Investment Under Uncertainty in a Power-to-Gas Plant in Germany: A Real Options Analysis

Georg Schultes[1] and Reinhard Madlener[2,3,*]

[1] *RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany*

[2] *Institute for Future Energy Consumer Needs and Behavior (FCN), School of Business and Economics / E.ON Energy Research Center, Mathieustraße 10, 52074 Aachen, Germany*

[3] *Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway*

September 2019, last revised April 2020

Abstract

In this paper, a binomial tree real options analysis in discrete time is conducted for the investment case of a 5 MW power-to-gas plant and a 5 MW extension in Germany and an American-style option is used. Four revenue mechanisms are studied to determine the optimal capacity and component composition of the P2G facility: operation at negative prices, operation at low electricity prices, sale of oxygen, and provision of minute reserve. The four scenarios considered are (1) reduction of the revenue flows from the extension to 75% of the actual level; (2) increase in the standard deviation of electricity prices by 1% p.a.; (3) introduction of a gas price subsidy of 2.5 €-ct/kWh; and (4) decrease in investment costs for electrolyzer and methanation unit of 1% p.a. We find no profitable investment alternatives, not even for the investigated cases of increased economic merit.

Keywords: Power-to-gas; Sector coupling; Real options analysis; Germany

Abbreviations used

AEL	Alkaline electrolysis	NCG	NetConnect Germany
CO_2	Carbon dioxide	OPEX	Operation expenditure
ext	Extension	opt	Option
GW	Gigawatt	PEM	Polymer electrolyte membrane electrolysis
inv	Investment	q	Quarter
kW	Kilowatt	ROA	Real options analysis
kWh	Kilowatt-hour	TWh	Terawatt-hour
MW	Megawatt		
MWh	Megawatt-hour		

* Corresponding author. Tel. +49 241 80 49 820, email: RMadlener@eonerc.rwth-aachen.de (R. Madlener)

1 Introduction

In April 2016, the Paris Agreement was signed by 195 states. The main goal agreed on is to keep the increase of global temperature below 1.5 °C or at least below 2 °C. (UNFCCC 2015) To achieve this goal, global greenhouse gas emissions have to be significantly reduced. Germany has defined its own goals for reducing greenhouse gas emissions in alignment with international agreements. For each decade until 2050, emissions should be reduced by a predefined percentage in comparison with the 1990 emission level. The goal is to reduce emissions by at least 40 % until 2020, by at least 55% until 2030, by at least 70% until 2040 and by at least 95 % until 2050 (BMU 2018). In 2017, the emissions in Germany were $905 \text{ million } t_{CO_2,eq}$ in total of which $328 \text{ million } t_{CO_2,eq}$ stem from the energy sector, $193 \text{ million } t_{CO_2,eq}$ stem from the industry sector, $171 \text{ million } t_{CO_2,eq}$ stem from the mobility sector, $91 \text{ million } t_{CO_2,eq}$ stem from private households and the remaining emissions stem from other sectors (BMU 2018). Thus, as the largest emitting sector, the energy sector bears a large potential to further reduce greenhouse gas emissions. Currently, this is done by replacing conventional energy sources with renewable energy sources. Unfortunately, the production of electricity through photovoltaics and wind turbines are subject to significant fluctuations. Therefore, the risk that peak loads cannot be covered in times of low availability of renewable energy sources increases. This problem underlines the necessity to develop energy storage systems that store electricity in times of high availability of renewables and dispose electricity in times of low availability of renewables. With those systems in place, the percentage of renewable energy generation technologies in the energy system can be increased significantly (Thema et al. 2016).

One suitable energy storage solution is the utilization of excess electricity in power-to-gas (P2G) plants. The main advantage of this technology is that gas can be stored over long time periods without notable energy losses (Krzikalla et al. 2013: p. 78). Furthermore, gas can be transported to locations where energy is required and thereby spatial energy imbalances can be resolved (Jentsch et al. 2014). Finally, the large existing gas infrastructure in Germany can be used to store the gas that is produced in P2G plants (Krzikalla et al. 2013: p. 72).

The technological components to build P2G plants are well researched and commercially available. Nevertheless, only few demonstration plants have been built, the largest of which has an electric capacity of 6 MW. (Götz et al. 2016) The root cause of this discrepancy might be the economic conditions to which the technology is subject. Firstly, the investment costs for a P2G plant and its infrastructure might be uneconomically high. Secondly, the revenues that can be generated with the P2G plant might be insufficient to cover the expenditures or subject to large uncertainties. Thirdly, the German legislation might be unsupportive for the investment in a P2G plant. The focus of our study is to investigate these root causes, following two research questions: (1) *Is the investment in a P2G plant in Germany profitable under the current economic conditions?(2) Which changes in the economic conditions can incentivize the investment in P2G plants in Germany in the future?*

The research on the profitability of P2G plants should incorporate the uncertainties that are connected to building such a plant. These include the uncertain future development of the electricity price and gas price and the decision about the timing of the investment. As those uncertainties cannot be included in the standard net present value approach, the more sophisticated real options analysis (ROA) is chosen. From a company's perspective, an investment decision about a P2G plant is usually only evaluated few times during a year. Therefore, the ROA is not performed in continuous time but for discrete time intervals of three months.

Due to the price uncertainties, the revenue streams generated from the plant are highly uncertain as well. For that reason, various possible future developments will be calculated with a Monte Carlo simulation to find a probability distribution of future developments. Thus, the results of the ROA will be subject to the simulated future developments.

For the first research question, all parameter values for the calculation will be chosen as close to real values as possible. For the second research question, the parameter values will be altered in realistic but optimistic ways. For example, a decrease of the investment costs in the future and a subsidy on gas from renewable resources are investigated.

Nevertheless, we do not investigate how to achieve the technical improvement of P2G technology, or how exactly future policies regarding P2G technology should look like. The analysis also does not clarify where a P2G plant could be located in Germany, but it assumes that suitable locations exist. Hence we focus on analyzing the influence of economic parameters on the profitability of P2G plants.

The remainder of this paper is structured as follows. Section 2 gives an introduction in the theoretical foundation and a literature review for P2G technologies and ROA. Section 3 describes the components, inputs and outputs of a P2G plant in detail. Additionally, the economic parameters of the plant investigated are determined and a brief review of the regulatory framework for P2G plants in Germany is given. Section 4 details the methodological approach for the ROA performed and explains the steps of the algorithm to calculate the real options values. Afterwards, the results are illustrated and analyzed. Finally, a sensitivity analysis is conducted by varying particular parameters of the model to analyze the influence on the results. Section 5 concludes on the topics covered and gives an outlook for future research.

2 Theoretical background and related literature

This chapter gives an overview over the economic theory this study is based on. Section 2.1 details the role of P2G technologies in energy systems. Section 2.2 discusses the theory behind ROA. Subsequently, relevant literature in which the theory has already been applied successfully is reviewed in Section 2.3. This is done to gain insights about how to proceed.

2.1 Integration of P2G technology into the energy system

This section gives a brief introduction on the importance of P2G technologies for the future energy system based on recent scientific literature. Vandewalle et al. (2015) investigate the influence of P2G technology on other energy sectors. They are especially interested in changes in the gas, electricity and CO_2 sector. The interaction between the different sectors is modeled with a mixed-integer linear programming approach. Subsequently, the model is applied to a fictitious energy system with 100% renewable electric energy generation and large P2G capacities, based on the current electricity and gas infrastructure in Belgium. The results indicate that P2G technology increases the value of renewable energy generation because a larger share of it can be utilized. Furthermore, by coupling the electricity and gas sector, problems induced by the fluctuation of renewable energy generation technologies can be reduced. One example for such a problem is the seasonal fluctuation in renewable energy generation. The problem can be solved by generating gas from electricity in times of oversupply and generating electricity from gas in times of undersupply. Finally, P2G technology reduces the costs to store CO_2 because it is bound in the gas produced. (Vandewalle et al. 2015)

Schiebahn et al. (2015) perform an economic assessment for P2G process chain alternatives in Germany, comparing H_2 as a fuel for transportation versus H_2 or methane feed-in. Based on a simple discounted cash flow approach and different price levels of excess wind power as well as the feed-in of synthesized methane, they find that the relatively most economical use of H_2 is in the transportation sector. In contrast, the authors find that feeding methane produced from renewable energy into the gas grid is still uneconomical because the production costs are a multiple of the current price for natural gas.

The requirement for the integration of P2G technology in the German energy system is researched by Thema et al. (2016). The authors assume a scenario in which Germany has a 100% renewable electricity supply in the year 2050. Furthermore, the cost for CO_2 as well as the cost decrease and the efficiency increase of the P2G technology are considered. This scenario is calculated using a simulation model. The results indicate that at least 89 GW of P2G capacity are necessary to generate gas from all of the predicted electricity oversupply in 2050. Still, a system with this amount of P2G capacity would cause less overall costs than a system without

P2G technology. Furthermore, without this technology, a renewable electricity supply of only 86% could be achieved by 2050. (Thema et al. 2016)

Walker et al. (2016) use a simulation model to investigate the economic feasibility of replacing industrial hydrogen from steam reformation by hydrogen from renewable sources. This creates additional revenues because it reduces the amount of CO_2 certificates required. When comparing the cost of hydrogen production with that of renewable ethanol, P2G energy storage investments show reasonable payback periods and internal rates of return.

For the case of the 6 MW PEM electrolysis project “Energiepark Mainz” (Germany), Kopp et al. (2017) perform an economic analysis investigating three different options for procuring electricity: purchase at the European power exchange, buying excess electricity from a direct marketing company, and participating in the control reserve market. They find that economic viability can mainly be improved by participating in the secondary reserve market. Using revenues from secondary reserve, operational revenues can be generated by the plant. However, those revenues are not yet sufficient to cover the total cost of the plant.

Van Leeuwen and Mulder (2018) study the feasibility of P2G in electricity markets with high shares of renewables and for electricity prices and volatility in various day-ahead markets in Europe. They find that under the prevailing market conditions P2G plants are not profitable (even under the most optimistic assumptions for costs and revenues). However, in an optimistic future scenario, with a reduction of investment cost by more than 50% and an increase in hydrogen prices by more than 100%, they see prospects for P2G, provided wholesale electricity prices remain low.

The authors in dena (2019) also come to the conclusion that P2G technology is only economically viable in rare cases. Thus, they call for a regulatory framework aimed at fostering profitability. Additionally, the authors emphasize the importance of an adequate energy infrastructure to be able to integrate P2G technology in the energy system.

In summary, P2G technology can be used to couple sectors of the energy system. This leads to a smoothing of fluctuations and reduced need for electricity and CO_2 storages. Consequently, costs for the energy system are reduced and a larger share of renewable energy sources can be utilized. As a result of the several potential benefits, P2G technology is investigated.

2.2 Real options analysis

ROA is advantageous compared to the net present value approach, because it takes the value of flexibility and uncertain future developments into account. As a result, some investment decisions that are not recommended following a net present value calculation, turn out to be profitable after performing a ROA.

An example for a real option is the investment in a real asset like a production plant or a power plant. To evaluate the value of real options, mathematical models from financial option analysis can be used, and similar types of options can be evaluated. Types of options can be differentiated regarding the time at which they can be exercised. A European option can only be exercised once when it reaches its expiration date (Black and Scholes 1973). In contrast, an American option can be exercised at any point in time including its expiration date (Black and Scholes 1973). Other types of options are often a combination of those two types. A Bermuda option, for example, can be exercised at predefined points in time until the expiration date (Franzen and Madlener 2017).

The mathematical evaluation of the option value depends, among others, on the type of option that is used. The most prominent model to calculate the value of a European option was developed by Black and Scholes (1973). The authors assume that the stock price can be modeled as a random walk in continuous time. This implies that stock prices are log-normally distributed.

An application of options theory on real assets is provided by Dixit and Pindyck (1994). The authors focus on the mathematical methods to calculate different types of real options. They also provide mathematical descriptions of the different processes that the value of an asset can follow. Examples of these processes are the arithmetic Brownian motion, the geometric Brownian motion, the mean-reverting process, and the Poisson jump process.

