage volume, depending on the application, as well as the optimal timing of investment.
In our analysis, we investigate two scenarios: (1) a load balancing scenario, where the RSHPP is used for balancing off the volatility of wind and PV and delivers a predetermined, constant amount of power for one week; (2) a flexible use scenario, where electricity is offered on the day-ahead spot market for profit maximization by exploiting the difference between the ELIX peak and the ELIX night price.

2. The ringwall storage hybrid power plant concept

The concepts of RSHPPs are based on the fundamental principle of hydro pumped storage systems. But unlike PSPPs, however, RSHPPs are independent from many natural preconditions and can even be built on flat terrain or in shallow coastal waters. Currently, there are a few proposals for both onshore as well as for offshore systems. Several companies and institutions have developed similar models for artificial storage power plants. The RSHPP concept was developed by Dr Matthias Popp, who also holds a patent\(^1\) on it. The considerations in our study are primarily based on the (onshore) concept introduced by Popp [11].

A possible design of a landsite RSHPP, as illustrated in Fig. 1, provides an energy storage capacity of about 700 GWh. The power plant has a diameter of 11.7 km and the ringwall has a height of up to 215 m. The average height difference between the upper and lower basin is about 200 m. Obviously, enormous movements of earth are required to form the ringwall and the two reservoirs. In addition to the required stability of the dam, its impermeability is also of high importance. Especially the bottom of the upper basin must be as waterproof as possible in order to minimize the water loss and thus the loss of potential energy. Also, evaporation from the upper reservoir and the precipitation could influence the volume of the stored capacity, particularly for large surfaces. In all subsequent considerations this fact is no longer discussed, because we assume for simplicity that, on average, precipitation equals evaporation.

The hybrid nature of the RSHPP investigated here results from the installation of wind turbines and PV systems. Wind turbines are set up on the rim and all around the lower basin. The PV modules can best be installed on the southern side of the ringwall; additional floating

\(^1\) Patent ID No. DE102009005360; to be found in the database of the European Patent Office (EPO) or the German Patent and Trade Mark Office.
panels can be placed on the surface of the upper reservoir. The combined use of wind and solar PV provides the great advantage that daily and annual fluctuations of the two can be partially compensated. During the autumn and winter months wind energy production is higher than in summer; vice versa, there is more PV energy in spring and summer than in winter. Iterative analysis revealed that for most European locations a ratio of 80% wind power and 20% PV power will incur the least required storage capacity [15]. In addition to power generation and storage, there are further possible usages of the large basins. The lakes and the surrounding areas could be used as a recreational resort or for other touristic purposes. Provided that the water quality is adequate, the basins could even serve as a drinking water reservoir. Note that the circular shape of the ringwall plant is not a prerequisite, but in our analysis assumed for simplicity and computational convenience; it could be adapted to the natural preconditions if needed (or desired).

2.1. Scale and specific storage capacity of onshore RSHPs

The required energy storage capacity is determined by the field of application of the plant. A commonly used measure is the day load, which represents the daily average amount of electricity provided [11]. Per megawatt of electricity generated, a storage capacity of 24 MWh is required to provide one day of load. The water volume required depends on the potential energy stored in the water mass and can be determined by the average height difference between the upper and the lower reservoir. To provide a specific storage capacity of 1 kWh per m³ of water an average height difference of about 400 m is required.²

The required area depends on the water level fluctuations. These are related to the exchange volume from the upper to the lower basin, and vice versa. Therefore, the necessary space has to be given twice. The higher the level fluctuations the lower the required space is.

Doubling the diameter results in a quadrupling of the surface, whereas doubling the height leads to an eightfold increase in the storage volume; taken together, this results in a 16-fold increase in storage capacity. Consequently, huge RSHPs are technically, energetically, and economically most beneficial, although it may be quite difficult to realize such projects.

² Calculated by using the formula of potential energy, multiplied by the efficiency ($\eta_{WT} = 0.94$) of a standard water turbine, i.e.: $E_{pot} = m \cdot g \cdot h \cdot \eta_{WT}$, with the mass of 1 m³ water ($m \approx 1000$ kg), the gravity ($g = 9.81$ m/s²), and the average height difference ($h$).
2.2. The siting question

With an implementation of such a project the siting question is paramount. Of course the RSHPP should be built in areas with best operation conditions. These are, in particular, regions with a high and constant wind supply as well as a high level of solar irradiation (sunlight hours) during a year. To avoid transport losses, the power plant should also be set up where large amounts of energy are required, e.g. near large cities or industrial centers. However, a possible location must also provide enough space for the construction of the two basins and the ringwall. The example RSHPP, shown in Fig. 1, covers an area of almost 108 km², which corresponds to the inner city area of Paris.

Compared to onshore projects, their offshore counterparts provide several advantages. Usually, there is no shortage of space in coastal regions and no resettlements are required. Also, only one reservoir has to be built, because the sea itself represents the other one. As well, the wind intensity is typically higher than in most onshore locations. However, in some cases the lack of proximity to major energy consumers could be a crucial problem. Appropriate onshore locations can primarily be found in regions which are predominately used for agriculture or in areas with a low population density. But in fact, precisely these areas are often far away from major energy consumers. Further potential locations can be found in lignite mining areas. There, a lot of earth movement has already been undertaken, and must be done in the future, according to the natural regeneration obligations. In addition, there are already plans for some open-cast mining sites to transform them into recreational lake areas. Because these regions are already in use, no further resettlements are necessary. Moreover, a variety of technical equipment (e.g. large-scale excavators) is already available. Hence, these locations seem to be well suited for the installation of onshore RSHPP. One of them can be found in the Rhineland lignite mining area in western Germany. This region offers the additional advantage that it is close to major cities like Cologne and near to the industrial centers of the Ruhr District.

2.3. Costs of an RSHPP

It is obviously very difficult to estimate the investment costs of a RSHPP in detail. Because of a lack of experience with such projects, especially the costs of building the ringwall and the two artificial basins are difficult to determine, whereas the range of specific costs of wind turbines and PV systems can be specified accurately. On Popp’s homepage an iterative calculation tool is provided that enables a rough analysis of an RSHPP [19].
Numerous interrelated factors affect the specific costs of the storage device. These are primarily the highly capacity-dependent construction costs and, on the other hand, the outlays for technical infrastructure, incurring almost independently of the storage volume. In this case, specific costs are related to the energy storage capacity and not to the rated power of the device, because the power output can vary depending on the scenario. Fig. 3 gives a brief overview about the specific costs for four different and conceivable constellations. Here, 25/25/100 means that both reservoirs have a level fluctuation of 25 m and the average height difference between both water surfaces is about 100 m. The dotted lines represent the ratio between diameter and energetic storage capacity for the respective constellations. It can be appreciated that the specific costs for all configurations decrease rapidly up to a diameter of 2 km. For further enlargements the costs only marginally decline. At a diameter of about 10 km, the specific costs could even start to increase again. In these cases, the supplementary expenses for land purchase and infrastructure exceed the benefits of a higher storage capacity. About 70% of the investment costs of the storage device account to earthwork and sealing work, another 20% are attributable to the technical equipment [19].

