Configuration Model and Case Study for the Assessment of Business Models in the Deployment of Power-to-Gas Technology

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The President:

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Abstract

The purpose of this dissertation is to cover a holistic economic analysis of the Power-to-Gas (PtG) technology. This technology is converting electric energy, for example from renewable energy (RE) production, to hydrogen and further to synthetic natural gas (SNG), which can be used for various applications. Besides PtG, different types of converting technologies exist like Power-to-Liquid (PtL) or Power-to-Heat (PtH). This dissertation focuses on the coupling of existing infrastructures (electricity and natural gas grid in Germany) and, therefore, concentrates on the PtG technology, which offers the possibility to link both infrastructures. The analysis is shedding light on the economic potential of the PtG technology from different perspectives. A general business model (BM) is constructed, applied on different scenarios, and tested in a single case study. PtG can play a major role in the future RE system and this thesis develops a basic framework for economic considerations.

The basis for this research is a top-down design science research approach. First, an inquiry obtains the main parameters influencing the economics of the PtG technology and their interrelations by performing a system analysis. Second, a general BM is derived from these parameters following the technology-driven school of business model innovations. In this context, a detailed technology investigation is done based on an literature review, market analyses, and industrial surveys to identify quantitative data along the value chain and network of the PtG technology. Third, the general BM is tested by different calculations in theory and a single case study of an operating plant in practice. Finally, a potential technology pathway with political recommendations is drawn. Due to the nested and complex technology inspection mixed methods are chosen as research tools.

As a result, around 100,000 different scenarios can be designed with the constructed general BM due to various setting options, such as plant constructions (45), power purchase concepts (20), CO_2 sources (8), target markets (4) and more. Out of those, 19 selected scenarios are calculated in detail to test the general model and to achieve further insights about the PtG technology. Innovative power purchase concepts are developed, analyzed, and partly tested in practice. Due to many fluctuating economic parameters, a Monte Carlo simulation with multivariate bootstrapping is used to highlight the distribution of the financial performance. In the single case study first practical experiences and economic results of an operating, industrial scale plant are published.

Zusammenfassung

Das Ziel dieser Dissertation ist eine ganzheitliche, wirtschaftliche Analyse der Power-to-Gas (PtG) Technologie. Diese Technologie konvertiert elektrische Energie, zum Beispiel von erneuerbaren Energien, zu Wasserstoff und weiter zu synthetischem Methan, welches in verschiedenen Anwendungen eingesetzt werden kann. Neben PtG existieren verschiedene Umwandlungstechnologien wie Power-to-Liquid (PtL) oder Power-to-Heat (PtH). Diese Dissertation fokussiert sich auf die Kopplung existierender Infrastrukturen (Strom- und Gasnetz in Deutschland), die durch die PtG Technologie ermöglicht wird. Die Potentiale dieser Technologie werden aus unterschiedlichen Perspektiven beleuchtet. Ein allgemeines Geschäftsmodell wird konstruiert, angewendet und in einer einzelnen Fallstudie getestet. PtG kann eine wichtige Rolle im zukünftigen erneuerbaren Energiesystem spielen und diese Arbeit entwickelt ein universelles Konzept für die wirtschaftliche Bewertung dieser Technologie.

Die Basis dieser Untersuchung ist ein konzipierter Forschungsansatz (design science research approach). Als Erstes werden die wichtigsten Parameter, die die Wirtschaftlichkeit der PtG Technologie beeinflussen, und deren Zusammenhänge in einer Systemanalyse ermittelt. Zweitens wird ein allgemeines Geschäftsmodell aus diesen Parametern nach einer technologieorientierten Methodik für neue Geschäftsmodelle entwickelt. Hier erfolgt eine detaillierte Analyse der Wertschöpfungskette der PtG Technologie mit Literaturrecherche, Marktanalysen und Industrieumfragen. Drittens wird das entwickelte Geschäftsmodell durch Berechnungen verschiedener Szenarien theoretisch und in einer Fallstudie praktisch geprüft. Abschließend wird ein potenzieller Technologiepfad skizziert sowie politische Maßnahmen empfohlen. Aufgrund der komplexen Untersuchung werden verschiedene Forschungsmethoden angewendet.

Als Ergebnis können rund 100.000 unterschiedliche Szenarien durch diverse Einstellungen für Anlagenkonstruktionen (45), Strombezugskonzepte (20), CO_2 Quellen (8), Zielmärkte (4) und weitere Optionen konstruiert werden. Von diesen Möglichkeiten werden 19 ausgewählte Szenarien berechnet und Erkenntnisse für die PtG Technologie abgeleitet. Innovative Strombezugskonzepte werden entwickelt, bewertet und teilweise in der Praxis getestet. Aufgrund vieler fluktuierender Parameter wird eine Monte Carlo Simulation mit multivariantem Bootstrapping angewendet, um die Verteilung der finanziellen Ergebnisse zu ermitteln. In einer Fallstudie werden erste praktische Erfahrungen und wirtschaftliche Ergebnisse einer existierenden, industriellen PtG Anlage veröffentlicht.

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Abbreviations

a	Annum or year
a.m.	Ante meridiem
AbLaV	Verordnung zu abschaltbaren Lasten (regulation of shiftable loads)
AC	Alternating current
ACEA	European automobile manufacturers association
AEL	Alkaline electrolysis
AG	Aktiengesellschaft (stock corporation)
Approx.	Approximately
BC	Business case
BEV	Battery electric vehicle
BImSchV	Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (federal immission control act)
Biokraft-NachV	Biokraftstoff-Nachhaltigkeitsverordnung (sustainability regulation of biofuels)
Biol	Biological
BLE	Bundesanstalt für Landwirtschaft und Ernährung (German federal office for agriculture and food)
BM	Business model
BMF	Bundesfinanzministerium (German federal ministry of finance)
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (German federal ministry for the environment, nature conservation, building and nuclear safety)
BNetzA	Bundesnetzagentur (federal network agency)
BMWi	Bundeswirtschaftsministerium (German federal ministry of economics)
BOP	Balance of plant
CAPEX	Capital expenditures
CCU	Carbon capture and utilization
Chem	Chemical
CHP	Combined heating and power
ct	Eurocent
CW	Calendar week
DC	Direct current
DSR	Design science research
e-gas	Trademark of the synthetic methane of AUDI AG

EEG	Erneuerbare-Energien-Gesetz (renewable energy directive in Germany)
EEX	European energy exchange
EGIX	European Gas Index
EN ISO	European norm of the international organization for standardization
EnWG	Energiewirtschaftsgesetz (energy industry law)
EPEX SPOT	European power exchange spot
Eq.	Equivalent
EU-27	European Union of 27 member states
EUA	European Union Allowance
ETS	European trading system
EXAA	Energy exchange Austria
FLH	Full load hours
Fraunhofer IWES	Fraunhofer Institut für Windenergie und Energiesystemtechnik (research institute for wind energy and energy system technology)
GasNEV	Gasnetzentgeltverordnung (regulation of the public gas network)
GasNZV	Gasnetzzugangsverordnung (gas grid access regulation)
GHG	Greenhouse gas
GmbH	Gesellschaft mit beschränkter Haftung (limited liability company)
GO	Guarantees of origin
h	Hour
Hz	Hertz
ID_3-price	Average power price at the intraday market 3 hours before closing
IPCC	International panel of climate change
IRR	Internal rate of return
ISIC Rev. 4	International Standard Industrial Classification of All Economic Activities
J	Joule
KAV	Konzessionsabgabenverordnung (concession levy regulation)
KWKG	Kraft-Wärme-Kopplungsgesetz (CHP regulation)
LCOE	Levelized costs of renewable energy
LNG	Liquid natural gas
MAPE	Mean absolute percentage error

max.	Maximum
MC	Monte Carlo
Meth.	Methanation
MENA	Middle East and North Africa
min	Minute
NCG	NetConnect GmbH
Neg.	Negative
NGV	Natural Gas Vehicle
No.	Number (from the Latin “numero”)
NPM	National platform of future mobility
NPV	Net present value
OPEX	Operational expenditures
OTC	Over-the-counter
p.m.	Post meridiem
PBM	Primary balancing market
PEM	Polymer electrolyte membrane electrolysis
Pos.	Positive
PPA	Power purchase agreement
PT	Primary timeslot
PtG	Power-to-Gas
PtH	Power-to-Heat
PtL	Power-to-Liquid
PtX	Power-to-X (different synthetic products)
qh	Quarter per hour
Qual	Qualitative
Quan	Quantitative
RE	Renewable Energy
RED	Renewable energy directive
ROI	Return on investment
RQ	Research question
s	Seconds
SBM	Secondary balancing market
SOEC	Solid oxide electrolysis cell
SNG	Synthetic Natural Gas
ST	Secondary timeslot
StromStG	Stromsteuergesetz (power tax regulation)

T€	Thousand Euro
TBM	Tertiary balancing market
tkm	Ton kilometer
UBA	Umweltbundesamt (German Environment Agency)
UNFCCC	United Nations Framework Convention on Climate Change
V	Volt
VDA	Verband der Automobilindustrie (association of the German automotive industry)
W	Watt
WACC	Weighted average cost of capital
WOMBAT	Research project and a German acronym for: efficiency optimization of methanation and biogas technology
ZSW	Zentrum für Solar- und Wasserstoffforschung Baden-Württemberg (centrum for solar and hydrogen research)

1 Introduction

This dissertation provides a comprehensive, economic benchmark to the Power-to-Gas (PtG) technology. The introduction highlights the personal motivation and explains the interests and background. Then, the structure of the research program clarifies the course of action and helps the reader to follow the argumentation and validation of results.

1.1 Motivation

The aim is to evaluate whether the PtG technology offers the potential to implement economical solutions for the future demand for long-term storage of renewable energy (RE), for climate-friendly mobility, or additional approaches. Therefore, a general business model (BM) is designed, and different business cases are calculated. Single business cases are analyzed in an existing PtG plant to demonstrate how the BM works in practice. In sum, the motivation is to achieve a full economic understanding of this technology.

Due to a social willingness to fight man-made global warming, which can be indicated by the subscription of climate agreements by the majority of democratic countries like the Paris agreement[1] and multiple existing climate action plans like the European Green Deal,[2] the fossil-dominated, demand-oriented energy system, especially in Germany, is challenged by the substitution of fossil energy with a renewable, fluctuating energy production. The potential road to a future energy system is briefly discussed in the appendix (see chapter A.3). The large increase of renewable electricity (see chapter 5.3.1), especially from wind power plants, leads to significant fluctuation in energy feed-in and is challenging the stability of the whole energy system. Energy storage is necessary to guarantee a sufficient, reliable, and all-renewable energy supply in Germany.

In comparison to the electricity sector, in which the transition to RE already started, the mobility sector still requires sustainable solutions to satisfy political and environmental needs as well as customers' desires. Studies show that the transportation sector is responsible for almost 30% of the energy consumption and 18% of the CO_2 emissions in Germany.[3] In the European Union (EU-27), the climate goal of the transportation sector is a reduction of 38% in 2030 compared to 2005.[4] According to the *effort sharing decision*, each member state has individual CO_2 targets.[5] That means, in the case of

1 UNFCCC (2019)

2 European Commission (2019c)

3 BMU (2018), p. 38

4 European Commission (2019a)

5 European Commission (2019a)

Germany, an allowed amount of greenhouse gas (GHG) emissions of 95 to 98 million tons in the year 2030.[6] In 2017, the German transportation emitted approx. 171 million tons.[7] At the end of 2019, the European Commission has announced the new *Green Deal*. The overall aim is to further reduce the emissions of GHG up to 55% compared to 1990 in the EU-27.[8] This announcement will further accelerate the energy transition in electricity as well as in the transportation sector.

Automotive companies are regulated to reach a significant reduction of GHG in the passenger car and truck sector. The change to electric mobility appears to be a sound solution for metropolitan regions and short distances. Compared to conventional mobility concepts, the challenges are a limited range, recharging time, and sufficient infrastructure. Furthermore, due to the high battery costs the affordability need to be taken into account.[9] For other applications within the transport sector like long-distance mobility, heavy-duty vehicles, shipping, and aviation, electrification faces even greater challenges. In total, these forms of mobility, which are difficult to electrify, are responsible for two-thirds of European energy consumption in the transport sector.[10] In addition, to speed up the climate protection efforts, it will be necessary to find solutions that can take effect within an existing infrastructure and be implemented in existing cars, which are already in use. Otherwise, the substitution of existing vehicles with battery-electric or fuel-cell cars and the corresponding infrastructure expansion will take decades and the two-degree global warming limitation, which has been agreed by different nations at the United Nations Framework Convention on Climate Change (UNFCCC) in Paris in 2015, would fail.[11] Currently, climate-friendly solutions for the transport sector are lagging behind.[12] Further development of fuels to renewable synthetic fuels is an evolution that demands further economic consideration. It is important to remark that this is not a plea to withdraw from electrification as such. It is more a request to consider the potential of PtG in transportation additionally.

The PtG technology provides solutions for these issues by converting renewable electricity to renewable fuel, which can be used for climate-friendly mobility. Therefore, one of the challenges of the energy system is the economic market potential of PtG technology. A comparison with scientific publications and the installation of industrial scale plants in chapter 2.1 shows that the technical questions appear to be initially answered. Further efforts need to be made to investigate economic cases and to develop an

6 BMU (2019)

7 UBA (2019)

8 European Commission (2019c)

9 Gerbert et al. (2018)

10 European Commission (2013), p. 40

11 UNFCCC (2019)

12 UBA (2019)

appropriate BM. For that reason, this dissertation puts a spotlight on economic issues of the PtG technology by analyzing drivers and influencing factors in a system analysis, by calculating business cases in a second step, and by testing the constructed BM under realistic conditions. The corresponding research questions (RQ) are defined in chapter 2.2.

In the end, necessary political, scientific, and industrial action is identified to achieve a full technology readiness of PtG and to enable its market entry.

1.2 Structure of the Research

The structure of the research is illustrated in Figure 1. The first chapter starts with the introduction of the PtG technology and descriptions of the challenges of the energy transition. In this section, the motivation and the structure of the dissertation are outlined.

In the second chapter, the theoretical approach towards scientific research is clarified. The current research status is discussed with a focus on the market potential and current publications about PtG. In the context of the research status, the research gaps are identified. According to the identified research gaps, the RQs are lined up in chapter 2.2. As a matter of rigorous scientific work, also the practical relevance is discussed in chapter 2.3. The chapter of the research methodology (see chapter 2.4) is divided into the research design and an explanation of different qualitative and quantitative driven approaches to face the RQs. Chapter 2.5 is framing the theoretical approach by providing a consistent scientific construction for the dissertation. RQs, design, and methods are discussed with a focus on the philosophy of science.

The third chapter explains the theoretical basics of the different research stages. Here, the theories behind the three approaches are discussed. First, the general system theory is explained to show the theoretical background of the system analysis in chapter 3.1. Second, the concept of business modeling is described based on different procedures of business model innovation. Thus, a methodology of how to construct a general BM is chosen. Third, a case study research is engrossed to set the framework for the practical testing of the BM. The advantages and disadvantages of case study research are also discussed here.

The general empirical section is further divided into three chapters. In the fourth chapter, the system analysis, the influencing factors on the economics of the PtG technology are detected. In the fifth chapter, a general BM is constructed along the value chain of the previously detected economic factors and divided into different target markets. In the sixth chapter, the general BM is tested in theory by various business case calculations, and further in practice by a single case study of an industrial scale PtG plant. This proceeding serves to validate the general BM as appropriate as possible.

In the last chapter, the results of scientific work are arranged. A potential technology pathway is drawn to highlight the necessary next steps of the technology development. In the end, the dissertation is critically evaluated, and limitations are stated. According to these constraints, further research recommendations are given from different perspectives. The dissertation results in a comprehensive and understandable investigation of the economic state and provides an outlook of PtG technology.

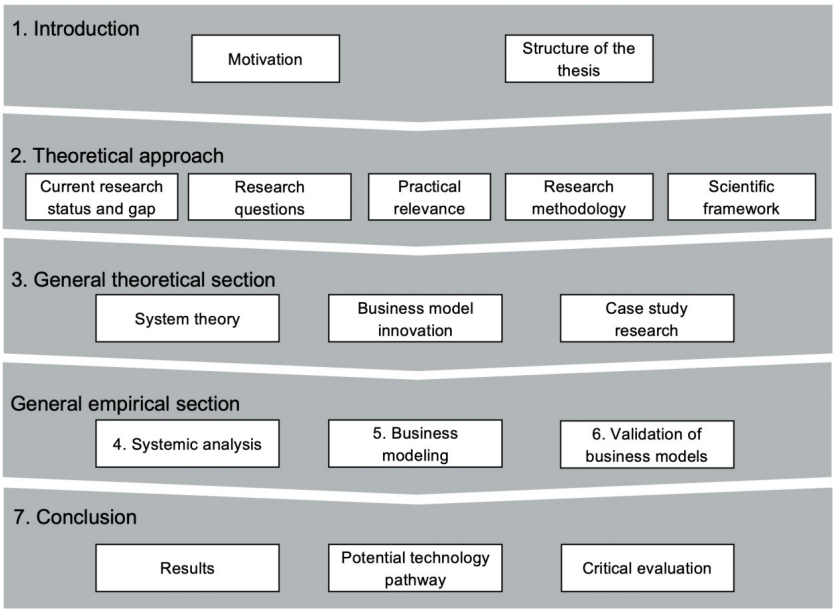


Figure 1: Structure of the research

2 Research Design

This chapter explains the scientific course of action. First, the current research status and research gaps are detected. Second, the RQs are defined to close the identified gaps. Third, the practical relevance is highlighted to place emphasis on the impact of this scientific issue. Fourth, the design science research approach as a research orientation is described. The suitable mixed-method approach is then explained in the research methodology chapter. At the end of the theoretical approach, the scientific framework wraps up this chapter with aspects of the philosophy of science.

2.1 Current Research Status and Research Gaps

This section is divided into three parts. The first one is a description of the development of the PtG technology. The second part is a literature study of the future market potential of this innovation. The third part is a literature comparison of existing studies about the PtG technology. This research sets the boundaries on the analysis of the PtG technology in Germany, as further explained in the chapter of research limitations (see chapter 7.3.1). One exception is the calculation of a scenario in the Middle East and North Africa (MENA) region to test if the general BM can be transferred to different regions (see chapter 6.1.8). A multi-national analysis is further described in the research recommendations (see chapter 7.3.2).

The development of PtG has arisen during the expansion of solar and wind power in the first decade of the 21st century, and thereupon has sparked the questioning of long-term storage of RE. Fundamental research has taken place in the 1990s. On the systemic side, Enßin, Füller, Hahn and Rohrig at the Fraunhofer Institute in Kassel have demonstrated in a simulation that a fully renewable system, which consists of wind and photovoltaic power, flexible biogas plants and hydro pump storage systems, can provide a constant and safe power supply.[13] On the technical side, first publications from researchers at the Centrum for Solar and Hydrogen Research (ZSW) have been undertaken since 1993. Specht et al. (1993) published the first article about CO_2 recovery and reduction methods for fuel generation.[14] This publication focused on synthetic, liquid fuels like methanol. First ideas like the production of climate-neutral energy carriers and economic advantages of the usage of existing infrastructure and transport systems in the mobility have been mentioned. Later in 1996, the same researchers and their colleagues from the University of Karlsruhe and Stuttgart described PtG for the first time in terms of the storage of fluctuating RE.[15] But it took more than a decade until the synthetic production of methane led to further scientific interest. In 2009, Michael

13 Sterner and Stadler (2014), p. 409

14 Specht et al. (1993)

15 Weimer et al. (1996)

Specht and colleagues published different papers about renewable methane.[16] PtG got first greater attention in the dissertation of Michael Sterner titled *"Bioenergy and Renewable Power Methane in Integrated 100% Renewable Energy Systems - Limiting Global Warming by Transforming Energy Systems"* at the University of Kassel in 2009.[17]

From those early researches, the ZSW has established itself as a center of development for the PtG technology. The first 25 kW PtG plant has been installed and successfully operated in Stuttgart in 2009. Later in 2012, an upscaling to 250 kW has been accomplished at the laboratories of the ZSW as well. In May 2011, ETOGAS (formerly names "SolarFuel"), which is a spin-off from the ZSW, and the car manufacturer AUDI AG announced a first multi-MW scale PtG project. In December 2013, this 6 MW PtG plant was fully constructed and has successfully injected synthetic natural gas (SNG) into the public gas grid for the first time.[18] In addition, from 2012 to 2017, the funded research project WOMBAT has taken place at the Audi PtG facility. Here, different industrial pioneers like AUDI AG, EWE AG, and ETOGAS GmbH, as well as research institutes like Fraunhofer IWES and ZSW, were involved. The research aimed at investigating the optimization potential of both the PtG technology in combination with a biogas plant. This dissertation is absolved in close collaboration with the WOMBAT project. Especially the case study is part of this research project. Therefore, the contribution of preliminary work is stated in chapter 6.2. In 2018, 26 MW installed capacity of PtG in 25 projects had been put into action by different industrial and academic players in Germany. Until 2022 more than 50 projects with a capacity of more than 55 MW are planned in total.[19] Further analysis is shown in the explanation of water electrolysis and methanation in the appendix (see chapter A.4).

In conclusion, PtG has been developed from the first theoretical thoughts over laboratory units and pilot plants to full industrial scale plants within ten years (2009 to 2019). The technology has achieved an almost fully-completed technical readiness level. Yet the industrialization of the technology is missing. Therefore, business development is in practical and scientific focus today.

The research status of the PtG technology is often emphasized on the future potential of PtG and the necessity of long-term energy storage technologies in a RE system. These researches, which are analyzing the share of SNG in future energy systems, are assuming a future market potential of the PtG technology. Therefore, a literature study has been undertaken to compute the market potential of PtG in Germany. In the

16 Specht et al. (2009)

17 Sterner (2009), p. 111

18 Dena (2019)

19 TÜV Süd (2020)

following figure is illustrating the potential of PtG technology from different studies. The marked area is showing the 25% to 75% weighted median.

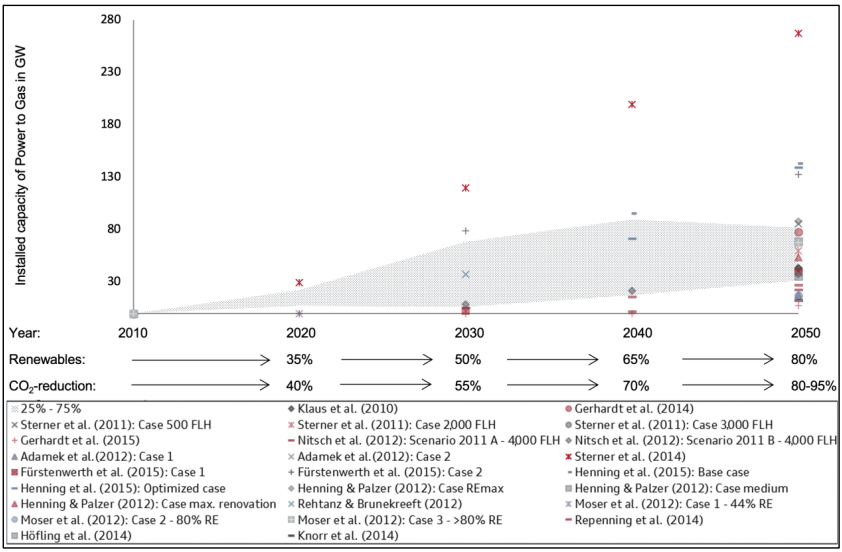


Figure 2: Literature comparison of 15 different studies for PtG technology

Figure 2 concludes that there is a big spread of results in different studies. For example, Gerhardt et al. (2015) indicate a relatively low potential of installed capacity of PtG of 4.65 GW[20] in 2050, whereas Sterner et al. (2015) see a market of 286 GW for this upcoming technology in 2050. The differences can be explained due to complex and nested relations of influencing drivers for the different future energy calculations. Some studies only include the power sector (Fürstenwerth et al. (2015), Adamek et al. (2012)) and, therefore, only the energy storage potential of PtG technology. Others have done simplifications like perfect grid expansion or unrestricted trading of energy across borders. Yet others have used questionable input parameters like high prices for carbon dioxide certificates (Henning and Palzer (2015)) or low costs for competing technologies like the heavy-duty mobility with power from an overhead power line or electric mobility (Gerhardt et al. (2015)). Some studies point out contradictory results. For example, studies announced the first possible application of PtG up from 2030 (Fürstenwerth et al. (2015)); others see a necessity of the immediate start of implementation (Sterner et al. (2015)).

20 Calculated with 4,000 full load hours (FLH); an efficiency of 60% and the forecasted energy amount of 31 TWh/a

These different research messages lead to unclear and ambiguous strategic recommendations of how to proceed with the PtG technology. This dissertation discusses some of these unclear drivers, which are responsible for different perspectives towards PtG technology. Further research about future energy systems can use the exposed BM and economic results for a better understanding of the PtG technology.

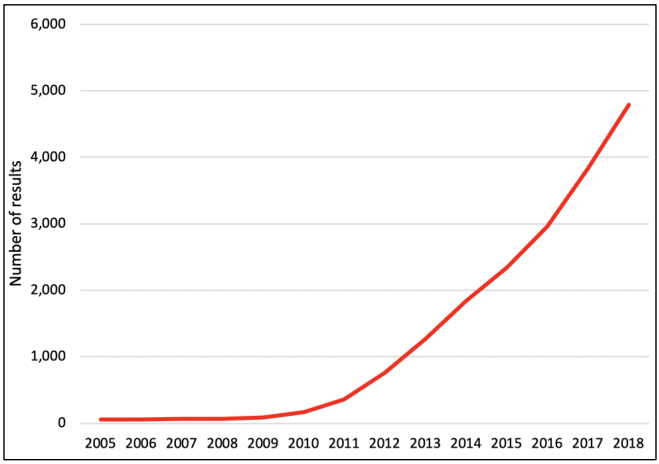


Figure 3: Development of publications about Power-to-Gas[21]

The development of publications of the PtG technology is illustrated in Figure 3. A steep increase in publications starting in 2010 can be recognized. In this year, first practical PtG projects have been started. Most of the publications are based on technical aspects like balancing plant engineering, an increase of efficiency,[22] heat management, or on systemic aspects like the integration of PtG into the energy system and storage potential in a RE system.[23] Except for Lehner et al. (2014), few scientific works focus solely on economic aspects. Comprehensive economic analysis however, which includes a system analysis, an approach for business modeling, an approach of business case calculation, and a practical case study, is missing.

Existing research about the economic situation of the PtG technology is summarized in the following table. This is a compilation of publications that indicates the most relevant studies from the author's perspective with respect to the number of citations. The

21 Yearly Google Scholar analysis with the key word "power-to-gas"

22 Van Basshuysen et al. (2016), Müller-Syring et al. (2013), Fischedick et al. (2013) and Bünger et al. (2014)

23 Fürstenwerth et al. (2014), Mahnke et al. (2014), Repenning et al. (2014), Henning and Pfalzer (2015) and Sterner et al. (2015)

table is divided into the used research method, investigated economic drivers and the author's comments. The studies are alphabetically ordered. Different economic drivers and abbreviations are explained in the empirical section of the dissertation.

Table 1: Literature comparison of different economic publications of the PtG technology

Literature	Research method	Investigated drivers	Comments
Brunner et al. (2015)	Cost calculation and analysis of the impact of full load hours on the business case	Target market, full load hours, Investment costs (CAPEX), operational and maintenance costs (OPEX), power costs	Analysis of SNG production costs of centralized and decentralized plants with focus on Germany. Focus on operation time and integration in the energy system
Brynolf (2017)	Literature review and cost calculation for different synthetic fuels	CAPEX, stack replacement, OPEX, water costs, power costs, CO_2 costs, heat revenues	A comprehensive study with a literature review about economic drivers
De Saint Jean et al. (2015)	Economic analysis of PtG and SOEC electrolysis	CAPEX, OPEX, lifetime, power costs, CO_2 costs, O_2 valorization	Sensitivity analysis of different economic prices
Fasihi et al. (2016)	Business case calculations of worldwide production costs of synthetic fuels	CAPEX, OPEX, RE costs, worldwide operation time, water and CO_2 costs	Focus on liquid synthetic fuels produced in regions with low costs of RE production
Gerbert et al. (2018)	Macro-economic analysis of how to achieve the climate goals in Germany	Amount of installed capacity of Power-to-X (PtX) and their macro-economic costs	Intensive study with the cost of CO_2 avoidance of different technologies
Grahn and Jannasch (2018)	Cost estimates of electro-methane (SNG)	CAPEX, OPEX, CO_2 capture, power price, water, oxygen sale	Interesting paper about production costs of SNG with different electricity prices
Hecking et al. (2018)	Analysis of technologies to achieve German climate goals	Amount of installed capacity of PtX and their macro-economic costs	Shows the necessity of high amounts of PtX in a RE system and includes imports
Hentschel (2014)	Analysis of the PtG technology with surplus power generation for mobility applications	Power price, amount of surplus power generation, CAPEX, OPEX	Dissertation about PtG with a future focus on a future energy system. Different target markets and practical power purchase models are missed
Hermann et al. (2014)	Literature review and cost calculation	Available CO_2 sources, power prices, CAPEX, lifetime expectation	Estimation of market potential and SNG production costs
Hobohm et al. (2018)	Literature review and cost calculation	Cost analysis of different renewable fuels in the transportation sector	Cost structure inclusive of taxes and fuel import from the MENA-region on behalf of the German fuel industry
Jentsch (2014)	Modeling of power supply concepts and business case calculations	Power prices, political regulations, CAPEX, power purchase concepts, dynamic range of electrolyzes	Focused more on market potential than on economics

Literature	Research method	Investigated drivers	Comments
Lehner et al. (2014)	Literature review and business modeling	CAPEX, dynamic range of electrolyzes, efficiencies, OPEX, macroeconomics, and systemic impacts	Detailed analysis of several economic drivers but less information about business modeling
Mahnke et al. (2014)	Literature review	Efficiency, dynamic range of electrolyzes, CAPEX, lifetime expectation	Overview of key drivers of different energy storage technologies
Mueller-Syring et al. (2013)	Literature review and business modeling	CAPEX and OPEX, heat sale, oxygen sale, lifetime expectation, dynamic range of electrolyzes	Focus on the injection of SNG into the gas grid. Business modeling without different power supply concepts
Parra and Patel (2016)	Revenue model, electrolyzer degradation model, calculation of levelized costs	Power costs, CAPEX, OPEX, heat price, CO_2 benefits	Techno-economic analysis of PtG in Switzerland
Ridjan et al. (2014)	Calculation of 8 renewable fuel pathways in a future energy scenario	CAPEX, CO_2 separation, power costs, biomass feedstock prices	Comparison of production costs of power-based and biological fuels in Denmark in 2050
Schenuit et al. (2016)	91 expert interviews	Production costs and potential target markets	Regional clustering of potential future PtG plants
Schiebahn et al. (2015)	Production cost calculation for different PtG process chain alternatives	CAPEX, power costs, infrastructure costs, storage costs, application in the mobility	Economic comparison of synthetic hydrogen and methane production costs
Siegemund et al. (2017)	Calculation of production costs and potential amounts in the EU until 2050 based on literature data	CAPEX and OPEX, market prices, CO_2 sources, RE potential	Study, which shows the necessity of importing renewable fuels to the EU-27
Smolinka et al. (2011)	Literature review and business case calculation	CAPEX and OPEX, efficiency, lifetime expectation	Shows the development of investment and production costs
Steinmueller et al. (2014)	Literature review and quantitative economic consideration	CAPEX and OPEX, efficiency, power costs, lifetime expectation, political regulations	Detailed system analysis, focus on Austrian power markets and regulations
Sterner et al. (2015)	Modeling of power supply concepts and economic consideration	CAPEX, efficiency, lifetime expectation, power costs, political regulation, CO_2 potential	Shows the development of investment and production costs
Tremel (2018)	Description of design and optimization of power-to-fuel plants based on expert knowledge	CAPEX, OPEX, reaction time of electrolyzers, lifetime, power costs, efficiency	Detailed knowledge of electrolyzer technology from a Siemens engineer

Literature	Research method	Investigated drivers	Comments
Zapf (2017)	Description of the energy system with a literature review and case study of a PtG plant with a wind park	Power costs, CAPEX, political regulation, operation time, gas price	Calculation with integration in a wind park

Important work has been done to identify economic drivers. Many publications are focusing on topics like carbon dioxide resources, power purchase concepts, the combination with the gas grid, or technical integration. The most common research method is to collect data from previous publications about different topics and comprehensively review the data in a business calculation. Data mining is an important step in business case calculations. Due to different considered literature sources, the results of the economics and, therefore, the potential of this technology differ. This work will explore new data and critically review the body of existing literature. In addition, none of the economic researches quantitatively compare different business cases, for example, the application on the mobility or heat market in a detailed way. The crucial point, however, is the practical relevance of existing literature. The detailed analysis of described power purchase concepts or operation modes is another blank spot. In conclusion, rigorous validation of these business case calculations hasn't been done so far.