A model to value options in discrete time was developed by Cox et al. (1979). This model is called the binomial option pricing formula. The basic idea is that after each time period, the price of a stock S or a similar asset either moves up to the value uS with probability q or it moves down to the value of dS with a probability of $(1-q)$. The option value can then be determined with backward induction starting in the final time period.

An application of this idea to real options in discrete time is described in Guthrie (2009). The author develops methods to evaluate the market value of an asset at each discrete point in time. These market values are used to calculate the corresponding option values. The method is applied to several types of real options which, among others, are: the option to invest in a plant, the option to abandon a plant, the option to extend a plant, the option to stop production, the option to start research or the option to extract a resource.

2.3 ROA in energy economics

The following section gives an overview over scientific works that apply ROA successfully to address economic research questions in the energy domain. The choice of papers reviewed aims at covering the most common methods and energy-related applications of ROA. Insights from these papers are used to determine the best way to proceed with the analysis.

The authors Glensk and Madlener (2017) investigate the application of ROA on lignite-fired power plants. The authors aim at determining an optimal operation strategy under uncertain electricity and fuel prices. In order to do so, three different options are considered: the option to continue operation, the option to extend the power plant's flexibility and the option to abandon the power plant. For the model, an American option is chosen, and the option value is determined using a binomial lattice model. The value of the underlying asset is determined by first finding the optimal operation strategy and afterwards simulating the expected value of the project. The dark spread, which is the difference between the electricity price and the fuel price, is used as the source of uncertainty and the indicator to determine the operation strategy. The dark spread is modelled as an arithmetic Brownian motion process. As a case study, the developed model is applied to a lignite-fired power plant in the German federal state of North Rhine-Westphalia. The results indicate that further profitable operation of lignite-fired power plants in Germany is only possible due to governmental subsidies. (Glensk and Madlener 2017) The authors illustrate that the incorporation of different types of real options in one model is possible. Furthermore, they show that an arithmetic Brownian motion process is a viable choice to model the underlying asset for the determination of an investment's project value.

Another use of ROA is documented in Franzen and Madlener (2017) regarding a wind park in combination with an electrolyzer. For the simulation of uncertain annual revenue flows, stochastic wind conditions, feed-in management, minute reserve calls and the price of hydrogen are taken into account. In this example, volatile electricity is supplied by a fictitious wind park with a capacity of 24 MW. Additionally, a cavern storage with a capacity of 4000 tons of hydrogen is added to the system to enable the storage of the hydrogen produced by the electrolyzer. The investor has the option to build the facility and to extend the electrolyzer in steps of 5 MW up to a maximum capacity of 20 MW. A Bermuda option is used for the model which means that the option can be exercised at discrete points in time until the date of maturity. The option has an expiration time of 15 years. Furthermore, the option value is calculated using a binomial option pricing model. With these assumptions made, the present value including the option value is negative for the 15-year period. Further calculations reveal that the option would be exercised after a 20-year period. (Franzen and Madlener 2017) The authors investigate the option to extend a hydrogen production plant in more detail which can be applied to the expansion of the methane production plant investigated in our study. Additionally, the different sources of income, especially the sales of minute reserve and the sales of hydrogen can also be viable sources of income for a methane production plant. As in the paper a maturity period of 15 years is insufficient to recommend an investment, we have chosen an increased time horizon.

In Zhang et al. (2014) a real options approach to evaluate governmental policies is developed. As an underlying asset the authors choose the difference between revenues and costs of building additional renewable energy capacity. For the ROA, an American option is used. The uncertain influence factors chosen for the analysis are renewable energy costs, renewable energy subsidies, the carbon price and non-renewable energy costs. The first two factors are determined for each time step by using a learning curve. The last two factors are assumed to follow a geometric Brownian motion and are simulated accordingly. Finally, the model is calibrated with historical data and applied to a case study in China. The results suggest that with current subsidies, investors will benefit from investing into renewable energy generation technologies in all future scenarios. As a downside, the government suffers losses through the subsidies in most of those scenarios. Thus, a decrease of subsidies is recommended as this action will increase the benefits for the government while still maintaining sufficient incentives for the investors. (Zhang et al. 2014) A major lesson from this study is that multiple sources of uncertainty can be incorporated in a real options analysis. Furthermore, a joint usage of certain and uncertain factors is possible. The application of ROA on the evaluation of subsidies also emphasizes the variety of possible applications for this method in the energy domain.

Last but not least, Muñoz et al. (2011) research the investment in a wind park using a real options-based decision tool. Uncertainties stem from the volatile hourly wind input and the volatile electricity price. A Weibull distribution is assumed to be characterizing the wind speed, such that the hourly wind speed can be used to calculate the hourly production of wind energy. For the electricity price, a mean-reverting process is assumed. In the base case, the calculation is performed for 5 wind turbines with 2 MW capacity each. In this paper, an American option is chosen. The real options considered are the option to invest, the option to defer investment and the option to not invest at all. Thus, the decision tree for this problem is trimodal. Finally, six case studies with different parameter variations are analyzed with the decision tool. (Muñoz et al. 2011) The authors show that the uncertain parameters underlying the ROA can also be calculated using statistical distributions, in this case using the Weibull distribution. Furthermore, this study demonstrates the successful implementation of a mean-reverting process to model electricity prices.

As a result of the review of ROA theory and literature, the following methods are adopted. A ROA in discrete time in combination with an American option will be used because those methods best mirror the investment decision in a plant in reality. The option value will be calculated in accordance with the formulas in Guthrie (2009) and the underlying asset is assumed to follow an arithmetic Brownian motion. For the analysis conducted, the real options considered are the option to invest in a 5 MW P2G plant and the option to extend the plant by a 5 MW unit. As inputs, a deterministic gas price and a probabilistic electricity price are used. The latter is assumed to follow a normal distribution. All details concerning these methods will be explained in Section 4.1.

3 Technical and economic parameters of a P2G plant

In this section, the elements, inputs, and outputs of a P2G plant are explained, and the costs imposed by each element are determined. Finally, the regulatory framework for P2G plants in Germany is presented. An overview of the P2G plant analyzed is given in Figure 1.

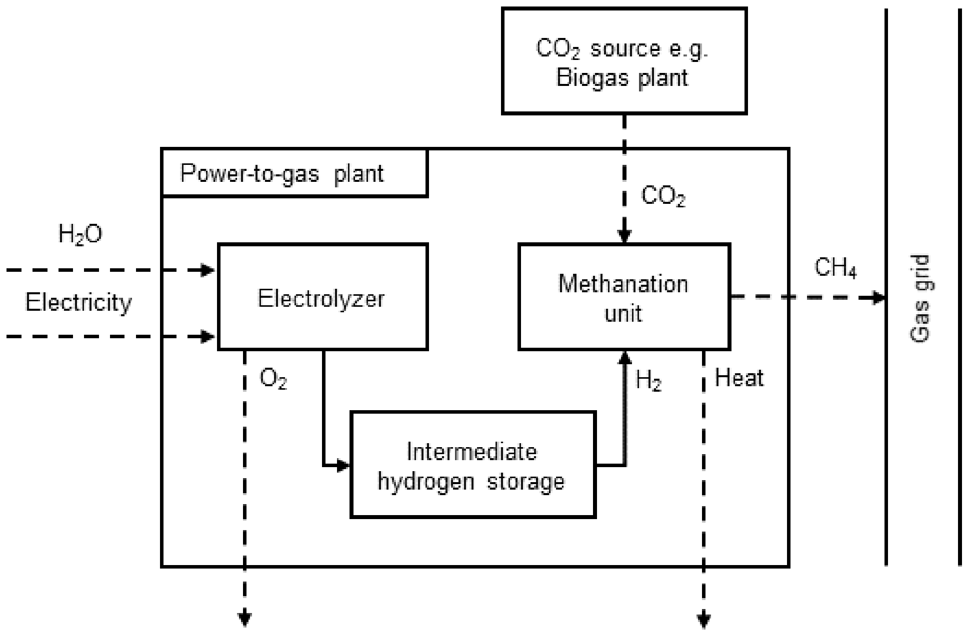


Figure 1: Overview of the P2G plant including all inputs and outputs

Source: Own illustration, based on Götz et al. (2016)

3.1 Elements of a P2G plant

In Götz et al. (2016) the different components of a P2G plant are detailed. The authors identify three key components: the electrolyzer, the intermediate hydrogen storage and the methanation unit. For the electrolyzer, two commercially available alternatives exist: alkaline electrolysis (AEL) and polymer electrolyte membrane electrolysis (PEM). AEL can be operated between 20% to 150% of its design capacity, which is especially advantageous for a fluctuating electricity input (Götz et al. 2016). Another advantage is the long lifetime of 20-30 years (FfE Forschungsstelle für Energiewirtschaft 2016: p. 284). Disadvantages are the long restart time of 10 minutes after a shutdown (FfE Forschungsstelle für Energiewirtschaft 2016: p. 283) and the necessity of a partial overhaul of the AEL system after 10-15 years (FfE Forschungsstelle für Energiewirtschaft 2016: p. 284).

PEM has the advantages of a faster cold start time and higher operation flexibility (Götz et al. 2016). Furthermore, the system can be operated between 0% to 200% of its design capacity (FfE Forschungsstelle für Energiewirtschaft 2016: p. 283). The main disadvantage is a lower expected lifetime of 10 to 20 years (FfE Forschungsstelle für Energiewirtschaft 2016: p. 284). A choice between those two technologies will be made in Section 3.2 with the additional consideration of the costs involved. Regardless the technology, it is assumed that water can always be supplied to the electrolyzer in sufficient quality and quantity.

The electricity input to the electrolyzer fluctuates. For that reason, only a fluctuating amount of hydrogen might be available for the methanation unit. As the methanation unit, requires a constant hydrogen inflow (Götz et al. 2016) an intermediate hydrogen storage has to be built to smooth out those fluctuations. The authors Götz et al. (2016) identify high pressure gas cylinders as the technology of choice for hydrogen storage in P2G plants.

Concerning the methanation unit, a reactor concept has to be chosen. Catalytic methanation with a fixed bed reactor is recommended by Götz et al. (2016), because it is the best researched and most commonly used concept. Consequently, it is also used in our study. The expected lifetime of a P2G plant is 23 years according to FfE Forschungsstelle für Energiewirtschaft (2016: p. 319).

Besides hydrogen, the methanation unit requires CO_2 gas of high purity as an input. CO_2 gas from the iron and steel industry must be improved in purity to be suitable for a P2G plant which would impose additional costs (Götz et al. 2016). Another issue is that CO_2 emitting industries might have to drastically reduce their CO_2 output in the future due to emission restricting policies. Therefore, the same problem might arise when a methan production plant uses CO_2 from a coal-fired power plant. In contrast, biogas plants are less likely to be shut down, because they do not burn fossil fuels. Furthermore, they provide high quality gas with a sufficient CO_2 content with only minor cleaning requirements (Götz et al. 2016). Thus, for our strudy it is assumed that the methanation plant is built close to a suitable biogas plant.

The by-products from the synthesis of methane, heat and oxygen, can be used in other chemical processes or sold on the market (Götz et al. 2016). We assume further that the excess process heat cannot be used, because it is unlikely to find a suitable customer due to the technical difficulties concerning transportation. In contrast, oxygen can be liquified and sold on the market or used in the adjacent biogas plant. Therefore, it is assumed that part of the oxygen produced can be sold at a fixed price. This will be detailed in Section 4.1.3.

Finally, to be able to feed the produced methane into the gas grid, a grid connection has to be installed. The costs for the grid connection as well as the costs for the other elements of the P2G plant will be detailed in next section.

3.2 Cost factors of the P2G plant

The largest investment costs for the plant are incurred by the electrolyzer. In Götz et al. (2016) and Ball and Wietschel (2009: p. 292), investment costs of 1000 €/kW are given for AEL. The costs for PEM are approximately 1250 €/kW according to Götz et al. (2016). FfE Forschungsstelle für Energiewirtschaft (2016: p. 313) report values between 800 €/kW and 1500 €/kW for AEL and values between 1500 €/kW and 6000 €/kW for PEM. Overall, the investment costs for AEL are lower than the investment costs for PEM. Consequently, because of the smaller investment costs and the longer lifespan (cf. Section 3.1), AEL is chosen as a technology for the electrolyzer.