Fig. 3: Specific investment costs of the storage device for different size constellations.

In the calculation tool, the investment costs of wind turbines are set to 1500 €/kW and those of PV systems are set to 2800 €/kW. From a current perspective, these values are at the upper end of the price range for such systems. Nowadays, especially PV modules can be built significantly cheaper.

Unlike conventional power plants, the variable costs of RSHPP are not determined by fuel prices. The majority of the annual costs consist of operation and maintenance (O&M) and of
repair costs, as well as of insurance premiums. The annual operating costs for the storage system are estimated to be about 1% of the individual investments. For wind turbines and PV systems 6% and 2%, respectively, are assumed [19]. The use of the iterative tool to estimate the total investment costs of the example RSHPP, illustrated in Fig. 1, results in €16.4 billion for the storage device, €8.2 billion for about 2000 wind turbines and about €15.4 billion for PV systems. Altogether, such an RSHPP would cost the enormous amount of €40 billion. Thus, the analysis of smaller-scaled hybrid power plants seems to be more realistic and thus rational.

3. Determinants of cost-effectiveness of an RSHPP

The economic viability of an RSHPP is primarily determined by two major factors: By the amount of electricity generated, depending on wind velocity and solar irradiation, and by the revenues coming from the electricity output, which depend on the expected electricity prices of the different energy markets. Several other aspects have an influence on these key factors, including the investment costs of all systems, the costs of capital, the individual technical lifetime of the devices, possible subsidies or other government grants, etc. The following sections provide a more detailed insight into the respective determining factors and their individual properties.

3.1. Wind energy

The annual energy production (AEP) of a wind turbine or a wind farm is highly dependent on the wind conditions of a certain location. Numerous factors, especially those of natural preconditions can influence the wind situation and have to be taken into account. Also the technical characteristics of the wind turbine itself, like the hub height or the rotor diameter, can affect the energy generation significantly. To determine the annual supply of wind energy for a certain location, wind velocity distributions are used. These statistical distributions are based on long-term data series and can generally be described by Weibull functions of the form

\[ f_W(v) = \frac{k}{a_w} \left( \frac{v}{a_w} \right)^{k-1} \exp \left[ -\left( \frac{v}{a_w} \right)^k \right]. \]  

(1)

The Weibull distribution of the wind velocity (v) is calculated with the use of a shape (k) and a scale parameter (a_w), which both depend on the location. For most locations the shape
parameter can be assumed to 2. This leads to a Rayleigh distribution ($f_R(v)$) of wind velocity
[20], where $a_R$ represents the scale parameter of this function

$$f_R(v) = \frac{v}{a_R^2} e^{-\frac{v^2}{2a_R^2}}$$

(2)

Using these frequency distributions, the energy yields can be predicted accurately for a
certain location. In energy economics it is also common to specify the AEP of wind turbines
by multiplying the rated power with the average annual full-load hours. There are a lot of
statistical data that approximate the full load hours for certain size classes of plants and
regions. For the subsequent calculations, onshore wind turbines with a capacity of 2-5 MW
are considered. In Germany, the number of annual full-load hours varies between 1300 h for
less favorable sites and up to 2700 h in windy or coastal areas. The average for the years
2006 and 2011 was between 1500 and 1800 full-load hours per year [21]. For a common
German inland location one can assume an energy yield per MW of installed capacity
between 1300 MWh in a bad year and 2000 MWh in a windy year. Very good offshore sites
can reach an AEP of up to 4000 MWh per year. The investment costs ($I_W$) of onshore wind
turbines depend on their performance class. For large-scale wind turbines with a capacity of
about 3000 kW, the current specific costs per kilowatt vary between €950 and €1500,
depending on the location.

In the literature, there are several approaches to determine the annual expenses that
primarily consist of O&M and repair costs. These costs can best be estimated as a percentage
of the investment costs. The annual proportion can vary between 2% and 5% [16].
Furthermore, an annual increase of operation costs of 1.5% is assumed. The technical lifetime
of a wind power plant can only be specified approximately. To simplify the later
calculations, an average lifetime of 30 years is presumed. This assumption applies to the
technical as well as to the economic lifetime. Another important influence is represented by
the discount rates. These rates are determined technology-specific by using the weighted
average cost of capital (WACC) approach. The average discount rate is assumed at about 6%,
but varies between 4% and 8% [21]. A more detailed review of the discount rate
considerations is presented in section 3.5.

3 Although the offshore yields are almost twice as high as the yields of onshore devices, the electricity
generation costs are higher, too. This is due to the significantly higher investment and O&M costs.
3.2. Solar PV

In the concept of RSHPP, the amount of installed solar PV capacity depends on the amount of installed wind power capacity, as explained in section 2. However, the maximum capacity is limited by the proportions of the ringwall. The size of the floating panels on the upper basin results from the water surface’s diameter ($d_{WS}$). The installed PV capacity on the south-facing part of the wall is related to the water surface’s diameter, the base diameter ($d_{base}$), and the height of the wall ($h_{RW}$). The proportions of an idealized ringwall can be determined by using the geometrical correlations of a truncated cone. The surface area of the southern section of the wall ($A_{RW,S}$) is calculated as follows:

$$A_{RW,S} = \frac{1}{4} \left[ \left( \frac{d_{base}+d_{WS}}{2} \right)^2 \times \pi \times \sqrt{\left( \frac{d_{base}-d_{WS}}{2} \right)^2 + h_{RW}^2} \right].$$

The surface area of the upper reservoir can easily be determined by

$$A_{WS} = \frac{\pi}{4} \times d_{WS}^2.$$

The AEP of a PV module with an optimum angle of inclination results from the annual solar irradiance. In Northern Germany the annual irradiance is about 1100 kWh per m² and provides an annual electricity output of 900 MWh per megawatt of rated power. Going south, the irradiance increases up to 1300 kWh per m² and year, which leads to an AEP of up to 1100 MWh. The same device would have an output of up to 1600 MWh a year in southern Spain and up to 2000 MWh a year in North Africa. Unlike wind turbines, PV systems are subjected to a degradation of electricity output of about 0.2% per year [21].

The current specific investment costs ($IPV$) per kilowatt for large-scale, ground-mounted installations can vary between €1000 and €2000 [22]. More likely and realistic are costs of about €1500-1700. The annual expenses vary between 2% and 4% of total investments [16] and increase annually by about 2% [21]. These annual costs also include the replacing costs of the inverter, which usually needs to be replaced once during the entire maturity.

3.3. Specific costs of an RSHPP

The specific costs for the storage device depend on the proportions. Generally, specific costs decline with increasing height difference and growing level fluctuation. Table 2 exemplifies the specific costs in dependence of the diameter, respectively in dependence of the energetic storage capacity for two selected size constellations. Due to the lack of experience for such projects, the costs can only be regarded as a guideline value. Since no learning rate can be determined yet, the costs are expected to remain constant over time. The
annual expenses for the operation of the storage device are calculated by using a rate of one percent of the total investment costs.

Table 2. Specific costs of the storage device as a function of storage capacity.