A *research gap* of a wide-ranging economic PtG benchmark can be identified, which consists of first a system analysis and, second, a validation by using data of an existing industrial plant. This work closes this research gap and shows the business potential of this technology. This dissertation adds valuable knowledge to the existing body of literature on how to identify and benchmark business models of energy innovations. The research goal, therefore, is to close the research gap of a wide-ranging, economical PtG analysis. The following table is summarizing the identified research gaps and the possible contributions by closing these gaps.

Table 2: Indicated research gaps and contributions

No.	Research gap	Contribution
1	Systemic identification of influencing economic drivers of the PtG technology	Assess all economic drivers of the innovation for further detailed investigations using a systemic approach
2	Development of a universal business model of the PtG technology	Construction of a general BM for PtG plants, which can be adopted and modified in different ways
3	Detailed quantification of the identified drivers and calculations of different business cases	Explore new data; discuss and value existing literature data; compare different business cases of the PtG technology
4	Practical validation of indicated business cases	Confirmation of the theoretical BM in a single event
5	Demonstration of a technological pathway from an economic perspective	Development of a strategic roadmap for different stakeholders

2.2 Research Questions

The indicated research gaps allow defining the RQs, which are investigated within the dissertation. According to the gaps and their contribution, four RQs are defined to close these gaps.

The first RQ aims to fill research gap No. one. It is exploring drivers, which are influencing the BM of the PtG technology. Here the system boundaries, subsystems, and system behavior are identified in order to name relevant drivers and to indicate new drivers compared to the existing body of literature. Chapter 2.4.2 explains the suitable research method to tackle this RQ. In chapter 3.1, a suitable scientific theory is introduced. In chapter 4, the empirical investigation of the RQ takes place.

1. What are the drivers of the economic situation of the Power-to-Gas technology and what is the relation between those drivers?

The second RQ closes the second and third research gaps. A convenient RQ is defined below. The term *most promising* implies an interpretation of economic results. Again, the research method is amplified in chapter 2.4.2. The theoretical background of how to build business models is explained in chapter 3.2. In section five, the general BM is developed, and in section 6.1, a variety of scenarios and cases are calculated to detect the most promising business case.

2. What is a general business model of Power-to-Gas technology, and what are the most promising business cases?

Next to the theoretical case calculations, the practical validation of the second RQ is additionally closing the fourth research gap. An appropriate RQ is mentioned below. The methodology of this step is shown in chapter 2.4.2. Further theoretical analysis of the case study research is done in chapter 3.3. The RQ is answered in chapter 6.2.

3. How does the business model of the PtG technology work in practice?

The last RQ is summarizing the results and gives an outlook of the PtG technology. Therefore, strategic recommendations for all participating parties are on research focus. In the end, a potential technology pathway is described. This is executed in chapter 7.2.

4. What are the final strategic recommendations? How could a reasonable technology pathway look like?

All in all, the four RQs draw a comprehensive picture of this scientific approach. A detailed economic analysis can be achieved by answering those questions. The following table visualizes the relation between the indicated research gap and the corresponding RQ.

Table 3: Link between research gap and research question

No.	Research gap	Corresponding research question
1	Systemic identification of influencing, economic drivers of the PtG technology	What are the drivers of the economic situation of the Power-to-Gas technology and what is the relation between those drivers?
2	Development of a universal business model for the PtG technology	What is a general business model of Power-to-Gas technology, and what are the most promising business cases?
3	Detailed quantification of the identified drivers and calculations of different business cases	
4	Practical validation of the indicated business model	How does the business model of the PtG technology work in practice?
5	Demonstration of a technological pathway from an economic perspective	What are the final strategic recommendations? How could a reasonable technology pathway look like?

2.3 Practical Relevance

In addition to the theoretical scientific relevance, practical relevance is equally important to achieve a rigorous study.[24] Stokes (1997) calls it the “Pasteur quadrant” in behavioral science to combine the highest standards of rigor with a high level of relevance. In this section, a brief outlook on the practical impact of the PtG technology in different sectors of the energy system is given.

First, as already mentioned, the stakeholders of the energy system, especially in Germany, are confronted with challenges of the energy transition, the intended transformation of the energy sector from fossil domination to a RE supply. The demand-orientated energy production is turned into a fluctuating supply-orientated electricity generation mostly by wind and solar energy. Due to the naturally fluctuating yield of renewables, flexibilities and storage options become way more important. PtG offers such an option by storing surplus RE, for example, in the natural gas grid (energy storage case) as the literature review and studies of the future energy system have shown (see chapter 2.1 and Figure 2). For that reason, PtG can have exceedingly practical relevance in the future energy mix and can become a key driver of RE innovations. The involvement of industrial key players from the energy sector Uniper SE, RWE AG, Thüga AG, Viessmann GmbH & Co. KG, Siemens AG, and EWE AG is also showing the highly practical relevance of that topic.

Second, in the transportation sector, the automotive industry is affected because it is forced to achieve a CO_2 reduction to 95 g/km in a fleet average of the yearly sold cars in 2021.[25] Therefore, CO_2 reduction costs are higher than in other industries. For example, the automotive industry pays up to €475 per avoided ton of CO_2 to get the

24 Wüstenhagen (2015), p. 5 f

25 European Parliament (2013)

necessary technology into vehicles[26]. In contrast, a CO_2 certificate for other industries costs around €25 per ton in the beginning of 2020 (see chapter 5.2.2).[27] As a result of these efforts to avoid CO_2, a car manufacturer has built a first 6 MW PtG plant in 2013 to produce 1,000 tons of synthetic methane per year using wind energy. A total of 1,500 vehicles can be provided with almost climate-neutral mobility because the same amount of CO_2 is bound in the production process that is emitted while driving.[28] Hence, the combination of PtG with existing natural gas vehicles (NGVs) adds to the solution mix of climate-friendly long-distance transportation. This industrial plant has demonstrated the technical feasibility on an industrial scale and has attracted great attention to this technology. However, a detailed economic analysis of the technology path, especially involving experience curve considerations, is still missing. Therefore, this dissertation is publishing the economic key facts of this existing plant. Thus, the first practical relevance of the PtG technology can be given to the mobility sector, and strategic, relevant recommendations can be derived.

Next to the automotive industry, the fuel industry has an apparent interest in the economic side of the future development of the PtG technology. The climate goals of the fuel industry are discussed in the dissertation. First publications in order of fuel associations like Hobohm et al. (2018) and the participation in strategic groups like the German *dena powerfuel alliance* indicate a rising interest of the fuel industry. Tremel (2018) mentioned in his stakeholder analysis further parties. On the technical side, RE project developers or operators of RE plants can gain additional insights. Technology developers and plant manufacturers can learn from the economic analysis and new power purchase concepts. Insurance companies and investment funds, who would like to invest in technologies of the energy transition, can be interested as well. And at least, public institutions and policymakers can be interested in the developed technology pathway.[29]

It is important not to handle the practical usages separately but to analyze them in a mixed, systemic way. This dissertation is aiming to deduce appropriate business cases for different applications.

2.4 Research Methodology

This chapter is further divided into the development of a conceptual, methodological framework, which is using design science research as a research orientation, and a description of the applied methods to highlight the process steps of this work in detail. In total, the methodology of this research is explained step by step.

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26 Calculated by dividing the penalty costs of 95 €/g/km with the mileage of 200,000 km

27 Bardt and Schaefer (2018)

28 Dena (2019)

29 Tremel (2018), p. 12

2.4.1 Design Science Research

Design science research (DSR) has its roots in information systems research, which solves problems at the intersection of economics, information technology and organizations.[30] According to Winter and Aier (2016), products and services, processes and business models are typical artifacts of DSR projects. As artifacts in this context, the research object is meant. They proclaim that in contrast to the traditional *"natural or social science as physics or sociology, science of artificial as medicine or engineering do not aim at explaining the current world, but to change it into a better or preferred one."*[31] Winter and Aier (2016) further quote that the differentiation of *"science=understanding" and "design=improving"* is that the former aims at explaining or predicting without any application, and that latter focuses on solving problems and the creation with purpose.

Winter (2008) points out that behavioral research aims at "truth" like exploration and validation of generic cause-effect relations and DSR aims at "utility," such as the construction and evaluation of generic means-end-relations.[32] The strengths of DSR are the focus on the development and performance with explicit intention of improving the performance of the artifacts. Therefore, this approach fits the RQ two (development of a general business model of the PtG technology), RQ three (practical application) and RQ four (technology pathway). However, first, it must be demonstrated that DSR can be of scientific rigor as traditional scientific activity in business research, and second the process steps of DSR are explained to depict the methodology.

Because of the mentioned differentiations to traditional science, DSR has been misinterpreted as practical activities like applied research or consulting instead of rigorous scientific work. For that reason, *"design should deliberately (re-)use relevant, applicable explanations and technologies – rather than being a purely pragmatic search."*[33] In addition, the research outcome of DSR should solve more than a particular problem or singular situation.[34] Therefore, the outcome of RQ two (general business model of the PtG technology) should generally apply to different PtG plants or even other carbon capture and utilization (CCU) technologies. DSR should address a *"type, kind or class of problems"* and *"should be relevant to stakeholders, who experience plants of the class of problem."*[35] Winter and Aier (2016) summarize that as long DSR is evidence-based and proposed solutions are grounded and generic, the paradigms are complementary rather than contradictory.

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30 Peffers et al. (2007), p. 1

31 Winter and Aiers (2016), p. 476

32 Winter (2008), p. 470

33 Van Aken and Romme (2012), p. 153

34 Venable (2010), p. 1053

35 Winter and Aier (2016), p. 478

Gregor and Hevner (2013) introduce different artifact types of DSR, and Winter and Aier (2016) compare those types with classifications in social science following Chmielewicz (1994) to highlight the scientific rigorousness of DSR. They differ artifact types in constructs, models, methods, and instantiations. These artifacts build a bottom-up interdependent system. Constructs provide the vocabulary and symbols to define and understand the investigated phenomenon like entities, systems, or relations. Chmielewicz (1994) compares this artifact type to ontological facts and theoretical statements (cause-effect relationship), which are used as basic building blocks in traditional business research. Models and methods, which are designed representations of the problem class and are describing instructions for a solution task, are comparable to technological statements like "means-end" relations following Chmielewicz (1994). Instantiations of these models and methods are similar to judgments (object-value relation).[36] This comparison shows that research types of DSR are identical to research types of traditional research. Following the RQs, different types of artifacts are investigated in this dissertation. Constructs and fundamental theories are introduced in a general theoretical section to enable the construction of models for the problem and solution domain. In RQ two, a model needs to be developed to define different business cases for PtG technology (see above *models or technological statements*). In RQ three, the cases are instantiated (see above *instantiations or judgment*). The answer of RQ four develops relevant stakeholder predictions. Therefore, the structure and RQs of this dissertation are following different justifications of scientific and rigorous DSR.

Additionally, Winter and Aiers (2016) propose to introduce different levels of abstraction in context and time. Therefore, they recommend differentiating between generalization and specialization and between aggregation and decomposition. The *"level of generalization indicates how many different instantiations the artifact allows; the level of aggregation indicates into how many components the artifact can be decomposed."*[37] In the context of this dissertation, the investigated artifact is more specialized and less generalized due to the focus on one country and a single existing instantiation. On an aggregation level, the dissertation is neither highly aggregated nor highly fragmented in different components because the developed general BM should be adopted in various applications of the PtG technology.

It has been demonstrated that DSR includes different parts of traditional research but expands the theory with a further practical approach of instantiation to improve and validate the developed artifact. The work must be generic and evidence-based as well as balanced in the context of generalization and aggregation. In line with van Aken (2004), the strengths of DSR is that *"the most powerful technological rules are those, that are tested in their intended field of application and grounded in an understanding*

36 Winter and Aier (2016), p. 479 ff

37 Winter and Aier (2016), p. 481

of the underlying generic mechanisms that produce the outcome." This research is following the DSR. In the next section, the process steps are explained to develop the research methodology.

Different process models for DSR exist (Cole et al. (2005); Cooper et al. (2002); Hickey and Davis (2004)). In line with Winter and Aier (2016), the work of Peffers et al. (2007) is followed because it coincides with previous contributions. The process model consists of six activities, which are explained in the following sections and compared to the structure of this dissertation.

First, the problem identification and motivation are on focus. Here the specific research problem is defined, and the value of a solution is justified. It should motivate the research community and help to accept the results.[38] Gregor and Hevner (2013) have developed a 2 x 2 matrix to position the problem and the possible solution. The matrix is divided into solution maturity (high or low) and application domain maturity (high or low). If both are high, it is a routine design and no knowledge contribution takes place. If the application maturity is high, but the solution maturity is low, new solutions for known problems are developed (improvement). If the application maturity is low and the solution maturity is low, new solutions for new problems are invented (invention). If the application maturity is low, but the solution maturity is high, extended solutions for known problems are generated (exaptation). The motivation of this dissertation is highlighted in the introduction. In addition, the current research status is defining the scientific interest towards that topic. Problem identification also takes place in chapter 2.1. Here the research gaps are defined. In section 2.3, practical relevance is presented, which also contributes to the problem identification and motivation. According to the solution/application maturity matrix of Gregor and Hevner (2013), this dissertation is positioned of the invention due to few realized PtG projects in industrial scale and less investigations of business cases of PtG (see also the literature review in chapter 2.1).

Second, the objectives of a solution are defined. The identified problems or research gaps have to be transformed into system objects. RQ one (What are the drivers of the economic situation of the Power-to-Gas technology and what is the relation between those drivers?) is addressing this issue. By answering this question, different objects (economic parameter) of business modeling the PtG technology are exposed. This process step is theoretically explained in chapter 3.1 and empirical executed in chapter 4.

Third, according to Peffers et al. (2007), the core of DSR is design and development. Here the artifact is developed. *"This activity includes the artifact's desired functionality and its architecture."*[39] Winter and Aier (2016) further quote that design and

[38] Peffers et al. (2007), p. 12

[39] Peffers et al. (2007), p. 13

development is an iterative process that is driven by the feedback of artifact demonstration and evaluation. In this dissertation, the artifact is the general BM of the PtG technology. The process of design and development takes place by building a general BM and, in addition to that, answering the first part of RQ two (What is a general business model of Power-to-Gas technology?). In the general theoretical section 3.2, the artificial model is developed. Further, the empirical development of the artifact is achieved in chapter 5.

Fourth, the demonstration of the artifact aims at proving the validity by solving the problem. According to Peffers et al. (2007), this can be done by experimentation, simulation, case study, proof, or other appropriate activities. Two types of demonstration are implemented in this dissertation. On the one hand, a theoretical calculation of different cases is proving the functionality and consistency of the artifact (general BM). This process step is undertaken in chapter 6.1. On the other hand, a single case study is demonstrating different business cases in practice. This process step is developed in detail in chapter 3.3 and executed in chapter 6.2. Therefore, also RQ three (How does the business model of the PtG technology work in practice?) is integrated into the DSR framework.

Fifth, the evaluation is comparing the achieved solutions by observing and measuring how well the artifact supports a solution to the problem.[40] According to Winter and Aier (2016), the evaluation is crucial for rigorous design-oriented business innovation research. Venable et al. (2012) proposed an evaluation method selection framework, which is divided into naturalistic and artificial as well as ex-ante and ex-post methods. In this research project, two different evaluation methods are implemented. On the one hand, an artificial method of logical proof of the deduction and calculation of the BM is done. On the other hand, a naturalistic, ex-post case study at an existing, industrial scale PtG plant is carried out. The critical discussion of the different evaluation methods and their outcomes take place in the conclusion in chapter 7.3. Due to the process iteration, the researcher decides at this point to improve the research and go back to activity two or to continue with the last process step.

Sixth, the last process step is about the communication of the research results in typical publications. Therefore, the researcher has to be followed by common research structures in empirical research. *"The problem and its importance, the artifact, its utility and novelty, the rigor of design"* has to be communicated.[41] The communication, in this case, is done by publishing the dissertation.

40 Peffers et al. (2007), p. 13

41 Peffers et al. (2007), p. 14

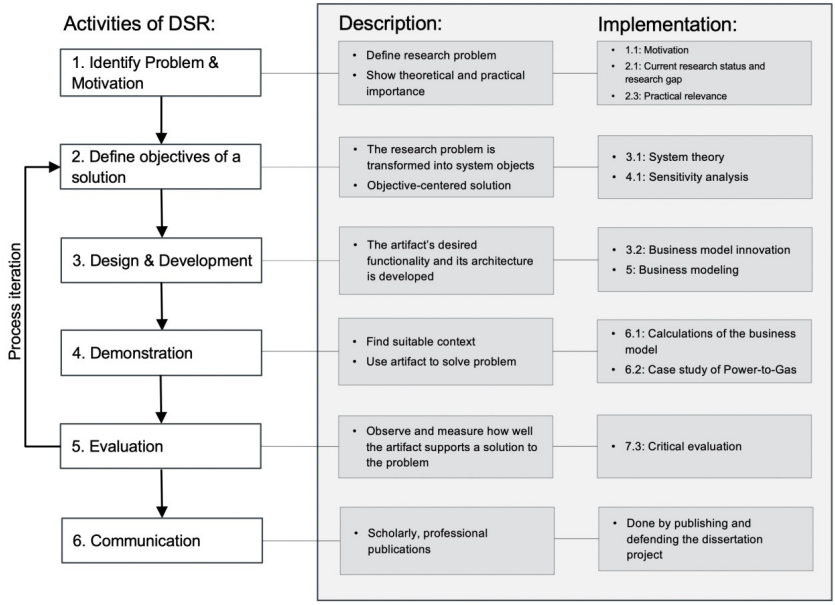


Figure 4: Design science research process model[42]

2.4.2 Mixed Method Approach

This chapter focusses on the methodological course of action. In the previous chapter, the research design has been introduced. Here, the methodological instruments are proposed and justified, which fit in the designed research framework. A method, in this context, is a tool with defined rules, which provides revisable results.[43] Methods can be divided into qualitatively or quantitatively driven. Quantitative methods are generating measurable results like price, revenue, or amount. The advantages of quantitative methods are the reproducibility, objectivity and explicit abort criteria. The main methods of quantitative research are surveys and experiments.[44] The type of data is often standardized and numerical. Specific questions are the scope of inquiry.

Often quantitative methods fail because of complexity and ambiguity – sometimes, researches are not exactly measurable. For that reason, qualitative methods can explain subjective results like conditions, relationships, or predictions. Instruments such as interviews are usually used to observe the environment through qualitative research in

42 Peffers et al. (2007)

43 Pengg (2003), p. 61

44 Creswell (2013), p. 12

their natural context. Creswell (2013) clarifies the main reasons of using qualitative research method: first, the study of a particular group of people; second, the discovering of difficult assessable variables; third, an in-depth understanding of the research topic; fourth, understanding the surroundings and environment of the research object; fifth, delivering explanations for causal relations of quantitative studies.[45] The type of data is narrative and textual. Broad topics are the scope of inquiry.

Different advantages and disadvantages of qualitative and quantitative methods exist. Barton and Lazarsfeld (1955) argue that qualitative methods are suited to set a proposition and quantitative methods are ideal to prove this proposition.[46] Punch (1998) further emphasized: "*Quantitative research readily allows the researcher to establish relationships among variables but is often weak when it comes to exploring the reasons for those relationships.*" A qualitative study can be used to explain the factors underlying the broad relationships that are established.[47] The advantage of quantitative research is the generalizability due to a large sample and statistical validity. The disadvantages of qualitative research are the limited generalizability and difficulties of validation due to reality distortion through interviewers. The disadvantages of quantitative approaches are the superficiality, risk of misunderstandings, and insufficient explanation of underlying facts. The advantages of qualitative research are the understanding of complex processes and events and detailed consideration of the topic.[48] Therefore, the advantages of qualitative research are the disadvantages of quantitative inquire and vice versa. An opportunity to overcome this issue and to neutralize both weaknesses is to mix both methods.

Due to the focus of gaining a comprehensive, economic benchmark of the PtG technology, mixed methods research allows shedding light on the phenomenon from different perspectives. The advantage is to achieve a compact understanding of the research interest by choosing qualitative as well as quantitative research methods. Hence, the indicated RQs can be answered in a more wide-ranging way. Mixed methods have gained increasing attention in recent years.[49] Following Schoonenboom and Johnson (2015), the purpose of the mixed method is a research development from the discovered qualitative propositions to the confirmed quantitative results. This research design is a sequential exploratory-confirmatory approach, which is explained later. Another purpose of mixed methods is explaining and gathering the complexity of technology benchmarking.[50]

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45 Creswell (2013), p. 48

46 Barton and Lazarsfeld (1955)

47 Punch (1998), p. 247

48 Vanderstoep and Johnston (2008), p. 7 ff

49 Creswell (2013), p. 14

50 Schoonenboom and Johnson (2015)

Tashakkori and Teddlie (1998) further try to complement the mixed methods, calling them the third social scientific approach next to the well-established quantitative and qualitative methods. Mixed methods are ideal for outbalancing the disadvantages of each singularly applied research method.

Bryman (2006) is summarizing reasons for using mixed methods.[51] First, methods can build upon each other. For example, hypotheses of qualitative research can be tested with quantitative studies. Second, the mixed methods approach increases the interpretative support, for instance, with qualitative data (e.g., with interviews), which can support quantitative findings. As a third reason, Bryman (2006) mentions different perspectives and complementarity. For instance, quantitative data can unveil the macro-level and qualitative data in-depth perspectives. Fourth, inexplicable or contradicting results can be explained by using different methods. But the most important reason is validation through triangulation by applying different research methods or data sources.[52]

"The ultimate goal of mixed methods research, of combining qualitative and quantitative research components, is to expand and strengthen a study's conclusion […]."[53] This source of Schoonenboom and Johnson (2015) is clearly stating the purpose of why mixed method approaches are chosen.

As explained in the DSR approach, different quantitative and qualitative steps are undertaken to discover the research phenomena. In the following figure, these steps are structured graphically and translated into suitable methods. The following paragraphs are explaining the methodologic course of action.

In the first phase, a system analysis is undertaken to discover the influencing economic drivers of PtG technology. This is shedding light on RQ one. A sensitivity analysis like Frederic Vester's method is suited to indicate these drivers.[54] This mainly qualitative approach is made by interviews with experts, although a questionnaire is used to detect relations between economic parameters, which indicate a quantitative character. Different experts from different companies and research projects have been consulted. Although the choice of experts is mainly subjective, results are compared and differences discussed following the Delphi-method, which is explained later.[55] This approach has been successfully used to describe the complexity and to identify solutions.[56] This first explorative approach is used to define system boundaries and assess

51 Bryman (2006), p. 104 ff

52 Eisenhardt (1989), p. 538

53 Schoonenboom and Johnson (2015), p. 4

54 Vester (2012)

55 Steinmueller (1997), p. 70 ff

56 Vester (2012), p. 259 ff

core parameters of the economics of the PtG technology. Instruments are used to analyze the parameters and their mutual relations of the economic situation in a holistic, systemic approach. Vester's sensitivity model is part of the Malik Management School in St. Gallen. The theoretical basis and course of action of the sensitivity analysis are described in chapter 3.1. Also, the justification and argumentation of this method take place in this chapter. The data collection is done through expert interviews and evaluations of questionnaires. As a result, the most important economic drivers and their structure are identified and further analyzed.

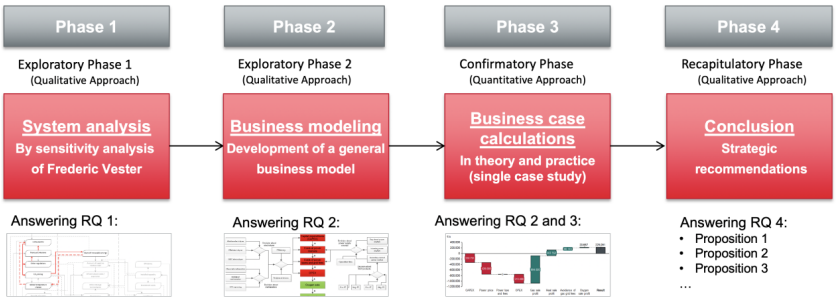


Figure 5: Research methods

Phase two is a second exploratory phase. The research goal is to construct a general BM to answer the first part of the RQ two. Different economic parameters along the value chain are estimated by collecting data from literature, analyses of markets and through conducted surveys. For example, a survey undertaken with producers of electrolyzers and methanation reactors is estimating investment and maintenance costs to add new insights to the existing literature. In the end, the revenue streams are detected, and a general BM is constructed. The construction of the general BM and collection of literature data and execution of surveys are mainly qualitative. But the analyses of power and gas spot markets and possible operation time of PtG plants are done by quantitative methods. The theoretical basis (business model innovation) of this research approach is further explained in chapter 3.2. In this chapter, the theoretical steps of how to build a BM are deduced from literature.

As a third step of the empirical section, the general BM is tested by different theoretical and practical applications. First, different business cases are considered, for example, for different target markets or power purchase concepts. This approach is purely quantitative. Due to many fluctuating parameters at spot markets like gas or power prices, the distribution of the results is shown by using a Monte Carlo simulation and a multivariate bootstrap method, which is explained in chapter 5.5. As a second check of validation, a case study is undertaken to answer RQ three. Therefore, data of an industrial plant is used to feed the general BM. This step quantifies the different

economic parameters in a realistic case. Different power purchase concepts and operation modes are validated at one single event, which adds additional value. The data exploration by a case study is mainly qualitative, but the BM calculations afterward give this step principally a quantitative touch. Due to a few existing industrial PtG plants and data availability, the third RQ can only be answered in one case. The limitations of this scientific work are discussed in chapter 7.3.1. Noticeably, this research is following different methods in each step of the research design. Thus, the mixed methods research approach is chosen. The theoretical background of case studies and their advantages and disadvantages are discussed in chapter 3.3. As a result, a real case BM is evaluated and presented. The emphasis of this theoretical work lies on phase two and three.

Finally, the different results need to be comprehensively interconnected to give an outlook of the further possible technology development and describe strategic options of how to deal with this innovative technology. Qualitative approaches formulate these results from different perspectives. The last phase is a recapitulatory phase.

In total, the dissertation is almost equal driven by qualitative and quantitative methods. The identified timing of the methodology is sequential as the mainly qualitative results are later mainly quantitatively tested wherever possible – later phases depend on the results of the previous phases. Following the taxation of Morse and Niehaus (2009) for mixed method approaches, this dissertation can be seen as: qual → QUAL + quan → QUAN + qual → qual.[57] This means that the first phase is mainly qualitatively, the second phase is primarily qualitative because of the development of a general BM but quantitative spot market considerations take place. In the third phase, the business case calculations are definitely quantitative, although the data collection of the practical testing is done by qualitative case study research. The last phase involves qualitative, strategic recommendations. The writing in the upper and lower case indicates the emphasis of different phases according to this taxation. For that reason, this dissertation follows a sequential exploratory-confirmatory type of the mixed method approach. The sequence is an explorative inquire to construct a general BM and confirmative validation of the finding.

The strength of this research is that a comprehensive understanding of the research phenomena is achieved due to multiple methods. Therefore, a sequential, detailed statement is conciliated to manage the complexity of a technology benchmark, which depends on different drivers. The storyline is simple to follow, and the used research methods are understandable. In addition, the real data of an existing plant is used to verify the results of the previous stages as best as possible. This exploratory-confirmatory approach allows to find answers to the RQs and to give insights into the current and future economic situation of the PtG technology.

57 Morse and Niehaus (2009)

The research structure is further explained in the following figure. According to Oesterle et al. (1992), the structure of scientific research is illustrated. The different parts of the research process have been explained in the present subchapters. The graph is divided into theoretical and practical relevance. However, a rigorous scientific proceeding is defined.

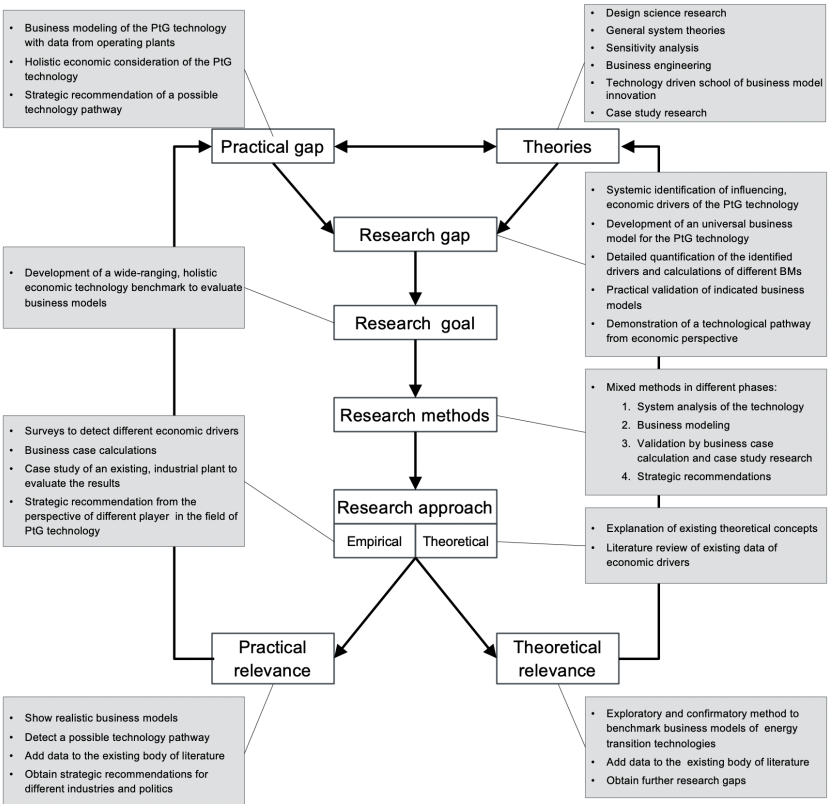


Figure 6: Research structure of this dissertation following the design science research approach[58]

58 Derived from Oesterle et al. (1992), p. 35

2.5 Scientific Framework

The previous subchapters have described the scientific proceeding of this dissertation. This chapter frames the scientific process and validates this concept from the perspective of the philosophy of science. This chapter outlines the epistemological framework that justifies the method described in section 2.4.

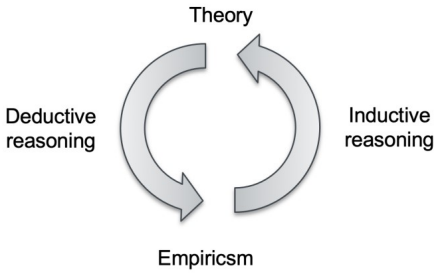


Figure 7: Inductive and deductive reasoning[59]

There are two methods of knowledge building: inductive and deductive reasoning[60]. In the following section, the difference between the two methods is outlined, and the advantages and disadvantages are analyzed.

Inductive reasoning always starts with empirical observations. Guided by these empirical observations, hypotheses are derived. In the history of science, there have been attempts to derive valid hypotheses from observations. The impossibility of this task is called *the induction problem*.[61] The induction problem relates to the following questions: what are enough repetitions of an experiment or observation to build a set of hypotheses? How many boundary conditions have to be assumed? Under which circumstances is an inducted hypothesis scientifically valuable?