Cost for a hydrogen storage unit are stated to be around 6 US$/kWh by Ball and Wietschel (2009: p. 310). In Götz (2014) costs of €8.7 million for a hydrogen storage container with a capacity of 1.5 million kWh are referenced. This results in 5.8 €/kWh which is similar to the value stated beforehand. For that reason, 6 €/kWh are used to calculate the investment costs for hydrogen storage.

For a methanation unit, the investment costs are in a range of 130 €/kW and 1500 €/kW (Götz et al. 2016). The authors recommend 400 €/kW as a best estimate**.** This number stems from a 5 MW synthetic natural gas plant. The results are in line with the investment costs of 1400 €/kW for a P2G plant including electrolyzer, grid injection and methanation unit which are stated by Deutscher Verein des Gas- und Wasserfaches e.V. (2014: p. 208).

The CO_2 that is needed for the methanation process can increase costs for the plant. These costs can include costs for the connection of the plant to the biogas plant, costs for cleaning the gas and costs for delivering CO_2 in time periods when the biogas plant is out of order. As an upside, the biogas plant omits the costs of emitting CO_2 and the costs for CO_2 reduction measures, because it can deliver CO_2 directly to the methanation plant. As those costs strongly depend on the individual situation of the P2G plant, we assume that the costs and benefits for the use of CO_2 are zero.

Besides the investment costs for the P2G plant, an investment has to be undertaken to connect the plant to the gas grid. An analysis of the cost was performed by FfE Forschungsstelle für Energiewirtschaft (2016: p. 324). The authors report that the plant operator has to pay 25% of the specific costs of 108 €/kW electric capacity of the plant. Nevertheless, the maximum payment for the gas grid connection is restricted to €250,000 (FfE Forschungsstelle für Energiewirtschaft 2016: p. 324).

According to Franzen and Madlener (2017) the minimum bid size to offer minute reserve at the capacity market is 5 MW. Thus, the plant should have a minimum size of 5 MW to be able to generate revenues from the capacity market. On the other hand, the plant cannot be too large so that sufficient CO_2 can be supplied by the biogas plant. According to Götz et al. (2016) an amount of 11 MW of methane can be produced with the CO_2 output from a typical biogas plant. Consequently, a possible extension of the P2G plant by 5 MW is considered.

To guarantee a smooth operation of the methanation unit, the hydrogen storage has to be sufficiently large to smooth out fluctuations in the hydrogen supply. As each unit has a capacity of 5 MW, a storage of 25 MWh size is sufficient for each unit as it can supply hydrogen for roughly six hours. In addition to the smoothing of fluctuations, this guarantees the operation of the plant during downtimes of the electrolyzer, for example, due to maintenance. The investment costs for the initial plant and the extension unit are detailed in Table 1.

Table 1: Overview over the investment costs for the components of the P2G plant

Component	Cost [€ per kW(h)]	Plant investment costs [million €]	Source
Electrolyzer (initial/extension)	1000	5	Ball and Wietschel (2009: p. 292)
Hydrogen storage (initial/extension)	6	0.15	Götz (2014)
Methanation unit (initial/extension)	400	2	Ball and Wietschel (2009: p. 310) Götz et al. (2016)
Grid connection (initial)	25% of 108 or 250,000	0.135	FfE Forschungsstelle für Energiewirtschaft (2016: p. 324)
Grid connection (initial plus extension)	25% of 108 or 250,000	0.25	FfE Forschungsstelle für Energiewirtschaft (2016: p. 324)

The overall investment costs for the initial plant amount to $Inv_{initial} = €(5 + 0.15 + 2 + 0.135)$ million $= €7.285$ million and the overall investment costs for the extension amount to $Inv_{initial} = €(5 + 0.15 + 2 + (0.25 - 0.135))$ million $= €7.265$ million.

3.3 Policy and regulatory framework for P2G plants in Germany

The regulatory framework can have a decisive influence on the profitability of a P2G plant. On the one hand, a subsidy for the gas produced by the plant could increase the revenue flow. On the other hand, subsidies for the electricity consumed or the investment cost could decrease costs and thereby increase profitability.

According to Krzikalla et al. (2013: p. 77) energy taxes, network charges and general fees can be avoided in Germany when electricity is used for electrolysis. Furthermore, gas produced from biogenic CO_2 generates additional renumeration when it is used to produce electricity again (Krzikalla et al. 2013: p. 77). This makes it superior to regular natural gas for electricity producers. In BVES (2016) these rules are detailed. The authors state that electrolyzers are excluded from paying electricity grid fees for 20 years and are also excluded from paying gas grid fees. In addition, the German EEG-fee does not have to be paid for electricity that is used to produce gas that is converted into electricity again.

In conclusion, no direct subsidy for P2G plants in Germany exists. Nevertheless, producing gas from electricity is exempted from most of the fees concerning the electricity and gas grid. Therefore, we assume that no fees have to be paid to operate the P2G plant.

4 Real options analysis

The following chapter details how the theoretical results from Sections 2 and 3 are used to conduct the ROA for the P2G plant. Section 4.1 details the steps of the analysis. In Section 4.2, the results of the analysis are presented. Section 4.3 illustrates scenarios with alternated parameters and their consequences.

4.1 Algorithm for the ROA

In the following, the procedure followed to conduct the ROA is described (see also the flowchart depicted in Figure 2). First of all, historical data for the electricity price and gas price are used to calculate future revenue flows of the P2G plant. This process is repeated in a Monte Carlo simulation in order to obtain a probability distribution of revenue flows. The statistical parameters of the distribution are used to create binomial trees for the revenue flow and the present value of revenue flows while also including operational expenditures. By adding the investment costs to the calculation, the binomial trees for the project value and the option value are calculated which leads to the final results. All steps are explained in greater detail in the following sections.

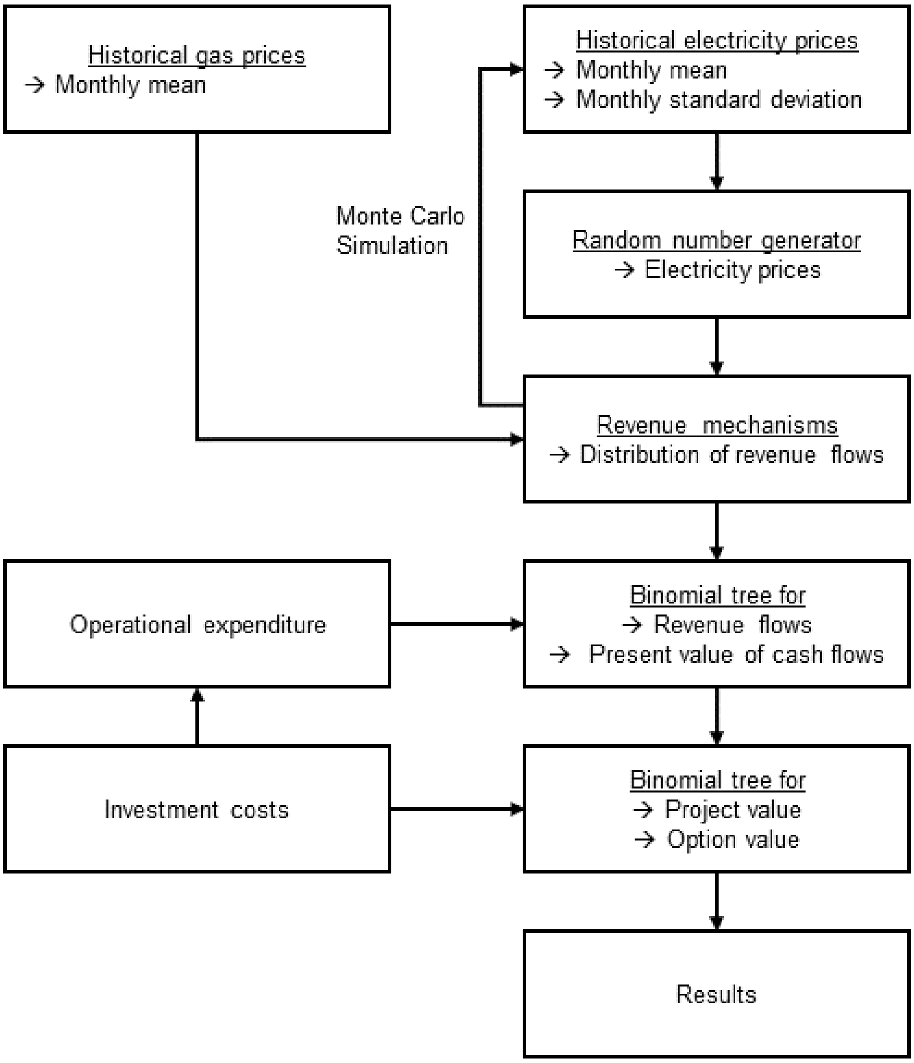
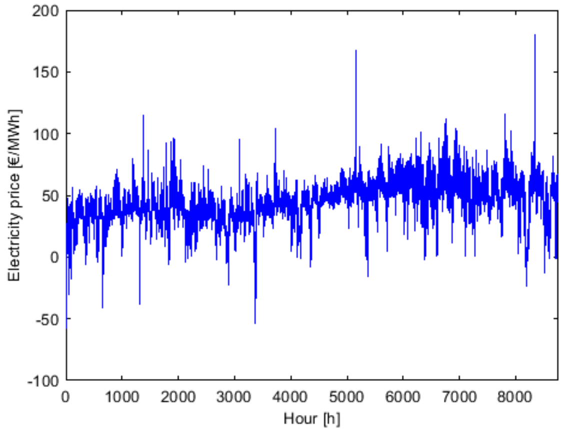


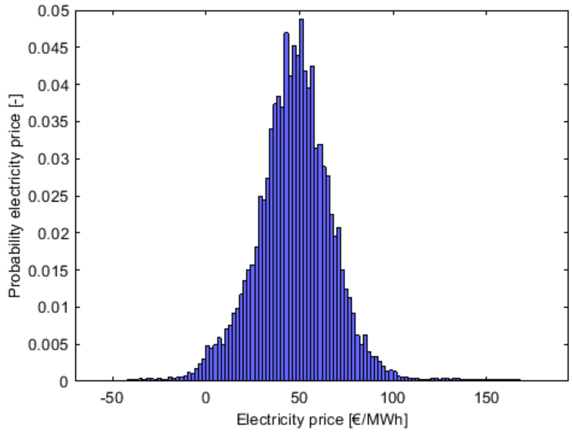
Figure 2: Flowchart for the real options analysis

4.1.1 Determination of electricity price

As an uncertain input for the simulation the electricity price is chosen because it largely influences the possible revenue streams of the P2G plant. When the electricity price is below a certain threshold, profits can be made by buying electricity and converting it to methane. When the electricity price is above this threshold, no profits from conversion can be made. Therefore, a realistic simulation of future electricity prices is crucial to conduct the ROA. To analyze the behavior of the electricity price, historical data from the European Energy Exchange (EEX) were acquired. These data contain the hourly intraday electricity market prices for Germany for the years 2010 to 2018. In Figure 3 plot (a), the prices for the year 2018 are displayed as an example.