<table>
<thead>
<tr>
<th>Diameter of upper basin [km]</th>
<th>Energy storage capacity [GWh]</th>
<th>Specific costs [€/kWh]</th>
<th>Energy storage capacity [GWh]</th>
<th>Specific costs [€/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>201.62</td>
<td>0.9</td>
<td>103.51</td>
</tr>
<tr>
<td>1</td>
<td>2.7</td>
<td>76.24</td>
<td>5.4</td>
<td>39.94</td>
</tr>
<tr>
<td>2</td>
<td>13.2</td>
<td>53.81</td>
<td>26.3</td>
<td>29.01</td>
</tr>
<tr>
<td>5</td>
<td>97.3</td>
<td>48.83</td>
<td>194.8</td>
<td>26.53</td>
</tr>
<tr>
<td>10</td>
<td>419.8</td>
<td>48.82</td>
<td>841.3</td>
<td>26.51</td>
</tr>
</tbody>
</table>

3.4. Electricity price

Nowadays, a large amount of electricity and other energy-related commodities are traded on energy exchanges, such as the European Energy Exchange (EEX) and the European Power Exchange (EPEX). Both provide several energy trading products, including intraday and day-ahead spot markets, as well as derivatives markets, with several indexes. The European Electricity Index (ELIX) represents the market price of electricity in an integrated, single European market. The determination of the ELIX is based on the EPEX spot auctions for France, Germany, Austria, and Switzerland. These market areas represent about 36% of the European electricity consumption [23]. Hence, ELIX can be used as a reference price for the European energy.

Of great importance are also the daily and weekly fluctuations of the ELIX, as illustrated in Figs. 4 and 5. The ELIX Peak represents the daily average price for the peak-load hours, which are between 8 am and 8 pm. The ELIX Night characterizes the average daily price during the night hours, from 8 pm to 8 am. Finally, the ELIX Base displays the total daily average of the electricity price.
Similar to the daily fluctuations, the weekly course of the electricity price varies as well. As shown in Fig. 5, the ELIX always reaches a low point on the weekends and particularly on Sundays. A related development can also be observed on nationwide holidays. The analysis of the historical data of the ELIX shows that the frequency distribution of the electricity prices can best be approached by the use of a minimum extreme value function (type 1). The probability density $f(x)$ and the distribution function $F(x)$ are calculated as follows [24]:

$$f(x) = \frac{1}{\beta} * e^{\left(\frac{x-a}{\beta}\right)} * e^{-e^{\left(\frac{x-a}{\beta}\right)}}$$

(5)
\[ F(x) = 1 - e^{-\frac{x-\alpha}{\beta}}. \]  

(6)

The shape parameter (\( \alpha \)) and the scale parameter (\( \beta > 0 \)) result from the analysis and are different for each type of ELIX contract (Base, Peak, and Night). The analysis was performed using Risk Simulator 2013© (Real Options Valuation, Inc.). One indicator for the future electricity price is the development on the power derivatives market. The Physical Electricity Index (PHELIX), traded at the EEX in Leipzig, is the underlying index for electricity futures. It can be traded for different delivery periods, up to six years in advance. Thus, a first impression of the electricity price by the year 2019, expected by the market participants, can be obtained. Just like the ELIX, the PHELIX is also given for base load, peak load and off-peak load. Fig. 6 exemplifies the PHELIX rates of May 30, 2013 [25], and gives a linear prognosis of their future course up to the year 2030.

The trends show a slow but steady increase of electricity prices in all three categories. On average, the rates increase annually by about 2%.

![Fig. 6. PHELIX base, peak, and off-peak prices on the trading day May 30, 2013.](image)

The daily and weekly fluctuations in the electricity price make it difficult to predict the revenues the investor of a RSHP can gain during the lifetime of the power plant. Though, by a flexible use of his power plant, the investor could even benefit from these fluctuations.

3.5. Discount rate

The discount rate used for an economic analysis of a project can strongly affect the results. So there is the need, but also the difficulty to determine an adequate discount rate for a RSHP project. Numerous factors have an impact on the characteristics of the rate. In the
case of an RSHPP, these are, in particular, technology and policy risks, the capital expenditures (CAPEX), other price risks, and many others more. A commonly used method to estimate the discount rate is the WACC approach. Besides the uncertainties and risks, this approach additionally considers the share of equity and debt as well as the debt rate and the return on equity. Thus, all major influencing components of the capital structure are weighted and taken into account [26].

Due to the fact that an RSHPP consists of three different main technologies, the discount rate should be determined separately for each: the wind turbines, the PV system and the storage device. Also the future evolution of the individual rates should be taken into account. Table 3 reflects indicative current and future range estimations of the discount rate of different energy generation technologies. The rates are given in real and pre-tax terms.

**Table 3.** Current and expected future discount rates of different generation technologies [26].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Current risk perception</th>
<th>Current rate range [%]</th>
<th>2020 rate range [%]</th>
<th>2040 rate range [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind (onshore)</td>
<td>Low</td>
<td>7 - 10</td>
<td>6 - 8</td>
<td>5 - 8</td>
</tr>
<tr>
<td>PV</td>
<td>Low</td>
<td>6 - 9</td>
<td>6 - 9</td>
<td>5 - 8</td>
</tr>
<tr>
<td>Wind (offshore)</td>
<td>Medium</td>
<td>10 - 14</td>
<td>7 - 10</td>
<td>6 - 8</td>
</tr>
<tr>
<td>CCS (coal or gas)</td>
<td>High</td>
<td>12 - 17</td>
<td>11 - 17</td>
<td>10 - 16</td>
</tr>
<tr>
<td>Tidal</td>
<td>High</td>
<td>12 - 17</td>
<td>9 - 14</td>
<td>7 - 11</td>
</tr>
<tr>
<td>Nuclear (new build)</td>
<td>Medium</td>
<td>9 - 13</td>
<td>9 - 13</td>
<td>8 - 12</td>
</tr>
<tr>
<td>CCGT</td>
<td>Low</td>
<td>6 - 9</td>
<td>6 - 9</td>
<td>5 - 8</td>
</tr>
</tbody>
</table>

The determination of the discount rates is based on available literature and is supplemented by estimations made by industry participants. The future projected rates are based on a scenario with a high contribution of renewable energy production, which assumes a policy encouraging investments in all types of renewables.

The discount rates associated with less mature technologies, like Carbon Capture and Storage (CCS) power plants or tidal power plants are about twice the rates of lower-risk technologies like PV energy, also their range tends to be wider. Since there is no experience with an RSHPP, and particularly the construction of the ringwall is associated with great risks, the discount rates for the storage device are assumed to follow those of tidal and CCS.
power plants. The rate ranges and their evolution for wind and PV systems are almost equal; hence, the average discount rate for a RSHPP ($\delta_{\text{tot}}$) is defined by the respective rate for wind power and PV systems and for that of the storage device, in terms of their share of total investments ($I_{\text{tot}}$):

$$\delta_{\text{tot}} = \frac{I_W + I_{PV}}{I_{\text{tot}}} \cdot \delta_{W,PV} + \frac{I_S}{I_{\text{tot}}} \cdot \delta_S.$$  

(7)

The individual investment costs, or the CAPEX, are given by $I_W$ and $I_{PV}$ for wind and PV energy, respectively, and by $I_S$ for the ringwall. The expected individual discount rates are represented by $\delta_{W,PV}$ and $\delta_S$.