Nevertheless, inductive reasoning is needed to derive hypotheses from observations. It is reasonable to ask if there is a better or worse method to derive these hypotheses. Chalmers (2007) proposed the following rules to obtain useful hypotheses. First, the theory has to ground on the highest possible number of repetitions of the experiment. Second, the experiment or observation has to be repeated under different circumstances. Third, none of the identified results have to disagree with the hypothesis.[62]

59 Derived from Chalmers (2007), p. 46

60 Chalmers (2007), p. 46

61 Chalmers (2007), p. 42

62 Chalmers (2007), p. 39

These arguments help to derive useful hypotheses, but nevertheless do not contribute to overcoming the induction problem.

The second method, deductive reasoning, starts with a basic hypothesis (e.g., an axiom, which means a hypothesis that is not derived from another hypothesis but is assumed to be valid). From this basic hypothesis, other propositions can be derived using logic rules. These propositions are then evaluated – falsified or verified – using observations.

On the question of how to overcome the induction problem, Popper (2002) proposes the falsification criteria to differentiate between scientific and no scientific hypotheses: scientific hypotheses need to be falsifiable, which means they can be tested by observations. He states that it is not important how the initial hypothesis is derived from observations. It is more important that hypotheses can be tested and confirmed with observations. He argues that the problem of induction cannot be solved and that the real power of scientific progress is the method of learning from mistakes.[63] In the following section, the argumentation line of Popper is further exposed.

Karl Popper's main work, the *Logic of Scientific Discovery,* gives further tools to achieve a scientific, rigorous level. First, he describes the fundamental way of testing theories: in the beginning, a logical comparison along the theory should be tested to analyze the internal consistency of the tested system. Second, the logical form of the theory is investigated whether it is empirical and scientific or tautological. Third, a comparison with other theories about the scientific advance and at least the testing of empirical applications of the conclusion should be executed.[64] Furthermore, Popper declares that a positive decision of testing theories can only temporarily support the theory, whereas a negative decision is always overthrowing it. For Popper, this is the course of scientific progress, or in other words, every theory, statement, hypothesis, or proposition has "*proved its mettle"* or that it is "*corroborated."*[65]

Second, Popper defines fundamental requirements of theoretical systems or sets of propositions: first, the system has to be free of any contradiction (whether self-contradiction or mutual contradiction). Second, the system must be independent of the deductions of other systems. Third and fourth, the different system propositions should be sufficient for the deduction of all statements belonging to the theory and necessary for the same purpose.[66]

63 Popper (1997), p. 88

64 Popper (2002), p. 9

65 Popper (2002), p. 10

66 Popper (2002), p. 50 f

Third, Popper gives exact definitions of propositions.[67] He argues that a basic proposition must be logically formulated.[68] For example, the phrase *it is raining tomorrow* is not clear. The quote, *it is raining here tomorrow at 4:00 p.m.,* is more precise and further testable. Basic, understandable propositions have an important meaning of Popper's epistemological theory. He describes the following conditions of his propositions: first, from a universal proposition without initial conditions, no further basic proposition can be deduced. As the example above shows, a universal statement like *it is raining tomorrow* is not further deducible. Second, a universal and basic proposition can be contradictory. Therefore, the basic proposition needs a logical form to derive the negation of it.[69]

Fourth, Popper asks himself how and why one theory is accepted over another. He proclaims that the choice of the theory is defined by the competition with others. The theory, which proves itself the fittest to survive, will be most accepted. He further states: "*A theory is a tool which we test by applying it, and which we judge as to its fitness by the result of its application."*[70]

Some philosophers criticized Popper[71] because the history of science has detected that theories can be valuable even if the prediction is wrong initially. Chalmers (2007) is giving a useful collection of historical issues of Popper's falsification. For example, the theory of Copernicus,[72] this has been falsified by the constant size of Venus and Mars with eye-observation at his time. Only the invention of the telescope could prove Copernicus' theory more than a century later.[73] Popper answers back that he assumes the necessity of dogmatism or in his own words: *"If we accept the criticism too quickly we would never discover the real power of the theory."*[74] However, Popper has stated that a theory is a scientific progress that can be adopted and modified. Therefore, his criterion of falsification is nothing fixed or inflexible and would not destroy an entire theory forever. Galileo Galilei has adopted and expanded Copernicus' theory by inventing the telescope and therewith has changed the initial terms and conditions of the origin theory. Johannes Kepler has tested and verified Copernicus' theory later. Interestingly, Popper is using the same example on which he received criticism.[75]

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67 Popper (2002) is hereby switching between different terms: Statements, hypothesis, axioms or propositions. The research object is meant.

68 Popper (2002), p. 81

69 Popper (2002), p. 82 f

70 Popper (2002), p. 91

71 For example, Chalmers (2007), p. 76 ff; Lakatos (1974) p. 137 ff; Feyerabend (1983)

72 The theory of Copernicus states that instead of the earth the sun is the center of the universe.

73 Chalmers (2007), p. 73 ff

74 Popper (1974), p. 55

75 Popper (1997), p. 104 ff

Another argument is that Popper's falsification can just verify the entire theory and cannot declare which part of the theory is wrong. This goes back to Duhem (1978) and Quine (1979), who state in one line with Klee (1997), "*a sensitive appreciation for the epistemological impact of the underdetermination of theory is essentially what killed Popperian falsificationism as a plausible model of science.*"[76] Considering the example above again, it could be possible that Copernicus' methods of measurements, instruments, or calculations were wrong. This argument is right, but it is not depicting Popper's falsification as scientifically incorrect.[77] This dissertation is facing that argument by sampling and testing as much revisable qualitative and quantitative data as possible to strengthen the statements in order to avoid the criticism of the Duhem and Quine theorem.

The last critical argument against Popper's falsification is the definition of the degree of verifiability. What degree is necessary to, for example, confirm astrology or the Marxism as scientifically plausible? Especially in social science, there is often a lack of consistency by testing theories. Even Karl Popper agrees in the chapter of the degree of testability that "*we cannot easily get around this difficulty.*"[78] He is comparing statements concerning their dimensions and their relations. This work is defining the outcomes as consistent and revisable as possible and is testing the constructed proposition (general BM) under different conditions. In the end, it is a psychological issue of acceptance of a theory.

This dissertation is following Poppers' non-stringent definition of scientific correctness and scientific valuable theories or propositions. Popper's logical proceeding of scientific discovery is followed as close as possible. Therefore, the tools of scientific rigor are applied. The constructed general BM should survive Popper's rules of falsification and his criterion of logical formulated statements.

In this thesis, both methods of knowledge generation are used, the inductive as well as deductive reasoning. In the beginning, a system analysis is undertaken to detect the economic parameters of PtG technology. This procedure is corresponding to the development of propositions by inductive reasoning, based on empirical observations from experts. Therefore, a systems dynamics approach is used to formulate evidence-based statements about PtG technology. In a second step, a general BM is constructed from these previously explored economic parameters next to additional data from the literature and own surveys. That BM is then tested by calculations with literature as well as existing data from an operating plant. That last step is corresponding to deductive reasoning that includes the falsification of Karl Popper.

76 Klee (1997)

77 Pengg (2003), p. 65

78 Popper (2002), p. 97

All in all, a coherent, closed picture is generated. This holistic scientific framework is also recommended by many known economic scientists. Gomez and Probst (1995) place emphasis on a multi-disciplinary and multi-perspective problem solving.[79] Beer (1994), Ulrich (1968), Bleicher (2011) and Malik (2013) have recommended and developed practical, adaptive solutions, which are based on pragmatic, scientific realism frameworks. The scientific framework further fits in the DSR approach (see chapter 2.4.1) and methodological course of action (see chapter 2.4.2), which demonstrates a coherent procedure.

Figure 8 is a comprehensive illustration of the scientific framework. It is presenting the four RQs at the bottom. In the center, the research methods are explained that are divided into qualitatively and quantitatively driven approaches. At the top, the scientific foundation is exposed. During the system analysis, the propositions are inductively explored, a general BM is developed, and during the BM case calculations and single case study, the propositions are statistically validated as best as possible. Here the falsification of Karl Popper takes place. The underlying scientific framework, therefore, is the pragmatic, realistic paradigm. All in all, a coherent, validated scientific work is demonstrated.

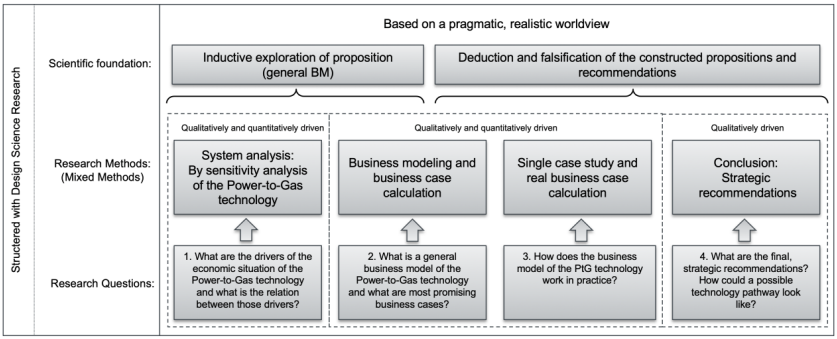


Figure 8: Scientific framework of the dissertation

79 Gomez and Probst (1995), p. 40

3 General Theoretical Section

This chapter includes a theoretical discussion about the three methodological steps of this dissertation. In addition, the line of action of each research approach is explained in detail. Reasons for why this proceeding has been chosen are also highlighted. First, the system theory is in focus. Here the general system theory is described to explain the theoretical course of action of Vester's system analysis. Second, the theory of business model innovations is discussed to enlighten the theoretical background of constructing a general BM for PtG technology. Third, a case study research as a methodological approach is presented and advantages as well as disadvantages of this approach are discussed. In the end, the used theories are deduced and rationalized.

3.1 System Theory and Frederic Vester's Sensitivity Model

The first research interest is to find economic key drivers of the PtG technology. Due to the complex and nested relations between the economic drivers of energy technologies, a system analysis is recommended.[80] This is in line with the system-oriented management, according to Ulrich (1968), Beer (1994), Bleicher (1991) and Malik (2013). Ulrich (1968) defines management as the configuration and navigation in a sociotechnical system.[81] As a sociotechnical system, the holistic, cybernetic entity can be determined. Vester (2012) describes systems as the ensemble that consist of different parts, which are dynamically interlinked to each other.[82] Stafford Beer (1995) states that a system consists of a group of elements dynamically related in time according to some coherent pattern.[83] For example, the energy system can be identified as a subsystem of the holistic socio-technical system. The system analysis is an important aspect to analyze the research phenomena comprehensively.

The system-oriented management builds upon the general systems theory, which goes back to biologist Ludwig von Bertalanffy in the early 20th century.[84] Gassmann et al. (2015) call this theory an investigation of complex entities and the creation of models[85] to describe the same. Further on, they stated that systems could generally be described as open, dynamic, and goal-orientated artifacts that interact with their environment and continually evolve. And it is a holistic analysis of arrangement, relation and structure of the systems' constituting elements (e.g., in- and output, system-

80 Vester (2012), p. 30

81 Ulrich (1968)

82 Vester (2012), p. 25

83 Beer (1994), p. 7

84 Gassmann et al. (2015), p. 50

85 A model in this case is defined as an illustration of the perceived reality. It describes systems with all necessary objects and their relations but in a simplified way. It consists of quantitative data like mathematic models or also qualitative statements like interdependencies between objects.

environmental-boundary, process, state, the hierarchy of constituting elements, goal-directedness and information flows, etc.).[86] The necessity of a system analysis, when dealing with complex systems, is emphasized by several authors including Fredmund Malik.[87] This dissertation is using tools of systems analysis like the sensitivity analysis from Frederic Vester to investigate the PtG technology. Among other topics, the influencing parameters of the economics of PtG are deduced from the findings in the systems.

Therefore, a system is characterized by the system boundaries, identification of parts and elements of the system and determination of the intensity and direction of influencing parameters.[88] It is important to mention that a system description is depending on the observer's perspective and on his defined targets and objects. Beer (1994) adds, *"a system is not something given in nature, but something defined by intelligence."*[89] A system can be open and influenced by external forces. Most of the systems are complex with a high degree of internal and external influencing parameters as weather systems, animal habits, or developments at spot markets, for example. Even enterprises, business units or technologies can be interpreted as complex systems and, therefore, analyzed with tools of system analysis. The superior target of a complex system is often the survivability in an environment. For that reason, Malik (2013) understands *"the ability to adapt changes in the environment, collect and utilize experience and to keep its identity"* as the primary survival criterion of a system.[90]

It is the same in economic systems. If the environment changes (e.g., in case of the energy transition), the energy system must adopt these conditions and transform itself. In this case, complex systems are often seeking stable situations. A simple example is a predator-prey relationship. If the predator dominates in a closed system, the predator will reduce his food stock. In that case, the population of predators would stop, and the population of preys will recover.[91] These biological ecosystems consist of control loops, stabilizing effects, and reference inputs. Also, economic systems can be described with these self-regulating instruments. Innovations, for example, new technologies of energy supply, have shown a similar pattern. Wood got substituted by coal, coal in turn by oil, gas and nuclear power and it appears possible that REs like wind, solar or biomass are yet other substitutions.[92]

86 Gassmann et al. (2015), p. 50

87 Malik (2013), p. 22 ff

88 Pengg (2003), p. 55

89 Beer (1994), p. 7

90 Malik (2013), p. 80 ff

91 Vester (2012), p. 158 ff

92 Modis (2009), p. 15

Models are useful to simplify a complex system and to avoid assessment of unnecessary information. Therefore, a model is a detailed scope or illustration of the perceived reality. It enables a further detailed investigation of a topic. Pengg (2003) in line with Beer (1994) is introducing the mathematical term of homomorphism to explain useful models. A homomorphous model consists of elements of a system, which have the same structure and behavior as the elements in the entire system. In this dissertation, an analogous (business) model of PtG is constructed following the sensitivity model from Frederic Vester, which is explained step-by-step in chapter 3.1 and executed in chapter 5.

In the end, this dissertation is adding a practical example to an existing sample of general system theory literature and a system analysis in the field of innovation and technology management, which support the scientific rigorousness as explained in the previous chapters. The results of this approach will help to answer RQ one by identifying the most important economic drivers of the PtG technology.

The sensitivity analysis from Vester (2012) is a practical application of the general systems theory. Professor Vester was a German biochemist and system researcher. He has been a professor for ecology at the University of St. Gallen from 1989 to 1991. He described his way of action in his book *The Art of Interconnected Thinking*[93]. The scientific goal is to analyze the system dynamics, elaborate key economic parameters and their relations to each other. The methodology of Vester's sensitivity model is followed because it is a well-described cybernetic tool of more than 30 years of practical experience. This model has been successfully applied for energy systems and technology management[94] as well as in the transportation sector.[95] The proceeding achieves comprehensible qualitative results, even with a small number of participants. For these reasons, this model is chosen as a basic tool of system analysis.

The course of action of Vester's analysis in preparation for the empirical part is explained in this chapter. This method goes back to the early pioneers of cybernetics like W. Ross Ashby and Jay W. Forrester.[96] According to Vester, the sensitivity analysis aims at describing and visualizing complex systems and their dynamics.[97] The methodology is divided into nine stages, in which the first seven stages are followed in the

93 Vester (2012)

94 See Schlange (1993) and Habersatter (1998)

95 See Riegel (1995) and Brabänder (1996)

96 See Ashby (1956) and Forrester (1961)

97 Vester (2012), p. 185 ff

system analysis. The last two steps are part of the overall conclusion. The single steps have to be undertaken with an expert group.[98]

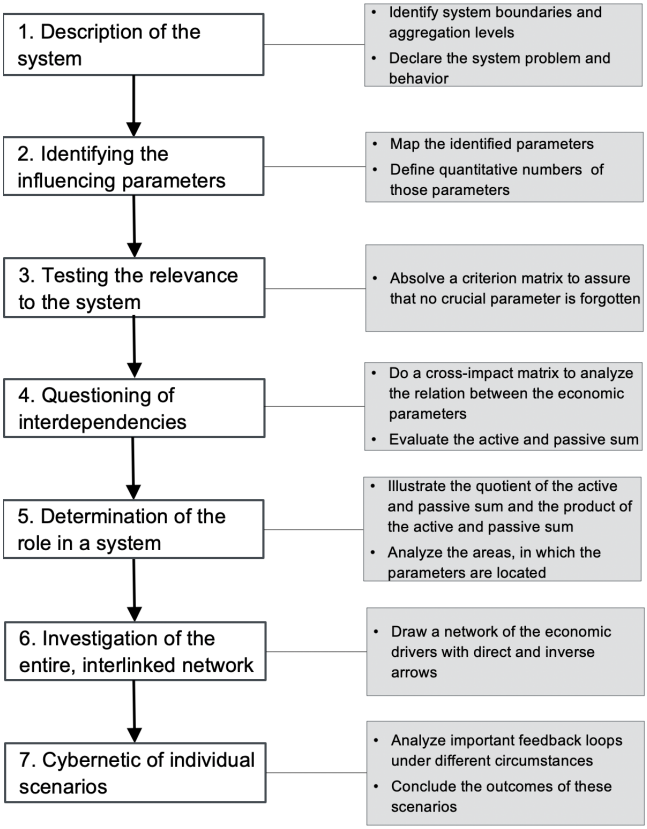


Figure 9: Methodological steps of Vester's sensitivity analysis[99]

The first step of Vester's methodology is an independent system description to identify the system boundaries and aggregation levels. Helpful questions are: what is the systemic problem? What can be done to solve this problem? What is related to this problem? Who is against solving this problem? What is balancing the system? What are

98 In this study different experts are asked to achieve a coherent picture and to analyze the economic situation of the PtG technology. In different workshops in different companies and research projects experts have been consulted. The results are checked in multiped stages following the Delphi-method.

99 Vester (2012), p. 203 to 263

the system characteristics?[100] Therefore, it is recommended to take the position of all market participants.[101]

The second methodological step seeks to identify and map different influencing parameters. Vester (2012) defines parameters or variables as particular quantities, whose interdependencies are determining the system dynamics.[102] Parameters have to be variable to indicate a direction. For example, the term *management* is not variable, but the term *efficiency of management* can increase or decrease and is, therefore, a more suitable parameter. This is in line with Poppers criterion of further testable statements (see chapter 2.5). The different parameters are divided into different levels of the system. The target of this second step is to collect a list of necessary parameters to build the cybernetic model. An ideal number of variables is 20 to 40.[103] Wherever possible parameters are mapped in groups. For example, all parameters that belong to the energy system like the power price at different markets, can be grouped together. The criterion hereby is that the group parameter involves all dynamics of the single parameters.

Third, Vester (2012) is offering tools to check the relevance of the discovered parameters. He recommends a criterion matrix to check if parameters of all necessary categorizations are included.[104] A first categorization is the so-called *area of life*, which includes participants, activities, regions, human or social conditions, environmental relations, infrastructure, and regulations. The more parameters from different areas are included, the higher is their relevance to the system. This is the first test of relevance of the identified parameters. A second group is the *physical categorization* that consists of material, energy, and information streams. The third group identifies the *dynamic relevance* to the system like floating or structural quantities and temporal or regional dynamics. The last group is sampling *system-related parameters* as parameters, which are opening the system through in- or output, as well as parameters with internal or external influences. In sum, the testing of relevance to the system makes sure that no crucial parameter is missing and helps to analyze the investigated system more broadly. This approach again is absolved with the expert group.

Fourth, as a next methodological step, a cross-impact-matrix is questioning interdependencies of the detected parameters. So far, the content and description of different system components have been developed. Now the relation between the drivers is on focus. For that reason, the impact of each parameter on the others is benchmarked. The scale is: three for strong, disproportionate relation; two for middle, proportionate

100 Vester (2012), p. 206

101 Pengg (2003), p. 209

102 Vester (2012), p. 213

103 Vester (2012), p. 225

104 Vester (2012), p. 219 ff

relation; one for weak relation and zero for no relation. The influence of the relation is measured in both directions.

Fifth, in the next step, the quotient and product of the sum of each row and column from the fourth step are taken into account to detect the role of each parameter within the system. The sum of a row is presenting the active character of a parameter because with a high number, this parameter is influencing other parameters. The sum of a column of a parameter is presenting the passive sum because with a high number, this parameter is influenced by a lot of other parameters. The quotient of the active and passive sum is identifying the active or reactive character of each parameter. Otherwise, the product of the active and passive sum is determining the influence of each parameter in a system. The resulting graph is divided into different areas and displayed below. The upper left area displays a high quotient of the active and passive sum and, therefore, an active character. The lower, right plain shows the opposite result and, therefore, a reactive character. In the area between those lines the parameters are neither active nor reactive. In addition, if an active character has a high product sum and, therefore, a strong influence on the system, it is displayed in the upper, right area. These parameters are critical to the system and need further consideration. Changes in these parameters have a major impact and can endanger the survivability of the whole system.[105] The following illustration is highlighting this methodological step. In chapter four, this step will be undertaken with the expert group of the PtG technology.

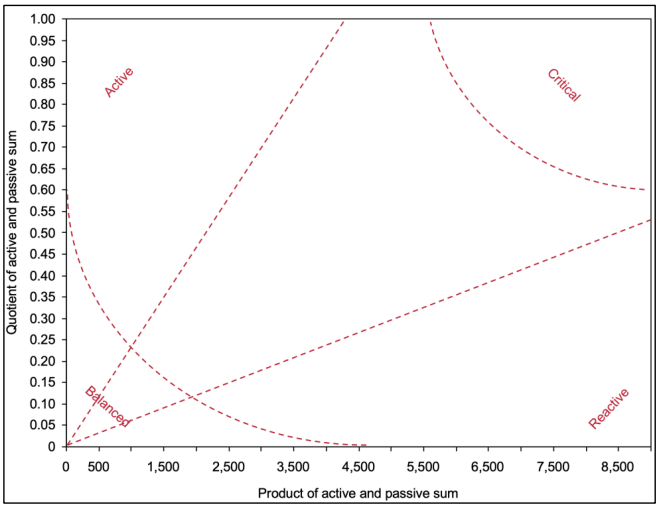


Figure 10: Illustration of a cross-impact-matrix following Vester's sensitivity analysis

[105] Vester (2012), p. 235

Sixth, in the following step, the direction of the impact of different parameters is investigated, and first graphical maps of the entire interlinked network are designed. For that reason, a control loop analysis is undertaken. Hereby each relation of the cross-impact matrix is illustrated. An impact in the same direction is displayed with a continuous arrow. For example, more traffic leads to a higher number of streets. A dashed line symbolizes the opposite direction. For example, subsidies for public transportation leads to lower traffic. Both examples are shown below.

Seventh, in this approach, single scenarios within the system that are mentioned from the expert group, are identified for a better overall understanding of the system behavior as well as a system check. Single scenarios have an important character to describe the dynamics in a system. The two following stages, *if-the-prognosis and policy-tests*, as well as a benchmark of the system and strategic recommendations, are included in the overall conclusion of this thesis.

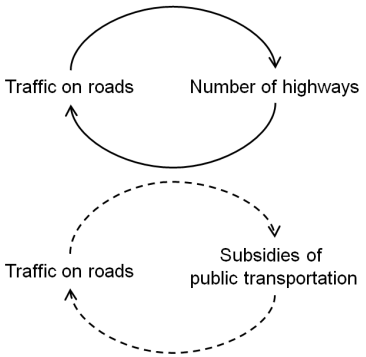


Figure 11: Illustration of positive and negative control loops[106]

Further, Vester (2012) defines eight rules for biocybernetic systems, which are avoiding system crashes and, therefore, are supporting the survivability of the system.[107] First, negative feedback has to dominate positive feedback loops. Positive feedback is self-energizing and keeps the system running. Negative feedback has a stabilizing property. The balance of positive and negative feedback of a system is characterizing the dynamic equilibrium. An example is the predator-prey relationship again. If the predator is fast and gets a lot of prey animals, he will get fat and slow, and the population of prey will recover. This simple market mechanism of supply and demand is transferred to energy technologies. For example, if there is a lot of cheap energy in certain hours, storage technologies have a business case until enough facilities are

106 Examples are taken from Pengg (2003), p. 215 f

107 Vester (2012), p. 157 to 172

built, and the market for surplus energy is satisfied. However, this self-stabilizing component is part of many ecosystems.

Second, the system must be independent of quantitative growth. Vester quotes that the amount of energy and material in a holistic system is constant. Because of the stabilizing effect of positive and negative feedback loops, exponential growth has to be avoided. The growth dependency is endangering the survivability. Vester argues that growth has to take place in metamorphic steps with innovations and restructurings of the entire system. A simple example here is the productivity growth in agriculture. The production area is limited, and climate circumstances are nearly constant in long-term perspective, therefore, new production methods have increased the production rate. According to the German farmers' association one farmer has fed four people in the year 1900. In 2017, one farmer has fed up to 140 people in average[108]. That displays a high growth rate with constant use of land by technical innovations.

Third, the system must be function-oriented rather than product-oriented. Vester states that the focus and priority have to be the functional capability. This leads to the necessary flexibility to react to environmental changes. If an automotive company is just focusing on manufacturing products, a change in mobility behavior could endanger this organization. If the automotive company is concentrated on delivering mobility solutions, it can remain flexible.

Fourth, the system should use existing energy. Vester's opinion is that the steering of existing energy is more efficient than the generation of additional energy. From a global perspective, a lot of RE stays unused in different regions because an energy converting technology (e.g., PtX), which make energy storable and transportable, is not available yet.

Fifth, multiple usage is reducing energetic, material, and informational efforts. Also, multiple usage is decreasing the system complexity and is increasing efficiency but requires cross-sectoral thinking. For example, a car can be used as a transportation medium as well as an energy storage system in the future by using synthetic fuels or feeding electricity back into the grid.

Sixth, the system should use a circular economy. Vester refers to the usage of recycling and closed systems, in which the input and output streams are merging. This is reducing irreversibility and dependency. As mentioned in the introduction, the PtG technology is recycling carbon dioxide to a fuel, which can be utilized again. It demonstrates a closed system.

Seventh, mutual usage of differences through coupling and exchange. Vester supposes the usage of symbiotic processes here, which is a critical element of natural ecosystems.

[108] Pascher et al. (2019), p. 17

Eighth, biological design of systems. Herewith Vester proclaims the orientation at biological processes. A biological design of products, methods and organizations leads to easy implementation of these bio cybernetic rules.

The identification and explanation of these rules for the PtG technology take place in chapter four. The seven stages of Vester's sensitivity model are conducted in separate chapters. The advantages of this action are the fixed course of action, reproducible of results, verification and qualitative statements as well as possible repetitions with different expert groups. The disadvantages are missing quantitative statements, a fixed temporal consideration and a limited number of experts with potentially subjective opinions. To overcome these issues, quantitative approaches like the business case calculations follow to check the influence and relation of different economic drivers logically. However, due to the detailed course of action of Vester's systemic approach, RQ one (*What are the drivers of the economic situation of the Power-to-Gas technology and what is the relation between those drivers?*) will be answered in the empirical section.

3.2 Business Model Innovation

The further purpose of this research is to analyze the economic situation of PtG, which includes the identification of possible business cases and technology pathways. Therefore, this dissertation is presenting a key model of how to benchmark business innovations like PtG in a complex and changing environment. This proceeding is intricately linked to topics treated in innovation and technology management. One of the key questions thereby is: *how to commercialize technologies or innovations?* Chesbrough and Rosenbloom (2002) tackle this question by their *business modeling for innovations,* building a bridge between the technical invention and the economic value. Chesbrough points out that technology by itself has no objective value[109] and a BM is a way to commercialize novel technology.[110] This is in line with Gassmann et al. (2013), who quote that business model innovation is about to *"create value and capture value."*[111] Chesbrough and Rosenbloom (2002) define BMs as a *"mediating construct between technology and economic value."*[112] Amit and Zott (2002) proclaim that a BM depicts *"the content, structure, and governance of transactions designed to create value through the exploitation of business opportunities."*[113] Teece (2010) states that *"a business model articulates the logic, the data and other evidence that support a value proposition for the customer, and a viable structure of revenues and costs for the*

109 Chesbrough (2010), p. 354

110 Gassmann et al. (2015), p. 14

111 Gassmann et al. (2013), p. 10

112 Chesbrough and Rosenbloom (2002), p. 532

113 Amin and Zott (2001), p. 511

enterprise delivering that value."[114] However, the analysis of a sufficient BM and possible business cases is important to achieve insights into the economic situation of the PtG technology.

The analysis of BM innovations gives answers to the questions who (customer group), what (customer values or value proposition), how (activities and processes along the value chain) and why (profit generation, revenue model) and, therefore, tells the systemic story of a business.[115] These questions are answered by building a general BM and calculating their revenues.

New technologies need appropriate BMs. The list of innovative technologies, which have failed because of the missing business model innovations, is quite long. For example, the Fraunhofer Institute for integrated circuits has primarily invented and developed the audio coding format mp3, which has achieved a considerable data compression compared to other audio formats.[116] But Steve Jobs and Apple Inc. with their portable audio players and iTunes have made this technology economically profitable.[117] They found an appropriate BM for that invention. Another example is Xerox Corporation. This case has been studied by Chesbrough (2010). Xerox was known for industry-leading printers in the 1980s. They focused on fast and high-quality printing machines. They missed the market of low-speed personal copiers, which used a different BM concept like the *razor and blade* effect.[118] Here the sale of the toners, which only fit in the company's machine, is funding the printer over a lifetime. Chesbrough found other examples of missed commercialization's of innovations in the history of Xerox like the invention of the eternal network connection.[119] These examples show that the identification and analysis of different BMs are essential. According to Chesbrough and Rosenbloom (2002), *"firms have great difficulty managing innovations that fall outside of their previous experience, where their earlier beliefs and practices do not apply*. The reason, therefore, is a *"dominant logic of heuristic rules, norms and beliefs that managers create to guide their actions and path-dependency on their previous experiences."*[120]

There are several schools or scientific movements of business model innovation, which provide helpful instruments to analyze and value businesses. Gassmann et al. (2015), for example, give an overview of existing schools and their underlying theoretical

114 Teece (2010), p. 179

115 Gassmann et al. (2015), p. 3 f

116 Rose (2016)

117 Gassmann et al. (2013), p. 11

118 See also Gassmann et al. (2013), p. 19

119 Chesbrough (2010), p. 356

120 Chesbrough and Rosenbloom (2002), p. 531

background. The different approaches of the schools, which are likely to help to answer the second RQ, are further discussed.

First, the activity system school of BM innovation is presented by the research group around Raphael Amit and Christoph Zott. They define four different design themes of business model innovation: novelty (Schumpeterian innovation[121]), complementarities (bundling of different facilities or features), lock-in (incentivize customers to repeat transactions) and efficiency (foster transactions).[122] The firm's activity system in terms of content, structure and government is in focus. This focus is identical to the analysis of the activity system of the PtG invention, which is undertaken in this dissertation. The theoretical basis is the resource-based view like dynamic capabilities[123] and transaction costs economics[124]. According to Gassmann et al. (2015), this is the widest accepted framework of business model innovation within academia.

Second, the process school of Demil and Lecoq (2010) is structuring BMs according to sources of revenue and cost drivers. Therefore, they stress the dynamics that affect the development of a BM within a firm.[125] They developed a framework, which consists of resources and competencies, organization pattern and value proposition.[126] The authors argue that BMs are in a *"permanent disequilibrium"* trying to adopt or eliminate inefficiencies and improving the exploitation of resources.[127] This research stream contributes to a more holistic view by combining static and dynamic approaches. This is a relevant fact as this work obtains a BM with different dynamic relations between the economic drivers. This school follows rather cognitive theories.[128]

121 Schumpeter (1912) defines innovation as a recombination of new products, new production methods, new revenue markets, new reference source and new market positions.