(a) Time series plot



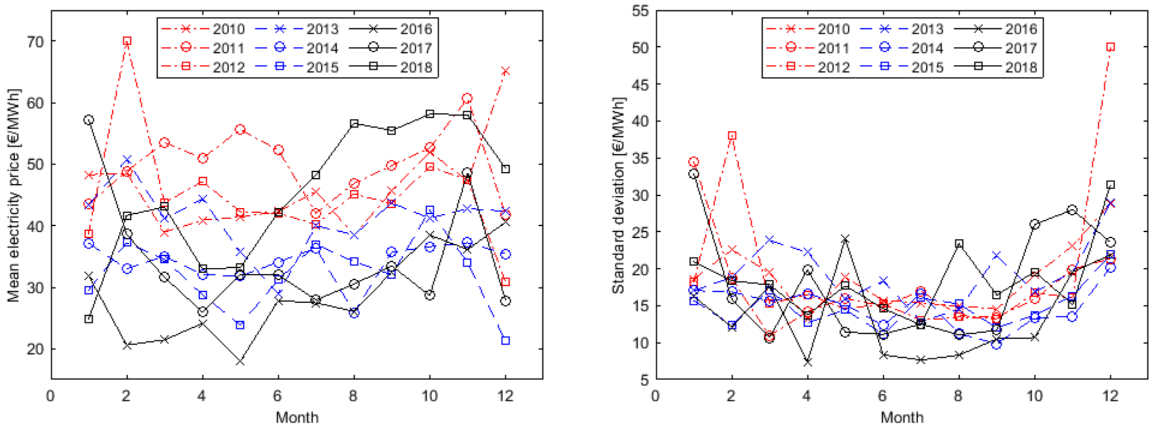
(b) Probability distribution

Figure 3: Historical hourly intraday electricity market prices for Germany, 2018

Source: Own illustration, based on Fraunhofer-Institut für Solare Energiesysteme ISE (2010-2018)

The electricity prices fluctuate over the year with a maximum value around 180 €/MWh and a minimum value around -60 €/MWh. The degree of fluctuation varies between the months, but overall, the electricity price appears to be normally distributed. To verify this hypothesis, Figure 3 plot (b) displays the probability distribution of the hourly electricity market prices for the year 2018. Indeed, the electricity price for the year 2018 is normally distributed with a mean of 47.64 €/MWh and a standard deviation of 21.66 €/MWh. This statistical nature of the electricity price is used to estimate future electricity prices, because the available historical database is insufficient to be used for the time horizon intended for the ROA. To be able to estimate future electricity prices more accurately, the mean and standard deviation are analyzed for each month of the year individually. The analysis might also reveal trends in the development of the electricity price over the years. In Figure 4 plot (a) the monthly mean of the electricity market price for the years 2010 to 2018 is plotted.

The monthly mean ranges from 17 €/MWh to 70 €/MWh, with most values lying between 30 €/MWh and 50 €/MWh. Viewed for each year, the monthly mean does not show a trend. Furthermore, no trend is visible over the years 2010 to 2018. Therefore, for each month the electricity price is averaged for all years put together. The result is one value for the mean electricity price for each month, which will be used for the estimation of future electricity prices. The monthly standard deviation of the electricity price for the years 2010 to 2018 is visualized in Figure 4 plot (b). The standard deviation lies in an interval between 7 €/MWh and 50 €/MWh. On average, the standard deviation is higher within the winter months, i.e. October to March, than in the summer months, i.e. April to September. Despite that trend, the standard deviation in a single month can peak due to extreme events. Nevertheless, no clear trend for the standard deviation over the years 2010 to 2018 is recognizable. Therefore, for each month, the standard deviation is averaged over all years. The result is one value for the standard deviation for each month which will be used in the simulation later on.



(a) Monthly means (a) Monthly standard deviations

Figure 4: Hourly intraday electricity market price for Germany, 2010–2018

Source: Own illustration, based on Fraunhofer-Institut für Solare Energiesysteme ISE (2010-2018)

To estimate future hourly electricity prices for each month of a year, random values are drawn from a normal distribution with the historical mean and standard deviation corresponding to the particular month. This procedure is repeated for every year in the time horizon of 20 years. To account for leap years, it is assumed that in each year's February has 28.25 days, which equals 678 h. The estimated hourly electricity prices are then used to calculate the monthly revenue flows of the P2G plant, but in order to do so, the gas price needs to be known.

4.1.2 Determination of gas price

In the European gas market, trading takes place via a central trading platform called PEGAS. Trading in Germany is divided up into two delivery zones which are operated by the two providers: GASPOOL and NetConnect Germany (NCG). Hourly gas prices are not available and daily prices diverge significantly between the two providers. Therefore, the average monthly gas trading price of both delivery zones is obtained from GASPOOL Balancing Services GmbH (2010-2018). To guarantee comparability with the electricity prices, the gas prices are obtained for the years 2010 to 2018 as well. Figure 5 displays the average monthly gas prices for those years. The average monthly gas price fluctuates between 12 €/MWh and 33 €/MWh. There is no continuous upward or downward trend of the gas price over the years. Therefore, in our investigation the monthly gas price is averaged over all years. For the calculation, the average monthly gas price is considered for every hour of the corresponding month.

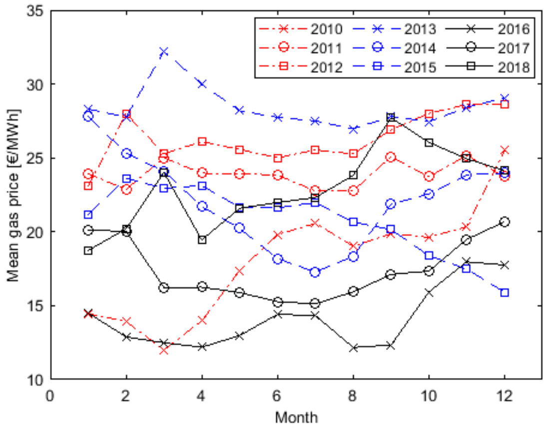


Figure 5: Monthly average gas price for Germany, 2010–2018

Source: Own illustration, based on GASPOOL Balancing Services GmbH (2010-2018)

4.1.3 Determination of revenue mechanisms

To calculate revenue streams with the given gas and electricity prices, the conditions under which the P2G plant can be operated profitably, have to be determined. We consider the following revenue flows: operation with negative electricity prices (R_1), operation with positive but sufficiently low electricity prices (R_2), sales of oxygen produced during electrolysis (R_3) and provision of minute reserve (R_4).

In the first two operational cases, methane is produced by the P2G plant and fed into the gas grid. According to Krzikalla et al. (2013: p. 72), the German gas grid has a capacity of 230 TWh**.** As the P2G plant has a maximum electric capacity of 10 MW, the amount of gas produced per hour is neglectable compared to the capacity of the gas grid. Therefore, it is assumed that the gas produced by the P2G plant can always be fed into the grid. The hourly revenue flow for each period in the case of negative electricity prices is calculated according to the following formula:

$$R_{1,t} = -p_{el,t} \cdot E_{el} + p_{gas,t} \cdot E_{gas} \tag{1}$$

with t being the current hour, $p_{el,t}$ being the negative electricity price, $p_{gas,t}$ being the gas price, E_{el} being the amount of electric energy consumed from the grid and E_{gas} being the amount of energy of gas fed into the grid. Thus, the revenue stream is composed of the revenue from consuming electric energy and the revenue from selling the gas from the P2G plant.

During the conversion from electricity to gas losses occur, which is included in the overall efficiency of the plant. The overall efficiency has two components: the efficiency of the electrolyzer and the efficiency of the methanation unit. For the efficiency of the electrolyzer, 0.70 is assumed (Götz et al. 2016, FfE Forschungsstelle für Energiewirtschaft 2016: p. 280) and for the efficiency of the methanation unit 0.78 is assumed (Götz et al. 2016, FfE Forschungsstelle für Energiewirtschaft 2016: p. 290). Consequently, the overall conversion efficiency from electric energy to chemical energy, i.e. methane, is

$$\eta_{total} = \eta_{el,H_2} \cdot \eta_{H_2,CH_4} = 0.7 \cdot 0.78 = 0.546 \tag{2}$$

such that $E_{gas} = E_{el} \cdot \eta_{total}$. This efficiency also plays an important role for the revenue stream if the electricity price is nonnegative. In this case, there is a certain threshold for the electricity price below which the P2G plant can be operated profitably. For this threshold, the following equation has to be fulfilled

$$E_{gas} \cdot p_{gas,t} \geq p_{el,t} \cdot E_{el} = p_{el,t} \cdot \frac{E_{gas}}{\eta_{total}} \Leftrightarrow p_{gas,t} \cdot \eta_{total} \geq p_{el}. \tag{3}$$

When the electricity price is inside the threshold, the corresponding revenue stream is

$$R_{2,t} = p_{gas,t} \cdot E_{gas} - p_{el,t} \cdot E_{el}, \tag{4}$$

which is the difference between the revenues from selling the produced gas and the costs from buying the electric energy to produce the gas. As a third source of revenue for the P2G plant, the sales of oxygen is considered (eq. (5)).

$$R_{3,t} = p_{O_2} \cdot x_{O_2} \cdot \frac{E_{el} \cdot 0.5 \cdot \rho_{O_2}}{E_{H_2,specific}}. \tag{5}$$

For the price of oxygen $p_{O_2} = 50 \frac{€}{t_{O_2}}$ is assumed (Deutscher Verein des Gas- und Wasserfaches e.V. 2014: p. 207) and x_{O_2} is the fraction of the oxygen that can be sold. To account for cost from oxygen liquification and a possible reduced number of oxygen consumers, it is assumed that only half of the oxygen produced can be sold which implies that $x_{O_2} = 0.5$. The last part of eq. (5) determines the amount of oxygen that is produced per MWh of electric energy (E_{el}) consumed by the P2G plant. The specific energy required to produce one cubic meter of hydrogen is on average $E_{H_2,specific} = 5 \frac{kWh}{m^3}$ (Götz et al. 2016). As during electrolysis there are two molecules of hydrogen produced per molecule of oxygen, the volume of hydrogen has to be multiplied by 0.5 to obtain the volume of oxygen. Lastly, the density of oxygen $\rho_{O_2} = 1.439 \frac{kg}{m^3}$ (Mills 2014: p. 923) and the volume of oxygen are used to calculate the mass of oxygen. A revenue stream from selling oxygen always exists when the P2G plant is in operation. That is the case when the requirements of the electricity prices for R_1 or R_2 are met.

The revenue flow from minute reserve (R_4) depends on specifics of the German balancing power market. Minute reserve offers are traded in an auction where participants submit two-part bids. Theses bids consist of a capacity price bid and an energy price bid. Capacity bidders that offer the lowest price are selected and have to procure the capacity they offered. In exchange, they receive a remuneration at the level of their bidding price. If balancing energy is actually required, it is called from the bidders, again starting with the lowest price offered. The energy provided is remunerated at the level of the price bid. (Müsgens et al. 2014)

In summary, the revenue flows from the offer of minute reserve depend on the behavior of other market participants. This makes future revenue flows difficult to predict. Consequently, historical data are used, and it is assumed that the revenue flows from minute reserve will remain at the historical level in the future.

The Deutscher Verein des Gas- und Wasserfaches e.V. (2014: p. 232) analyzed the earnings through provision of negative minute reserve for an AEL system with 5 MW electric capacity. With data about the reserve energy demand in Germany from 2012 and 2013 the authors calculate earnings of around 514,000 €/a. In contrast, Franzen and Madlener (2017) use similar data from 2015 to analyze negative minute reserve services offered by a 5 MW hydrogen production plant, resulting in revenues of approximately 180,000 €/a. These authors account for the interaction with other revenue flows which might be an explanation for the much lower value. We consider monthly revenue flows from negative minute reserve of

$$R_4 = \frac{180{,}000 \frac{€}{year}}{12 \frac{month}{year}} = 15{,}000 \ \frac{€}{month}, \tag{6}$$

as this is the most realistic estimate available to us.

Additional possible revenue flows could be the use of process heat from the P2G plant or an optimized storage and feed-in strategy for the gas produced. As those mechanisms depend on detailed information about the behavior of the market in the future, their prediction can be highly inaccurate. Therefore, those revenue flows are not considered.

Revenue flows R_1, R_2 and R_3 are calculated for every hour of the year and summed up for every month of the year. Revenue flow R_4 is added to the monthly revenue flows. This calculation is repeated over the entire time horizon of the simulation. The procedure of simulating prices and calculating the revenue flows is repeated 10,000 times in a Monte Carlo simulation. The result is a probability distribution of revenue flows which will be important for the ROA.

4.1.4 Binomial tree for revenue flow

In general, a binomial tree displays the possible developments of a variable over discrete points in time. In a ROA, such trees are used to calculate the development of the state variable, which is the underlying of the option value. For the problem at hand, the quarterly revenue flow is considered as a state variable. An example of a binomial tree for the revenue flow is illustrated in Figure 6, where n denotes the time period and i denotes the number of down-moves. When the number of periods is increased and the number of down-moves stays constant, an up-move occurred.