The risk-free rate of interest, often used in real options analysis (ROA), can be interpreted as a rate that is paid on the market for an investment that is expected to have no default risk. It can also be used to discount investment costs, which are subject to the private risks of an investor. The risk-free rate can be determined, for instance, from the average returns for bonds with a ten-year lifetime in the euro area. The market expectations for such bonds yield on average 3.2% in 2013 and about 3.6% in 2014 [27]. The analysts of the ECB also suggest that the low point in the development of the interest rates will have been exceeded by the end of 2013, so they expect rising rates in the future. In recent years, the average rate of return of ten-year bonds was about 4.5% [28]. Considering all these factors, a risk-free rate of interest of 4.0% is appropriate to be used for the subsequent calculations.

4. Real options approach and model specification

Most real-life investments have three fundamental characteristics in common. An investment is completely or at least partially irreversible, there is a certain degree of uncertainty over the future rewards from the investment, and the investor has the ability of a flexible investment timing [18]. These basic aspects are often neglected by traditional discounted cash-flow models, like the NPV approach. Decisions that are based on such analyses can be flawed, as the model assumes a static, one-time decision-making process, whereas ROA takes the existing strategic managerial options and flexibility explicitly into account [29].

Real options, as the name implies, use the financial option theory to evaluate physical or real assets. By holding a real option an investor has the right, but not the obligation to take actions regarding a certain real-life project. These options can be of various types, e.g. an option to abandon or to expand a project, either if the investment pays off or not. Or an
investor could hold the option to delay a certain investment, if he expects better economical preconditions in future. All these options also provide different execution times; the most common are presented by American and European options. The former can be exercised at any time during its lifetime, whereas the latter can only be exercised at its maturity. There are also a lot of different approaches to evaluate a real option. Frequently used methods are closed-form solutions, such as the Black-Scholes model, partial-differential equations, binomial lattices, and simulations.

4.2. Model development

The aim of this model is to evaluate the investment in an RSHPP as described in the previous sections. The investor is supposed to hold a timing option, so he can defer his or her investment to a later period. This option can be described as a simple American call option. Due to the fact that this option is supposed to pay no dividends, the option value of an American option equals the result of a European option [29]. In order not to overcomplicate the analysis, several simplifying assumptions need to be made. First, it is assumed that the operator of the power plant is able to feed in and sell a self-determined amount of electricity on the market, anytime. Thus, a price-dependent demand elasticity does not need to be taken into consideration. The investment in an RSHPP is assumed to be entirely irreversible and cannot be withdrawn. In this study, the model refers to a power plant constructed in an area providing intermediate wind velocities and sun irradiations, which can be found in continental northern Europe, e.g. in the inlands of Germany. By adjusting the specific energy yields for wind and solar power and the individual ratio of their installed capacity, the model can easily be adapted to other locations. The CAPEX for an RSHPP is composed of the specific investments for wind turbines, PV systems and the storage device. The positive cash flows exclusively result from the revenues of sold electricity on the energy market. The negative cash flows solely consist of the operating costs, which in turn depend on the investment costs. Deviations from the expected values are investigated in a subsequent sensitivity analysis.

The investor faces two major sources of uncertainty that drive the economic viability of an RSHPP project. First, a market uncertainty due to the stochastic future development of the electricity prices. Second, a private risk caused by the stochastically varying energy output of wind and solar power. The range of uncertainty of the energy production remains constant over the years, which means the expected energy yield in a year may vary within a certain
range, but this range is the same for all future years. In contrast, the uncertainty of the electricity price rises over the years. The stochastic development of the electricity price can adequately be described by a geometric Brownian motion with a drift or growth rate. This approach is elementary for the execution of a binomial lattice solution and is frequently used to forecast commodity prices or interest rates [18]. The long-term evolution of the electricity prices of the different ELIX configurations can be depicted as:

$$\frac{dp_i}{P_i} = \mu_i * dt + \sigma_i * \epsilon_i * \sqrt{dt}$$  \hspace{1cm} (8)

A percentage change of $P_i$ results from the sum of a deterministic and a stochastic part. The former is driven by the drift component or growth parameter ($\mu_i$) that increases at a factor of time, the latter by a volatility parameter ($\sigma_i$) growing at a rate of the square root of the time. The expression $\epsilon_i * \sqrt{dt}$ is the increment of a Wiener process with $\epsilon_i$ as a simulate variable, usually following a normal distribution with the mean of zero and a variance of one. In a simulation, $\sigma_i$ remains constant for a certain step, whereas $\epsilon_i$ changes every time. Over a finite time interval, the change in the logarithm of $P_i$ follows a normal distribution with the mean

$$mean = (\mu_i - \frac{1}{2} \sigma_i^2) * t$$ \hspace{1cm} (9)

and a variance

$$var = \sigma_i^2 * t.$$ \hspace{1cm} (10)

The growth and the volatility parameters, which are used to forecast the electricity prices of the three different ELIX prices, are listed in Table 4. The variables are based on the certain ELIX development over the last years.

<table>
<thead>
<tr>
<th>ELIX</th>
<th>$\mu_i$</th>
<th>$\sigma_i$</th>
<th>Starting value [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>0.039</td>
<td>0.260</td>
<td>46.51</td>
</tr>
<tr>
<td>Peak</td>
<td>0.0714</td>
<td>0.275</td>
<td>52.82</td>
</tr>
<tr>
<td>Night</td>
<td>0.009</td>
<td>0.270</td>
<td>40.19</td>
</tr>
</tbody>
</table>

The stochastic character of wind and solar power is combined by using an MCS, taking account of the model specifications described in section 3. Due to the increasing uncertainty
over the future periods, the development can be described as a cone of uncertainty (see Fig. 7).

\[
\text{Fig. 7. The cone of uncertainty over time [17].}
\]

In our analysis, the real option values are calculated by using a binomial recombining lattice approach. The results obtained thereof tend to approach those derived from closed-form solutions, like the Black-Scholes model, but only if the number of time steps used is sufficiently high. In essence, a binomial lattice solution is a discrete simulation of the cone of uncertainty. Note that this approach requires at least two lattice evolutions, one for the underlying asset and the other to evaluate the option itself. The former is lined up first, the latter is solved by backward induction (recombining lattice) [17]. \( S_0 \) represents the present value of the underlying asset, i.e. the present value of all expected future free cash flows. The up parameter (\( u \)) and the down parameter (\( d \)) are calculated as

\[
\begin{align*}
    u &= e^{\theta \sqrt{\delta t}} \\
    d &= e^{-\theta \sqrt{\delta t}} = \frac{1}{u}.
\end{align*}
\]