122 Zott et al. (2010), p. 15

123 See Teece et al. (1997)

124 Gassmann et al. (2015), p. 22

125 Gassmann et al. (2015), p. 10

126 Demil and Lecoq (2010), p. 234

127 Demil and Lecoq (2010), p. 240

128 Gassmann et. al. (2015), p. 22

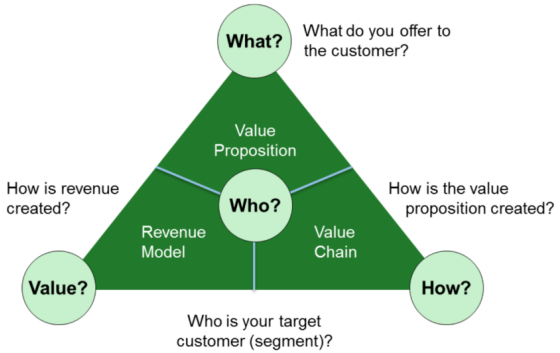


Figure 12: Triangle of the recombination school[129]

Third, the recombination school from Oliver Gassmann, Karolin Frankenberg, and Michaela Csik structured BMs along with the questions of what, why, who and how, which has been mentioned above. This research approach has been developed at the University of St. Gallen.[130] They achieved to show that 90% of all BMs fit in 55 repetitive patterns.[131] Therefore, these patterns can be applied to design new BMs. Hence, this approach is very practitioner-oriented and, therefore, suits this dissertation. The scientific basics are network theories as well as the design-thinking approach.[132]

Fourth, Henry Chesbrough, as a professor for innovation at the University of California Berkeley, developed the technology-driven school of business model innovation. This research group tries to identify the value creation for the customer and how the BM is delivering that value.[133] They quote that the cognitive challenge is to link the *"physical and economic domain in the face of great technical and market uncertainties because of the richness and complexity of each domain."*[134] The technology-driven school is focusing on entirely new models and coined the term of *open business innovation.*[135] Therefore, this school fits the development of a BM for PtG technology as a new technology of the energy transition.

This thesis is investigating potential business cases of the PtG technology by following the six steps of the technology-driven school and taking into account the emphasis of

129 Gassmann et. al. (2015), p. 18

130 Gassmann et al. (2013), p. 17

131 Gassmann et al. (2013), p. 17

132 Gassmann et. al. (2015), p. 23 and Gassmann et al. (2013), p. 16

133 Gassmann et al. (2015), p. 14

134 Chesbrough and Rosenbloom (2002), p. 536

135 Gassmann et al. (2015), p. 22

other schools of business model innovation, wherever possible. With this, also the questions of the recombination school are answered, and the processes between the economic drivers are shown. Findings from the previous stage (system analysis) with respect to the value propositions, market participants and revenue streams are used wherever possible. The activity as well as the process school of BM innovations fit more to existing corporations with established organizations.

The technology-driven school of business model innovation has developed six functions[136] to describe the properties of a BM. The last function is answered in the overall conclusion. The functions are displayed in Figure 13. In the first step, the value proposition is announced. Therefore, the products of the PtG technology will be described to analyze the contribution of this innovation. Second, according to different value propositions, different target markets will be claimed, on which the PtG technology can participate. At these target markets, the revenue mechanism in terms of sale price and price development will be investigated. Third, the description of the value chain is an important step of the thesis. Due to several expected economic drivers, the complexity of the value chain is high. Each parameter along the value chain has to be described and quantified. This is done by literature review, market analyses, and industrial surveys that are conducted during this work. With these findings, a revenue model is generated. The revenue formula includes all costs and yields of the value chain. A discounted cash flow model is delivering quantitative results of each business case. Due to fluctuating economic drivers like power prices or sale prices, the statistic distribution is taken into account. In the end, business modeling is producing different cases with individual probabilities of occurrence. Therefore, also, a risk analysis is included. In addition, the value network is considered. The last step is part of the overall conclusion.

In the following sections, the discovered potential business cases are calculated and later applied in the case study. Chapter five in the empirical section is divided into the different steps following the technology-driven school from Chesbrough. RQ two (*What is a general business model of the Power-to-Gas technology and what are the most promising business cases?)* is answered with this approach by building a revenue model and business case calculations.

"Often the physical domain is well defined with hard facts – especially if the technology reached an industrial scale – but the economic domain has vague and unclear variables."[137] In line with this statement, this approach aims at shedding light on the unclear economic situation of the PtG technology.

[136] Functions, in this case, are defined as methodological steps to build a business model.

[137] Gassmann et al. (2015), p. 14

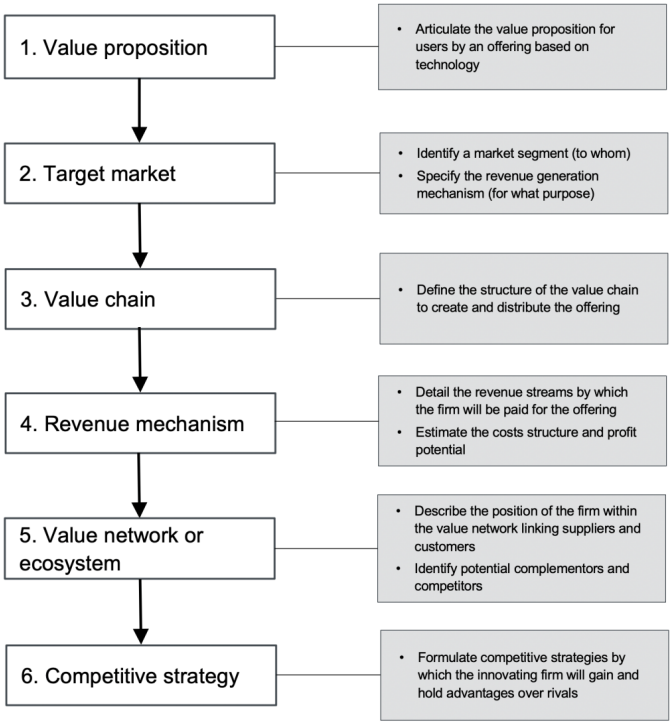


Figure 13: Six functions of the technology-driven school of business model innovation[138]

3.3 Case Study Research

In the end, the indicated BM is analyzed in real settings and tested on whether it can be applied or not. As mentioned before, due to less existing industrial plants, this research approach has no claim to be complete and to answer the RQ three under all possible circumstances. However, this methodological step is undertaken by case study research. This is in line with Robert K. Yin, who quotes that *"case study allows an investigation to retain the holistic and meaningful characteristics of a real-life event."*[139]

Case study research is defined as *"an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between*

[138] Chesbrough (2007), p. 13

[139] Yin (1994), p. 3

phenomenon and context are not clearly evident."[140] Eisenhardt (1989) defines case studies as a *"research strategy, which focuses on understanding the dynamics present within single settings."*[141] This is in line with Gerring (2004), who states, *"I propose to define the case study as an intensive study of a single unit for the purpose of understanding a larger class of (similar) units."*[142]

Case study research can include qualitative as well as quantitative methods that are exploratory, descriptive or explanatory.[143] These research methods intend to answer RQs beginning with *how* or *why*.[144] For this research context, the following question applies: how does the business model of the PtG technology work in practice?

Following Yin (1994), a case study is recommended if the research topic is less investigated and consists of unclear parameters[145] or according to Punch (1998), *"the goal of the case study analysis is to analyze one case of a small number of cases in detail to gain depth and comprehensive knowledge."*[146]

Although usually experimental research is used to test hypotheses, this research is using case study research to dive into a single case and to apply the BM with different parameters without a laboratory environment. Case studies have been used to test theories in different cases.[147] Yin (1994) differs in his view as in that case study research is used if the research requires control over behavioral events.[148] He quotes *"an experiment for plant, deliberately divorces a phenomenon from its context, so that attention can be focused on only a few variables"*[149] and further, *"the most important is to explain the causal links in real-life interventions that are too complex for the experimental surveyor strategies."*[150] Due to a missing laboratory environment like permanent observation and control about all data and variables, a case study with interviews and data analysis seems more reasonable.

The case of this approach is an industrial PtG plant, which is operated by a car manufacturer. More information about the plant will be described in the empirical section. Additional cases at different plants are not analyzed because of data availability.

140 Yin (1994), p. 13

141 Eisenhardt (1989), p. 534

142 Gerring (2004), p. 342

143 Eisenhardt (1989), p. 534 and 535 and Yin (1994), p. 3

144 Yin (1994), p. 6

145 Yin (1994)

146 Hinz (2012), p. 50

147 E.g., Pinfield (1986) or Anderson (1983)

148 Yin (1994), p. 6

149 Yin (1994), p. 13

150 Yin (1994), p. 15

Therefore again, different business cases with different power purchase concepts are only tested at one site and are only validating the theoretical results for this case. The data is collected from interviews and documentation of the research project WOMBAT, which has been taken place at this site for three years. Therefore, the data is taken from different sources. All input data is displayed in tables and protocolled for later analysis.

According to Yin (1994), a case study research design consists of five components.[151] First, the study's questions, which are mentioned in chapter 2.2. Second, the propositions of the case study, which are the scope of the study. In this case, the constructed BM and their outcomes are in scope and are investigated within the case study. Third, the units of analysis have been defined to set system boundaries and to identify the detailed scope of the research. In this case study, the investigated PtG plant is defined as one case and the different business cases, which are applied to the PtG plant, are presented as the units of analysis. Fourth, the logic linking the data to the propositions and, fifth, the criteria for interpreting the findings are important. The data linkage is done by comparing the value chain of the theoretical business cases with the real case. Each input parameter is considered and set in relation to each other. Hence, the comparison of the outcomes is the interpretation of the findings. Statements for different business cases can be given. All in all, the five components of case study research following Yin (1994) will be conducted and presented in the empirical part in chapter 6.2.

Yin (1994) is also setting criteria for judging the quality of the research design.[152] He defines four criteria. First, validity needs to be constructed. Therefore, multiple sources of evidence, a well-established chain of evidence, and a key information case study report are recommended. Second, internal validity needs to be tested, especially in explanatory case studies. Yin (1994) is preferring tactics like pattern-matching, explanation-building and time-series analysis. This data analysis is also done for different parameters during the system analysis and business modeling.

Third, external validity needs to be checked by using replications in multiple-case studies. This will not be undertaken in this research and represents a further research limitation (see chapter 7.3.1). Due to the limited accessibility of data and the small number of installed industrial scale PtG plants, the research is only undertaken in one case. Virtual plants have been analyzed by calculating different business cases. It is scientifically advisable to test the findings of this research at other plants in the future to overcome the pitfall of missing generalization of case study research.[153] Therefore,

151 Yin (1994), p. 20 to 27

152 Yin (1994), p. 32 to 38

153 Yin (1994), p. 10

further case studies are proposed in the research recommendations (see chapter 7.3.2).

And at least the reliability is on purpose. Therefore, the construction (theoretical section), the execution and interpretation (empirical section) needs to be protocolled and a database developed. All data can be requested and is available. Another criterion of research quality is subjectivity by collecting and analyzing data. Hayek (1979) proclaims that one needs to *"distinguish between the views held by the people which are the object of the study and one's views about them, but also of the fact that the people who are the object themselves not only are motivated by ideas but also form ideas about the undersigned result of their actions"* in social science.[154] That means that data collection must be as objective as possible and has to include data from different sources with different perspectives. This is another weakness of a single case study.

Case studies can be designed in single or multiple-cases as well as single or multiple units.[155] Yin (1994) proclaims that single case studies are appropriate to test a well-formulated theory: *"To confirm, challenge, or extend a theory's propositions are correct or whether some alternative set of explanations might be more relevant."*[156] In addition, Yin (1994) recommends single case studies if the case is extreme, unique, or revelatory. This is the case in this research due to the first detailed, economic PtG case study. In this case, the investigator has the *"opportunity to observe and analyze a phenomenon previously inaccessible to scientific investigations."*[157] Within a single case study, a single event or embedded multiple events can be further investigated. Yin (1994) recommends subunits to avoid misrepresentations and shifts away from the research phenomena.[158] But with embedded designs, it is important also to return to the larger unit of analysis and not to focus too much on these subunits.[159] Multiple case studies are reasonable to compare different outcomes or sites. The results are more compelling and robust.[160] There are strengths in evidence due to replications. A cross-case study could indicate that the BM is working at different sites. However, due to the unique revelatory case and different expected business cases, this inquiry is using the single case multiple-unit analysis. This allows an in-depth analysis of the investigated technology and a comparison between different subunits. A multiple-case study is further recommended, as already mentioned.

154 Hayek (1979), p. 62

155 Yin (1994), p. 38 ff

156 Yin (1994), p. 38

157 Yin (1994), p. 39 f

158 Yin (1994), p. 42

159 Yin (1994), p. 44

160 Yin (1994), p. 45

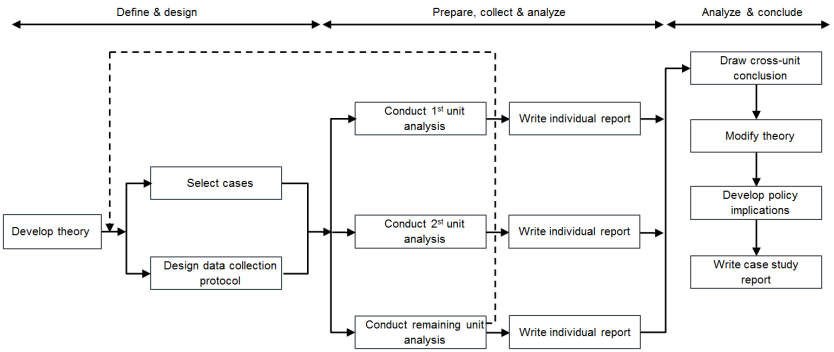


Figure 14: Case study design[161]

Figure 14 is illustrating the case study design. It is following Yin (1994) with a single case multiple-unit analysis. The developed theory comes from the constructed BM. The case selection takes part in the empirical section (see chapter 6.2.1). The different unit analysis is empirically evaluated in chapter 6.2.2. Individual reports and cross-unit conclusions are formulated in chapter 6.2.3. The constructed and yet tested BM is further modified. All in all, the case study approach allows to test and develop business cases of the PtG technology further.

3.4 Business Modeling of the PtG Technology

As a conclusion of the theoretical chapters, a general model of how to develop a BM of the PtG technology can be exposed and tested. This three-step model can be also adopted for future business case considerations of energy storage plants like PtL plants. In a comprehensive way, the course of action is explained.

In the beginning, a system analysis is recommended. This is important to set the system's boundaries and to identify all relevant economic drivers and participating parties. Under different circumstances like other countries with varying systems of energy and political regulations, a PtX BM could look different. Therefore, first, the system, in which the case is embedded, has to be analyzed. A useful concept is Vester's sensitivity model, which has been explained. The advantage of this approach is that it is checking whether the PtG unit is fitting into the energy system or if the whole system performance is improved. Therefore, the relation and determination of single economic drivers are investigated. This practice gives important insights into the revenue model of the business case calculation later. The proceeding has to be performed with an expert

[161] Yin (1994), p. 49

group. However, because of the necessary identification of system components and different circumstances in different regions, a system analysis is recommended.

Second, business modeling is on focus. This step has been explained in chapter 3.2 in theory. Although this dissertation is following the technology-driven school of business model innovation, which has been mainly shaped by Chesbrough, it also includes other aspects of business model innovation. This mainly qualitative approach is analyzing target markets, the value chain, and interactions within the ecosystem. In the end, a revenue mechanism is exposed and can be adopted in the third session.

Third, the developed BM has to be validated as appropriate as possible. Therefore, two methods are suggested. On the one hand, a theoretical check of consistency and reproducibility of the BM by calculations of different cases. And on the other hand, practical testing with a single case study of an industrial scale PtG plant. Both methods are demonstrating whether the BM is working theoretically and practically. In the end, strategic recommendations for relevant stakeholders of this technology are deduced.

System analysis

Recommended method	Methodological steps	Contribution
Vester's sensitivity model • A method to analyze systems with an expert group	1. Description of the system 2. Identifying the influencing parameters 3. Testing the relevance to the system 4. Questioning of interdependencies 5. Determination of the role in a system 6. Investigation of the entire, interlinked network 7. Cybernetic of individual scenarios	• Setting of system boundaries • Identification of economic drivers • Insights of an expert group

Business modeling

Recommended method	Methodological steps	Contribution
Chesbroughs technology school of business model innovation • Qualitative approach to develop the revenue mechanism	1. Definition of the value proposition 2. Identification of target markets 3. Development of the value chain 4. Deduction of the revenue mechanism 5. Investigation of the value network or ecosystem 6. (Competitive strategy)	• Step by step analysis of business modeling and influencing parameters • Detailed literature review for single economic parameters • Execution of industrial surveys to expand the existing body of literature with further data

Validation of the business model

Recommended methods	Methodological steps	Contribution
• Quantitative business case calculations • Case study research	• Calculation of the revenue stream with different parameters • Conduction of a single case study (selection, conduction, reporting, cross-unit check)	• Reproducible business case calculations • Practical testing of the business model in a single case study

Figure 15: Business modeling the PtG technology

4 System Analysis

This chapter is analyzing the PtG technology with a systemic approach and is answering the first RQ (*What are the drivers of the economic situation of the Power-to-Gas technology and what is the relation between those drivers?)*. The system analysis is carried out in a sensitivity model, which puts further research on influencing factors of the PtG technology. This empirical approach is following Vester's first seven stages. The single steps of Vester's sensitivity model are executed by following the descriptions of Vester (2012) without using the software package or the expertise of the developers of this tool.

The expert group consists of members from the automotive and energy industry as well as mechanical engineers from companies, which are developing components of the PtG technology. These experts have closely followed the dissertation. In a Delphi method, these experts are frequently asked if all system parameters of the PtG technology in the energy system are mentioned and described in the right context. In Delphi methods, the predictions remain anonymous to allow the free expression of opinions. Delphi methods are widely used in social science. A Google Scholar search of the term "Delphi" delivers 367,000 results from the year 2000 to 2020. Abramowicz (2004) assumed that the Delphi method only requires five to 20 experts and, therefore, is superior to thin markets, in which revealed information is weak. The PtG technology in its early, pre-industrial technology stage can be considered as a thin market. Thus, the number of experts for this system analysis is in this range. A drawback of the chosen expert panel is that all experts are from Germany, but they have different backgrounds and international experience. Therefore, the results of the system analysis are mainly focused on one geographical region. The experts are frequently consulted during all steps of Vester's sensitivity model. The result is further discussed with the experts. In the research recommendations (see chapter 7.3.2), a system analysis with a broader and more international group of experts is further advised, which also investigates PtG in other regions.

However, detailed economic parameters like different technical components of the PtG technology like the electrolyzer, methanation reactor or costs of single CO_2 sources are not mentioned on the aggregated level of this system analysis. Even though these parameters have an impact on the economy of the PtG technology, the investigation on this level takes place in the analysis of the value chain and network by literature review, market analyses and surveys in the next empirical step.

4.1 Description of the System

As an overall structure, a socio-technical system can be defined, in which people, the environment and different technologies are in interaction.[162] In this socio-technical system, the holistic, cybernetic entity is described. This system consists of the energy system, ecosystems, regulations of economies, population, resources, and others.[163] These subsystems are in constant interaction and balance. A simple example is: if the living quality of a society is endangered because of the rise of carbon dioxide emissions in the ecosystem, regulations could be changed to prevent further emissions. Although the system analysis of this dissertation takes place on the aggregated level of the energy system, it is important to understand the greater systemic context.

The energy system, as mentioned, is part of the overall socio-technical system and can be divided into the power, heat, and mobility sector. The energy system is in the transition from a fossil-fuel-based to a renewable-based energy system in Germany.[164] Due to the focus on short- and middle term business cases, the whole transformation of the energy system is explained in the appendix (see chapter A.2). The transition is mainly influenced by political regulations like subsidies for RE production, infrastructure regulations, or consumer taxes. The transition takes place over decades and delivers different solutions, innovations, and new BMs. In systems theory, the transition of the energy system can be identified as an important *system change*. During this period, innovative technologies arise in the energy system.

The following figure is depicting different levels of systems in a schematic way. The PtG technology is part of the energy system, and in turn, the energy system is part of the socio-technical system. Changes at different levels influence target markets, revenue streams and, therefore, the BM of the PtG technology.

162 Long (2013), p. 269

163 Meadowcroft (2009), p. 328

164 As the increase of renewable energies in the power generation shows (see introduction in 1.1)

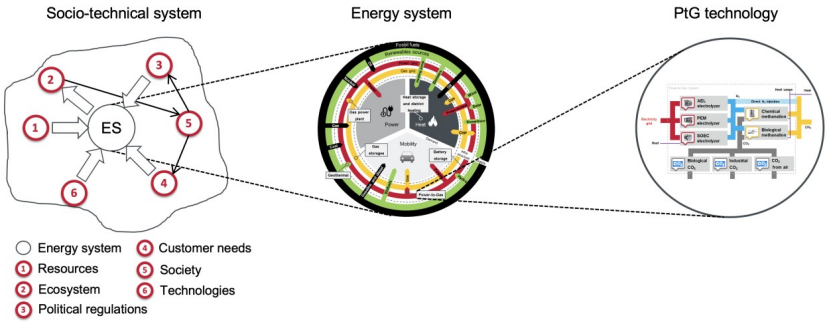


Figure 16: Position of the PtG technology in the overview of different system levels

During the transition of the energy system, different fossil technologies are reduced and probably disappear like conventional power plants, oil drilling, refineries or specific infrastructures due to divestment in fossil fuels.[165] New technologies arise like wind or photovoltaic power production, which are already influencing the *system behavior*[166]. The aim of the energy system is the temporal and regional energy supply of the sector's mobility, power, and heat. In the power sector, the supply has been central and demand-oriented in the past fossil energy system. Conventional power plants have supplied areas of high population density and industries in time and regionally. This system behavior changes with the supply by REs from wind and solar. This supply depends on regional weather conditions like wind speed and solar radiation. Therefore, the energy system changed to a decentral, supply-oriented energy generation. Many small windmills or solar panels are covering energy demand. Especially the wind generators are, in the case of Germany, far away from big industrial areas or areas with high population density. Therefore, the transport of energy – utilizing the energy infrastructure – gains importance. Two main energy infrastructure grids exist in Germany: on the one side, the power grid with different voltage levels, and on the other side, the natural gas infrastructure (see chapter 5.4.5).

However, the new system behavior of fluctuating energy production requires new system elements to stabilize the energy system. Although some players of the energy system can adjust their demand behavior (e.g., refrigerating storage houses or electric vehicles), it is assumed that the total energy demand might not change in a substantial way. Therefore, at least long-term storage technologies have to be installed to supply the demand at all times. Different technologies will be in competition in the future. Sterner (2015) is giving an overview of potential storage technologies like hydropower storage, battery storage, pressure systems, or PtG technologies. These storage

165 Bullard (2014)

166 BNetzA (2016)

technologies are located in the infrastructure of the energy system. The energy storage potential of the PtG technology is further discussed in chapter 5.2.1. The following figure is illustrating the future, RE system with potential new technologies.

Figure 17 describes the position of the PtG technology in the RE system and has been developed together with the experts. It states the location of the PtG technology in the energy system. Changes of other system elements would have an influence on the PtG technology like the promotion of competing technologies in different demand sectors e.g., electric vehicles. PtG is an intersectional technology between the power and the gas grid. In a fully RE system, only PtG and biogas plants are able to feed into the gas network in the future.[167] The biogas potential is limited due to the availability of sustainable biomass. Therefore, this technology is crucial to use the existing gas infrastructure in the future, which is the only long-term energy storage option for the power sector in Germany. It is right that also oil reserves exist, which can be produced renewably via PtL technology and used, for example, in the transportation and heat sector. But due to few oil power plants, this is not a reliable option for the power sector from today's perspective. Therefore, the oil distribution grid is not mentioned above.

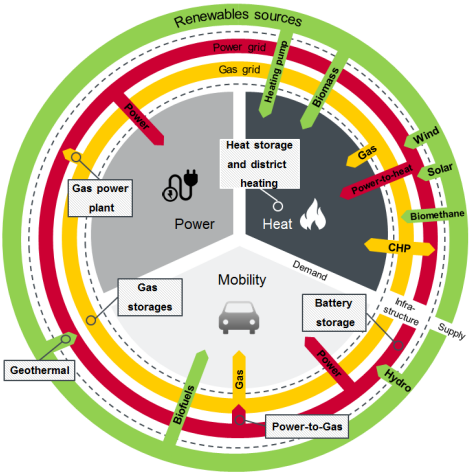


Figure 17: Schematic illustration of the RE system

The location of the PtG technology in the energy system is significant for the identification of influencing parameters, target markets and system boundaries. However, the transformation of the energy system requires the necessity of cross-sectorial

[167] Carbon capture and storage is not considered due to the ongoing discussion about the stability of underground storage reservoirs.

technologies like PtG to store fluctuating RE production. In the following chapters, the system is further analyzed.

4.2 Identifying the Influencing Parameters

As a next methodological step, the influencing parameters are identified. Table four shows the result, which the experts have announced. The experts have been individually asked: which parameters are influencing the economics of the PtG technology? This question is identical to RQ one. The chosen experts has identified parameters that belong to different groups. The groups are classified into parameters of the energy system and parameters of the PtG technology. In addition, units are declared on how to quantify the parameters. The answers of single experts are frequently checked with other experts to challenge and verify the outcomes.

In the energy system, the following parameters have been mentioned: the amount of fluctuating RE of the power generation is an indicator of surplus energy in certain hours, low power price and storage demand. The installed capacity of PtG and other storage technologies show the market potential to utilize the amount of fluctuating RE. Hereby, other storage technologies are in competition to the PtG technology. Thus, the long-term energy storage is identified as a first system characteristic of the PtG technology. The storage potential of the PtG technology arises with the amount of fluctuating RE in the electricity market. In the beginning, several experts mentioned that the amount of installed capacity of PtG is more influenced by the demand of renewable gases in the heating industry as well as the transportation sector. As described in the previous chapter, these market demands define possible target markets of PtG technology. If the demand for target markets is higher than local production can supply or if the production of SNG is economically more worthwhile in other regions due to lower costs of renewable electricity generation, the import of SNG via existing gas pipelines or in a liquefied form should be considered. For that reason, one scenario of the business case calculation is the production of SNG in the MENA region later (see chapter 6.1.8).

The availability of fossil energies explains the limits of this energy form due to social and, for that reason, political willingness to avoid fossil resources or due to scarcity of resources. The current political development as briefly explained in the introduction (see chapter 1.1), shows that the political limitation is more likely the bottleneck of fossil energy than the availability of resources. The infrastructural costs have been mentioned as an advantage of the PtG technology compared to other new technologies in the transition of the energy system because the PtG technology is using existing infrastructures – at least in Germany.

In the PtG system, the following parameters have been named and are classified as costs and income parameters as well as further information. Costs parameters are

capital and operational costs, power price, power taxes and grid fees. The capital and operational costs include more detailed economic parameters like the cost of CO_2 absorption or water consumption. Income parameters are yields of the gas, heat and oxygen sale, the GHG reduction quota, which is an incentive for renewable fuels in the transportation sector and further explained in chapter 5.2.4, and avoided gas grid fees. These sale parameters include a market price and the volume of SNG production, which further depends on the plant size and operation mode. The prices of different target markets can also include regulatory CO_2 prices. Further information, which is necessary to achieve economic information, includes efficiency or production rate, financial information like an interest rate of the capital costs and the technical lifetime of PtG plants. All these parameters are influencing the economics of PtG technology.

In total, 18 parameters are identified and analyzed. This is at the lower end of Vester's recommended number of parameters. This obtains that additional detailed system analyses are recommended. But as a first empirical step followed by a business modeling with intensive literature review, further analyses, own surveys, and a single case study, this investigation helps to inspect the economic parameters of the PtG-technology. These parameters are building the basis of BM of the PtG technology.

Table 4: Influencing parameters for the economics of the PtG technology

Group	Parameter	Quantitative units
Energy system	Amount of fluctuating RE	Installed renewable capacity like wind and solar in % of the overall generation system
	Installed capacity of PtG	Installed capacity in GW
	Installed capacity of other storage technologies	Installed capacity in GW
	Availability of fossil energy resources	Amount of fossil energy in GWh
	Infrastructure costs	Costs of infrastructure in €
PtG technology	Economy of PtG plants	Return on Invest, Net Present Value, Average Cash Flow
	Capital expenditures (CAPEX)	Investment costs of electrolysis, methanation and balance of plant in €
	Costs at power markets	Price at different power markets in ct/kWh
	Costs of power taxes and grid fees	EEG apportionment, power tax, grid fee, offshore surcharge, CHP surcharge, concession levy, §19 apportionment, reactive energy in ct/kWh
	Gas sale	Market price per injected SNG in ct/kWh
	Heat sale	Price per kWh
	Oxygen sale	Price per kg
	GHG reduction quota	Ecological premium in the transportation sector in ct/kWh
	Avoided gas grid fees	Price in ct/kWh

	Efficiency	Quotient of SNG production and electricity input in %
	Maintenance	Costs of maintenance in €
	Financial information	Interest rate in %
	Lifetime	Lifetime in years

4.3 Testing the Relevance of the Parameters

As a next step, the experts have discussed if these parameters are relevant to the overall system. Therefore, the experts have answered what part of the energy system is affected by the PtG technology. The result is displayed below. It is divided into four different tests. In the first test, seven categories check if all parts of a system are covered following the methodology of Frederic Vester. The parameter is grouped in a specific category if the majority of experts agreed on it. Most of the parameters are grouped as activities. According to Vester (2012), all parameters that deal with economy, structure, capital, production, or service, belong in this category. Second most parameters are grouped in the category of regional and infrastructural parameters. These are parameters with geographical importance. As mentioned in the system description, the transformation of the energy system deals with regional dependencies. Therefore, the amount of fluctuating RE or the availability of fossil resources is classified in this category. Due to the chosen German experts, the region is naturally limited. In addition, the heat or oxygen sale depends on available regional infrastructure, for example, district heating grid or regional demand for pure oxygen due to high transportation costs (see chapter 5.4.2 and 5.4.3). Several parameters belong to the category of regulations. The experts expect that the regulative framework plays an important role. Few parameters are grouped in social or organizational categories because of the technical and economic emphasis of this query.

As a next relevant test of the system, the physical basics are checked following the methodology of Vester (2012). Most of the parameters belong in this category because of the physical energy conversion technology. Also, parameters with material character exist like the installed capacity of PtG or competitive technologies. Parameters like financial information or efficiency have informational character.

The third group of categories consists of dynamic basics. It is divided into flow and structural as well as temporal and regional values. All the parameters, which are influencing the PtG technology, have temporal value. For example, the parameter *power price* has strong temporal dynamics. Also, flow values are mentioned often. Vester (2012) defines herewith values of the material, energy, or information content within the system.

The last group of categories is the definition of relations between systems. This analysis shows that most parameters are externally controlled and highly interlinked. This means that the parameters are influenced by or have an influence on other systems.

This demonstrates the complex, dynamic and nested situation of the PtG technology in a transforming energy system. Only six parameters are controlled within the system, like the economics, capital and operational costs and load hours. An operator of a PtG plant can change these parameters. On all other influencing parameters, the operator has less impact.

This system analysis is delivering more insights into the PtG technology. The economic situation of PtG depends on several dynamic and temporal parameters, which are mostly externally controlled and influenced by other systems. Therefore, the economy of this technology is based more on the overall system framework than on individual, technology parameters.

		1. Test							2. Test			3. Test				4. Test			
System	Parameter	Participants	Activities	Region	Human condition	Environmental relations	Infrastructure	Regulations	Materials	Energy	Informations	Floating quantity	Structural quantity	Temporal dynamics	Regional dynamics	Open the sys. through input	Open the sys. through output	Internal influences	External influences
Energy system	Amount of fluctuating renewable energy			x		x	x	x		x		x		x	x	x	x		x
	Installed capacity of PtG		x	x		x	x		x	x		x		x	x	x	x		x
	Installed capacity of other storage technologies		x	x		x	x		x	x		x		x	x	x	x		x
	Availability of fossil energy resources			x		x	x	x		x		x		x	x		x		x
	Infrastructure costs			x		x	x	x	x	x			x	x	x		x		x
PtG technology	Economy of PtG plants		x								x	x		x		x		x	x
	CAPEX		x						x			x		x				x	
	Costs at power markets		x							x		x		x		x	x		x
	Costs of power taxes and grid fees		x					x		x		x		x		x	x		x
	Gas sale		x				x			x		x		x		x	x		x
	Heat sale		x	x			x			x		x		x	x	x	x		x
	Oxygen sale		x	x			x			x		x		x	x	x	x		x
	GHG quota		x					x		x		x		x		x			x
	Avoided gas grid fees		x					x		x		x		x		x			x
	Efficiency		x								x	x		x				x	
	Maintenance		x	x							x	x		x	x	x	x	x	x
	Financial information		x								x	x		x		x			x
	Lifetime		x								x		x	x				x	
Sum		0	15	8	0	5	8	6	4	12	5	16	2	18	8	13	11	5	15

Figure 18: Testing the relevance of the parameters of the PtG technology

4.4 Questioning of Interdependencies

As explained in the theoretical chapter of the system analysis, the investigation of interdependencies or relations between the parameters is the next methodological step. As explained in the theoretical chapter 3.1 the scale is the scale for the answer is three for strong, disproportionate relation; two for middle, proportionate relation; one for weak relation and zero for no relation. The result, on which the experts could agree on, is displayed in the appendix (see Figure 100).