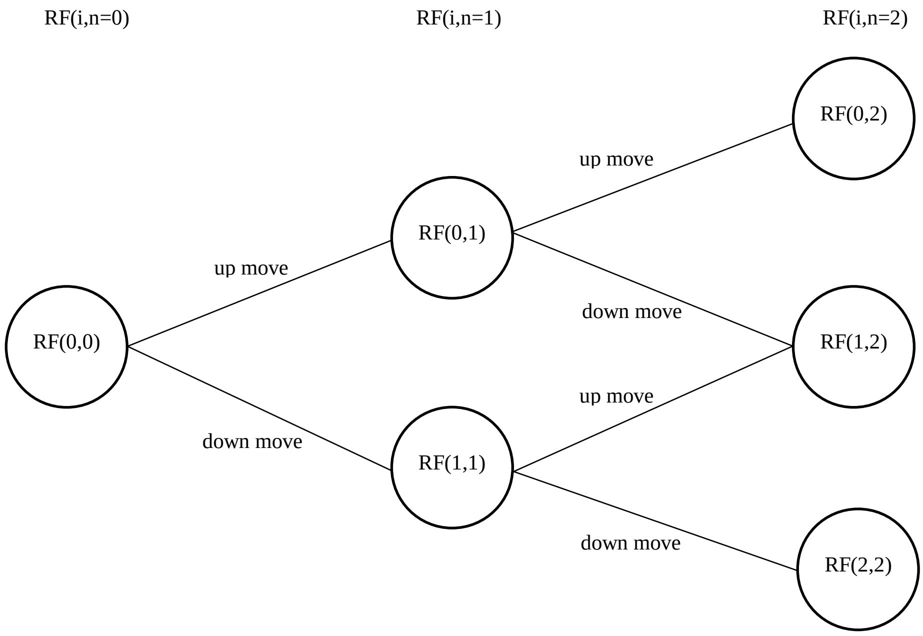


Figure 6: Example of a binomial tree for the revenue flow for three time periods where n indicates the time period and i indicates the number of down-moves

The binomial tree for the revenue flow starts at time zero with a starting value. Subsequently, the value of the cash flow is calculated for the case that an up-move occurs and for the case that a down-move occurs in the next time period. The size of the up-move or down-move depends on the process that the revenue flow is assumed to be characterized by as well as the statistical parameters of the probability distribution of revenue flows. The revenue flows are assumed to follow an arithmetic Brownian motion process which implies that the value of the revenue flow in period n can be calculated according to Guthrie (2009: p. 327)

$$RF(i,n) = RF(0,0) + (n-i) \cdot \sigma\sqrt{\Delta t} - i \cdot \sigma\sqrt{\Delta t} = RF(0,0) + (n-2i) \cdot \sigma\sqrt{\Delta t} \quad (7)$$

where $\sigma\sqrt{\Delta t}$ is the size of an up-move, $-\sigma\sqrt{\Delta t}$ is the size of a down-move and i is the number of down-moves. Furthermore, σ is the standard deviation of the difference of revenue flows and Δt is the time interval between the time steps n and $(n+1)$. Because the standard deviation is computed from monthly values, it has to be adjusted to the quarterly time interval. Therefore, the standard deviation is multiplied by $\sqrt{\Delta t} = \sqrt{3}$ to scale it up for three months. As a starting value for the binomial tree ($RF(0,0)$), the mean of the probability distribution of revenue flows is taken and multiplied by 3 to get the mean quarterly revenue flow. To determine the standard deviation for eq. (7), the differences of the simulated revenue flows $\Delta RF_t = RF_t - RF_{t-1}$ have to be analyzed. The results are plotted in Figure 7.

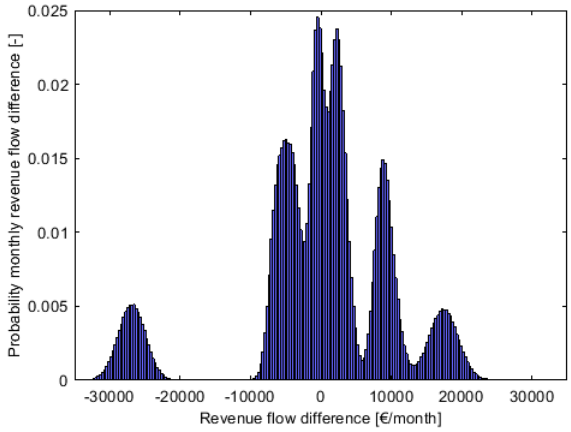


Figure 7: Probability distribution of the difference between monthly revenue flows for 10,000 Monte Carlo simulation runs

It is assumed that the difference of monthly revenue flows is normally distributed. For the difference of revenue flows, the standard deviation is $10{,}457$ €/month and the average is -0.0219 €/month. As a result, the size of an up-move is $\sigma \cdot \sqrt{\Delta t} = 10{,}457\ € \cdot \sqrt{3} = 18{,}112\ \frac{€}{q}$ and the quarterly drift is $\mu \cdot \Delta t = -0.0219\ € \cdot 3 = -0.0656 \frac{€}{q}$. With those data given, the values for the binominal tree of revenue flows can be calculated using eq. (7).

4.1.5 Binomial tree for present value of cash flows

As a last step, to make the transition between the calculation of revenue flows and the ROA, the present value of cash flows has to be determined. The quarterly cash flows consist of the quarterly revenue flows and the quarterly operation expenditures (OPEX). For the OPEX of a P2G plant, FfE Forschungsstelle für Energiewirtschaft (2016: p. 316) gives a value of 3% of the specific investment costs per year. For electrolysis alone, the author gives a value of 4% of the specific investment costs per year which is in accordance with a value of 3.7% used by Franzen and Madlener (2017). Consequently, $4 \frac{\%}{a} \cdot \frac{3}{12} \frac{a}{q} = 1 \frac{\%}{q}$ of the total specific investment costs are considered for the quarterly operation expenditures. Subsequently, the present value of cash flows can be calculated for each node of the binomial tree with the following formula from Guthrie (2009: p 77 - 93):

$$PV(i,n) = RF(i,n) - OPEX(n) + \frac{\pi_{up} PV(i,n+1) + \pi_{down} PV(i+1,n+1)}{1 + r_f}, \qquad (8)$$

where i is the number of down-moves, n is the number of quarters, $PV(i,n)$ is the present value of cash flows, $RF(\mathrm{i},\mathrm{n})$ is the revenue flow, $OPEX(n)$ is the operational expenditure, π_{up} is the probability for an up-move, π_{down} is the probability for a down-move and r_f is the quarterly risk-free rate of return.

For the yearly risk-free rate of return, $r_{f,yearly} = 0.5\%$ is assumed because it is the average return of German 10-year bonds over the last 5 years. The quarterly risk-free rate of return can be calculated from the yearly risk-free rate of return with the equation

$$r_f = \left(1 + r_{f,yearly}\right)^{\frac{3}{12}} - 1 = 1.005^{\frac{3}{12}} - 1 = 0.0012 = 0.12\%. \tag{9}$$

To calculate the present value of cash flows in each period, the present values of the next period have to be known. Therefore, backward induction has to be applied which starts in the final time period. In the final time period (N), the present value of cash flows equals the cash flow such that

$$PV(i, N) = RF(i, N) - OPEX(N). \tag{10}$$

Furthermore, to use eq. (8), the probabilities for an up-move or down-move have to be calculated. They can be calculated using the statistical parameters for the difference between quarterly revenue flows acquired with the Monte Carlo simulation. The formula for the probability of an up-move is according to Guthrie (2009: p. 269):

$$\pi_{up} = \frac{1}{2} + \frac{\mu}{2\sigma}. \tag{11}$$

The formula uses the quarterly standard deviation of the difference of revenue flows σ and the quarterly mean of the difference of revenue flows μ. The respective formula for the probability of a down-move is

$$\pi_{down} = 1 - \pi_{up} = \frac{1}{2} - \frac{\mu}{2\sigma}. \tag{12}$$

As σ and μ are assumed to be constant throughout the binomial tree, the same applies for the probabilities.

4.1.6 Binomial tree for project value

The project value is composed of two factors: the investment costs for the project and the present value of cash flows. Because construction is assumed to take six months, which equals two quarters, the difficulty of the calculation increases. During the time of construction, the P2G plant does not produce any output and therefore also no cash flows. Therefore, for the calculation of the project value, the present values of cash flows from two periods in the future have to be used. Those present values need to be discounted to the current period and adjusted with the probability of their occurrence such that

$$V_{project,inv}(i,n) = -Inv(n) + \frac{\pi_{up}^2 PV(i,n+2)}{\left(1+r_f\right)^2}$$
$$+\frac{\pi_{up}\pi_{down} PV(i+1,n+2)}{\left(1+r_f\right)^2} + \frac{\pi_{down}^2 PV(i+2,n+2)}{\left(1+r_f\right)^2} \qquad (13)$$

with the investment costs $Inv(n)$ in period n. If the investment is undertaken in one of the last two periods, no cash flows exist, because the construction would finish after the time horizon. For this reason, the project value in the last period is

$$V_{project,inv}(i,N-1) = -Inv(N-1) \; and \; V_{project,inv}(i,N) = -Inv(N). \qquad (14)$$

Finally, the project value is used to determine the option value of the investment.

4.1.7 Binomial tree for option value of investment

At each point in time, i.e. at the beginning of each quarter, the decision maker can decide if she wants to invest in the P2G plant or if she wants to wait another period. As a rational decision maker, she will choose the maximum of the project value and the value of the option to wait. Thus, the option value to invest ($V_{opt,inv}(i,n)$) in period n will be the maximum payoff of the two choices (Guthrie 2009: pp.119-122)

$$V_{opt,inv}(i,n) = \max\left\{\begin{matrix} V_{project,inv}(i,n) \\ \dfrac{\pi_{up}V_{opt,inv}(i,n+1) + \pi_{down}V_{opt,inv}(i+1,n+1)}{1+r_f} \end{matrix}\right\}. \qquad (15)$$

The equation illustrates that the option value in period n depends on the option values in period $(n+1)$. Therefore, the option value in the last period N has to be known. In the last period, waiting does not give a benefit as investing in the period after the last period is not possible anymore. Thus, the option value in the last period is zero.

$$V_{opt,inv}(i,N) = 0. \qquad (16)$$

With this boundary condition, the values in the binomial tree for the option value to invest can be calculated. The option to invest is realized at every point in the tree where the benefit from investing exceeds the benefit from waiting. Additionally, the extension of the P2G plant by another 5 MW is considered. This can be realized as an extension to the option valuation approach detailed above.

4.1.8 Binomial tree for option value of extension

With an option to extend the P2G plant in addition to the binomial tree for the option to invest, a second binomial tree for the option to extend has to be created. The revenue flows for the extended P2G plants are calculated using eqs. (1) to (5) with the new capacity $P_{el} = 10\ MW$. Then, the revenue flows from the initial P2G plant have to be subtracted to get the revenue flows that are attributable to the extension. The corresponding binomial trees are created analogously to beforehand, following the procedure from Sections 4.1.4 to 4.1.6.

For the calculation of the option value of the extension, it has to be considered that an extension of the P2G plant is not possible before the plant is actually built. Nevertheless, the option of the extension can already have a value in the time periods preceding the initial investment. In this case, the option value of the extension can be calculated with

$$V_{opt,ext}(i,n) = \frac{\pi_{up} V_{opt,ext}(i,n+1) + \pi_{down}(i,n) V_{opt,ext}(i+1,n+1)}{1+r_f}, \tag{17}$$

where π_{up} and π_{down} are based on the stochastic parameters which are determined with the probability distribution of the revenue flows of the extension. The value of the extension option is the discounted value of the future extension option values.