The percentage volatility of the natural logarithm of the underlying free cash flow returns is characterized by \( \theta \); this measure is an annualized value. The higher the volatility, the higher the difference between the up and down factors, and the higher also the potential value of the option. The time steps in the lattice are determined by \( \delta t \), e.g., if an option has a maturity of one year and ten steps are made in the lattice, each step has a step size of 0.1 years. Another value required in the analysis is the risk-neutral probability measure (\( p \)):

\[
p = \frac{e^{rf \cdot \delta t} - d}{u - d}
\]
This value is a mathematical intermediate and has no certain meaning by itself. The initial value of the underlying asset \( S_0 \) is commonly determined by a classical DCF approach, where the individual expected cash flows are discounted on their individual expected interest rate, neglecting the existence of uncertainty:

\[
S_0 = \sum_{i=1}^{n} \frac{CF_i}{(1+WACC)^i}
\]  \hspace{1cm} (14)

In this case, the approach assumes no cash flows \( (CF) \) in the initial period zero. Now, the static base case NPV can easily be calculated by using the total investment (or project implementation) costs represented by \( I_0 \), i.e.

\[
NPV = -I_0 + S_0.
\]  \hspace{1cm} (15)

In a further step, the NPV is simulated by an MCS to take account of the uncertain parameters, such as the electricity price, wind and PV power generation, investment costs, and annual expenditures. To determine the percentage volatility \( (\sigma) \) that primarily drives the value of the real option, a logarithmic present value cash flow of returns approach is used. The present values of all cash flows are computed and summarized once at \( t = 0 \) and once at time \( t = 1 \)

\[
\sigma = \ln \left( \frac{\sum_{i=1}^{n} PVCF_i}{\sum_{i=0}^{n} PVCF_i} \right).
\]  \hspace{1cm} (16)

The sum of the present values of the cash flows \( (PVCF) \) at period 0 represents the stock price of the asset at time zero, so the value today. The sum at \( t = 1 \) is equivalent to the stock price at that time, and provides a good proxy for the future stock price. In order to capture all future uncertainties, an MCS has to be performed. In most cases, the rates to discount the cash flows are static, but there is the possibility to enlarge and adjust the equation in order to calculate the volatility for a variable discount rate. However, in ROA the variability in the PCVFs is a key driver of the option value, not the varying discount rates. For this approach it is advisable to simulate the DCF by using a risk-free interest rate [17]. The nominator of eq. (16) reflects the base case and is therefore treated as static in the simulation. Whereas the value of the numerator is simulated, the standard deviation resulting from that simulation can be interpreted as the volatility.

After calculating all the required variables above, the first lattice for the underlying asset can be developed. For this purpose, the present value of the underlying asset \( (S_0) \) is multiplied by the up and down factor at each step (i.e. each node). Thus, the lattice spreads out more and more until the terminal nodes have been reached. The second part of the binomial lattice approach consists of the evolution of the option value lattice. As mentioned
above, this is done by using a backward induction calculation. In a first step, the terminal
nodes have to be computed through the maximization between executing the option and
letting it expire worthless in case the costs exceed the benefits of execution [17]. This rule for
determining the terminal nodes ($TN$) can be summarized as follows:
\[ TN = \text{Max} \left[ S_{TN} - I; 0 \right]. \] (17)

The term $S_{TN}$ represents the individual value of the underlying asset at a certain terminal
node and can be taken from the lattice developed first. The costs of executing the option (i.e.
the implementation costs) are represented by $I$. The second step comprises the actual
backward induction. The values of intermediate nodes can be obtained by
\[ N_t = [p \ast u + (1 - p) \ast d] \ast e^{(-\tau_f \ast \delta t)}. \] (18)

Calculating each node throughout the entire lattice, all the way back to the starting node,
results in the option value at time zero. To verify the results obtained from the binomial
lattice approach, the values are cross-checked with the results obtained from the closed-form
Black-Scholes model. The call option value of such a closed-form model can be described by
the following Black-Scholes formula (eq. (19)) [17]:
\[
CALL = S_0 \ast \phi \left[ \frac{\ln \frac{S_0}{X} + \left( \frac{r_f + \sigma^2}{2} \right) \ast T}{\sigma \ast \sqrt{T}} \right] - X \ast e^{-r_f \ast T} \ast \phi \left[ \frac{\ln \frac{S_0}{X} + \left( \frac{r_f - \sigma^2}{2} \right) \ast T}{\sigma \ast \sqrt{T}} \right].
\] (19)

In this case $\Phi$ represents a standard-normal distribution and $T$ is the maturity of the option.
Next, a second sensitivity analysis can be performed to identify the individual influence of
the option valuation parameters on the option value itself. The parameters analyzed are the
underlying asset, the implementation (investment) costs, the risk-free interest rate, the
volatility, and the maturity of the option. Each of these factors is analyzed separately, while
all other variables are remaining constant. To check the plausibility of the results the option
value has to comply with the following two inequalities [17]:
\[
CALL \geq \text{MAX}[S_0 - I \ast e^{-\tau_T}, 0]
\] \[ CALL \leq S_0 \] (20) \[ (21) \]

The former one indicates that the value of a call option cannot be lower than zero when it
is left to expire. The latter states that the value cannot be higher than the value of the
underlying asset. The total strategic value of the investment is nothing more than the sum of
the deterministic base case NPV and the strategic option value. This assumption can also be
described as the expanded net present value (eNPV):
\[ eNPV = NPV + \text{option value}. \] (22)
In the two scenarios that follow, the investor is assumed to hold a 10-year maturity option to defer his investment in a RSHP. Determination of the optimal time to execute the option is very difficult, though. If there are high-risk projects with significant amounts of uncertainty, waiting is often preferred to executing the option immediately. The optimal investment strategy is to maximize the value of the option with respect to time. To solve the timing problem, it is assumed that the value of the underlying asset ($S_0$) follows a geometric Brownian motion. The optimal value of the option can be derived through the differential equation of the NPV with respect to the time ($T$):

$$\frac{dΦ(W)}{dT} = (\xi - \delta) * S_0 * e^{(\xi - \delta) * T} + \delta * I_0 * e^{-\delta T} = 0.$$  \hspace{1cm} (23)

Taking the uncertainty of the future development of the underlying into account, a volatility parameter ($\sigma$) is introduced. The optimal trigger value is defined by [17]

$$\frac{S_0 * e^{\xi * t}}{I_0} = \frac{\left\{ \frac{2 - \xi}{\sigma^2} + \left( \frac{t}{\sigma^2} - 0.5 \right) \right\}^{0.5}}{\left\{ \frac{2 - \xi}{\sigma^2} - \left( \frac{t}{\sigma^2} - 0.5 \right) \right\}^{0.5}} + 0.5 * \frac{\xi}{\sigma^2} + 0.5 * \frac{\xi}{\sigma^2} - 0.5 * \frac{\xi}{\sigma^2}.$$  \hspace{1cm} (24)