The cross-impact matrix demonstrates the influence of each parameter on each other. The sum of the vertical column shows the passive or reactive value. This number highlights how many other parameters have an impact on this parameter. The sum of the horizontal row is the active value. This number shows how much influence this parameter has on other parameters. For example, the amount of installed capacity of PtG plants has the highest active sum. This because it has an impact on the installed capacity of different storage technologies, on the capital expenditures (CAPEX), on maintenance costs and efficiency due to economies of scale effects and expected increase of research activities. On the other hand, the economics of the PtG technology is the parameter with the highest passive sum because it has only an impact on the installed capacity but is influenced by nine parameters. The identification of interdependencies of parameters with influence on the economics of PtG is contributing with insights to RQ one.

All in all, the cross-impact matrix is an approach, which is identifying interdependencies in a system. It highly depends on the type of detected parameters and on the expert group, which is interviewed. It is helpful to classify the most important drivers of the PtG technology and their relation to each other, and within the energy system. It shows that the amount of installed capacity of PtG instances is relevant to the system. It demonstrates that the experts proclaim an important role of this technology in the energy system. On the other hand, this intermediate step highlights that the economy of the PtG technology is influenced by many other parameters that are mentioned in the matrix.

4.5 Determination of the Role in a System

Figure 19 maps the detected parameters in relation to the product and quotient of the active and passive sum. The product demonstrates the importance of the parameter and the quotient shows how many other parameters are influenced.

At first, it can be identified that parameters, which belong to the energy system, have more influence and are more important. This points out that the economy of PtG depends on parameters and the relation of higher system levels. This also shows that changes in these parameters have a critical impact on the system. For example, infrastructure costs have a high impact on power taxes and grid fees, as well as avoided gas grid fees. In turn, this parameter is influenced by the amount of fluctuating RE. If the infrastructure or system costs increase, the expansion of RE could slow down.[168] The availability of fossil energies has an impact on the gas and heat price as well as costs at the power market. The amount of fluctuating REs has also influence on the

[168] For example, the expansion corridor of wind and solar energy in the EEG (2017) regulation in Germany.

costs in the power market (see chapter 5.3.1.1) and costs of power taxes (namely the EEG apportionment).

Second, the parameters of the PtG system have less impact. The only exceptions are the efficiency and the gas sales price. The efficiency is influencing the gas, heat and oxygen sale. The gas sale has an impact on the economics, GHG reduction quota and avoided gas grid fees.

Third, the most critical parameter in this analysis is the installed capacity of PtG. This parameter has an influence on CAPEX, efficiency and maintenance, and has an impact on the economy of PtG. This leverage is an important connection between the energy and the PtG system.

Other parameters like financial information (see chapter 5.4.1), CAPEX or lifetime of a PtG plant are well balanced. That does not mean that they are rather unimportant for the economy of PtG. It depicts that these parameters have no important, *systemic character*.

All in all, the impact of different parameters in the system is identified in a first step. Several results of this intermediate step are important. First, critical parameters belong to the group of the energy system and less to the technology group. Therefore, the main driver of technology development is the energy system. Infrastructure costs, the amount of fluctuating RE and the installed capacity of PtG (demand of SNG) have a significant influence. PtG technology is less market-driven, for example, by the economy of PtG plants. Due to the influence of more holistic parameters, it is assumed that the development of the PtG technology depends more on comprehensive approaches (e.g., political regulations) than on single aspects (e.g., technical parameters).

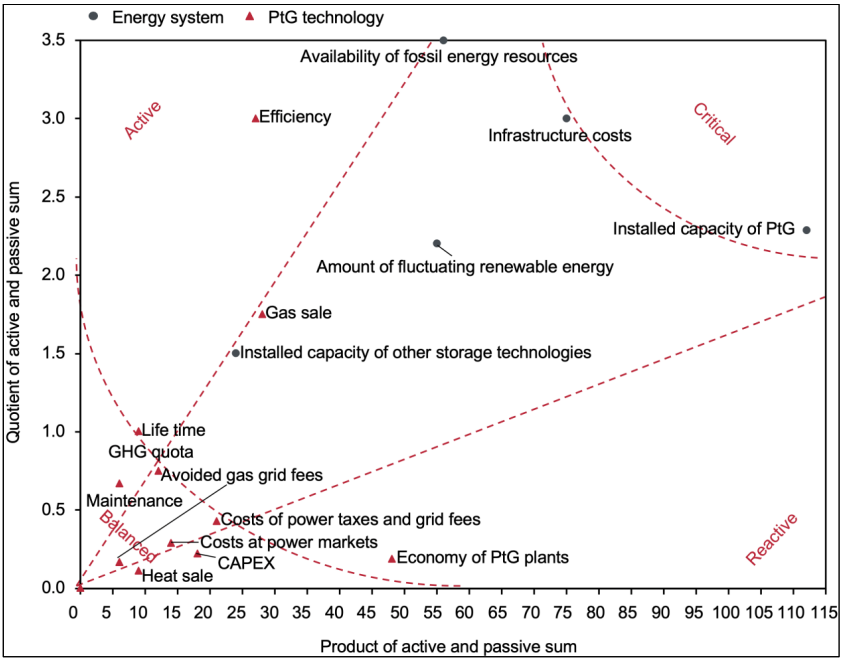


Figure 19: Determination of different parameters in different systems

4.6 Investigation of the Entire Interlinked Network

In a next step, the entire interlinked network of the identified parameters and their relations is drawn. The result is displayed in Figure 20. A dashed arrow symbolizes an inversely proportional relation, which derived from the experts reply on the questioning of interdependencies. For example, an increase of RE leads to a decrease in costs at power markets (an explanation is the merit-order effect and the guaranteed feed-in tariff see chapter 5.3.1.1[169]). A straight line shows a direct relation like more installed capacity of PtG leads to more efficiency due to more research activities and economies of scale. Parameters of the energy system are marked in dark grey. Parameters with a direct influence on the economy of PtG are highlighted in green.

The illustration displays the relation of the necessary elements of PtG technology. In the next steps, single scenarios are analyzed to explain system behavior. The single scenarios have been chosen and discussed with the experts.

[169] The system analysis has been conducted in 2015. Since 2017 the average power price at the spot markets is increasing again. This latest development is not respected in this statement.

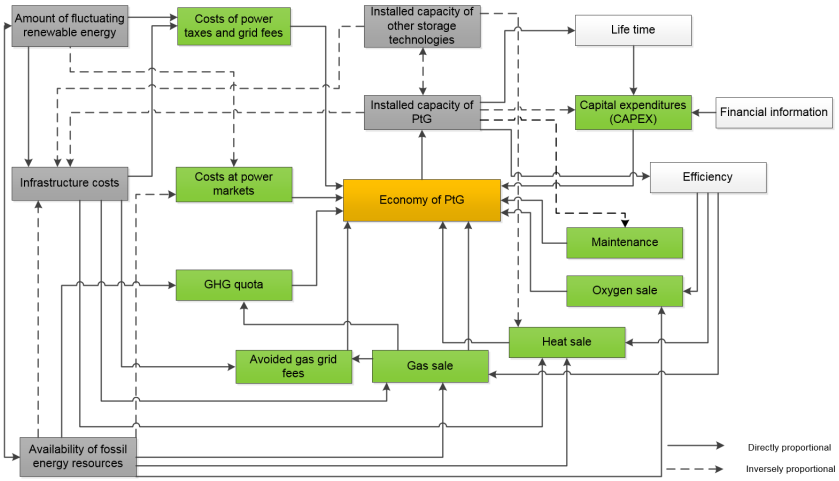


Figure 20: Entire, interlinked network of the PtG technology

4.7 Cybernetics of Single Scenarios

The first analyzed single scenario is called *fluctuating RE*. The amount of renewable power generation is influencing power taxes and grid fees, for example, with the EEG apportionment, and it is increasing infrastructure costs. While the influence on power taxes and grid fees is directly proportional, which means that more REs are leading to more taxes and fees, the influence on the power market is inversely proportional, as the experts stated. More renewables lead to a lower market price because of the merit-order-effect (see chapter 5.3.1.1). Both parameters influence the economy of PtG plants. Another influence on the costs at power markets comes from the availability of fossil energy resources. This parameter, in turn, interplays with the amount of REs. Higher amounts of RE lead to more availability of fossil resources and vice versa. As mentioned, the availability of fossil resources can also be politically limited.

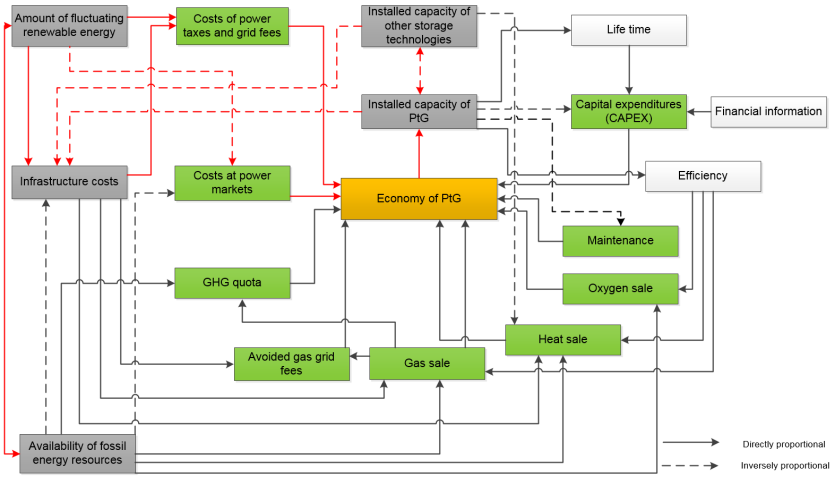


Figure 21: Illustration of the scenario fluctuating RE

The installed capacity of PtG and competitive technologies have an inverse impact on infrastructure costs. This means that storage technologies can reduce grid expansion and ancillary services[170] that are increasing the infrastructure costs and further the power taxes and grid fees. This system dynamic has a *stabilizing character*. While the number of renewables is stressing the infrastructure costs, the installed capacity of storage or PtG technologies is reducing infrastructure efforts.

In conclusion, the economy of PtG is influenced by the increase of REs in two ways in the power market design in Germany. On the one hand, power taxes and grid fees are rising, which has a negative effect on the economy of PtG as long as PtG plants are not exempt from power taxes. On the other hand, the costs at power markets are reducing, which has a positive impact on the economy of PtG.[171] For that reason, one positive and one negative feedback loop exist for the economy of PtG. The installed capacity of storage and PtG technologies has the opposite effect. It is reducing infrastructure and system costs due to the stabilizing systemic character. In addition, the competition between the market players *storage technologies* and *PtG technology* is shown in the previous figure. The red lines are highlighting the dependencies within the analyzed scenario.

A second analyzed scenario is called *economies of scale*. Here, the impact of the installed capacity of PtG is under investigation. This crucial parameter influences the lifetime of components of PtG plants, CAPEX, efficiency, and maintenance due to

170 For an explanation of this term (see chapter 5.3.1.4)

171 Due to the merit-order effect (see chapter 5.3.1.1)

experience curve effects as the expert group estimated. This has a direct influence on the economy of PtG in the case of CAPEX and maintenance and also an indirect impact because an increase of efficiency is raising the oxygen, heat and gas sale. Further, the gas sale is also increasing the yields of GHG reduction quota and avoided gas grid fees. Therefore, a positive feedback loop for the economy of the PtG technology is detected if more PtG is installed. If PtG plays a significant role in the future, it is strategically advisable to achieve an appropriate capacity of PtG to benefit from these *systemic effects*.

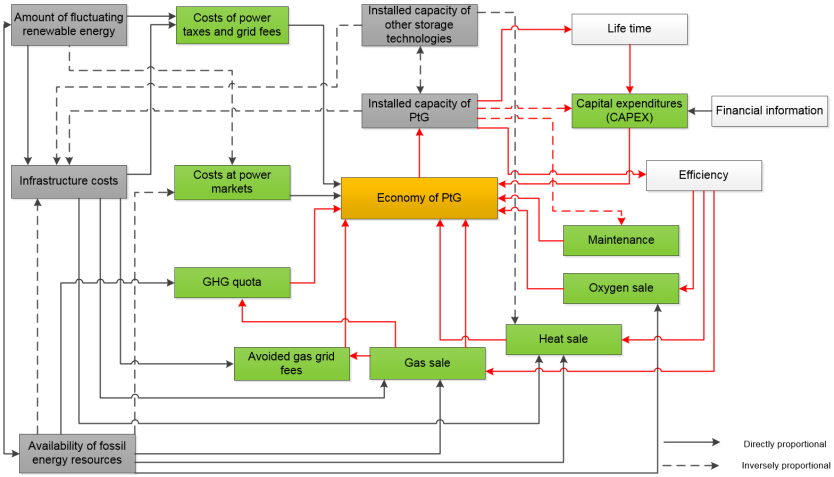


Figure 22: Illustration of the scenario economies of scale

The third single scenario analysis is done with a focus on fossil energy resources. The *availability of fossil resources* has an influence on infrastructure costs, GHG reduction quota, gas, oxygen and heat sale.[172] For example, if less fossil energy is available due to political regulation or scarcity of resources, the gas, heat or oxygen price can increase. Otherwise, the usage of fossil resources is causing infrastructure costs because of long-distance transportations. Therefore, regional gas plants are receiving gas grid fees back. The GHG reduction quota is higher if more fossil fuels exist. In total, the single scenario analysis is obtaining that less availability of fossil energy resources has a positive impact on the economy of PtG due to rising market prices and reduced infrastructure costs.

[172] It appears disputable that costs at power markets were not mentioned by the expert group. For example, the CO_2 price of the European Trading System (ETS) has influence on costs in power markets (see chapter 5.2.2). This is also discussed in the critical evaluation of the dissertation (see chapter 7.3).

In conclusion, the analysis of three single scenarios of the PtG system has shown the impact of fluctuating RE and the balancing effect of storage units like PtG, the strong impact of economies of scale and the influence of remaining fossil fuels. These system dynamics lead to a positive economic development of PtG technology. Further scenarios can be investigated but are not discussed with the expert group.

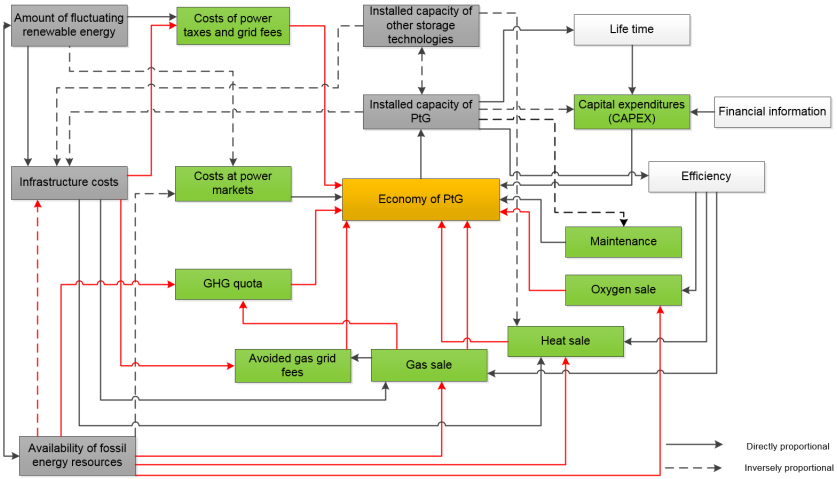


Figure 23: Illustration of the scenario fossil energy resource

4.8 Conclusion of the System Analysis

The system analysis of the panel of PtG expert has detected important insights into the business modeling process. First, several important parameters have been identified, which are more or less influencing the economy of the PtG technology. These parameters are building the elements of the revenue stream in the general BM in the next chapter. Some of those parameters require further research, which is executed by a literature review, quantitative analyses, and own surveys along with the target markets, value chain and network of the PtG technology.

Second, the relations between those parameters, which are investigated by the experts, made clear that parameters of the energy system are more critical than parameters on a technology level. The critical parameters are the availability of fossil resources, infrastructure costs and installed capacity of PtG. These parameters have a strong influence on others and are relevant to the system. For example, if fossil resources are limited and RE are expanded, infrastructure costs are continually increasing and competitive technologies in the storage, industry, heat or transport market are less available the technology development of PtG will accelerate.

Third, the investigation of the entire interlinked system and single scenarios are demonstrating the *system behavior*. This shows that the installed capacity of PtG has an important stabilizing character in a RE system. In addition, the high capacity of PtG and less availability of fossil resources have a positive feedback on the economy of PtG, according to the expert group. Further system dynamics have been explained in this chapter.

All in all, basic, mainly qualitative work is done. First parameters of the economy of the PtG technology are indicated. The business modeling and quantification of those drivers are the focus of the next chapter.

5 Business Modeling

The construction of the general BM for the PtG technology follows the methodological approach of the technology-driven school of business model innovation. In the end, different business cases for different value propositions, target markets and different revenue mechanisms are exposed.

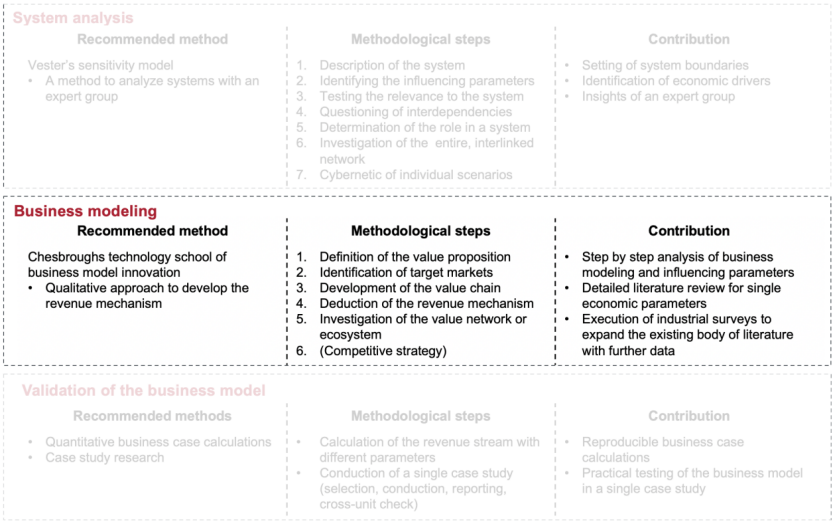


Figure 24: Business modeling

5.1 Value Proposition

The value proposition of the PtG technology is the production of a sustainable and climate-friendly equivalent to fossil natural gas if only electricity from RE is used. This chemical energy product can be used for different purposes. Therefore, the value proposition is addressing different customers. On the one hand, the system analysis has detected the balancing effect of PtG in the energy system by storing fluctuating RE temporally. SNG, in turn, generates electricity by combustion if RE is not available (e.g., in simple words: if the wind is not blowing or the sun is not shining). This is a critical value proposition for a RE system because it is the only way a fully renewable system can work in Germany. That case generates long-term economic value for energy storage companies like energy suppliers but also plant manufacturers. This first value proposition of the storage case is called *power-to-gas-to-power*. The economic feasibility is discussed in the business case calculation in chapter 6.1.1.

On the other hand, the system analysis of PtG identifies the economic driver *gas sale*. SNG can be sold to different customers. Hydrogen, as a first product, is demanded in the production of fertilizer and fossil fuel refineries. Methane is requested in the chemical industry as well as in glass and steel production.[173] In this case, the customer value is an almost climate-neutral production of their products without any significant process changes. This proposition is called *power-to-gas-to-industry*. The business case is calculated in chapter 6.1.2.

Another indicated parameter with a direct impact on the economy of PtG is *heat sale*. In this case, SNG is sold to the heat market as a climate-friendly energy carrier. Renewable heat, if energy from renewables is used, can be sold to customers e.g., with gas heating systems in their households. Here, different heat sources exist along the value chain. The value chain is analyzed in chapter 5.3. This proposition is called *power-to-gas-to-heat*. The economic feasibility is discussed in chapter 6.1.3.

The last income parameter with a possible value proposition, which the system analysis has indicated, is *GHG reduction quota*. Herewith, the utilization of renewable hydrogen or SNG in mobility is identified. The natural gas mobility and infrastructure is discussed for that target market (see chapter 5.2.4.1). In this case, almost climate-neutral mobility is the value proposition. It has to be mentioned that this case offers a mobility concept to the customer without any constraints. In comparison to the full electric mobility or hydrogen mobility in fuel cell cars, customers can benefit from a sufficient expanded infrastructure and short time of refueling. For that reason, the same mobility behavior can be offered to the customer. For other mobility devices, for example, heavy-duty trucks, the success of the electrification is even more questionable. SNG in liquefied form (synthetic LNG) displays a value proposition for heavy-duty mobility. Therefore, renewable hydrogen, SNG and synthetic LNG present a possible solution for sustainable future mobility. In addition, automotive companies and fuel companies can benefit from fulfilling legislative requirements, which are discussed in chapter 5.2.4.3. This value proposition is called *power-to-gas-to-mobility*. The economic feasibility is calculated in chapter 6.1.4.

The four different value propositions are also demonstrating four different target markets of the PtG technology. In all these applications, a sold of byproducts like oxygen or thermal energy is generating added value. This is analyzed along the value chain in the value network. In addition, a mix of these propositions is conceivable, like the heat sale of chemical processes along the value chain in the *power-to-gas-to-mobility* case, for example. The detailed analysis of target markets and the calculation of business cases follows this division of different use cases or value propositions.

[173] Gardiner (2012)

5.2 Target Markets

According to the different value propositions, different target markets exist. This chapter describes those markets and quantifies possible incomes at these markets by literature research, which serves as necessary input for the business case calculations later.

5.2.1 Target Market 1: Power-to-Gas-to-Power

As discussed in the previous chapter, the first sale market is the generation of power with SNG in gas turbines or combined heating and power plants (CHPs). As already mentioned in a future RE system, the power supply is influenced by wind and solar availability. For a constant power supply, energy needs to be stored and repowered if wind generators are not turning and no sufficient sunlight can be captured. This utilization can be done by the combustion of SNG. It is comparable to the power generation of biogas.

The future amount of surplus energy and, therefore, the storage requirement of a renewables-based energy system presents the market potential of the PtG technology as a storage facility.

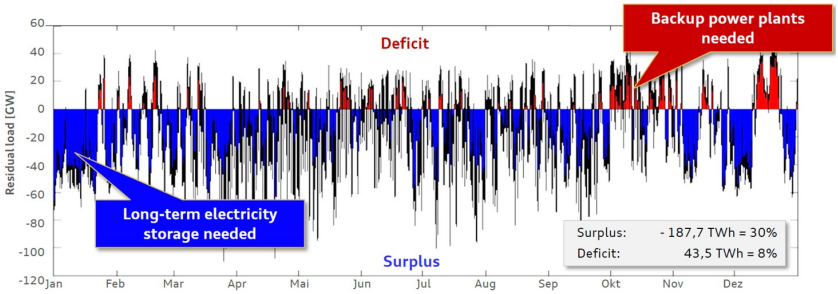


Figure 25: Residual load of a future RE system[174]

Figure 25 illustrates the stressed situation in the future power grid. It displays the residual load of a future, RE system with a share of 78% of REs under certain conditions[175]. The residual load is defined as the total demand load minus the production of RE[176]. Therefore, negative values, which are marked blue in the above figure, depict a surplus of energy. The red marked areas display a deficit of energy. For the deficit

174 Block (2016)

175 Further assumptions are: Weather year 2007, cooper plate, no im- and export of energy, in Germany.

176 Schill (2013)

period backup power plants are needed and for the surplus case a long-term storage solution is necessary. However, the high amount of surplus energy of 188 TWh/a draws a picture of the future energy storage market in an ideal simulation. This simulation is done with competence from the Fraunhofer IWES research center.

Sterner and Stadler (2014) have comprehensively summarized the results of different energy studies. They analyzed relatively low surplus of electricity production with approx. 15 to 30 TWh in an energy scenario with up to 85% RE.[177] However, calculations of energy scenarios are complex and often ambiguous. Single parameter like the progress of electric grid expansion or the trans-border energy trading can change the results enormously. Another outlook of the future market potential of PtG has been given in the research interest (see chapter 2.1).

A further consideration needs to be undertaken regarding the load management. In a future energy system, the demand can be adjusted. Different consumers are offering solution to react in a flexible way. These are for example BEVs, white goods, electricity heating system or industrial consumers with flexible production like refrigerating storage houses.

Of course, different solutions can store the surplus of RE. Sterner and Stadler (2014) are exposing a storage capacity of the German gas grid of 217 TWh.[178] Whereas the installed hydro pump storage capacity is only 0.04 TWh and the potential of grid feedback from electric vehicles is up to 0.42 TWh.[179] The existing gas infrastructure is offering a temporal as well as territorial storage opportunity. Other countries like Norway or Switzerland may prefer hydro storage due to geographical conditions.

The political legislation is promoting this energy storage case with the exemption from the EEG apportionment, which is an important power surcharge and further discussed in chapter 5.3.2. For a later business case calculation, the efficiency of the PtG and CHP plant are considered in chapter 5.3.5. The German RE legislation guarantees the same power sale price as the original RE source.[180] Therefore, the feed-in prices of wind or other renewables can be taken into account. In the same legislation, SNG is defined as *storage gas* if the PtG plant is directly connected to the RE source.[181] Therefore, the direct connection to a RE source displays the only power supply option for this target market if the guaranteed power price is intended.

From a systemic and economic perspective, this concept is questionable. On the system side, the self-regulating and balancing systemic effect of the PtG technology is

177 Sterner and Stadler (2014), p. 114

178 Sterner and Stadler (2014), p. 423

179 Sterner and Stadler (2014), p. 424

180 See § 19 section 3 sentence 3 EEG (2017)

181 See § 3 Nr. 42 EEG (2017)

limited to one RE source like one wind park. On the economic front, due to efficiency losses (see chapter 5.3.5), gas prices have to be higher than power prices under these conditions. The only predictable case, in which this target market is economic feasible, is the curtailment of renewables due to grid stresses. The EEG (2017) defines that the guaranty payments are reduced if the RE unit is cut out for more than six hours.[182] Goetz et al. (2014) assume that in 19% of the year, curtailments are possible and would reduce 40% of the revenues of wind power in the year 2040.[183] Therefore, this target market is further limited to regions with a high number of curtailments. However, the target market *power-to-gas-to-power* needs to be considered for future business cases and is investigated in chapter 6.1.1.

The gas grid infrastructure is operated by gas grid companies and financed by grid fees. Similar to the electricity grid, each consumer is paying those fees if the grid is used. A further economic advantage for PtG plants is the avoidance of gas grid fees, as mentioned in the system analysis. Due to the legal equalization of SNG and bio-methane (see chapter 5.4.6), the PtG plant operator yields a further income because compared to the import of fossil, natural gas, the grid is not further utilized. Therefore, the PtG operator receives a refund of the gas grid fee in Germany. This is, on the one hand, the avoidance and recompensation of the gas grid fees according to section 118 and sentence six of the German energy industry law (EnWG 2016) and section 20a of gas grid regulation[184] and, on the other hand, the limitation of the grid connection costs of 25% or max. €250,000, according to section 33 of the gas grid access regulations.[185] The grid fee is restituted because PtG, as well as biogas plants, are not using the gas infrastructure in the same dimension as fossil natural gas. The gas grid fee is 0.7 ct/kWh in Germany.[186] The following table is summarizing the price composition of SNG at this target market.

Table 5: Composition market prices for the target market power-to-gas-to-power

Type of charge	Value
Power sale price	Depends on the feed-in tariff of the RE source
Avoidance of gas grid fees	0.7 ct/kWh

182 See § 51 EEG (2017)

183 Goetz et al. (2014), p. 1 f

184 Section 20a of GasNEV (2015)

185 Section 33 of GasNZV (2010)

186 See §20a GasNEV (2015)

5.2.2 Target Market 2: Power-to-Gas-to-Industry

The German gas grid expansion schedule is forecasting in all different scenarios a constant demand for natural gas in the industry market (174 to 198 TWh/a). In past years, the consumption of natural gas and biogas in the industry had a share of around 26% of the overall energy consumption.[187] Most of the demand derives from the chemical, glass and steel industry (heat and power). The usage of renewable hydrogen in the fertilizer industry and refineries is conceivable if the industry has to decrease GHG reduction emissions. Different studies are recommending *power-to-gas-to-industry* as one of the macro-economically cheapest solutions for GHG reduction in comparison to other applications.[188] Often these studies only consider technical abatement costs and do not take CO_2 prices, which derive from climate regulations.

According to Sterner and Stadler (2014), the conventional production of hydrogen by natural gas reformation is about six to ten times more favorable than water electrolysis with RE.[189] Therefore, an economic case seems to be difficult. An exception is the usage in refineries and the application in the mobility if green hydrogen as a mixture in fossil fuels is considered as a renewable fuel in the corresponding political regulation (see chapter 5.2.4.3).

However, gas-consuming industries are in global competition and, therefore, potentially more price-sensitive than the transportation or heat sector. Therefore, political regulations are necessary to give incentives to use renewable gas instead of fossil natural gas in industrial plants. Existing political regulation is the European trading system (ETS) for CO_2 certification. In the ETS, emission allowances (EUA) per ton of CO_2 are traded. The ETS is available in 31 countries and regulates the emissions of electricity generation and energy-intensive industries as well as inner European flights. It is a cap-and-trade system, which means that the amount of EUAs is limited and can be traded between the participants. The limitation of EUAs and their yearly reduction is guaranteeing that those industries will fulfill the Paris climate goals. In 2019, 45% of all GHG emissions in the EU-27 are part of the ETS, which displays the worldwide largest trading platform for GHG emissions.[190]

187 NEP Gas (2014), p. 23-24

188 Henning and Pfalzer (2015) or Fürstenwerth et al. (2015)

189 Sterner and Stadler (2014), p. 302

190 European Commission (2020)

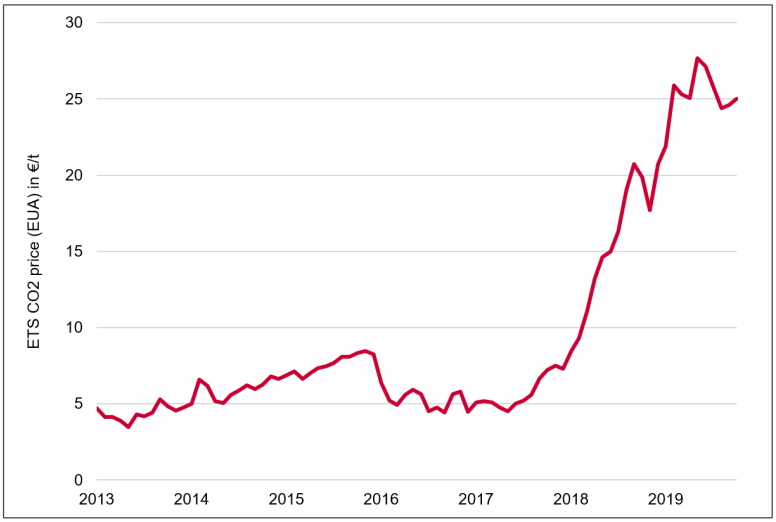


Figure 26: Development of the ETS CO_2 price (EUA)[191]

The spot market price has been about 4 to 8 €/t of CO_2 during the years 2013 to 2017 (see Figure 26).[192] In Figure 26, the monthly average prices of all auctions are displayed. Then in mid-2018, a price rally took place. The EU-27 has set into place different mechanism to cut and further limit the amount of EUAs (so-called backloading and market stabilization reserve)[193]. For that reason, the ETS price rises to around 25 €/t in 2019.