When the investment in the extension is possible due to a former investment in the P2G plant, eq. (17) is elongated by the project value of the extension $V_{project,ext}(i,n)$ which is calculated using eq. (13). Consequently, the option values can be calculated using

$$V_{opt,ext}(i,n) = \max \left\{ \begin{matrix} V_{project,ext}(i,n) \\ \dfrac{\pi_{up} V_{opt,ext}(i,n+1) + \pi_{down}(i,n) V_{opt,ext}(i+1,n+1)}{1+r_f} \end{matrix} \right\}. \tag{18}$$

All in all, the value of the extension option is the maximum of either the value of the investment in the extension or the discounted value of the future option values of the extension. The boundary condition is again

$$V_{opt,ext}(i,N) = 0. \tag{19}$$

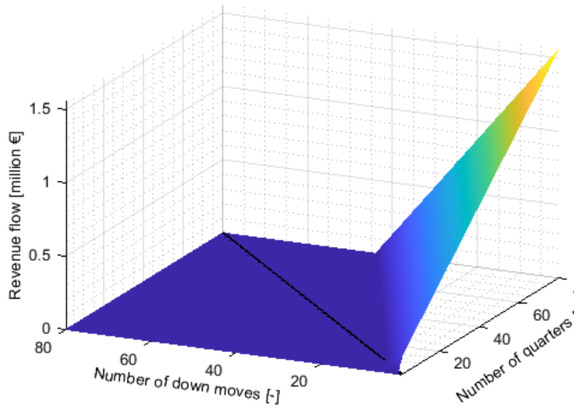
This concludes the calculation steps for the ROA. In the following section, the results obtained using this algorithm will be illustrated and discussed.

4.2 Results of the real options analysis

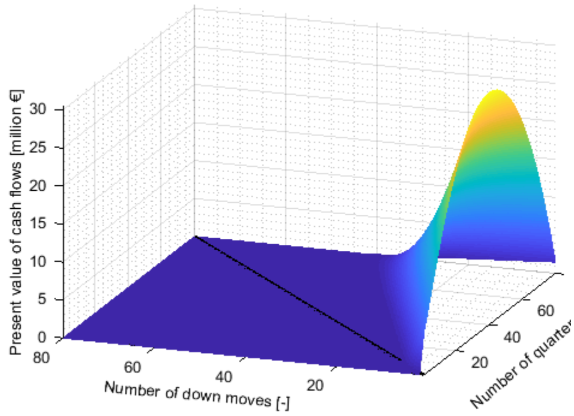
The following section discusses the results of the ROA. The different binomial trees are visualized for the investment case and for the extension case. All parameters used for the ROA are listed in Table 2 in the appendix.

4.2.1 Results for the option to invest

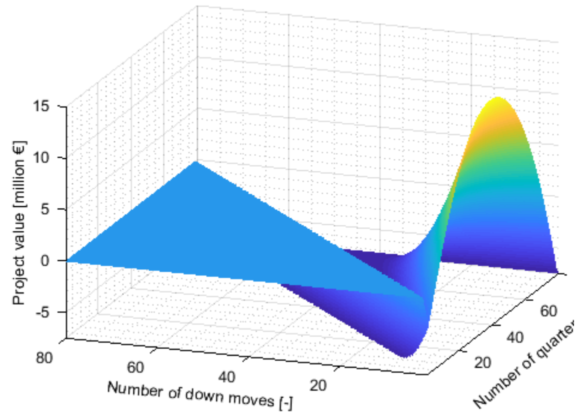
In Figure 8 plot (a), the development of the underlying quarterly revenue flows for the option to invest is illustrated. On the black line in the middle of the graph, the number of quarters equals the number of down-moves. Thus, left of this line the number of down-moves exceeds the number of quarters which is not possible in reality and therefore the values cannot be calculated. For the visualization, the values left of the line are set to zero by default in every binomial tree.



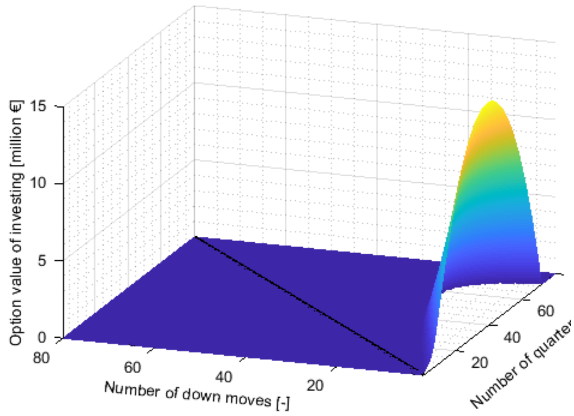
(a) Revenue flows



(b) Present value of cash flows



(c) Project value



(d) Option value

Figure 8: Binomial trees for the investment case

On the right side of the black line, the calculated values from the binomial tree for the revenue flows are displayed. The values increase linearly because they are assumed to follow an Arithmetic Brownian motion (cf. Section 4.1.4). However, the Arithmetic Brownian motion can also result in negative values if many down-moves occur. In reality, this is not possible because the P2G plant would not be in operation if no profit could be generated. For this reason, the revenue flow in the binominal tree is set to zero at every point where the calculated value is negative.

If no down-move occurs, the revenue flow after 80 quarters reaches a maximum value of €1.56 million. The lower end of the values of quarterly revenue flows is €0. To give a reference value, the average quarterly revenue obtained from the Monte Carlo simulation which is also the starting value of the binomial tree is €126,340. With the revenue flows given, the binomial tree for the present value of cash flows is calculated (see Figure 8 plot (b)).

As the present value of cash flows is determined via backward induction, it is equal to the cash flow in the last period. During the backward induction process, the present value of cash flows increases and reaches its maximum value of €30.51 million in quarter 39 when no down-moves occur. Until quarter 1, the present values of cash flows decrease again such that the present values of cash flows follow a parabolic shape. The areas where the present value of cash flows is close to zero are results of the underlying cash flows being close to zero as well.

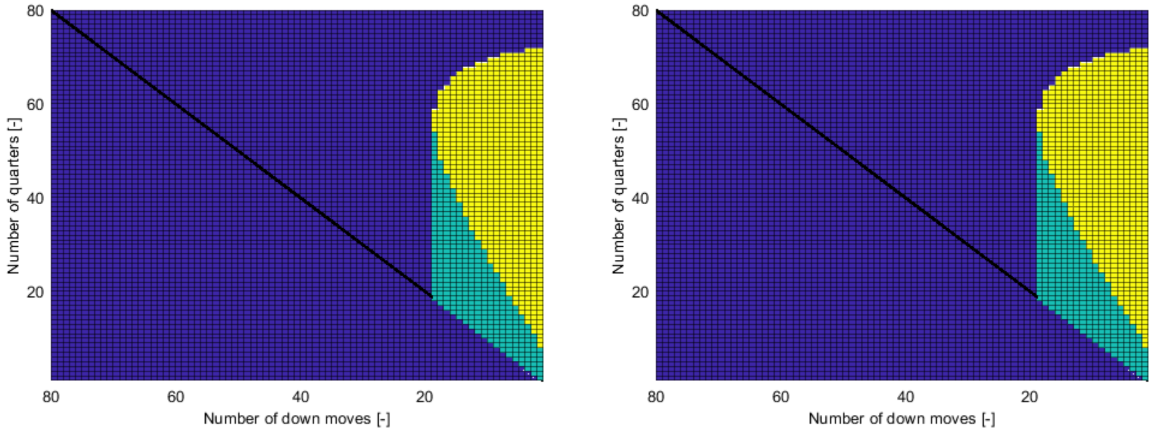
The project value is determined by adjusting the present value of the cash flows with the investment costs and the construction time of the P2G plant in each quarter. The resulting binomial tree for the project value for the investment case is presented in Figure 8 plot (c).

Again, the left-hand side of the plot where the number of down-moves exceeds the number of quarters is set to zero. In the final two quarters, the present value of investment simply equals the investment costs in those quarters because the building of the P2G plant takes two quarters. Therefore, building the P2G plant in the final two quarters would generate no cash flows during the time horizon. For all other quarters, the project value behaves similarly to the present value of cash flows, but the values are lower due to the investment costs. The maximum project value of €14.47 million is reached after 38 quarters.

Finally, the project value influences the option value. If the project value exceeds the option value, the decision maker will invest immediately. If the option value exceeds the project value, the decision maker will not invest but rather wait one quarter. The option value of investing is visualized in Figure 8 plot (d). The option value of investing is close to zero in most cases but if the value is above zero it increases rapidly with the number of quarters and up-moves. It reaches a maximum of €14.47 million in period 38 which is in line with the results for the project value. In general, the instances where the option value is above zero are similar but not identical to the instances where the project value is above zero.

To determine whether the option to invest is actually exercised, the cases where the option value equals the value of investing have to be determined. Those are visualized as the yellow area in Figure 9 plot (a). Additionally, the cases where the option value of investing is larger than zero are marked in light blue.

The results indicate that the option can only be exercised if 17 or less down-moves of the revenue flow occur. If more down-moves occur, the option is exercised under no circumstances. Furthermore, the option is never used if 72 or more quarters of the time horizon have passed. The option is earliest exercised in the 7^{th} quarter if the quarterly revenue flow never moves down. In this case, the quarterly revenue flow equals €253,130 which is roughly twice the starting value for the binomial tree of quarterly revenue flows.

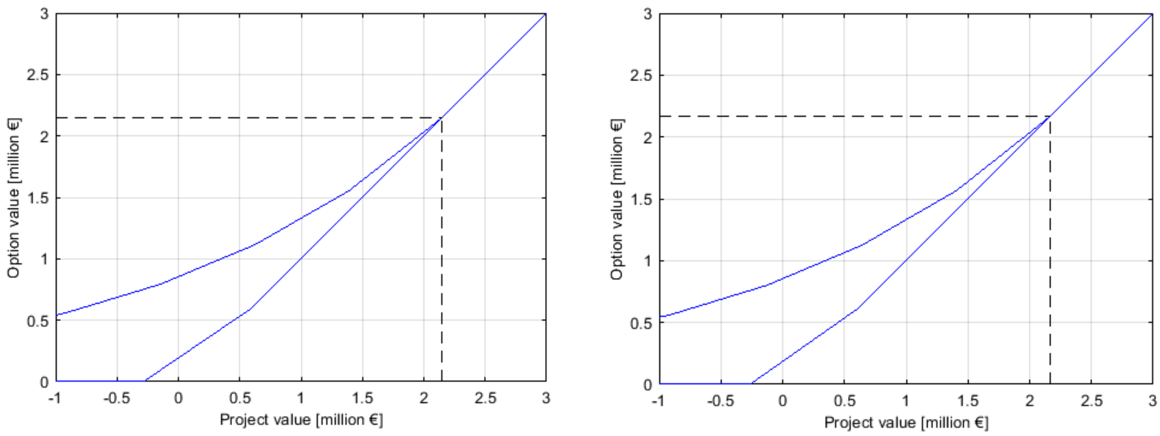


(a) Investment case (b) Extension case

Figure 9: Evaluation of the option value with the light blue area indicating an option value larger than zero and the yellow area indicating that the option should be exercised

If one down-move occurs, the option is earliest exercised in the 10th quarter with a corresponding revenue flow of €271,250 per quarter year. This means that for a later exercising time, a larger revenue flow is required. If 17 down-moves occur, the option can only be used in quarters 53 to 57 with corresponding revenue flows of €470,480 to €542,930 per quarter year.

Even though the option to invest is only exercised in the yellow area in Figure 9 plot (a), the option value of investing is above zero in the light blue area as well. Still, a comparison with Figure 8 plot (d) illustrates that the option value of investing is relatively low if the option is not exercised. Another possibility to determine the threshold where the option is exercised is to compare the project value and the option value. Such a comparison for the investment case when no down-move occurs is illustrated in Figure 10 plot (a).



(a) Investment case (b) Extension case

Figure 10: Option value and project value when no down-move occurs

The graph shows the option value for each corresponding project value. When the option is not exercised yet, the option value and the project value diverge from each other. The option value and the project value follow a parabolic shape with an increasing number of quarters (cf. Figure 8 plot (c), (d)). Therefore, two possible option values for each project value exist most of the time which is why Figure 10 plot (a) depicts two blue lines. The point where the two lines meet marks the time period when the option can first be exercised. Thus, the option value equals the project value. This threshold is highlighted with the dashed lines. For the investment option the threshold is €2.15 million.

To sum up, with the chosen parameter values, the option is realized inside the time period of 80 quarters. In the best scenario possible, the option is exercised as soon as the quarterly revenue flow reaches €253,130. Revenue flows of this magnitude and larger never occurred during the Monte Carlo simulation. Consequently, it is unlikely that they will occur in reality and thus it is unlikely that the option to invest will be exercised in reality. This negative outlook will change when different scenarios are calculated in the sensitivity analysis in Section 4.3.