The left part of this equation can be interpreted as a profitability index. If this index is less than 1.0, a negative NPV is implied. In contrast, an index that exceeds 1.0 implies a positive NPV, because the value of the underlying asset exceeds the investment costs. An assumption that needs to be made is that the growth parameter does not exceed the discount rate ($\delta > \xi$), as otherwise the terminal value becomes infinite, so that an optimal time to exercise the option cannot be found. A transformation of the equation above provides an approach to determine the optimal execution time ($T$):

$$T = \frac{1}{\xi} * \ln \frac{\left\{ \frac{2 - \xi}{\sigma^2} + \left( \frac{t}{\sigma^2} - 0.5 \right) \right\}^{0.5}}{\left\{ \frac{2 - \xi}{\sigma^2} - \left( \frac{t}{\sigma^2} - 0.5 \right) \right\}^{0.5}} * S_0 + 0.5 * \frac{\xi}{\sigma^2}.$$  \hspace{1cm} (25)

4.3. Load balancing scenario

In the first scenario, the storage device of a RSHP is used to balance the load fluctuations caused by the unsteady supply of wind and solar power. Thus, the power plant can be operated as a base-load plant, providing a constant and predetermined amount of electricity. In this scenario, futures with a delivery period of one week are used to compute the revenues. During this time period, the prevailing wind conditions and expected sunlight radiation can be forecasted adequately. The considered power plant is supposed to have a total generating capacity of 1000 MW. Furthermore, natural preconditions are supposed to
allow realizing a ringwall storage device with an average height difference of 200 m between upper and lower reservoir and an average fluctuation of the water level of 25 m in both basins.

The expected specific energy production over a certain period ($e_i$) of an RSHPP consists of the expected amount of wind and solar power. In this case, the expected specific yield per megawatt of installed capacity of wind energy is given by $f_{sp,W}$. Since wind power production is directly related to the uncertain wind velocity, the expected yield follows a Rayleigh distribution (with a scale coefficient of 0.188). The expected specific yield of PV energy ($f_{sp,PV}$) is assumed to follow a lognormal distribution (with mean 0.22 and standard deviation 0.20). The predefined ratio between wind and solar power, as described in section 2.1, is also applied in this model, so 1 MW of total installed capacity consists of 0.8 MW of wind and 0.2 MW of PV power:

$$e_i = 0.8 \cdot f_{sp,W} \cdot t_i + 0.2 \cdot f_{sp,PV} \cdot \frac{1}{2} t_i.$$ (26)

The length of the certain period is given by $t_i$; it is assumed that solar energy is only generated during 12 hours a day, so the production time is half of that for wind energy.

The required storage capacity of the RSHPP for the load balancing scenario is difficult to estimate. It depends on the expected deviation of the real energy production from the expected average amount. A detailed analysis of the exact required capacity is beyond the scope of this study. An approach to roughly estimate the storage size can be provided by the standard deviation resulting from the simulation of the total expected weekly amount of electricity. This approach, however, does not consider extreme weather conditions, with long-lasting yields either high above the average or far below. To absolutely ensure the predefined weekly amount of electricity, the ringwall storage facility would have to provide a capacity that corresponds to the spread between the maximum and the minimum value that can be reached during one week:

$$Spread = \max(e_i) - \min(e_i).$$ (27)

For this scenario, the specific energetic storage capacity ($\omega_{el}$) is assumed to be the maximum value of the doubled standard deviation ($Stdev$) or 7-day loads, divided by the efficiency ($\eta_{WT}$) of the water turbine (the average efficiency of a modern water turbine can be stated with 92%). Thus, the storage device provides at least a capacity of 7-day loads:

$$\omega_{el} = \text{MAX}\{2 \cdot Stdev; \sum_{i=1}^{7} e_i\} \cdot \frac{1}{\eta_{WT}}.$$ (28)
The longer the delivery period is chosen, the higher the degree of uncertainty in energy production and the higher the required storage capacity. Total investment costs of the RSHPP consist of the individual specific costs of wind power, PV systems, and the storage device:

\[ I_{tot} = \{0.8 \times c_W + 0.2 \times c_{PV} + v_{el} \times c_S\} \times P_{tot}. \]  

(29)

The expected values of the specific investment costs of wind and PV systems are given by \(c_W = 1250 \text{€}/kWh\) and \(c_{PV} = 1600 \text{€}/kWh\), respectively, i.e. both are related to the installed rated power, whereas the specific costs for the storage device (\(c_S\)) are related to the storage capacity and depend on the ringwall proportions (Fig. 3). To consider the uncertainty of the investment costs, the individual values are supposed to follow a normal distribution. In order to simplify the calculations, the average specific costs for each system are set to their mean, with a standard deviation of 10%. The influence of these fluctuations is examined in a subsequent sensitivity analysis.

The annual expenditures (\(A_i\)) for O&M, insurance premiums etc. are calculated by using a percentage of the individual investment costs. The individual percentage and the individual development, as described in section 3 are taken into account, as is the uncertainty due to the varying percentages of the annual costs for wind (\(a_w\)) and PV systems (\(a_{PV}\)):

\[ A_i = [(0.8 \times c_w) \times a_w + (0.2 \times c_{PV}) \times a_{PV} + (v_{el} \times c_S) \times a_S] \times P_{tot}. \]  

(30)

The annual costs for the storage device (\(a_S\)) are set to a constant rate of 1%. In order to consider fluctuations of the individual annual costs, they are also simulated by an MCS. The values are assumed to follow a normal distribution with a standard deviation of 10%. A sensitivity analyses displays the influence of these fluctuations on the NPV.

In this scenario, the power plant delivers the contractual pre-determined amount of electricity for one week with constant power. Thus, the revenues are calculated with the use of the ELIX Base. The expected evolution of the electricity price is simulated by using the definitions provided in section 3.4 and the geometric Brownian motion approach. The annual revenues consist of the 52 weekly revenues realized from trading.

### 4.4. Flexible use scenario

With a flexible use of the power plant, the operator of an RHSPP can take advantage of the fluctuating electricity prices if he offers his electricity generated on the day-ahead spot market. If the hourly electricity price falls below the ELIX Base, the storage device will be charged. The stored energy is sold when the price exceeds the daily average. This procedure
is economically sensible only if the price difference exceeds a certain percentage, because the usage of the storage device causes energy losses.

The hours when the clearing price falls below the daily average essentially occur at night. Thus, by using the ELIX Night for hours with prices below the average and the ELIX Peak for hours above the average, the calculation can be simplified. The efficiency of the storage plant is set to 85%, following the efficiency of modern PSPP. Thus, with a loss of energy of about 15%, the ELIX Peak needs to exceed the ELIX Night by at least 15%. Analyzing the ELIX shows that this was given on 76.6% of the days over the last years [30], and a similar development is expected for the future.

In order not to overcomplicate this model, further simplifying assumptions need to be made. The whole amount of PV energy is generated and sold during the peak price period, from 8 am to 8 pm. The same assumption applies to the wind energy produced in that period. If the storage device is used, the wind power generated during the night period is used to charge the device, and no electricity is fed into the grid. The stored energy is then fed in throughout the entire following day, so that the ringwall storage is able to provide its full capacity again by 8 pm. On days where an economical usage of the storage facility is not given, the wind energy produced at night is directly fed into the grid.