Due to different CO_2 prices at different target markets in the BM calculation, the regulatory willingness to pay is called *eco-premium* as an ecological benefit of SNG in this dissertation. Nitsch et al. (2012) are forecasting a CO_2 price of up to 75 €/t in 2050.[194] This equates to an average price increase of 4.23% per annum compared to the low ETS-prices of 2013 to 2017. In the latest publication, higher CO_2 prices are determined, but the basic price already increased.[195] Therefore, the price development of Nitsch et al. (2012) is still considered as an assumption. The price increase is necessary for future, dynamic BM considerations. The growth rate is critically discussed in the evaluation of the dissertation (see chapter 7.3).

191 DEHSt (2014 - 2020)

192 DEHSt (2014 - 2020)

193 European Parliament (2015b) and European Parliament (2018d)

194 Nitsch et al. (2012), p. 51

195 Gerbert et al. (2018)

If the ecological benefit is monetarized as an eco-premium, SNG can only be sold as natural gas in the target market because the ecological benefit can only be sold once. This constraint is further discussed in the chapter about ecological information (see chapter 5.4.7). The price of natural gas is settled at spot markets for different contract durations. Figure 27 is illustrating the price development at the European day-ahead spot market for natural gas. The natural gas is fluctuating between 0.91 and 3.21 ct/kWh between 2009 and 2018[196]. The gas price has been influenced by the oil price, development of the world economy, weather conditions and new technologies like hydraulic fracturing.[197] Further development is difficult to assume but important for long-term BM calculations. Nitsch et al. (2012) are forecasting a development from 5.9 ct/kWh in 2010 to 13.1 ct/kWh in 2050.[198] This is equal to a yearly increase of approx. 2%.

Next to the yearly development of natural gas prices, the monthly and weekly price patterns are of interest if a PtG plant is operated. Therefore, the daily spot market prices of 1 MWh of the NetConnect GmbH (NCG) gas pool from 2015 to 2018 is investigated. This product includes constant deliveries from 6:00 a.m. (Middle European time) to 6:00 a.m. of the following day. The trading period ends three hours earlier.[199] Since 2013, the gas markets of France, Germany, and the Netherlands are coupled in the Pan European Gas Cooperation.[200]

The following figure displays the price developments within a year for 2015 to 2018 in the NCG gas pool. It shows that the yearly average price is increasing again from 2016. In addition, an annual pattern is not foreseeable – every year has different price peaks and valleys. In 2018, a combination of extreme cold weather conditions and infrastructural issues led to a peak in prices. More than 100,000 MW have been traded on a single day with up to 59 €/MWh. In addition, the pipeline between the Netherlands and Great Britain was out of operation as well as the gas network entry to Scotland, and a gas preparation plant in Norway had technical issues.[201] In total, the different price developments within a year demonstrate the need for a detailed market analyses.

The weekly analysis of the day-ahead NCR gas price does not identify a further pattern. The average price on the weekend was 18.71 €/MWh from 2014 to 2019. The average price on weekdays was 18.98 €/MWh.

196 EEX EGIX (2018)

197 Brown and Yücel (2008)

198 Nitsch et al. (2012), p. 28

199 EEX (2014), p. 5 f

200 EEX (2014), p. 3

201 Lohmann (2018)

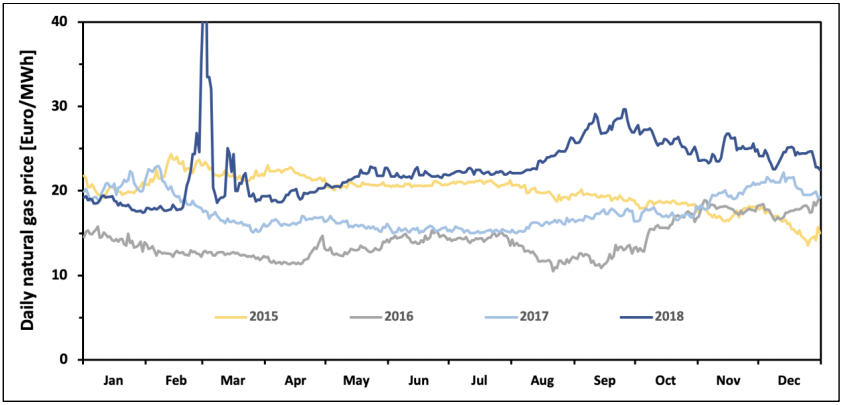


Figure 27: Development of the NCR day-ahead natural gas price from 2015 to 2018

Due to different price developments of different economic drivers like gas sale price or ETS price, a price corridor is taken into account. In a Monte Carlo (MC) simulation, the historical price corridor can be used to highlight the distribution of the results. Due to the mentioned correlation of the gas and power prices, a clustered multivariate bootstrap method is integrated into the BM (see chapter 5.5). This consideration gives insights about the fluctuation of the financial performance. In the BM calculation (see chapter 6.1), the distribution is taken to demonstrate the risk of investments. The business case of this target market is calculated in chapter 6.1.2. The following table summarizes all input parameters of this target market.

Table 6: Composition market prices in the target market power-to-gas-to-industry

Type of charge	Value
Average natural gas price (2008 to 2016)	2.1 ct/kWh
Price corridor of the natural gas price (2008 to 2016)	0.91 to 3.21 ct/kWh
Price development of natural gas price per year	2.01%
Average eco-premium price (CO_2 ETS from 2013 to 2020)	9.6 €/t CO_2
Price corridor of eco-premium price (CO_2 ETS from 2013 to 2020)	3.41 to 27.69 €/t CO_2
Price development of eco-premium	4.23%

5.2.3 Target Market 3: Power-to-Gas-to-Heat

The heat market has an energy consumption of 1,187 TWh per year, which is almost 50% of the overall energy consumption, and a RE share of 14.3% of the total German final energy consumption in 2018.[202] The energy transition of the heat sector is a crucial

[202] BMWi (2020a), p. 5 and p. 10

part of the overall transition from fossil to REs. The heat demand can be divided into 26% for space heating, 23% process heating and 5% for warm water preparation of the overall final energy consumption. 4.45% of these heat amounts are distributed over a district heating grid. Natural gas has hereby an important function with a total amount of 596 TWh of the mentioned heat demand.[203] Theoretically, this amount can be replaced by SNG or biogas in a RE system. Therefore, heat sale has been mentioned as an important economic driver in the system analysis.

The development of gas usage in the heating sector is described differently in the literature. According to Nitsch et al. (2012), the overall energy demand of the heating sector decreases to 45% until 2050.[204] Other studies are exposing an even higher reduction potential. For example, Gerhard et al. (2015) declare a reduction from 1,324 TWh in 2012 to 577 TWh in 2050.[205] Most of the gas share is replaced by electric heat pumps and Power-to-Heat (PtH). These are competitive technologies, which also have been described in the system analysis. The overall efficiency increases and the electrification of energy in the future heat market is a strong competitor towards the usage of SNG. An advantage is the installed infrastructure and the slow substitution time (e.g., in buildings) in the heat sector. For that reason, Hecking et al. (2018) calculates additional cumulative costs of €261 billion in the buildings sector in the electricity scenario (-95% GHG reduction until 2050) compared to a technology-mix scenario with high shares of synthetic fuels.[206] However, the *power-to-gas-to-heat* market competes with other innovative technologies. Therefore, the future potential of this target market appears to be ambiguous.

In Germany, the share of RE in the heat market should increase to 14% until 2020.[207] Therefore, house owners are supported and regulated use solar thermic energy, biomass solutions or gas heating with renewable fuels, among others. In Baden-Württemberg, a federal state of Germany, SNG from PtG plants is allowed as a renewable source.[208] Different energy suppliers like *Greenpeace Energy GmbH* are offering mixed gas tariffs for the heat market, in which SNG is included[209]. In this case, SNG is competing with biogas. Therefore, the price of biomethane is assumed in this research.

The market price of biomethane depends on the political regulations in the heat sector and feedstock prices. From 2010 to 2014, the German federal grid agency has published biomethane reports. During that time, an average feed-in price of 6.13 ct/kWh

203 BMWi (2020b)

204 Nitsch et al. (2012), p. 65

205 Gerhard et al. (2015)

206 Hecking et al. (2018), p. 261

207 Section 1 of EEWärmeG (2015)

208 Section 5 of EWärmeG (2015)

209 Greenpeace (2020)

has been achieved.[210] The price deviated from 5.3 ct/kWh in 2013 to 7.5 ct/kWh in 2014. Beil et al. (2012) assume a similar biomethane price of 1,100 €/t or 7.9 ct/kWh in Germany.[211] As mentioned, the distribution of results is calculated by using price corridors in a MC simulation. For biomethane, a price corridor of 5.3 to 7.5 ct/kWh is taken into account.

Next to the sale of SNG as biomethane, another yield can be generated if the exothermic process heat of the PtG plant is sold. The heat management of PtG plants is mentioned in the value network (see chapter 5.4.3). The generated process of heat energy can be injected into the district heating grid or used in industrial or internal processes. The price of heat from district heating was 7.63 ct/kWh in Germany in 2015.[212] This price represents the end-consumer price and includes margins and distribution costs. According to the same study, the basic or commodity price has a share of 75% on average.[213] The PtG plant can only yield the commodity price. The following figure shows the price development of the district heating price between 2008 and 2017 in Germany. In the case of the MC simulation, a price corridor of 5.01 to 5.89 ct/kWh is chosen.

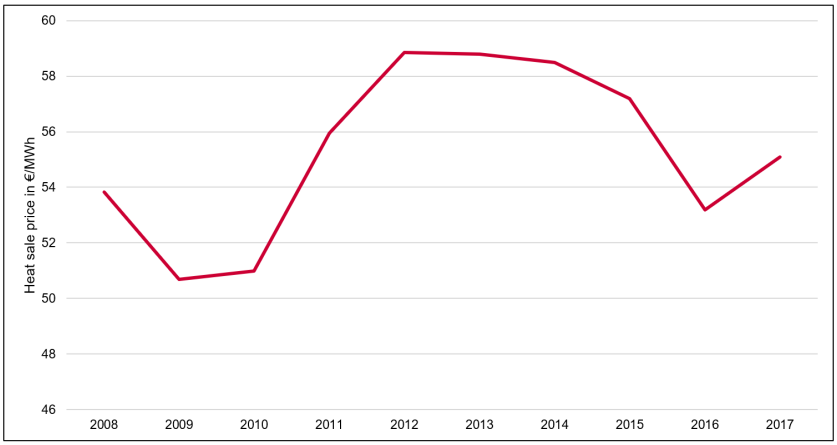


Figure 28: Development of the commodity price for district heating[214]

210 BNetzA (2014a), p. 3

211 Beil et al. (2012), p. 38

212 AGFW (2018), p. 8

213 AGFW (2018), p. 7

214 AGFW (2018), p. 8

In addition, the process heat of the PtG plant can be used in combination with industrial processes. The price of process heat in the industry is unknown and depends on the specific amount, temperature level and timing. Next to these options, the process heat can be internally used to increase the overall efficiency of a PtG plant (see chapter 5.3.5).

The further price development in the heat market depends on fossil fuel prices. Nitsch et al. (2012) expect an increase from 4.2 ct/kWh in 2010 to 11.4 ct/kWh in 2050.[215] This is equal to a yearly price increase of 2.53%. This price increase is taken into account for the process heat as well as for the biomethane sale as an assumption.

Table 7: Composition market prices in the target market power-to-gas-to-heat

Type of charge	Value
Average biomethane price in the heat sector (2010 to 2014)	6.13 ct/kWh
Price corridor of biomethane price in the heat sector (2010 to 2014)	5.3 to 7.5 ct/kWh
Average commodity price for district heating (2008 to 2018)	5.53 ct/kWh
Price corridor of commodity price for district heating (2008 to 2018)	5.01 to 5.89 ct/kWh
Price development of biomethane and district heating price per year	2.53%

5.2.4 Target Market 4: Power-to-Gas-to-Mobility

SNG can be sold to natural gas filling stations and, therefore, can be utilized in the mobility sector. For that kind of purpose, the future development of the gas mobility market is of interest. First, the development of gas mobility is described. Second, the market potential is analyzed and, third, prices of SNG in the mobility market are derived. Fourth, special political regulations of the mobility sector are highlighted to indicate the future development of that target market.

5.2.4.1 Development of the Gas Mobility Market

The history of natural gas vehicles (NGVs) is embossed by different political, social, cultural, and technical components. It begins with the political will of independency of oil importance during the Nazi regime in the 1930s. In 1938, fifty gas filling stations were installed in Germany. They primarily run on sewage and city gas, a synthetic product of coal distillation. The first application in mobility has been in public transportation due to insufficient infrastructure. First public buses with low-pressure storage tanks had a driving range of 13 km and up to 27 km with a trailer. During World War II, the main reasons for the gas mobility turned from the independency of oil to scarcity of resources.[216] Under today's conditions, it is interesting that the start of gas mobility

215 Nitsch et al. (2012), p. 221

216 Van Basshuysen et al. (2016), p. 33 ff

is influenced by independency and scarcity of fossil fuels, which are similar reasons in today's discussions to stop global warming.

After World War II, the NGV mobility lost most of its relevance and was substituted by oil derivatives. Only in the northern parts of Italy natural gas was popular due to political support and local gas exploration.[217] Knowledge and experience of vehicle reconstruction from gasoline to natural gas, which has been collected in this time, is successfully used later. The resumption of gas usage in mobility is constituted due to the first and second oil crises in 1973 and 1979. Again, the political and economic dependency of a few oil-exporting countries has resulted in a rethinking of fuel consumption. In addition, a cultural change took place and environmental aspects became more important. This is a general change in the overall socio-technical system as discussed in the system analysis (see chapter four). Next to the oil dependency and the scarcity of resources, the ecological benefits of NVGs have been established as a third significant factor.[218] First national research and development programs have been started in this period.

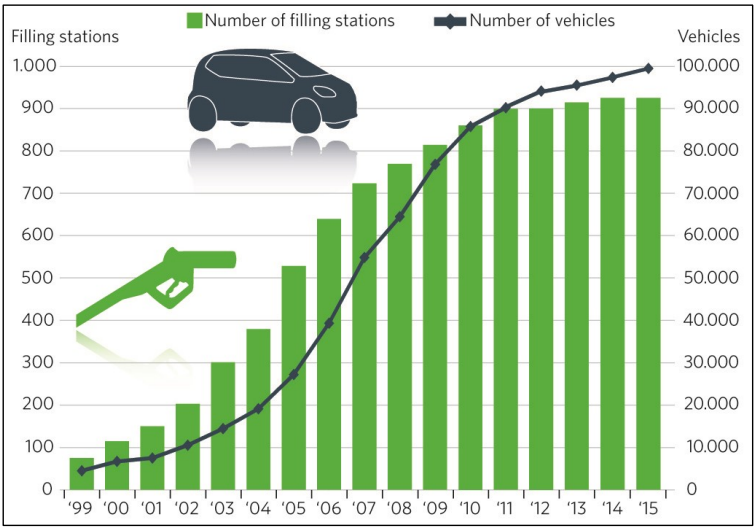


Figure 29: Development of a number of filling stations and vehicles in Germany[219]

[217] Van Basshuysen et al. (2016), p. 36

[218] Van Basshuysen et al. (2016), p. 36 ff

[219] erdgas mobil (2016)

Since the beginning of the 1990s, the consumption of natural gas in the sector of energy production and heat supply stagnates in Germany. For that reason, energy suppliers and gas grid companies seek new BMs to expand their volume of sales.[220] First, NGVs have been introduced by companies from the natural gas industry. At the end of the 1990s, a formation of different players from the automotive and petroleum industry, non-governmental and political organizations have started a collaboration to support gas mobility in Germany.[221] Since this starting point, the number of installed gas filling stations and NGVs grows exponentially (see Figure 29). Another reason for this increase is the economic advantages for the customer of gas mobility. A lower fuel tax for natural gas and the rise of gasoline and diesel prices have supported the development of the NGVs in the 2000s. Figure 29 is illustrating the development of filling stations and NGVs in Germany for the past 15 years. It is visible that after a strong period of growth in the first decade of the 21st century, the development slows down. In 2016, almost 100,000 NGVs and 914 filling stations existed in Germany.[222]

Furthermore, the lower rate of growth from 2012 onwards is explained by different reasons. First of all, political support has become questionable because of the early and stringent concentration on alternative powertrains like electric mobility. In addition, the time delay of the extension of the lower energy tax on natural gas in the transportation sector has doubted consumers. The energy tax regulation is promoting natural gas usage in mobility. Natural gas has lower energy taxes than diesel or gasoline. In Germany, natural gas has a tax level of 13.9 €/MWh.[223] The comparable energy taxes for diesel are approx. 48 €/MWh and for gasoline 77 €/MWh. The reduced energy tax for natural gas is remaining fixed until 2024 and has been expanded in 2017.[224]

Second, the complexity and expenses of different powertrains like combustion engines for gasoline, diesel and natural gas, electric mobility, and fuel cell vehicles have made the implementation of strategies in the automotive industry difficult and have probably forced smaller companies to decide for single powertrain routes.

Third, the first wave of early pioneers of the NGVs has been abated. Gas mobility is still a niche market with a share of 0.2% of all existing vehicles or approx. 100,000 cars in Germany.[225] To convince and gain new consumers, gas mobility requires efforts in marketing and communication. Italy has proven that gas mobility can enter the mass market with approx. 1,000,000 cars.[226] However, the most important countries of NGV

220 Van Basshuysen et al. (2016), p. 29

221 Van Basshuysen et al. (2016), p. 30

222 NGVA Europe (2017), p. 32

223 BMF (2017), p. 2

224 BMF (2017)

225 Van Basshuysen et al. (2016), p. 43

226 NGVA Europe (2017), p. 32

mobility are developing countries like Iran (3 million vehicles), Pakistan (2.9 million vehicles), Argentina (2.14 million vehicles), Brazil (1.73 million vehicles) and India (1.25 million vehicles) in 2012.[227] The availability of national resources mainly grounds this. New statistics are showing that China is an uprising market for methane in transportation. In 2013, 163,000 new NGVs and 1,700 filling stations entered the market.[228] In individual mobility, most of the cars are taxis because state-owned transportation companies in 19 cities introduced first gas initiatives. China's motivation is grounded as well on avoidance of dependency on oil imports and sustainable reasons.[229]

Trucks can run on liquefied natural gas (LNG), which can also be produced with REs by PtG or biogas technology. During the last years, the development of LNG has been rapid. In 2019, 4,510 new LNG trucks were registered, and 249 filling stations installed across Europe.[230] In May 2020, the German parliament has approved the extension of the truck toll release for LNG trucks until 2024[231]. Therefore, gas mobility becomes increasingly important in heavy-duty mobility.

First serial NGVs from established automotive companies have entered the market at the end of the 1990s. Until the end of 2016, 23 serial models for individual mobility from eight different companies were available on the German market. There are several more options for public transport and heavy-duty mobility. The economic advantage is the lowest full cost of mobility compared to other vehicle concepts.[232] In addition, local gas suppliers are supporting the purchase of a NGV.[233] Both benefits are compensating for the extra charge of a NGV compared to a gasoline car. The technical potential of the gas engine is high due to optimizations like a direct injection of methane, hybridization of the concept and monovalent dedicated vehicle.[234] The ecological advantages are the higher efficiency and less emissions of an NGV. The emission of GHG is 25% less than a comparable gasoline engine with fossil, natural gas. Compare to a diesel engine, the microparticles are 100% less and the nitrogen oxide emissions are 89% less.[235] However, NGVs have the potential to reduce emissions like particles, nitrogen oxides and GHG reduction emissions. 20% of the gas used in the mobility comes from biogas plants and has, therefore, even more CO_2 reduction potential.[236]

227 Van Basshuysen et al. (2016), p. 39

228 IEA (2014), p. 145

229 Wang et al. (2015)

230 NGVA Europe (2020), p. 14

231 Lohmann (2020)

232 Heidt et al. (2013), p. 15

233 Erdgas mobil (2018)

234 Westerhoff (2016)

235 Westerhoff (2016)

236 BDEW (2019a)

All in all, the history of gas mobility shows that three reasons have influenced the development. First, the enormous utilization of fossil fuels has obtained the political and economic dependency on oil-exporting countries. Second, the scarcity of resources has influenced the usage of gas as an alternative to oil derivatives. Third, the environmental movement has created further awareness of sustainability. NGV's benefit here because of higher efficiency and less emissions. The usage of SNG instead of fossil natural gas in mobility is increasing all of these benefits.

5.2.4.2 Future Market Potential of SNG in Mobility

So far, the usage of SNG in the transportation sector and its advantage has been explained. The different advantages have led to an annual growth rate of NGVs of 21.6% from 2003 to 2012 worldwide.[237] The German gas grid expansion schedule is forecasting an increase from 2 TWh in 2012 to 15 TWh in 2025.[238] Now the possible future market of synthetic methane in the mobility is on focus. Therefore, different studies are introduced to quantify the potential market size.

The usage of SNG in the mobility sector is in competition with other sustainable mobility concepts. For that reason, different future mobility concepts must be assessed and compared. For the time being, biofuels, battery electric vehicles (BEV), hydrogen used in fuel cell systems and synthetic, power-based gaseous (methane), or power-based liquid fuels (kerosene, ethanol, diesel, or gasoline) are in discussion. All these different solutions have their advantages and disadvantages. PtG is the necessary fuel production technology for renewable hydrogen and SNG mobility. It must be added that PtG requires the production of hydrogen as a basis as explained in the analysis of the technical value chain (see chapter 5.3). Once large-scale hydrogen production plants are built up, they can supply not only SNG applications but also hydrogen fuel cell vehicles or PtL fuels. The development of fuel cell vehicles is in an even earlier stage than NGVs.

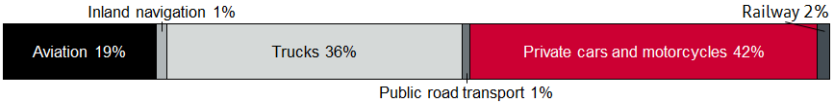


Figure 30: Energy consumption in the EU-27 in 2030[239]

Capros et al. (2007) have forecasted the energy consumption in the EU-27 for 2030. Figure 30 is showing their estimates divided into different transportation sectors. The aviation sector includes inner European flights. Intercontinental flights, as well as long-

237 Wang et al. (2015), p. 81

238 NEP Gas (2014), p. 23 f

239 Own illustration with data from Capros et al. (2007), p. 97

distance shipping, are missing in this chart. This clarifies that the different future mobility solutions must fulfill the requirements of the different transportation sectors. It is important to remark that some future sustainable driving concepts will be suited better for some mobility applications. For example, the BEVs fit to short-range mobility with private cars due to high battery costs and huge infrastructural requirements, biofuels can supply the aviation, navigation and road transport, and the railway has shown how to electrify a transportation system. However, different mobility demands require a mix of climate-friendly solutions. If the hydrogen and SNG mobility are adapting the aviation, navigation, trucks and long-distance private transportation, they would supply approx. two third of the future energy demand. According to Capros et al. (2007), it would cover 3,589 TWh in EU-27. Calculated with an efficiency of PtG of 60% and 4,000 full load hours (FLH), the amount of installed PtG capacity would be 1,496 GW for Europe in 2030 if renewables fuel the transportation sector. The efficiency, as well as the operation time, are discussed in the value chain in chapter 5.3 and value network in 5.4. The latest study on the EU-27 energy reference scenario is confirming the assumption of Capros et al. (2007).[240] This analysis displays considerable market potential. Other studies about the market potential have been mentioned in the chapter of the current research status (see chapter 2.1).

Nitsch et al. (2012) have analyzed three different future energy scenarios with a CO_2 reduction potential of 40% in all devices (public transport, trucks and individual mobility) of the transportation sector to 2050. All the scenarios have a share of 50% BEV in the end. Scenario A is influenced by hydrogen mobility, scenario B by renewable methane and scenario C by electric mobility.[241] The study is showing the spread of future mobility concepts depending on which technology dominates. Both scenario A and B are disclosing the future market potential of the PtG technology. The following figure identifies the future fuel development in the individual mobility following scenario B of Nitsch et al. (2012). It shows a constant consumption of biofuels, a continuous decrease of diesel and gasoline, an increase of natural gas up to 2025, and later a replacement by SNG, which is produced by PtG facilities. In 2050, gas mobility will have a share of 53% of the total energy consumption in individual mobility in this scenario.

240 Capros et al. (2016), p. 61

241 Nitsch et al. (2012), p. 131 ff

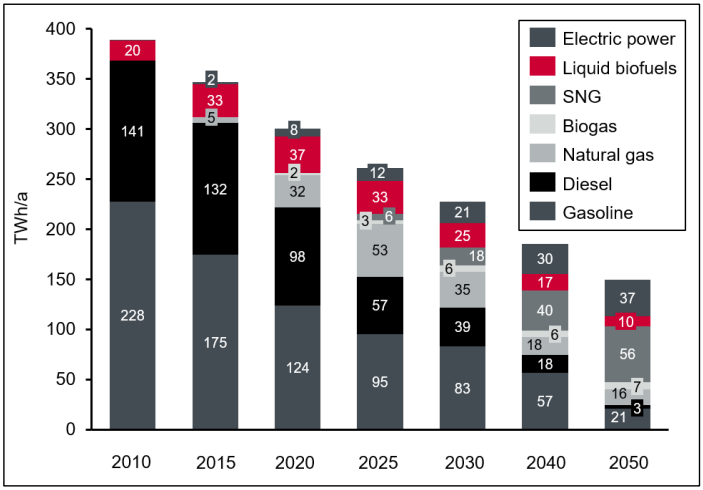


Figure 31: Different future fuel development for mobility[242]

The institute for applied ecology does another interesting future fuel market study (Blank et al. (2014)) on behalf of the German environmental agency UBA under the assumption of total climate-neutral mobility. Accordingly, 80% of the energy demand in mobility is from renewable, power-based fuels. This has an energy amount of 361 TWh per year in 2050.[243] Again, calculated to the required installed capacity of PtG, it would be equal to 150 GW. The main installation takes place between 2020 and 2030. This comparison shows how single studies are estimating an enormous market potential of the PtG technology due to the usage in the target market *power-to-gas-to-mobility*.

But different studies exist. In order of the German federal ministry of economics, different research institutes (Gerhard et al. (2015)) have analyzed a future mobility scenario, which differs in comparison to the mentioned studies above. Although the study predicts a high share of 40% NGVs in the future energy system, the amount of energy consumption by PtG is with 31 TWh/a comparably low.[244] Also, most of the synthetic fuel is used in the target market *power-to-gas-to-power* instead of the usage in the transportation sector. Therefore, they forecast a late and low development of the PtG technology. The reasons for the result are different assumptions for comparable mobility solutions. For example, the heavy-duty mobility runs on overhead power lines,

242 Nitsch et al. (2012), table 2-24 in the appendix, detailed data for natural gas and biogas received per mail at the 24th of March 2016.

243 Blank et al. (2014), p. 49

244 Gerhard et al. (2015), p. 83 and p. 152

and most of the surplus of RE is used in the heat market by PtH and heat pumps. These are competitive technologies, which have been mentioned in the system analysis and the description of the heat market (see chapter 5.2.3).

Latest studies confirm the importance of SNG to be compliant with climate targets. The national platform of the future mobility (NPM) is an official expert platform, in which different stakeholders are embedded. This research group aims at finding solution to reach the climate target of the German transportation sector until 2030, which has been mentioned in the introduction (see chapter 1.1). In their first report they proclaim a market potential of PtX products of up to 190 PJ or 8.4% of the fuel market in 2030.[245] They also identified a potential market of up to 3 million NGVs and up to 255,000 gas trucks in 2030.[246]

5.2.4.3 Regulations of the Mobility Case

This chapter is investigating the political influence on the use case of SNG in mobility. Therefore, first, the European RE directive (RED), second, the European fleet regulation, and third, different political vehicle strategies in other countries are depicted.

The European Union is promoting the use of climate-friendly energy carriers in mobility. The EU-27 has a target of 10% RE by the end of 2020.[247] Therefore, fuels with low climate impact get support according to their potential for GHG reduction. The national implementation of this legislation differs between countries in the EU-27. Nowadays the reduction target is mostly achieved with biofuels and electricity, which is illustrated in Figure 32. Biofuels got a lot of incentives in the middle of the last decades, which lead to a rapid market growth and a peak of more than 45 TWh in 2007. Most of the biofuels are conventional biodiesel and bioethanol. Biomethane is an upcoming, new fuel with 660 GWh in 2019[248]. The use of direct electricity is increasing as well.

245 NPM (2019), p. 31

246 NPM (2019), p. 21

247 European Parliament (2009a), p. 8

248 BMWi (2020a)

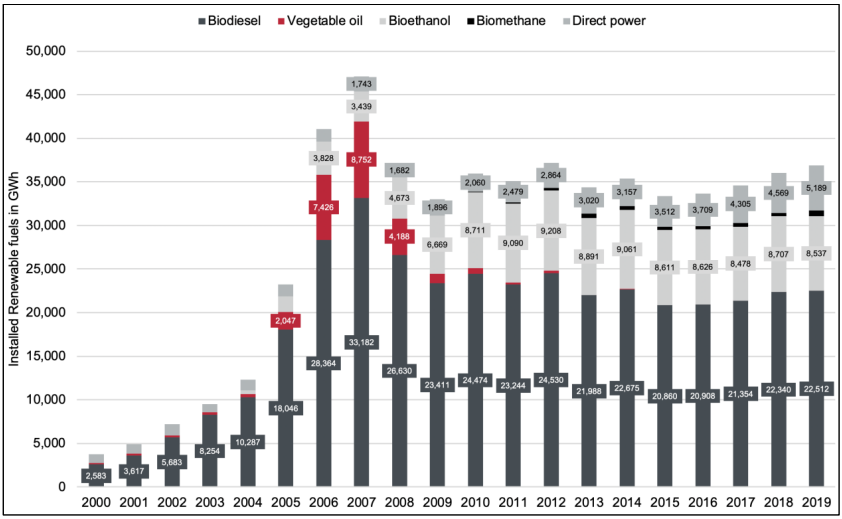


Figure 32: Development of different energy carriers in the mobility in Germany[249]

The estimation of the future development in this market is difficult due to dependencies on biological feedstock prices, worldwide trades as well as changes in the national and European legislation. For example, the change from the biofuel promotion to the GHG reduction legislation at the beginning of 2015 in Germany has decreased the amount of biofuel in the fuel mix in Germany because less renewable fuels with higher reduction quotas have been used.[250]

However, biofuels of the first generation, which consists of sugary, starchy and oleaginous crops and plants,[251] are criticized because their area of cultivation is in competition to the area of food crops and plants. Therefore, these biofuels could influence the food price (also called *tank or plate* discussion). As a result, biofuels of the first generation have been limited to 7% of the overall fuel mix in Germany in 2014.[252] The incurred gap to the European target has to be covered with fuels of the second and third generation and is showing a short-term market potential of suitable fuels. The second generation of biofuels is characterized by agrarian waste material like wood, grass or straw.[253] Algae and power-based, synthetic fuels like SNG belong to the upcoming third generation. On the European level in the RED (No. 2009/28/EG) biofuels of the

249 BMWi (2020a)

250 Ufop (2016)

251 Böttcher et al. (2014), p. 110

252 Böttcher et al. (2014), p. 112

253 Böttcher et al. (2014), p. 110

2nd and 3rd generation are called *advanced biofuels*.[254] The national implementation in Germany has allowed SNG as a third-generation fuel at the beginning of 2018.