4.2.2 Results for the option to extend

When the decision to invest in the P2G plant is made, the decision maker has the option to extend the plant by an additional unit of 5 MW capacity, in the current or a future quarter. The underlying variable used for calculating the value of the option to extend the P2G plant is the revenue flow that can be generated by the plant extension. The revenue flow increases linearly with the number of quarters and reaches a maximum value of €1.56 million if no down-move occurs. This is exactly the same as the maximum of the revenue flows for the investment case (cf. Figure 8 plot (a)). The results suggest that the revenue flows increase linearly with the size of the plant such that the extension generates the same revenue flows as the plant itself. Nonetheless, the investment costs for the plant extension are slightly lower than for the plant itself. This might have a positive effect on the project value and subsequently on the option value. To analyze this presumption, the option value and the project value are visualized in Figure 10 plot (b). The graph shows the case when no down-moves of the revenue flow occur.

The threshold is again the point where the two lines meet, and the option value equals the project value. For the extension case the threshold value is €2.17 million. As predicted, this value is slightly higher for the extension case compared to the investment case (cf. Figure 10 plot (a)). This means that the extension option is worth slightly more than the investment option.

In the following, the influence of the increased option value in the extension case is investigated. Figure 9 plot (b) displays the cases in which the option to extend is exercised in yellow and the cases in which the option value is larger than zero in light blue. Similar to the option to invest, the option to extend will only be used if 17 or less down-moves of the revenue flow arise. Additionally, the extension option is also never exercised after 72 or more quarters have passed. Furthermore, the extension is built earliest in quarter 7 when the revenue flow reaches €235,020. In summary, the option to extend is always used as soon as the option to invest is used. These results are not in line with reality. In reality, the extension is likely to generate less revenue flows than the basic P2G plant. Possible reasons are a less stable supply of CO_2 to the extension or less consumers for the oxygen produced by the extension. This and other possible scenarios are analyzed in the following section.

4.3 Sensitivity analysis

In this section, the parameters for the ROA will be alternated to validate the plausibility of the results and to simulate possible future scenarios. The parameters used in Section 4.2 will be referred to as the standard case.

The last section showed that the option to extend is always used when the option to invest is used. To illustrate that this fact changes under different conditions, the revenue flows from the extension are modified. It is assumed that the extension can generate only 75% of the revenue flows it could generate beforehand. The impact of this change on the option value is visualized in Figure 11.

When the light blue area is compared with the yellow area in Figure 9 plot (a), it becomes clear that the option to invest is exercised at the same points in time. In contrast, the points in time when the option to extend is exercised change significantly. Now, the option to extend can only be used if 12 or less down-moves arise. Furthermore, the option to extend is exercised at the earliest after 11 quarters.

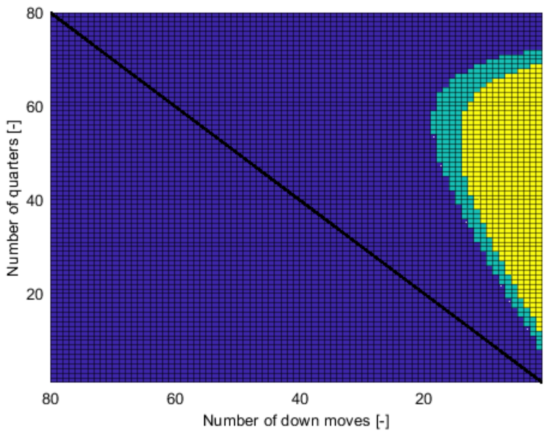


Figure 11: Evaluation of the option value for the investment case in light blue and the extension case in yellow when the revenue flows of the extension are reduced to 75% of the original value

Those results emphasize that a change in market conditions leads to different exercise times for the investment option and the extension option. In addition, it shows that the calculation yields plausible results.

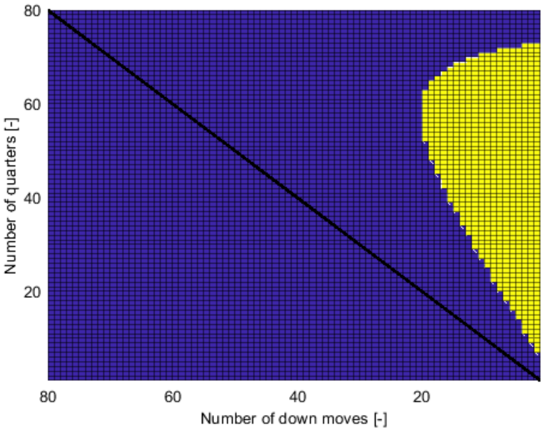
As a second alteration from the standard case, the standard deviation of the electricity price is assumed to increase by 1% per year. A similar development could take place in reality, because of the increasing share of electricity produced from fluctuating renewable energy sources. An increased standard deviation results in more hours with electricity prices below the profitability threshold and thus in an increase in revenue flows.

Through the increase in the standard deviation, the revenue flow reaches a new maximum of €1.90 million. This is an increase by €0.34 million compared to the standard case (cf. Figure 8 plot (a)). As a result, the present value of cash flows as well as the project value increase. Consequentially, this should also materialize in the number of quarters after which the option is exercised in the investment case (Figure 12 plot (a)). Indeed, the yellow area, i.e. the number of quarters in which the option is exercised, increases in comparison to Figure 9 plot (a). In this scenario, the option to invest can be used if 18 or less down-moves of the revenue flow occur. This is one more possible down-move compared to the standard case. A similar change is noticeable for the earliest exercise period of the option. For this scenario, the option to invest is exercised earliest in the 6th quarter which is one quarter earlier than in the standard case. The corresponding revenue flow is €264,140 which is almost twice the mean of the simulated quarterly revenue flows. This revenue flow is reached by only 0.17% of the values from the Monte Carlo simulation.

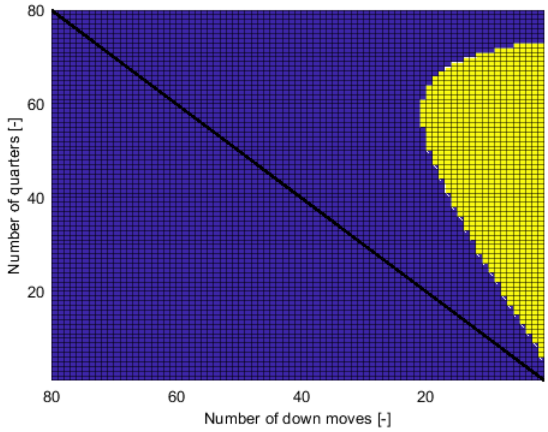
All in all, the revenue flows increase which results in an increased project value and thus an earlier exercise date of the option. Nevertheless, the revenue flows required to exercise the option still exceed most revenue flows that could potentially be generated.

Another possible future scenario is a governmental subsidy on gas produced by P2G technology. The subsidy would increase the revenue flows such that the threshold for investing in the P2G plant might be reached with a higher likelihood. For the analysis, a subsidy of 2.5 €- ct/kWh for gas produced from renewable energy is assumed.

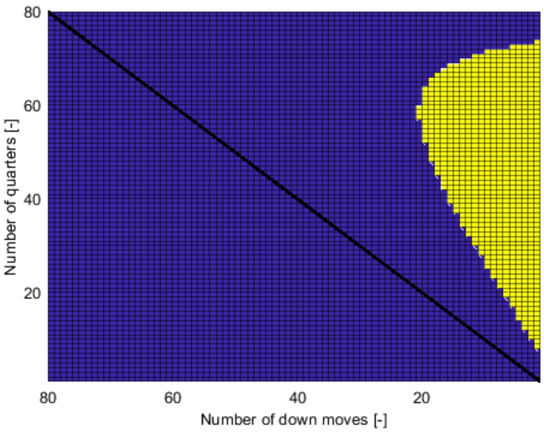
As a result, the maximum revenue flow reaches a value of €1.80 million which is €0.24 million larger than in the standard case but €0.1 million lower than in the scenario with an increased standard deviation of electricity prices. The subsequent influence on the time periods in which the option to invest is exercised is illustrated in Figure 12 plot (b). The option is exercised earliest after 5 quarters at a revenue flow of €257,000. This is the earliest time of exercising the option for all scenarios yet. Still, this revenue flow is only reached by 0.21% of the values in the Monte Carlo simulation. Nevertheless, the option to invest can still be used if 19 down-moves of the revenue flow arise. This is one more than in the scenario with an increased standard deviation of electricity prices.



(a) Increase of the standard deviations of the electricity prices by 1% p.a.



(b) Subsidy of 2.5€-ct/kWh of gas produced



(c) Annual decrease in investments costs of 1%

Figure 12: Evaluation of the option value for the investment case

As a final scenario, the future development of the investment costs is investigated in detail. The investment costs for the electrolyzer and the methanation unit are assumed to decrease by 1% per year. As the operation expenditures are coupled with the investment costs, they decrease in magnitude as well. The binomial tree of revenue flows for this scenario is similar to the standard case (Figure 8 plot (a)). Nevertheless, the decrease in the investment costs and the operation expenditures leads to an increased project value (Figure 13). For this scenario, the maximum project value reached is €15.38 million compared with €14.47 million for the standard case.

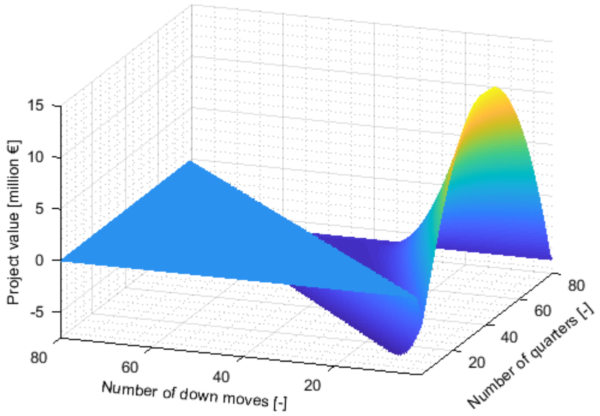


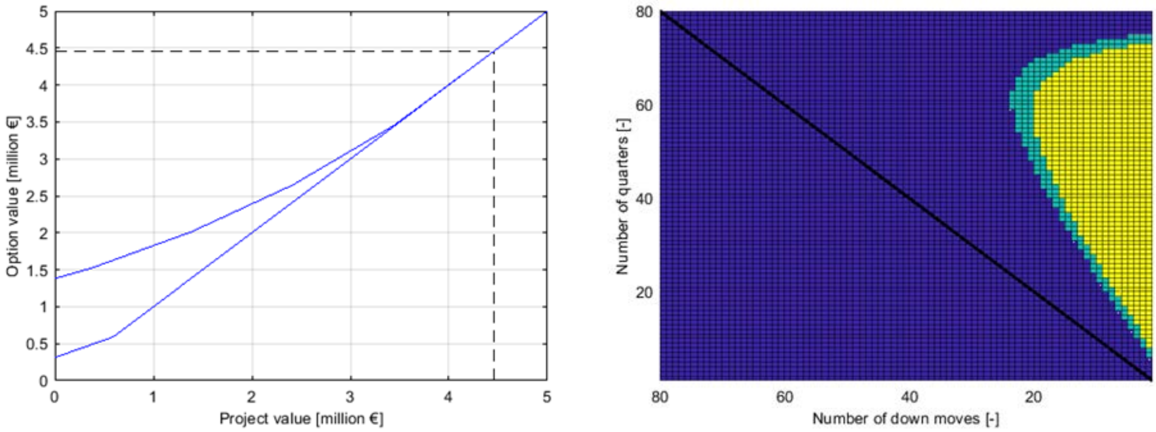
Figure 13: Binomial tree of the project value for the investment case with an annual decrease in investments costs of 1%

This increase in the project value also influences the time periods at which the option is exercised in Figure 12 plot (c). The option to invest is exercised earliest in the 7th quarter at a revenue flow of €253,130, which is no change compared to the standard case. The earliest quarter for the option to be used does not change because the 1% decrease in the investment costs per year does not have a significant effect in the first quarters. After a larger number of quarters, the decrease of the investment costs will be larger, and the effect on the exercise timing for the option to invest will be more significant.