For comparability reasons, the considered RSHPP in this scenario provides the same amount of rated power as the power plant above. Due to the flexible use of the storage device, it does not have to provide such a large amount of energy storage capacity as the storage considered in the previous section. Only the energy production of wind power during the night is decisive for the required storage volume. A simulation of the wind energy production during one night obtains an average yield of 1809 MWh in that period, and the maximum value resulting from that MCS is 6526 MWh. As already assumed in the previous section, the natural preconditions are supposed to allow the 25/25/200 constellation.

Due to the smaller-sized ringwall, it has first to be checked if the areas are large enough for the installation of 200 MW of PV panels. Today, the technically most advanced modules provide a power density of up to 200 W/m² [31].

For the subsequent calculations, the annual energy production has to be divided into PV power and wind power generated during the day hours and wind power produced at night. Since the former amounts are directly fed into the grid, they can be sold at ELIX Peak rates. The wind energy amount produced during the night hours is either stored (and later also sold) at peak rates or directly fed into the grid during the night at ELIX Night rates. Thus, the
expected total AEP consists of these three parts and is independent of the use of the storage device, whereas the annual amount of fed-in energy depends on the utilization and the efficiency of the storage device. The investment costs for the wind turbines and the PV systems, as well as the annual costs of those devices follow the same definitions as described in the scenario above. Merely the specific investment costs for the storage device have to be re-determined. In this scenario, the influences of the individual variations are again depicted in two sensitivity analyses, one for the simulated NPV and the other for the option value.

5. Results and discussion

5.1. Load balancing scenario

Before performing the economic analyses, the capacity of the ringwall storage device and the resulting total investment costs have to be determined first. The Monte Carlo simulation of the total weekly energy production provides an expected amount of 29,129 MWh; the standard deviation is 13,962 MWh. By using eq. (28) an energetic storage capacity of about 32 GWh is required. Considering the ringwall proportions described above, specific investment costs for the storage device of 28.5 €/kWh can be determined (cf. Fig. 3; these costs can also be determined by using Popp’s online tool [19]). Using eq. (29) yields total investment costs of €2.232 bn.

Now, the base case DCF analysis can be performed using static values and neglecting uncertainty. The electricity price (ELIX Base) starts at a value of 46.51 €/MWh, with an annual increase of 3.39%. The proportions of the individual systems to the total costs are used to determine the discount rate, as described in eq. (7). The contribution of wind turbines and PV systems is 59%, so that of the ringwall is 41%. The annual expenditures are computed using eq. (30), with a constant share of 3% for wind turbines and PV systems. The former value increases by 1.5% annually, the latter by 2%. The annual costs for the storage device are at a constant annual rate of 1%. Taking account to this assumption, the cash flows and their present values can be determined using eq. (14). The calculation results in a present value of all future cash flows of \( S_0 = €456,543,194 \).

The calculation of the static base case NPV by using eq. (15) results in an enormous deficit of €-1,775.5 million. In a next step, an MCS is carried out to consider all uncertain parameters that have an impact on the NPV. The basic results of that simulation are summarized in Table 5.
Table 5. Results of the MCS of the first scenario NPV.

<table>
<thead>
<tr>
<th>Results</th>
<th>[million €]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>-1446.35</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1016.14</td>
</tr>
<tr>
<td>Maximum value</td>
<td>8096.60</td>
</tr>
<tr>
<td>Minimum value</td>
<td>-3093.24</td>
</tr>
</tbody>
</table>

A sensitivity analysis to examine the individual influence of the certain fluctuating parameters on the NPV has be carried out next. The variation in the forecasted NPV can be explained by the individual simulated values (= first scenario NPV volatility): 70.86% wind energy production; 10.46% electricity price; 2.62% PV production; 2.42% investment cost; and 0.42% annual cost. In other words, the wind energy production is the main driver of volatility with more than 70%, followed by the electricity prices with a total share of 23.68%. The PV energy production and the total investment costs only marginally affect the volatility. The contribution of the total annual costs is negligible.

We can now use the static PVCF to calculate the volatility with the help of the logarithmic present value returns approach. Following the definitions of section 4.2 and eq. (16), we obtain a percentage volatility of $\vartheta = 106\%$. This value was determined using an MCS of the ELIX Base future evolution, simulating the AEP and the slightly varying annual costs. The high volatility implies the potential for a high value of the real option.

As a next step, the up and down parameters can be calculated. For this, the stepping time ($\delta t$) must be determined first. The option has a maturity of ten years. A first approach of 1000 lattice steps is assumed to be sufficient, as validated in a convergence test. This leads to a stepping time of 0.01 years. Using eqs. (11) and (12) results in an up parameter of $u = 1.1118$ and a down parameter of $d = 0.8994$.

Now, the underlying asset lattice can be developed (1000 lattice steps). The recombining character of this lattice can be recognized, where the present value of the underlying asset remains constant. In a next step, the option value is determined by a backwards induction calculation using the risk-free probability measure and eqs. (17) and (18). The former parameter can be obtained with the help of eq. (13) and the risk-free rate of interest ($rf$) of 4.0%. This yields a value of $p = 0.4754$. Thus, a ten-year maturity call option to invest in an
RSPP that operates in a load balancing scenario is worth €382,357,329. Carrying out the evaluation of the option using the Black-Scholes formula (eq. (19)), we obtain a value of €382,361,426, which nearly equals the value resulting from the lattice solution. With an infinite number of time steps the two results would be exactly identical. Next, a second sensitivity analysis is performed to detect the influence of the individual option parameters on the option value. The implementation costs are negatively correlated to the option value (Fig. 8). The values of the underlying asset and the risk-free rate of interest are positively correlated to that value.

![Fig. 8. Results of the sensitivity analysis of the first scenario option value.](image)
After reaching a volatility of about 150%, the option value converges to an amount of about €455 million. Also, the option value in dependence of the option maturity converges to a value of about €450 million after exceeding a maturity of about 20 years. The option value of €382,357,329 satisfies the requirements of eqs. (20) and (21). Thus, it lies within a plausible value range. Following the assumptions of the expanded NPV approach, eq. (22) obtains a total strategic value of \( eNPV = € - 1,393.1 \) million. In this scenario, the option value can only marginally mitigate the enormous deficit of the base case NPV. It is apparent that such a project will never be realized under all the conditions mentioned above. This is also evident if one considers the results of the calculation of the optimal execution time of the option, which is 56 years in the future. The analysis of the profitability index of eq. (24) shows that only after 40 years of waiting a positive NPV can be obtained. Hence, in the absence of governmental support (e.g. in the form of subsidies or tax grants), an RSHPP used for this scenario is economically not viable.

5.2. Flexible use scenario

Again, the key factors of the RSHPP have to be determined first. Based on the simulation of the wind power production of one night, the required storage capacity is set to 6.7 GWh. Using Fig. 3 to estimate the specific costs for a ringwall storage device with an average height difference of 200 m and a 25 m level fluctuation in each basin, we obtain specific investment costs of €37.45/kWh. As the implementation costs of the generating devices are identical to those of the first scenario, eq. (29) returns total investment costs of €1570.9 million.