If the share of sustainable fuels is not achieved, companies, which are bringing fuels into the market, are penalized. Under the current legislation, the penalty rate is 0.47 €/kg of GHG ($CO_{2eq.}$) in Germany.[255] The reference value is 83.8 g $CO_{2eq.}$/MJ. In German legislation, SNG has a specific emission quota of 3.3 g $CO_{2eq.}$/MJ.[256] Therefore, SNG has a reduction potential of 80.5 g $CO_{2eq.}$/MJ. Considering the penalty cost and an energy density of 13.85 kWh/kg,[257] SNG can yield 1.89 €/kg or 13.65 ct/kWh, which is brought into the mobility market. This price is demonstrating the max. charge in the German fuel market. Therefore, the fuel company will prefer all low-priced alternatives to fulfill the GHG reduction target.

As mentioned, the EU-27 has a target of 10% renewable fuels in 2020. In Germany, this target is implemented as the *GHG reduction quota* in the federal immission control act (BImSchV). This parameter has also been mentioned during the system analysis. Although SNG is already mentioned as a countable fuel in this act, there is another disadvantage. Only direct connected PtG plants have the possibility to generate revenue with the GHG reduction quota. Otherwise the GHG reduction potential is calculated with a national power mix and not with individual renewable power supply concepts (see chapter 5.3.1.5).[258] An exception is PtG plants, which have been installed before October 2015.[259] In the section about the renewable power supply of PtG plants a delegated act of the RED II is discussed, in which the power supply of grid-connected plants will be covered (see chapter 5.3.1.5). It is expected that this European act will overrule the national regulation and that new installed PtG plants can also yield the full GHG reduction quota. The latest development of the RED II is described in the technology pathway of PtG (see chapter 7.2).

Second, the CO_2 fleet emission control can play a significant role for the PtG technology. The EU-27 has set the target of 95 g/km per new-registered vehicle in fleet average in 2020.[260] The resulted penalty for car manufacturers is high if the target is not achieved. For that reason, the automotive industry is seeking sustainable solutions. As shown with the GHG reduction potential above, SNG can provide such a solution. The issue is that the measurement of this regulation only takes place at the exhaust pipe. This emission calculation is called the *tank-to-wheel* approach. Therefore, NGVs,

254 European Parliament (2015a)

255 Zoll (2017), p. 20

256 BImSchV (2017)

257 Gosda (2014), p. 44

258 See section 3 number 3 of Biokraft-NachV (2016)

259 See section 8 of Biokraft-NachV (2016)

260 European Parliament (2013)

whether they run on fossil, natural gas or renewable SNG, are calculated with the fossil emission value. The benefits of the upstream emissions are not included. The comprehensive approach is called the *well-to-wheel* approach. Otherwise, electric or fuel cell cars have zero emissions according to this measurement – independent of their upstream emissions.

The split of the fuel regulation (*well-to-tank*) and the vehicle emission regulation (*tank-to-wheel*) is presenting a non-holistic and non-technology-open consideration because technologies are competing in two different sectors and not in the sum (*well-to-wheel*). The separation of the regulations rather prefers technologies under single aspects like low exhaust emission rather than technologies with systemic advantages like the integration into a RE system. Also, high CO_2 abatement costs of up to 475 €/t_{CO2} in the vehicle emission regulation are pretending low emission mobility instead of holistic, sustainable mobility concepts like the usage of SNG in the mobility in Germany.[261]

Other countries have approaches to include upstream emissions. For example, Switzerland has a yearly average biomethane share of more than 10% at gas filling stations. Therefore, the CO_2 value of each NGV is reduced by 10%.[262] In addition, the Swiss government is considering an act to calculate the upstream emission of renewable fuels.[263] Even on the European level, the consideration of the upstream emission has been included in the legislation. In article 6 of EG Nr. 443/2009, a CO_2 reduction of 5% is possible if more than 30% of all filling stations are offering fuel with 85% bioethanol.[264] In the United States of America it is planned to count the upstream emissions if more than 200,000 electric or fuel cell vehicles are sold up from 2022 onwards. Then the emissions of these cars are calculated with a national power mix.[265] However, it is interesting that many governments start to broadcast emission regulations to a holistic consideration. Renewable fuels like SNG could benefit from this development in the future. This development is further analyzed in the potential technology pathway in the conclusion (see chapter 7.2).

5.2.4.4 Sales Price of SNG in the Mobility Market

The price of SNG in the mobility case is necessary for the calculation of different business cases. The market price consists of two different components. On the one hand, the SNG is injected in the natural gas grid and balanced to gas filling stations. Therefore, the same revenues as in the natural gas market are yielded (see chapter 5.2.2). In addition, a further price can be generated if the sustainability of the fuel is accounted

261 Bardt and Schaefer (2018)

262 Hammer and Block (2016), p. 10

263 Swiss Parliament (2018)

264 Article 6 of European Parliament (2009b)

265 EPA (2012), p. 8

for. For example, the SNG option of the Audi e-gas plant cost €14.95 per month extra in 2015.[266] With a yearly driving range of 15,000 km and a supposed vehicle consumption of 4 kg gas per 100 km, the calculated extra price is 0.3 €/kg, or with an energy density mentioned above, it is 2.2 ct/kWh. This is in range with different literature sources about the willingness of extra charge for green energy.[267]

Additionally, the condition is given that the green property of the fuel is only allowed to be sold once (no *double counting*). A direct offer of sustainable mobility to the customer and a sale as biogas results in an illegal double counting of the green ability and is not compliant to sustainability standards. Therefore, the PtG company has to decide whom to sell the green property. An additional communication value can be generated if the renewable fuel is linked to the vehicle.

On the other hand, the green ability can also be used to comply with political targets. Under the current political situation, only the fulfillment of the fuel regulation (RED) and the yield of the *GHG reduction quota* is possible (see chapter 5.2.4.3). The STX Group in Amsterdam is offering a trading platform for the GHG reduction quota. According to Ruecker (2016), the GHG reduction quota price differs between 115 and 245 €/t $CO_{2eq.}$ from 2015 to 2017.[268] The following chart is demonstrating the result of the GHG reduction quota calculated with the above-mentioned CO_2 reduction potential of SNG in comparison to the fossil reference value.

The figure shows that revenues can be yielded with the GHG reduction quota, which are twice to five times higher than the sale price at the natural gas market. Therefore, this is an important economic driver. An average price of 5.64 ct/kWh is considered for the business case calculations. Next to the average target market price, the price distribution is of note. Therefore, a price corridor was chosen to highlight the impact of the price fluctuation on the BM result. In this dissertation, the yearly average price corridor is from 3.33 ct/kWh to 7.1 ct/kWh.

266 Audi (2014)

267 Reichmuth et al. (2014), p. 140

268 Ruecker (2016), p. 21

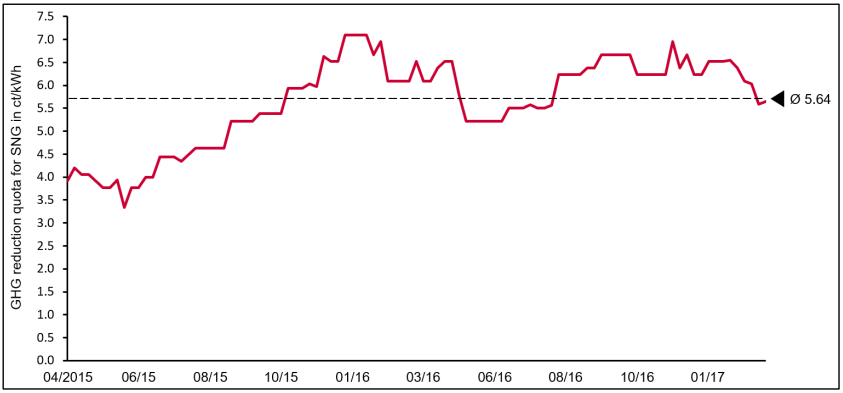


Figure 33: Development of the GHG reduction quota for SNG in Germany[269]

The further price development of the GHG reduction quota depends on the RE targets of the EU-27, feedstock prices of biofuels, and the development of different competing technologies (e.g., electric cars). Therefore, it is difficult to assume a price development. A similar price development, like the CO_2 certificate price of 4.23%, is assumed (see chapter 5.2.2). But the price development is limited at the penalty cost of 13.65 ct/kWh of SNG in the BM calculation. In the following table, the different prices of SNG in mobility are shown:

Table 8: Price composition of SNG in the mobility

Type of charge	Value
Average natural gas price (2008 to 2016)	2.1 ct/kWh
Price corridor of the natural gas price (2008 to 2016)	0.91 to 3.21 ct/kWh
Average GHG reduction quota (2015 to 2018)	5.64 ct/kWh
Price corridor of the GHG reduction quota (2015 to 2018)	3.33 to 7.1 ct/kWh
Price development of the GHG reduction quota per year	4.23%

In the future, a further incentive could be established for the automotive industry if vehicles, which are supplied with SNG and are accounted for the fleet emissions of car producers (see chapter 7.2). However, SNG, in combination with NGVs, is not accounted for the global fleet emissions yet. Therefore, it is a theoretical potential if the legislation changes. For that case, the CO_2 avoidance costs would be in competition with the costs of electric and hydrogen mobility.

269 Ruecker (2016)

5.3 Value Chain

The value chain of the PtG technology is setting all activities along with the SNG production. Here, all indicated parameters of the system analysis except of target market parameters are considered. According to the expert group of the first empirical step, the following parameters are directly influencing the business case of PtG:

- CAPEX
- Maintenance
- lifetime
- oxygen sale
- heat sale
- gas sale
- avoided gas grid fees
- GHG reduction quota
- costs at power markets
- costs of power taxes and fees
- infrastructure costs (grid fees)
- efficiency

The PtG technology is the conversion of electricity (power) to gas as a chemical energy carrier, as was explained in the introduction. Therefore, economic parameters like costs at power markets or costs of power taxes and grid fees belong to the *electricity side*. On the *gas side*, the target market parameters as gas sale, heat sale, GHG reduction quota and avoided gas grid fees are placed, which are already discussed. In between, the *site parameters* are located like CAPEX, efficiency, lifetime and maintenance. Additional parameters like oxygen sales or efficiency are also explained in this chapter of the value chain. Figure 34 is illustrating the value chain. The single process steps are marked with a number below. This chapter is structured along the value chain of the PtG technology.

Beginning at the electricity side, the first position is the economic driver *costs at power markets*, which is flagged in the following figure. Different prices at different power markets exist that are influencing the business case. Therefore, power markets are further analyzed. Second, the *costs of power taxes and grid fees* are explained in the case of Germany. Third, the CAPEX and maintenance of the PtG system are clarified. Fourth, revenues with oxygen sales are briefly described. Fifth, the efficiency of different PtG plant constructions are explained. This step leads to the amount of SNG production, which can be sold at the described target markets. The prices, which can be yielded at those markets, have been explained in the previous chapter.

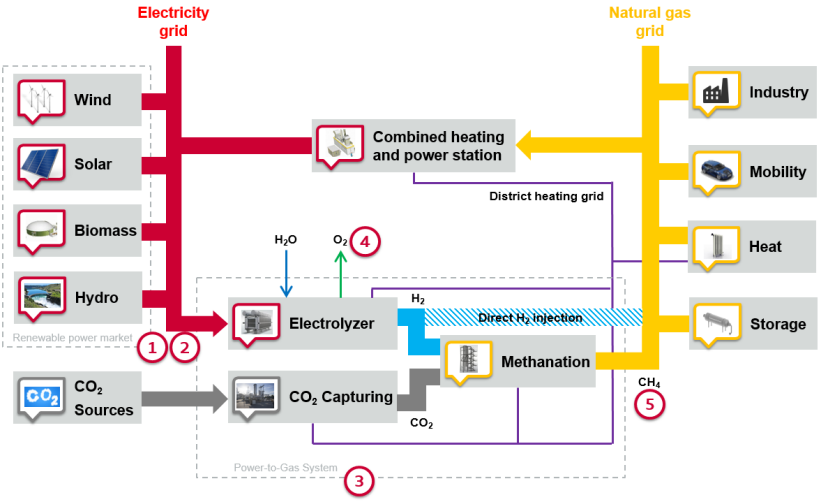


Figure 34: Value chain of the PtG technology

As seen in Figure 34, different parameters have an indirect influence on the PtG system. These components, like carbon dioxide sources or feed-in guidance for the public gas grid, are explained in the value network chapter of the PtG technology. The value network components have partly not been mentioned during the system analysis but are mentioned in PtG literature.[270] The direct use of hydrogen from PtG plants is possible. Hydrogen can be injected into the natural gas grid if the feed-in requirements are fulfilled (see chapter 5.4.4). In this case, the injected hydrogen is replacing natural gas in the grid, and the energy amount is treated as SNG in the different target markets. The hydrogen energy value is taken into account.

Hydrogen can also be filled in bottles under high pressure or liquified, transported by trailers and sold to the chemical industry or hydrogen filling stations. However, this case is not considered in this research. Only SNG, which can be injected in an existing grid, is investigated. The gas grid is well-expanded, whereas the installation of a sufficient hydrogen grid is estimated to cost about €100 billion in Germany.[271] But in a separated application or in the context of the adjustment of the German public gas grid from low calorific to high calorific gas (see chapter 5.4.5), a full hydrogen infrastructure could be partly economically worthwhile. In this case, the direct injection into an existing gas grid can be considered.

270 E.g., Sterner and Stadler (2014), Sterner et al. (2015), Trost et al. (2012)

271 Krieg et al. (2012), p. 110

5.3.1 Costs at Power Markets

The power supply of a PtG plant is one of the key economic drivers, as the system analysis has shown. Due to expected efficiency losses of the PtG technology, the power price has multiple impacts on the final business case. This chapter explains different concepts of the power supply with respect to the structure of the German power markets. Figure 35 illustrates the complex market design. The power supply situation is updated yearly in the monitoring report of the German federal grid agency.[272] The power supply can be divided into the physical and financial trades of power at the spot markets and bilateral trades as well as multiple ancillary services. Due to the economic importance of the different supply concepts, the development of the markets, the power prices and the possible operation time are explained in sub-chapters.

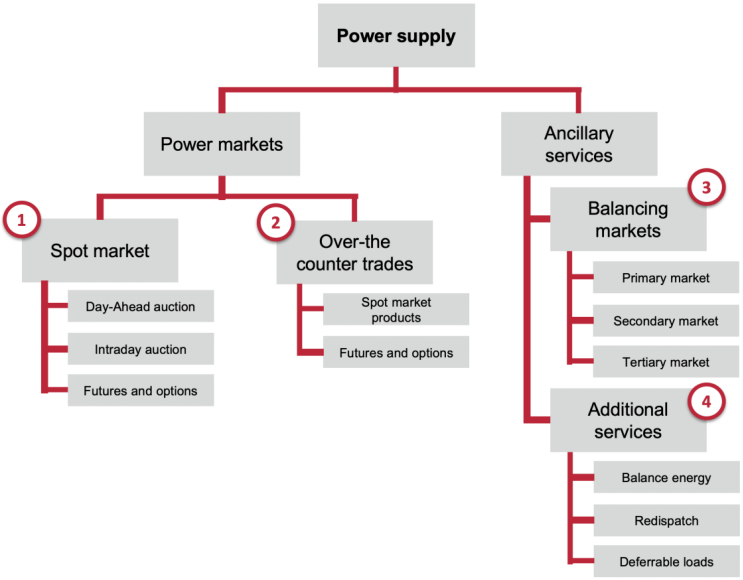


Figure 35: Structure of the German power markets

First, the German spot markets like day-ahead or intraday market are exposed. Second, the bilateral Over-The-Counter (OTC) trades are mentioned as a possible supply concept. Third, the balancing markets with respect to the technical feasibility of a PtG plant are explained. Fourth, additional ancillary services are discussed as a future option of the PtG power supply. In each power market, further analyses are undertaken

[272] BNetzA (2019)

to highlight the optimal operation schedule of a potential PtG plant. In the last subchapter, the proof of the supply of RE is discussed. The different power markets and their individual strengths and weaknesses are explained and later tested in different business case calculations (see chapter 6.1.5) and in a single case study (see chapter 6.2).

5.3.1.1 Spot Markets

Different spot markets for power products exist in Europe. The most important European spot markets are the European Energy Exchange (EEX) located in Leipzig and EPEX SPOT in Paris. Day-ahead and intraday spot market products are offered at EPEX SPOT and future market options at the EEX. This research is considering spot market products for the German region. In 2018, 225 TWh was traded day-ahead at EPEX SPOT.[273] An interesting other spot market is the EXAA in Vienna because of existing renewable spot market products[274]. The liquidity of the EXAA spot market is low with only 7 TWh in 2018,[275] this spot market is not considered further. Spot markets have an important price signal for all other power markets.[276] The trades are anonymous, and the origin of energy is unknown.

The price building at the spot markets is following a usual bid-and-ask mechanism. Different power suppliers are offering different amounts with certain marginal costs. Participants who are demanding energy are purchasing these amounts at different times. Each bidding period builds a market price, in which the total demand is satisfied. For that reason, the price of the last bid is representing the spot market price of this period. The marginal price of each supplier depends mostly on the power production costs. In a fossil energy system, these costs are calculated primarily with the commodity prices, the efficiency of the power plant and the costs of carbon dioxide certificates (ETS). In this context, the commodity price is the energy price and depends on fuel prices. In other words: for the owner of a power plant, the variable cost is the determining factor to put a plant into operation or not – fixed cost is not as relevant. During the energy transition, REs with zero commodity costs and guaranteed feed-in tariffs have entered the market. The commodity or fuel costs of renewables are negligible because wind and solar energy are available for free. Only the investment costs do matter in the RE system. Because of guaranteed feed-in tariffs, the renewables can offer energy at the spot market without any marginal costs. Therefore, renewable bids are shifting the price merit-order of the spot market.[277]

273 BNetzA (2019), p. 29

274 BNetzA (2019), p. 248

275 BNetzA (2019), p. 29

276 BNetzA (2019), p. 28

277 Sensfuß and Ragwitz (2007), p. 28 ff

Figure 36 is highlighting the price building and merit-order effect in a simplified form. In a fossil energy system without REs, the price (P1) is satisfying the demand (D1). Without marginal costs of RE, the merit-order shifts to the right, and the new price (P2) is defined by a lignite plant with lower marginal costs. The merit-order effect is decreasing the spot market price in times with high production of REs. For that reason, a correlation between the power price and the share of RE in the power mix can be assumed. Cost-intensive fossil power plants have less hours of operation in a RE system. In addition, technical restrictions in regard to ramp-up time or minimum operational time are also reducing the economics of fossil power plants.

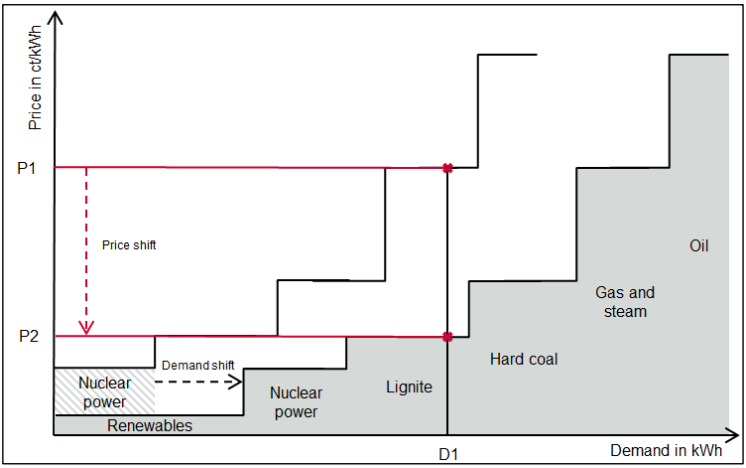


Figure 36: Simplified merit-order effect

As mentioned above, different products are traded at spot markets. In the day-ahead auction daily, 4-hourly, and hourly trades can be placed. The hourly day-ahead product is the most traded product at the considered spot markets.[278] In addition, in the intraday auction, quarter hours can be traded 45 min prior to the physical delivery. Futures and options can be traded up to four years in the future. Normally these long-term financial trades are hedging price changes for all market participants and are not physically delivered.[279]

Due to the merit-order effect, the price development of the hourly day-ahead product has been decreased until 2016. Figure 37 is showing the price development from 2007 to 2016 with a weekly moving average. All spot market data is available online and is provided for this research from Volkswagen Kraftwerk GmbH as well as the University

278 BNetzA (2016), p. 165

279 Judith et al. (2011), p. 50

of St. Gallen. The trend line is highlighting the reduction of this price due to the expansion of REs. The linear reduction per year is 5.26% on average. Whereas the yearly average price of the hourly day-ahead price was 6.58 ct/kWh in 2008, the average price is cut in half with 3.16 ct/kWh in 2015. The RE production increased from 15 to 27% at the same time.[280]

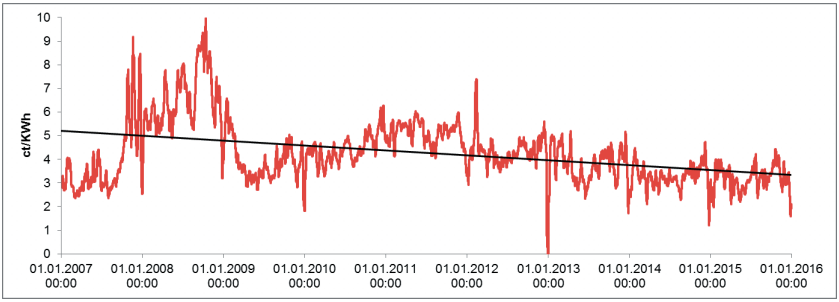


Figure 37: Development of the hourly day-ahead spot market price at the EPEX SPOT

Assuming that an economically driven PtG plant is only operating 4,000 FLH with the lowest spot market prices, the average power supply price was even lower at 2.14 ct/kWh in 2015.[281] Latest publications of the German grid agency and year-ahead futures at the EEX spot markets are showing that the development of power prices is inverse. Since 2017 the power prices are increasing again.[282] The spread between high and low power prices is rising, which can be used by storage facilities in the future. Table 9 is demonstrating the results of the analysis of the day-ahead spot market.

The analysis of the spot market takes place with historical data. Although, knowledge about the electricity prices and price developments exist, for future BM calculations, it is unrealistic to take these conditions as given. In reality, the cheapest 4,000 FLH are not known, and hours with higher electricity prices are likely chosen with vague predictions. For that reason, an electricity price forecast error is assumed by literature review and added to the average power price.

In the literature, different model families for electricity price forecasting are available.[283] Fundamental models are using physical and economic data like weather forecasts or load demands. Multi-agent or game theory models are trying to simulate the behavior of market agents. Statistical models are comprising historical time-series and risk

280 BMWi (2020a)

281 The operation time of a PtG plant is explained in the value chain (see chapter 5.4.7).

282 BNetzA (2019), p. 258 ff

283 Keles et al. (2016), p. 219

evaluation of electricity trades. Also, artificial intelligence models exist, which are using neural or fuzzy networks.[284] However, a detailed literature analysis has detected that for forecasting day-ahead prices, statistical and artificial intelligence methods have shown the best results.[285]

The accuracy of the forecast models depends on the market under study and on the period considered.[286] In the case of the PtG technology, a yearly forecast is necessary to meet the planned production capacity but, also, a short-term forecast of electricity prices is essential to optimize the costs at power markets. Therefore, a holistic model should be considered. The forecast error of these models is often measured as the *mean absolute percentage error* (MAPE), which highlights the average deviation to the real data. The percentage error is criticized because MAPE values become exceptionally large if the electricity price is close to zero and, respectively, small in a situation of price spikes.[287] However, an absolute error is difficult to transfer to different markets and time periods. Therefore, in the research recommendation, a further study of appropriate electricity price forecast models for PtG plants is advised (see chapter 7.3.2). Aggarwal et al. (2009) have analyzed 47 papers with different methods on different electricity markets published from 1997 to 2006. Their journal paper is often cited. It detects a monthly MAPE of 9.96 to 13.69%.[288] The mean of these forecast errors (11.83%) is used in this dissertation to obtain the difference between the theoretical and practical power prices.

Table 9: Development of different characteristics of the hourly day-ahead market

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
Share of RE of the power production [%][289]	15.2	16.4	17	20.4	23.5	25.1	27.4	31.5	31.6
Average EPEX SPOT price [ct/kWh]	4.29	3.89	4.45	5.11	4.26	3.78	3.28	3.16	2.95
Average price with 4,000 FLH [ct/kWh]	4.29	2.54	3.31	3.99	2.93	2.46	2.26	2.14	1.97
Number of hours with negative price	15	71	12	15	56	64	64	126	96
Average price with 4,000 FLH and forecast error [ct/kWh]	4.80	2.84	3.70	4.46	3.28	2.75	2.53	2.39	2.20

284 Lago et al. (2018), p. 891

285 Weron (2014)

286 Lago et al. (2018), p. 891

287 Weron (2014), p. 1038

288 Aggarwal et al. (2009), p. 19

289 BMWi (2020a)

A detailed analysis of the price structure at the day-ahead hourly spot market has been undertaken to achieve a better understanding of the daily operation time of PtG plants. Therefore, the hourly day-ahead price of the EPEX SPOT from 2012 has been considered and compared to different years. Often the December has lower power prices due to low energy demand during the Christmas and New Year's Eve holidays. However, substantial monthly differences, which would change the operation schedule of a PtG plant, have not been observed in this time period. Figure 38 demonstrates the distribution of the daily operation time of a virtual 6 MW PtG plant for different weekdays and the specific, average power price per day for a yearly production time of 4,000 FLH. It shows that the spot market price is lower at the weekend and, therefore, the daily operation time of a price orientated PtG plant is at that time higher.

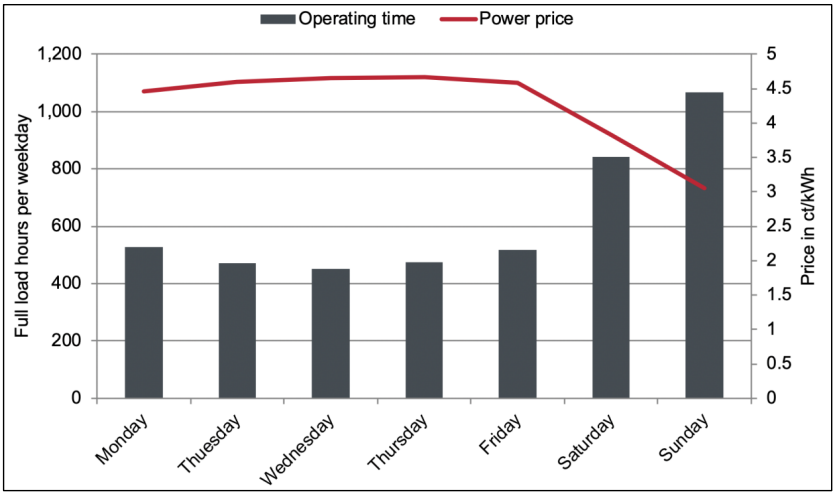


Figure 38: Weekly operating time of a PTG plant at the day-ahead spot market 2012

The subsequent analysis is considering the hourly distribution of the operation time. Therefore, again a virtual 6 MW PtG plant with 4,000 FLH per year is taken into account. The result is illustrated in Figure 39. It shows that the PtG plant is operating mostly during nighttime. Here, the average power price per hour is lower than during the day. In addition, the operation at midday is economically worthwhile because of a high generation of photovoltaic plants, which is decreasing the power price due to the merit-order effect. Further on, the comparison to the power price of 2007 indicates the influence of solar power during midday hours and the shift of the evening peak. In total, a power price-orientated PtG plant with power supply at the day-ahead hourly spot market would operate mostly at night and weekend hours.

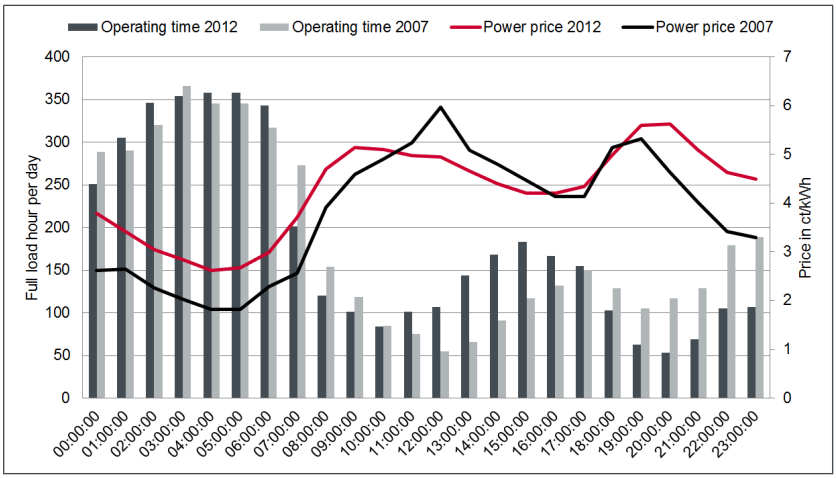


Figure 39: Daily operation time of a PtG plant at the day-ahead spot market

In the future, short-term trades could play a major role because energy suppliers must balance the fluctuating production of RE. Therefore, the intraday spot market might gain rising attention. The traded volumes increased from 20 TWh in 2013 to 53 TWh at the EPEX SPOT in 2019.[290] An analysis of the volatility per hour indicates that the traded volumes increase by up to 250% during night and mid-day hours.[291] The intra-day spot market can be used as a flexibility market of the energy system and buffer the unsteady generation of electricity by weather-depending facilities like wind or pho-tovoltaic plants.

The intraday auction is also used to balance the internal pool management of energy suppliers. Each participant at the energy markets must meet the physical deliveries and, therefore, their trades. Otherwise, they must pay the balance energy[292] to the grid operator (see chapter 5.3.1.4). The analysis of the average spot market prices at the intraday market is shown in Table 10. It highlights that the average power price is lower than the average power price at the day-ahead hourly market, also the number of hours with a negative power price is higher. The trading mechanism of the intraday market differs from day-ahead trading. The intraday market is characterized by continuous trading. Therefore, no settlement price exists, and trades take place all the time during the bidding period. For that reason, different price indices exist and are published on the EPEX SPOT website. In this case, the ID_3-price is chosen as a relevant price

290 BNetzA (2019), p. 248

291 Betz et al. (2016), p. 4

292 In German: Ausgleichsenergie

indicator for the intraday market. The ID_3-price displays the average price in the three hours before the closing of the bidding period. The ID_3-price is announced from the EPEX SPOT since mid-2015. In the early years, the weighted average spot market price is mentioned and considered in this study. This price index is the average price of all trades during the bidding period. Both price indices appear to be nearly similar.

The continuous trading at the intraday market enables another possible economic advantage in comparison to the day-ahead market, which is analyzed in the following section. Asset-backed trading during the trading period at the intraday market can lead to further financial yields. Due to the operational flexibility of the PtG technology, which is discussed in the appendix (see chapter A.4), a plant can ramp up immediately if an option is called (bought) or not. The analysis of additional trading yields is undertaken by building a Black-Scholes model.