This becomes apparent when analyzing the maximum number of tolerated down-moves of the revenue flow. In this scenario, the option can even be used if 19 down-moves of the revenue flow occur. This is an improvement by 2 tolerated down-moves compared to the standard case. Furthermore, the decrease of investment costs incentivizes the use of the option at a later point in time. For this scenario, the latest possible quarter to use the option in is the 72nd quarter, which is an improvement by 1 quarter compared to the standard scenario.

With the modifications from all scenarios applied, the revenue flow reaches a maximum value of €1.99 million which is €0.43 million more than in the standard case (cf. Figure 8 plot (a)). The effect of the changes on the value of the option and the project are illustrated in Figure 14 plot (a).

Compared to the standard case, the threshold to exercise the option is significantly larger with the assumptions from all scenarios applied. For the investment case the new threshold is €4.459 million which means that the option value increased. The reason for that increase are the improved investment conditions created by the assumptions made for the scenarios. Figure 14 plot (b) illustrates the effect of these assumptions on the time periods when the option is exercised. The diagram depicts the investment cased as well as the extension case.



(a) Option value and project value for the investment case when no down-move occurs with assumptions from all scenarios applied

(b) Option value for the investment case in light blue and the extension case in yellow with assumptions from all scenarios applied

Figure 14: Evaluation of the option value for the investment case

The option to invest is exercised earliest in the 5th quarter, at a corresponding revenue flow of €282,420. This value is reached for 2.09% of the values from the Monte Carlo simulation. The option to extend is exercised earliest in the 7th quarter, at a corresponding revenue flow of €246,470. This value is reached for 0% of the values from the Monte Carlo simulation. Furthermore, the option to invest can still be used after 23 down-moves and the option to extend can still be used after 19 down-moves.

All in all, the modifications from the scenarios increase the number of periods in which the options can be used. Still, the revenue flows required to execute the options are barely reached in the Monte Carlo simulation. This means that revenue flows of this magnitude are also unlikely to occur in reality even under the beneficiary conditions assumed in the scenarios.

5 Summary, conclusion and outlook

In this study, a ROA is used to investigate the profitability of a P2G plant in Germany. Firstly, the most suitable methods are extracted from the ROA theory and literature. An American-style real option with an evaluation interval of 3 months and a time to maturity of 20 years is selected. Secondly, the optimal size and components for the P2G plant are determined. The investment costs of the 5 MW P2G plant and 5 MW extension are calculated as €7.285 million and €7.265 million, respectively. Thirdly, historical electricity prices and gas prices for the years 2010 to 2018 are used to estimate the respective prices for the ROA. These estimated prices enable the calculation of the revenue flows for the P2G plant. There are four revenue mechanisms considered: operation at negative electricity prices, operation at low electricity prices, sales of oxygen and a provision of minute reserve. Finally, these revenue streams are combined with the operational expenditure and the investment costs to calculate the present value of cash flows, the project value and the option value.

The algorithm yields plausible results for the option to invest in the plant as well as for the option to extend the plant. For the standard case, a minimum revenue flow of €253,130 per quarter year would be required to exercise the option. This revenue flow is unrealistic as the simulation of revenue flows did not yield such a large value.

Consequently, the standard parameters are varied to calculate scenarios that could potentially increase the profitability of the P2G plant. This outcome would improve the possibility that the option to invest in the plant is actually exercized. The four scenarios investigated are: (1) reduction of the revenue flows from the extension to 75% of the actual level; (2) increase of the standard deviation of electricity prices by 1% per year; (3) introduction of a subsidy for the gas produced in the of 2.5 €-ct/kWh; and (4) decreased investment costs for electrolyzer and methanation unit of 1% per year.

The results of the scenarios show an increased number of points in time where the options can be used. Furthermore, both options can be used earlier in time. Unfortunately, even if the modification from all scenarios are applied, the smallest sufficient revenue flow to exercise the option is only reached by 2.09% of the values from the Monte Carlo simulation. The overall results obtained are used to answer the two research questions stated in the Introduction.

Research question 1 asked for the profitability of the P2G plant under the current economic conditions. Profitability of the P2G plant is reached if the option to invest is exercised under current economic conditions. For that to happen, the required quarterly revenue flow has to be above €250,000. In the simulation this revenue flow was never reached under current economic conditions. To conclude, a P2G plant cannot be built and operated profitably under the current economic conditions in Germany.

Research question 2 asked for incentives for the investment in a P2G plant in the future. Most of the mechanisms analyzed in Section 4.3 increased the attractiveness of the investment. Thus, it can be said that an increase in the volatility of the electricity prices, a subsidy for gas produced from P2G plants and a decrease of the investment costs can all incentivize the investment in P2G plants in the future. Unfortunately, none of the mechanisms could increase the profitability in a way that an investment in a P2G plant in the future is likely.

Therefore, future research should focus on investigating mechanisms to increase the profitability of P2G technology in Germany. First of all, the ROA could be performed for a larger plant, given a suitable source of CO_2. For a larger P2G plant, costs would come down significantly due to scale effects. Furthermore, the sales of excess heat as a possible source of revenue flow could be investigated in more detail. Of course, this approach can be applied in other countries which might offer better economic conditions to operate a P2G plant. Aside from the ROA, suitable geographic locations for P2G plants need to be identified. This might also reveal opportunities to reduce costs.

References

Ball, M. and Wietschel, M. (2009) *The hydrogen economy: Opportunities and challenges*, Cambridge UK, New York: Cambridge University Press.

BMU (2018) *Klimaschutz in Zahlen (2018) – Fakten, Trends und Impulse deutscher Klimapolitik*.

BVES (2016) *Faktenpapier Energiespeicher:* Bundesverband Energiespeicher e.V. Berlin.

Cox J., Ross S., Rubinstein M. (1979) ‘Option Pricing: A Simplified Approach’, *Journal of Financial Economics*,7(3): 229–263.

dena (2019): Component of an Integrated Energy Transition - Roadmap Power to Gas, Deutsche Energieagentur (dena) / German Energy Agency, Berlin.

Deutscher Verein des Gas- und Wasserfaches e.V. (2014) *Technoökonomische Studie von Power-to-Gas-Konzepten: Teilprojekte B-D:* Deutscher Verein des Gas- und Wasserfaches e.V.

Dixit, A. K. and Pindyck, R. S. (1994) *Investment under uncertainty*, Princeton, N.J., London: Princeton University Press.

FfE Forschungsstelle für Energiewirtschaft (2016) *Merit Order der Energiespeicherung 2030: Teil 2: Technoökonomische Analyse Funktionaler Energiespeicher:* FfE Forschungsstelle für Energiewirtschaft.

Fischer Black and Myron Scholes (1973) ‘The Pricing of Options and Corporate Liabilities’, *Journal of Political Economy*,81(3): 637–654.

Franzen, S. and Madlener, R. (2017) ‘Optimal expansion of a hydrogen storage system for wind power (H2-WESS): A real options analysis’, *Energy Procedia*,105: 3816–3823.

Fraunhofer-Institut für Solare Energiesysteme ISE (2010-2018) *Stromproduktion und Börsenstrompreise in Deutschland*. Available at: https://www.energy-charts.de/price_de.htm.

GASPOOL Balancing Services GmbH (2010-2018) *Prices for compensation energy - Monthly average price*. Available at: https://www.gaspool.de/en/services/balancing-group-manager/compensation-energy/prices-for-compensation-energy/monthly-average-price/.

Glensk, B. and Madlener, R. (2017) ‘Evaluating the Enhanced Flexibility of Lignite-Fired Power Plants: A Real Options Analysis’, *SSRN Electronic Journal*.

Götz, M. (2014) *Betrachtungen des Gesamtsystems im Hinblick auf Dynamik und Prozessintegration:* DVGW-Forschungsstelle am Engler-Bunte-Institut des Karlsruher Instituts für Technologie.

Götz, M., Lefebvre, J., Mörs, F., Koch A.M., Graf F., Bajohr S. et al. (2016) 'Renewable Power-to-Gas: A technological and economic review', *Renewable Energy*,85: 1371–1390.

Guthrie, G. A. (2009) *Real options in theory and practice*, New York, Oxford: Oxford University Press.

Jentsch, M., Trost, T. and Sterner, M. (2014) 'Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario', *Energy Procedia*,46: 254–261.

Kopp, M., Coleman, D., Stiller, C., Scheffer, K., Aichinger, J., Scheppat, B. (2017) Energiepark Mainz: Technical and economic analysis of the worldwide largest Power-to-Gas plant with PEM electrolysis, *International Journal of Hydrogen Energy*, 42(19): 13311-13320.

Leonzio, G. (2017) Design and feasibility analysis of a Power-to-Gas plant in Germany, *Journal of Cleaner Production*, 162: 609-623.

Krzikalla, N., Achner, S. and Brühl, S. (2013) *Möglichkeiten zum Ausgleich flukturierender Einspeisungen aus erneuerbaren Energien: Studie im Auftrag des Bundesverbands erneuerbarer Energien:* BEE-Plattform-Systemtransformation_Ausgleichsmoeglichkeiten.

Mills, A. F. (2014) *Basic heat and mass transfer*, Harlow, Essex: Pearson.

Muñoz, J. I., Contreras, J., Caamaño, J., et al. (2011) 'A decision-making tool for project investments based on real options: the case of wind power generation', *Annals of Operations Research*,186(1): 465–490.

Müsgens, F., Ockenfels, A. and Peek, M. (2014) 'Economics and design of balancing power markets in Germany', *International Journal of Electrical Power & Energy Systems*,55: 392–401.

Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., Stolten, D. (2015) Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany, *International Journal of Hydrogen Energy,* 40(12): 4285-4294

Thema, M., Sterner, M., Lenck, T., et al. (2016) 'Necessity and Impact of Power-to-gas on Energy Transition in Germany', *Energy Procedia*, 99: 392–400.

UNFCCC (2015) *Adoption of the Paris Agreement*.

Vandewalle, J., Bruninx, K. and D'haeseleer, W. (2015) 'Effects of large-scale power to gas conversion on the power, gas and carbon sectors and their interactions', *Energy Conversion and Management*,94: 28–39.

Van Leeuwen, C., Mulder, M. (2018) Power-to-gas in electricity markets dominated by renewables, *Applied Energy*, 232: 258-272.

Walker, S. B., Van Lanen, D., Fowler, M., Mukherjee, U. (2016) Economic analysis with respect to Power-to-Gas energy storage with consideration of various market mechanisms, *International Journal of Hydrogen Energy*, 41(19): 7754-7765.

Zhang, M., Zhou, D. and Zhou, P. (2014) 'A real option model for renewable energy policy evaluation with application to solar PV power generation in China', *Renewable and Sustainable Energy Reviews*,40: 944–955.

Appendix

Table 2: Parameters for the real options analysis

Parameter	Symbol	Value	Unit	From section
Capacity power-to-gas plant	P_{el}	5	$[MW]$	3.2
Capacity extension	P_{el}	5	$[MW]$	3.2
Capacity hydrogen storage	$-$	25	$[MWh]$	3.2
Time horizon	T	20	$[a]$	4.1.1
Total efficiency	η_{total}	0.546	$[-]$	4.1.3
Price oxygen	p_{O_2}	50	$[€\ per\ t_{o_2}]$	4.1.3
Sales fraction oxygen	x_{O_2}	50	[%]	4.1.3
Specific energy hydrogen production	$E_{H_2,specific}$	5	$[kWh\ per\ m^3]$	4.1.3
Density of oxygen	ρ_{O_2}	1.439	$[kg\ per\ m^3]$	4.1.3
Repetition Monte Carlo simulation	$-$	10,000	[-]	4.1.3
Standard deviation	σ	18,112	$[€\ per\ q]$	4.1.4
Mean	μ	-0.0656	$[€\ per\ q]$	4.1.4
Operational expenditure	$OPEX$	1	$[\%\ per\ q]$	4.1.5
Risk free rate of investment	r_f	0.12	$[\%\ per\ q]$	4.1.5
Time of construction	$-$	2	$[q]$	4.1.6