In order to examine whether or not this ringwall device is sufficiently large for the installation of PV panels with a rated power of 200 MW, its surface area has to be checked first. The calculation delivers a total surface area of 1,371,781 m². It is assumed that only about 75% of this area can be used for the installation of PV modules, the remaining 25% are required for infrastructural constructions. The specific power density of 200 W/m² leads to a required installation area of at least 1 million m². With a usable surface area of 1,028,836 m² provided by this storage device, the 200 MW of rated PV power can thus indeed be installed.

As in the previous section, a base case DCF analysis is performed first. In this scenario, the static and the stochastic evolution of the ELIX Peak and the ELIX Night are required. The static evolution without any volatility is used in this DCF analysis. The ELIX Peak starts at a value of 53.53 €/MWh and with a continuous annualized growth rate of 7.14%. The
ELIX Night starts at 39.67 €/MWh and increases annually by only 0.9%. The year-specific WACC rates depend on the contribution of each system to the total investments; they are determined using eq. (7). In this scenario, the contribution of wind turbines and PV systems is 84% and that of the RSHPP is 16%. The annual expenditures are calculated the same way as in the previous section, using eq. (30). In consideration of all assumptions described above, eq. (14) gives a present value of all future cash flows of $S_0 = 1,403.8$ million. The calculation of the base case NPV following eq. (15) results in a deficit of €167.1 million. The basic results of that simulation are summarized in Table 6.

Table 6. Results of the MCS of the Second Scenario NPV.

<table>
<thead>
<tr>
<th>Results</th>
<th>[million €]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>-179.44</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1046.13</td>
</tr>
<tr>
<td>Maximum value</td>
<td>13,208.78</td>
</tr>
<tr>
<td>Minimum value</td>
<td>-2222.84</td>
</tr>
</tbody>
</table>

The composition of the NPV volatility in the flexible use scenario (=results of a sensitivity analysis of the forecasted NPV) is: 77.07% wind power production; 6.92% electricity price; 3.26% PV power production; 0.8% investment costs; and 0.08% annual costs. As in the previous scenario, wind power production is again the main driver of the volatility, with a share of about 77%. The electricity prices are responsible for 6.61% of the NPV variation, wherein the share of the ELIX Night is almost negligible. The PV energy production contributes 3.26% to uncertainty. The percentages of the investment costs and the annual expenditures are insignificant (see [32] for the positive and negative correlation parameters).

Equation (16) and the definitions of section 4.2 provide a total volatility of $\vartheta = 90\%$, a value which is again primarily determined by the wind energy production and the electricity prices (see [32] for details on the Monte Carlo simulation). As before, this high volatility implies the potential of a high real option value.

Next, the option value can be computed by the backwards induction calculation with the help of the risk-free probability measure. The option valuation lattice calculation results in an option value of a ten-year maturity call option of €1,216.31 million. The values of the
terminal nodes are determined by the use of eq. (17), the values of the intermediate nodes are calculated by eq. (18). A cross-check with the results from the Black-Scholes formula in eq. (19) provides an option value of €1,216.28 million, which nearly equals the results from the lattice solution.

Now, a second sensitivity analysis to identify the influence of the option parameters is carried out. These parameters are the underlying asset, the implementation costs, the risk-free interest rate, the percentage volatility, and the option maturity. Each of these factors is analyzed separately, with all other variables remaining constant. Fig. 9 shows the results of the sensitivity analysis.

The tendencies of the individual values are the same as in the previous section. Again, from a volatility of about 150% the option value converges to about €1400 million. Likewise, the option value converges to the same amount after exceeding a maturity of 20 years. The option value of €1,216.3 million meets the requirements of eqs. (20) and (21) and thus lies within a plausible value range. Following the assumptions of the expanded NPV approach, eq. (22) provides a total strategic project value of \( eNPV = €1,049.2 \) million. In this scenario, the option value helps turning the negative base case NPV into a positive strategic eNPV.

Before calculating the optimal time for executing the option, the required parameters have to be determined first. The discount rate is set to 8.0%, which corresponds to the average rate in the previous calculations. The annualized growth parameter of the underlying asset is assumed to be about 4% and the volatility parameter is set to 10%. Using these parameters, eq. (25) obtains an optimal time to execute the option in period 22, or 22 years, which is far beyond the option maturity of ten years. The higher the level of uncertainty in the future evolution of the underlying asset, the better it is to wait before executing the option. However, the result of eq. (24) to determine the profitability index, indicates that starting from period 3 a positive NPV can be obtained.
Fig. 9. Results of the sensitivity analysis of the option value in the second scenario.

6. Conclusions and outlook

The recent developments in the energy sector will also continue in the future. Especially with regard to the nuclear phase-out in some countries, including Germany, and the international targets for the reduction of the CO₂ emissions, renewable energy is becoming more and more essential in energy systems. Since the energy production of wind turbines and PV systems cannot be predicted accurately and is also subject to large fluctuation, energy storage systems will be indispensable in the future. The RSHPP provides an innovative and
useful concept for storing energy. However, an economic valuation, as it was undertaken in our study, is a difficult undertaking due to large uncertainties. Consequently, the two exemplified scenarios depict only a small fraction of the possible range of RSHPPs.

The load balancing scenario, presented first, represents a realistic utilization of the plant. Also, the described dimension seems to be conceivable for a real-life construction. Nevertheless, the economic analysis of this RSHPP does not yield a positive result. This is the major reason why the value of the PVCF of €456.5 million is relatively low. The highly negative base case NPV is the result of this low PVCF and of the enormous investments costs that occur. Due to the high implementation costs and the relatively low present value of the cash flows, the real option value of €382.4 million is not high enough to compensate the negative value of the NPV. A realization of an RSHPP operating at this balancing scenario is almost inconceivable. This also becomes apparent when the results of the optimal investment timing problem are regarded. In the absence of governmental funding support, an RSHPP is unlikely to be realized in the near future. Our analysis examines the economic viability of the project in the absence of any kind of subsidies, in order to depict the mere competitiveness of the project.

In contrast, an RSHPP operated in a flexible scenario offers some advantages. The operator has the ability to sell the electricity generated at peak-load prices. In this scenario, the storage device is no longer used to balance the load fluctuations of wind and solar power. Rather, the RSHPP is operated to maximize revenues. Thus, this RSHPP does not help to mitigate the increasing problems of fluctuating energy supply (on the contrary, these problems may even be exacerbated). Nevertheless, the economic viability is analyzed to obtain a comparative value to the first scenario. The present value of the future cash flows turns out to be €1,403.8 million, and thus about three times higher than the one found for the balancing scenario. Although the base case NPV is negative, the high real option value of €1,216.3 million turns the negative value into a positive strategic NPV. The optimal executing time for the option is indeed beyond the maturity of the option, but the profitability index indicates a positive NPV after only three years. Note that this analysis also ignores any kind of governmental grant. Applying real options theory, an investment in this RSHPP is found to be profitable, even without public funding, due to the high option value inherent.

Since novel energy storage facilities will be required in the near future, it is quite likely that a first demonstration RSHPP plant will be realized in the coming years. Based on such
an experimental plant, it can then be investigated in further detail whether this technology, under the given circumstances, is economically viable or not.

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References


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