This model has been developed by Fischer Black and Myron Samuel Scholes in 1973.[293] They define an option as given security to buy or sell an asset and distinguish between an *American option*, which can expire at any time, and a *European option*, which expires at a specific date.[294] Some simplifications or *ideal conditions* are further set. First, the interest rate is known and constant over time. Second, the variance of the stock price is constant as well, and the stock price follows a logarithmic normal distribution. Third, no dividends are paid. Fourth, the *European option* is considered. Fifth, no transaction costs exist. Sixth, it is always possible to buy a fraction of the price at the mentioned interest rate. And finally, short selling is allowed and always possible.[295]

Under these assumptions, Black and Scholes (1973) derive formulas for a European call and put (selling) options:

293 Black and Scholes (1973)

294 Black and Scholes (1973), p. 637

295 Black and Scholes (1973), p. 640

Equation 5-1: Black and Scholes equations[296]

$$C\ (S,t)\ = SN(d_1) - Xe^{rT}N(d_2)$$

$$P\ (S,t)\ = Ke^{-rT}N(d_2) - SN(-d_1)$$

where:

$$d_1 = \frac{\ln(S/X) + \left(r + \frac{\sigma^2}{2}\right)T}{\sigma\sqrt{T}}$$

$$d_2 = d_1 - \ \sigma\sqrt{T}$$

with:

- S = stock price
- X = exercise price
- r = interest rate or risk-free rate
- T = time to maturity
- N = cumulative distribution function of the standard normal distribution
- σ = volatility

Black and Scholes mention that empirical tests were conducted on a large body of data to validate the equation.[297] At the closing of an option trade, the sole uncertain component of the equation is the volatility. The model has been criticized because unexpected volatilities like market crashes cannot be reproduced.[298] However, the Black-Scholes model has been used to calculate option values in electricity markets.[299] Hjalmarsson (2003) states in his analysis, "Does the Black-Scholes Formula Work for Electricity Markets? A Nonparametric Approach" that "*from a practical viewpoint, the Black-Scholes formula might still be the best available.*"[300]

The following calculation of the asset-backed trading value considers the hourly ID_3-price of 2016 as the average stock price. The exercise or trigger price is the assumed forecast price. In this case, due to missing forecast data at the intraday market, the hourly 2016 day-ahead price is chosen as the price forecast of the ID_3-price. The risk-free rate displays the value of borrow or lends cash. In the case of an operating PtG plant, the risk-free rate is zero % because SNG needs to be produced anyway. Another advantage of this risk-free rate is that the call and put options are symmetric in the at-the-money situation. The volatility during the trading period has been analyzed by Betz

296 Chance (2011), p. 4

297 Black and Scholes (1973), p. 653

298 Yalincak (2012)

299 See Betz et al. (2016) or Sezgen et al. (2005)

300 Hjalmarsson (2003), p. 5

et al. (2016) for 2014. The same volatility is chosen for the business case calculation in chapter 6.1.5. The time is one because the whole trading period is considered. Since a grid- and system-friendly operation time should be followed (see discussion in 5.4.8), equal distribution of call and put options are chosen to achieve around 4,000 FLH.

In the following figure, the ID3-price of 2016 and the option value of the Black-Scholes model are displayed. With the mentioned input parameters, an additional value of around 19.6 €/MWh is generated. This is in line with Betz et al. (2016), who have calculated an asset-backed trading value of 20 €/MWh with an average power price level of 40 €/MWh.[301] In the 12 hours with the lowest cumulative power costs (ID3-price and value of options trading), the call option should be prioritized, and in all other hours, the put option generates additional value. In total, under these assumptions, an average power price of -0.59 ct/kWh would have been possible in 2016. However, a forecast error, as described above at the day-ahead market, should be included. In addition, the generation of option values required trading units with continuous availability. Often only large energy suppliers have such trading units integrated into their organizational structure. In addition, it has to be mentioned that if more market participants yield the extra trading value with assets like PtG instances at the intraday market the volatility could decreases and therewith the possible earnings.

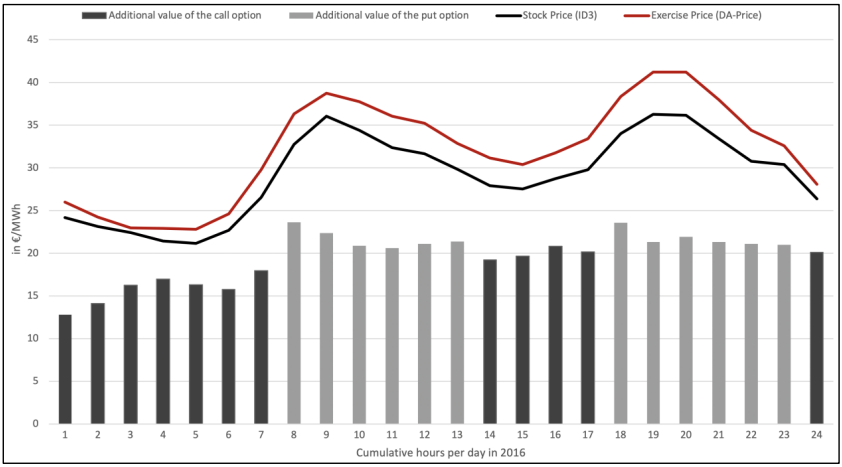


Figure 40: Black-Scholes model of additional trading values at the intraday market 2016

[301] Betz et al. (2016), p. 5

Table 10: Development of different characteristics of the EPEX SPOT intraday market

Year	2013	2014	2015	2016
Weighted average price [ct/kWh]	3.78	3.26	3.18	2.91
Weighted average price with 4,000 FLH [ct/kWh]	1.87	1.68	1.80	1.74
ID_3-price [ct/kWh]	-	-	-	2.92
ID_3-price with 4,000 FLH [ct/kWh]	-	-	-	1.73
Possible additional value with asset-backed trading [ct/kWh]	-	-	-	1.96
Weighted average price with 4,000 FLH and Forecast error [ct/kWh]	2.09	1.88	2.01	1.95
Number of hours with a negative price (weighted average price)	253	266	294	218

The results of the analysis of the intraday market are shown above. The weighted average price is decreasing from 3.78 ct/kWh in 2013 to 2.91 ct/kWh in 2016. The average price of the 4,000 hours with the lowest power price is 1.8 ct/kWh in 2015. This power price is 16% lower than at the hourly day-ahead market. Also, the number of hours with negative power prices as an indicator of surplus power generation is higher at the intraday market. In 2013, there have been four times more hours at the intraday than at the day-ahead market. In 2015, one of 30 hours had negative spot market prices.

Another interesting analysis for the PtG technology is how the hours of operation look like at the intraday market. Therefore, the 4,000 hours with the lowest power prices have been considered first. Later, a combination of the best power and gas prices is investigated. The analysis of weekdays is similar to the analysis at the day-ahead market. Most of the operation takes place on the weekend days. The following figure is showing the distribution of daily operating time of a virtual 6 MW PtG plant at the intraday market in the forenoon.

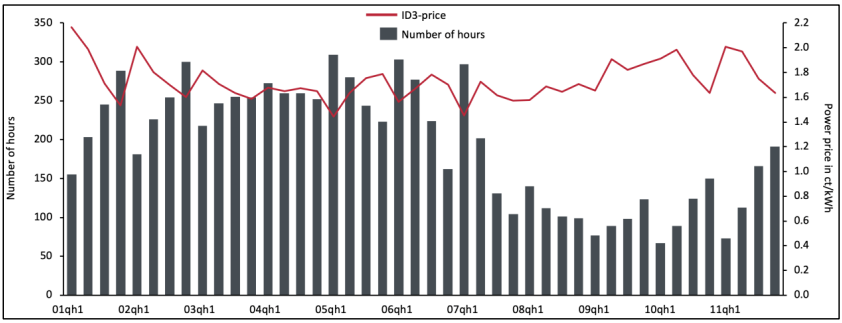


Figure 41: Daily operating time of a PtG plant at the continuous intraday market a.m. in 2016

The distribution of the daily operation time is similar to the day-ahead market in the first 12 hours. Most of the operation takes place at night with low power prices. From 5:00 a.m. on, most of the operation takes place in the first quarter per hour (qh). This characteristic goes on until 9:00 a.m. Then the characteristic changes and the last quarter of each hour is the quarter with the most operation time because of lower power prices.

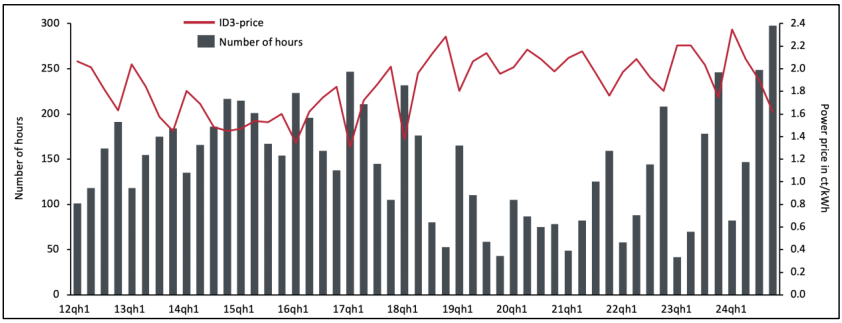


Figure 42: Daily operating time of a PtG plant at the continuous intraday market p.m. in 2016

The distribution of the daily operation time in the second half of a day is different as well. From noon to 3:00 p.m., the characteristic from the first half is continued. The last quarter has lower power prices and, therefore, more operation time. From 3:00 p.m. to 9:00 p.m., the first quarter again is the one with more operation for a price-orientated PtG plant. From 9:00 p.m. to midnight, it is vice versa.

An explanation of that characteristic could be the difficulty of the fossil power plants to follow the daily demand curve due to technical limitations in reaction time. If power plants are ramping up too slow, the first quarter of power purchase has to be sold at the intraday market, which leads to low power prices at the spot market. If power plants are ramping down too slow additional power has to be purchased in the last quarter. Therefore, the intraday market is interesting for energy suppliers to balance their internal power generation. In addition, changes in weather conditions, which are influencing renewable power production, can be balanced with trades at the intraday market. Because of these advantages, the trading volumes at the intraday market are increasing. The PtG technology, as a fast-reacting plant, can benefit from low market prices and high price fluctuations.

The previous analyses have only taken into account the dynamic power price at different electricity markets. Next to the power prices, other dynamic parameters like the gas sale price are influencing the hours of operation as well. For that reason, a further investigation is made to examine the operation time at the intraday market, including the daily gas prices in 2016 (see chapter 5.2.2). The optimization depends on the

chosen plant configuration. If the efficiency is higher, the influence of the gas price compared to the power price increases, and different hours would be chosen for the operation. The result for a 5 MW PtG plant with an efficiency of 53% compared to the *only intraday power market* operation of Figure 41 and Figure 42 is displayed in Figure 43. It shows that even more operation time takes place during the night shift and less during the daytime. The average power price of the 4,000 most economical FLH is increased from 17.43 to 17.46 €/MWh. But on the other hand, the average gas price of those operational hours is raised from 13.43 (only oriented at the power market) to 13.56 €/MWh. The economic impact on the overall business case is quite low. The costs at the power market increase for this operational concept with €709 per year in a 5 MW PtG plant. On the other side, in the gas market, an additional yield of €1,379 is generated. Therefore, with this plant configuration, the operational optimization of the power and gas market leads to an additional income of €670 in the analyzed year. However, in the BM calculations, the impact on other plant configurations is considered.

An overview of the costs at all spot power markets, which are used in the business case calculation, are given at the end of the chapter of costs at power markets.

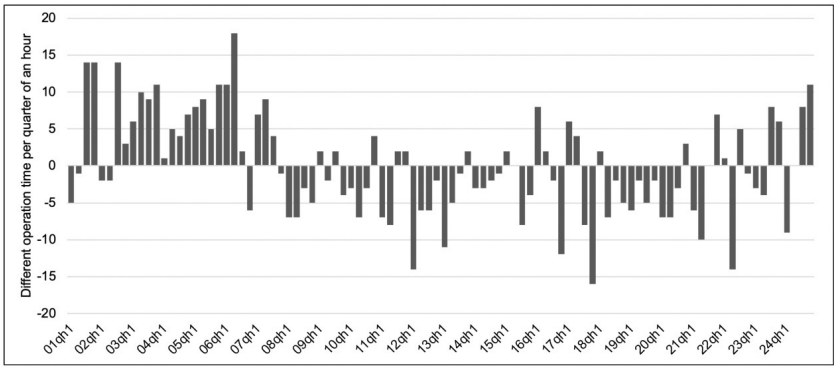


Figure 43: Different operation time of a 5 MW PtG plant with an economic optimization of power and gas prices compared to an optimization only at the power market in 2016

5.3.1.2 OTC Trades

The OTC trades are a bilateral energy exchange. The BNetzA is elevating the traded volumes each year with different surveys. According to the 2019 monitoring report, the volumes are up to 4,956 TWh in 2018.[302] Therefore, OTC trades have more liquidity than spot market trades. Bilateral trades allow different products and contract times.

302 BNetzA (2019), p. 262

For that case, it is also possible to trade RE direct from an energy supplier (see chapter 5.3.1.5). As mentioned in the section of the spot market, the price signals of the OTC trades are mainly orientated at the spot market daily and future auction prices. OTC trades are important for an operator of PtG plants if verified, green products are requested, and the energy source is of interest (e.g., if someone wants to produce SNG explicitly from that wind park). In addition, if a constant power load is essential at any time, for instance, in the positive balancing market (see next chapter), OTC trades are preferable. Also, during construction or research periods, an OTC power supply can be necessary to achieve a constant operating time.

As more and more RE plants are not receiving the 20 years guaranteed feed-in tariffs in Germany and looking for new business opportunities, new bilateral models like the *power purchase agreement* (PPA) are developed. From 2020 to 2025, it is expected that 16.3 GW capacity of wind onshore drops from guaranteed feed-in tariffs in Germany.[303] If PtG plants have to verify the origin of energy, PPAs from those sources can be demanded. This can be a sufficient new BM for the RE plants when the governmental subsidies end. In turn, the lifetime of several windmills can be expanded. The origin of energy is discussed in chapter 5.3.1.5. In principle, PPA is just another form of OTC trade.

5.3.1.3 Balancing Markets

The German balancing market is the first ancillary power supply concept. Balancing energy is needed if the frequency of the electricity grid is fluctuating. For example, if wind energy is producing more energy than expected, if a fossil plant has to shut down immediately or if the grid has failures. The demand for balancing energy is controlled by the grid operator. The German four different grid operators are responsible to keep the frequency as constant as possible[304].

As mentioned, if a surplus of energy is produced, because of different reasons, the frequency of the grid is oscillating. Normally, the frequency is 50 Hz in EU-27 in the public electricity grid. If more energy is produced, the frequency is below 50 Hz and vice versa. The grid frequency must stay in a tolerant band of ± 200 MHz to avoid damages that will be caused by connected customers.[305] Therefore, fast reacting ancillary services are necessary to balance the grid frequency.

In Germany, three different types of balancing energy exist. First, the primary balancing market (PBM) is demanded if first oscillations are recognized. Therefore, the demand for PBM is directly linked to the frequency of the grid and is starting automatically. The participant at this balancing market has to fulfill the offered balancing energy capacity

303 Pantua (2020)

304 BNetzA (2019), p. 144

305 Zapf (2016), p. 14

within 30 seconds. In 2018, the average demanded PBM has been 620 MW, and the grid operators are tendering ± 3,000 MW in Europe for a weekly provision time.[306] The participants at the PBM have to stabilize the grid in all directions like positive (pos.) and negative (neg.) balancing energy. Neg. balancing energy is taking energy off the grid if the frequency is below 50 Hz. For example, a PtG plant could start-up or a power plant could decrease power production. Pos. balancing energy is vice versa. For a PtG plant, it is difficult to participate at the PBM because of the reaction time and the requirement of offering ancillary service in both directions.[307] A capacity price remunerates the compensation of the grid operator. The minimum bid was 1 MW in 2016. Plants with smaller capacities have to be pooled. Different providers are offering pooling services, which must be paid on top of the market price.

The second market of balancing energy (SBM) is necessary if the oscillation is still recognized after 30 seconds. Here, different products for different provision times exist. The participant at the SBM can choose between a primary timeslot (PT) from 8:00 a.m. till 8:00 p.m. during weekdays from Monday to Friday and secondary timeslot (ST) between 8:00 p.m. and 8:00 a.m. during weekdays and the whole time at weekends as well as pos. or neg. ancillary service. The tender and provision time are again one week. The first reaction on the SBM signal has to be performed within 30 seconds, and full load has to be provided within five minutes. The compensation at the SBM is paid off with a capacity as well as a commodity price. The capacity price is yielding for the provision of balancing energy and the commodity price for the physical demand for balancing energy. The minimum bid is 5 MW. In 2018, up to 1,907 MW pos. SBM and 1,820 MW neg. SBM has been tendered per time period.[308] Pooling of smaller capacities is possible as well.

The tertiary balancing market (TBM) is the last option at the balancing market if the frequency oscillation still exists after five minutes. The provided balancing energy has to be realized within 15 minutes and the first reaction has to be shown in the first five minutes. The tender time is daily, and the provision time is divided into six periods with four hours. Therefore, the flexibility at the TBM is higher than at the other balancing markets. The minimum bid and the compensation are the same as at the SBM. In 2018, up to 1,419 MW pos. TBM and 1,199 MW neg. TBM has been tendered per time period.[309] Figure 44 is highlighting the different products at the balancing market and their reaction time. Table 11 is summarizing the different products at the balancing market in Germany in 2016.

306 BNetzA (2019), p. 203

307 This is further explained in the technical analysis of electrolysis (see chapter A.4.)

308 BNetzA (2019), p. 206

309 BNetzA (2019), p. 208

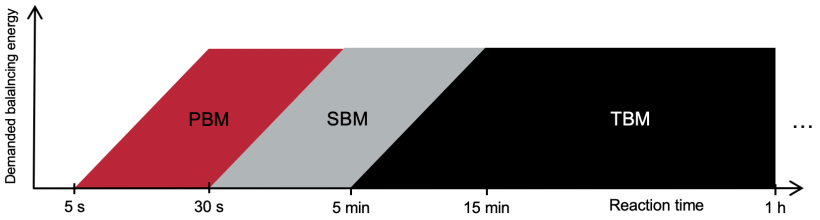


Figure 44: Mechanism at the balancing market

Table 11: Overview of the balancing market in Germany[310]

	PBM	SBM	TBM
Tender time	weekly	weekly	daily
Provision time	The whole week	PT and ST	Six periods with 4 h per day
Minimum bid [MW]	1	5	5
Products	1 product: pos. as well as neg. balancing energy	4 products: pos. as well as neg. for each provision time	12 products: pos. as well as neg. for each provision time
Reaction time	Immediately and full load in 30 s	Within 30 s and full load in 5 min	Within 5 min and full load in 15 min
Compensation	Capacity price	Commodity and capacity price	Commodity and capacity price

The underlying mechanism of the balancing market has been explained above. The development of the capacity, as well as the commodity price, have to be analyzed for the business case calculation of the PtG technology. According to the German federal network agency, the costs for the balancing energy decreased from €594 million in 2013 to €123 million in 2018.[311] The grid fees compensate for the cost of the balancing energy. For that reason, all power customers are paying the costs of balancing energy in Germany. Also, the provided capacity for balancing energy decreased from 3,311 MW pos. SBM in Mai 2009 to approx. 1,907 MW in 2018.[312] Other products at the balancing market are depicting similar developments. This development sounds contradictory towards the observed development at the spot market and raises the following questions: why are the balancing expenditures decreasing while RE is stressing other markets with fluctuating energy production in certain hours? Why is not more balancing necessary to stabilize the grid and balance forecast failures of RE?

310 Zapf (2016), p. 15

311 BNetzA (2015), p. 122 and BNetzA (2019), p. 200

312 BNetzA (2015), p. 124 and BNetzA (2019), p. 206

The answer to these questions is the internal optimization of the balancing market. In 2010, the BNetzA bundled all different grid areas in Germany.[313] Other countries will follow, the PBM is already balanced in Europe.[314] The provision and tendering time have been decreased. The average size of a prequalified unit (participant) has been reduced from 60 to 5 MW in the SBM and TBM. New pooling concepts allow the participation of smaller units like CHPs of biogas plants. The number of prequalified plants increased rapidly.[315] In the future, even wind farms could provide balancing energy.[316] Also, fossil power plants have increased their technical ability to participate in the balancing markets because the profitability of the spot market has declined. In addition, the necessary communication and information costs decreased. In sum, the changes in the balancing market and the conditions of the prequalification have opened the market. More supply could be generated than demand is requested by more REs, which has reduced the costs of balancing energy during the observed time period.

The future development of the balancing market is interesting in a RE system and could mean a market potential for the PtG technology. Table 12 compares different literature sources for a range of target years. The amount of balancing energy for each year is shown. The studies forecast little increase in demanded balancing energy. In the end, the balancing market displays a relatively small future energy market for energy storage plants.

Table 12: Future development of the balancing energy demand

Year	Negative balancing energy (SBM + TBM) [MW]	Positive balancing energy (SBM + TBM) [MW]	Source
2013	4,673	4,605	BNetzA (2015)
2018	3,019	3,326	BNetzA (2019)
2022	6,264	6,287	Breuer et al (2013)
2023	4,400	4,500	Kippelt et al. (2013)
2025	5,315	5,448	Jost et al. (2015)
2030	4,764	5,215	Bucksteeg et al. (2016)
2033	4,700	4,800	Kippelt et al. (2013)

The saturated market situation for balancing energy has an influence on capacity and commodity price. The price building process of the SBM works as follows: first, the grid operator is tendering the necessary balancing capacity for the provision time. The prequalified participants apply for the demand with certain capacity prices. The marginal capacity price is the last bid, which is fulfilling the demanded capacity. As a next

313 BNetzA (2015), p. 123

314 Karger (2015), p. 15

315 Karger (2015), p. 13

316 Brauns et al. (2014)

step, the participants, which have bid below the marginal capacity price, are sorted with respect to their commodity price, which displays mostly the variable costs (e.g., fuel costs). Each time balancing energy is needed, the participant with the lowest commodity price is called first. The capacity price is an additional yield for the participant. The commodity price and the number of calls, which come from the grid operator, are important figures. According to the ramp-up time of PtG plants, which is achieved with industrial surveys and displayed in the appendix (see chapter A.4.1 to A.4.3), a participation at the PBM is difficult. Therefore, further, the capacity price, commodity price and operation time at the SBM are in focus.

First, the development of the capacity price is discussed. Figure 45 is depicting the development from 2012 to 2016 of the average prices of different products per calendar week (CW) at the SBM. It shows that capacity prices have declined during the last years. The price of neg. PT has been close to 0 €/MWh in 2015. The price peaks occur around Christmas and new eve holidays, in which most of the qualified power plants are not operating. In sum, the development of the capacity price is representing a saturated market situation.

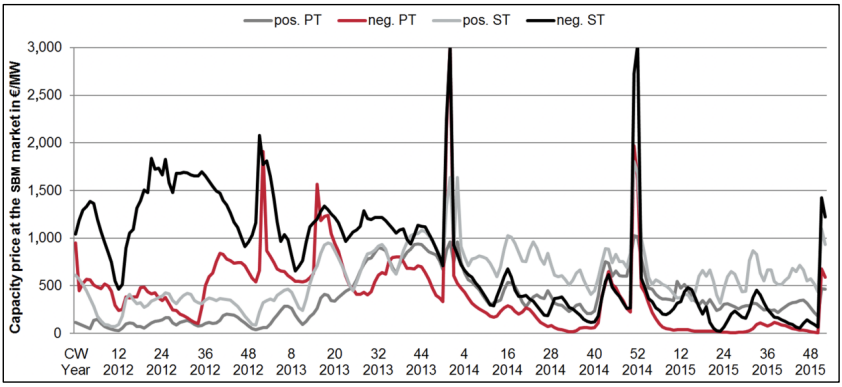


Figure 45: Development of the average capacity price at the SBM[317]

The distribution of the capacity price from 2012 to 2016 with a standard deviation of 407 €/MW (neg. PT), respectively 244 €/MW (pos. PT), is widely dispersed. The figure is cut off at 0 €/MW because negative capacity prices are not allowed at the SBM. However, the capacity price must be closely observed, and business cases have to be adjusted if conditions switchover.

317 All data of the balancing market is received from Volkswagen Kraftwerk GmbH and is available at www.regelleistung.net.

Second, the commodity price has a significant role and is linked to the number of calls and, therefore, responsible for the operation time at the balancing market. A call is a demand for balancing energy from the grid operator. An exemplary merit-order of the commodity price at the SBM is shown in Figure 46. It shows the bids and prices for the first 300 MW of neg. ST balancing energy capacity in CW 19 in 2016. In total, 1,927 MW balancing energy capacity has been demanded in this week. Only a few of the participants are offering low or even negative commodity prices. If the price is negative, the participant at the SBM is paying per call. These candidates are probably operating their plants with calls at the balancing market. Figure 47 is showing the merit-order in the same week for pos. ST balancing energy. It presents a different bidding behavior at the pos. SBM. The marginal costs seem to be higher and, therefore, the commodity price is higher. To provide pos. balancing energy, most of the participants have to increase their energy production. Therefore, production costs must be calculated e.g., fuel costs.

PtG plants can also participate here. They would operate on a certain load and would reduce their electricity demand in the case that pos. balancing energy is demanded. In this case, the PtG plant has additional costs of earlier purchased energy to provide a certain load. This constant load can be purchased at spot markets or per OTC trade (see chapter 5.3.1.2). If the earlier purchased power price is lower than the commodity price at the balancing market, the PtG plants are using negative power prices. This case could be a promising power purchase concept and is calculated in the business case calculation as well as discussed in the single case study later.

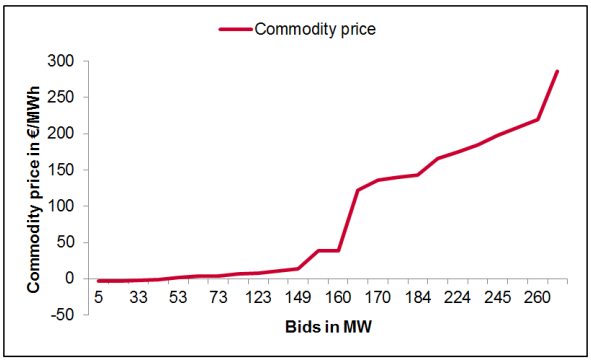


Figure 46: Merit-order of the commodity price at the SBM (neg. ST in CW 19 in 2016)

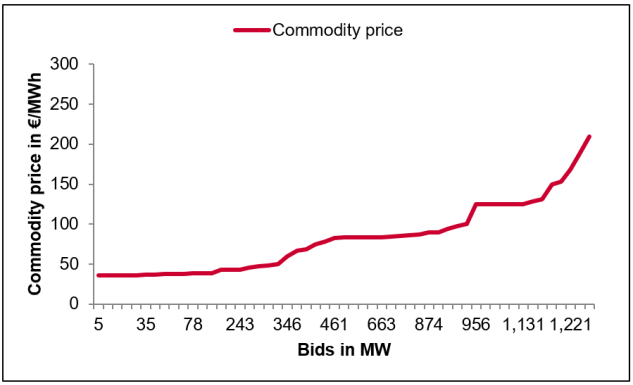


Figure 47: Merit-order of the commodity price at the SBM (pos. ST in CW 19 in 2016)

Different CWs have been analyzed. The bidding behavior has not changed dramatically during the observed time periods of this dissertation and is displayed here for CW 19 in 2016. The average power price of all power supply concepts is mentioned at the end of the chapter.

Third, the number of calls, respectively, the operation time of a virtual PtG plant at the balancing market is analyzed in a way to gain necessary information about this business case. Therefore, a comprehensive study of the grid frequency and demanded balancing energy has been undertaken for the first nine months of the year 2015. The company 50Hertz Transmission GmbH is publishing the SBM signal per second.[318] The data has been filtered with a moving average of 90 seconds. This analysis presents the operation time of PtG plants with different commodity prices at the balancing market.

Figure 48 demonstrates the result of the analysis. On the left side of the graph, the hours of operation are highlighted depending on the demanded balancing service from the grid operator. The figure is divided into months from January to September, also to analyze seasonal trends. On the right side, the result is displayed in percentage of the monthly provision time. The figure expresses that a PtG plant can be operated at the balancing market, with approx. 50% per month if the commodity price is settled within the first 50 MW of the demanded secondary balancing energy capacity.

As shown in Figure 47, a commodity price of approx. 50 €/MWh is possible within the first 250 MW of provided balancing energy capacity. It also indicates a relatively small market for PtG plants at the balancing market. If more than 250 MW of PtG is installed and is participating in the balancing market, then only 20% operation time per month

318 50Hertz (2016)

is available. Only a few storage plants will be able to produce SNG with this power purchase concept at the balancing markets. This mechanism reminds of the self-stabilizing control loops of the system analysis (see chapter 3.1).

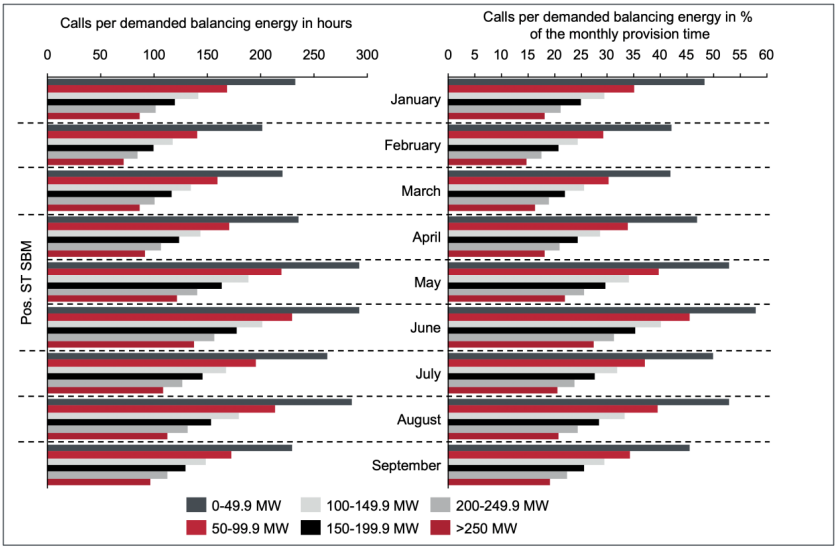


Figure 48: Calls per demanded balancing service at pos. ST SBM in 2015

Figure 49 shows the result of the same analysis for negative SBM in the secondary timeslot. According to this quantitative analysis, 44% of operation time per month is possible if the operator belongs to the first 50 MW of demanded balancing service. Only 15% of operation time per month is left if the virtual PtG plant belongs to the class of 250 MW or more balancing energy capacity. According to Figure 46, the commodity price is about zero €/MWh or even negative for the first 50 MW of balancing service. Therefore, the PtG plant has to pay the grid operator for the ancillary service. The commodity price for 250 MW is about 150 €/MWh, but in this case, the plant is only operating 15% of the time. In the observed periods, more positive than negative balancing energy is requested. In the summer months, less balancing energy is demanded. The situation can change if the participants are changing their bidding behavior, which is discussed above. This empirical analysis shows the situation at the secondary balancing market in the year 2015.

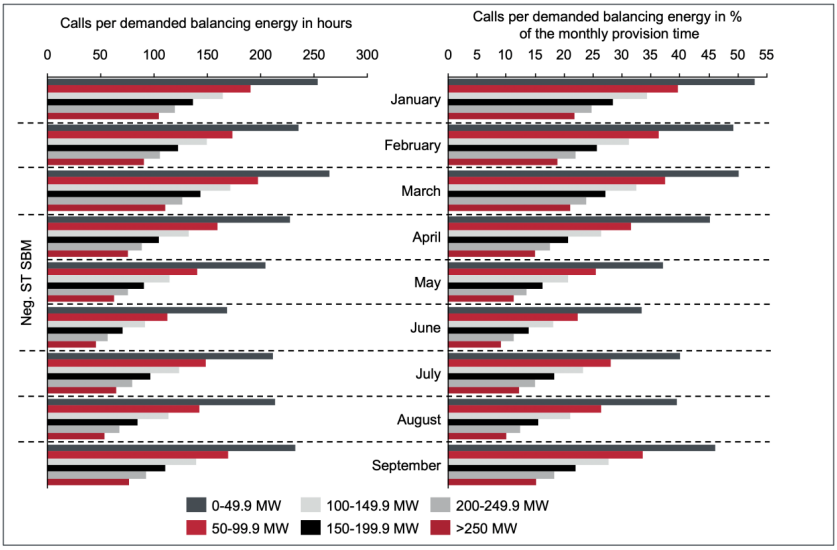


Figure 49: Calls per demanded balancing service at neg. ST SBM in 2015

As mentioned above, in ST, the whole weekend time is included. Therefore, more hours of operation are possible. The results of the primary provision time are displayed in the appendix (see Figure 106 and Figure 107).

Another interesting investigation is the duration of the calls and therewith the number of ramp-ups and ramp-downs. Therefore, the data from June 2015 at the neg. ST SBM has been analyzed. In this period, the PtG plant had to start up 4,768 times if the plant has been operated within the first 50 MW balancing service. This means approx. nine times per hour. If the plant is around the position of 250 MW of the merit-order, then the number of start-ups is about 2.6 times per hour. The number of start-ups for neg. ST SBM is nearly the same. The number can be reduced during PT. Here the evaluation results in 7.5 starts per hour with less than 50 MW and 2.2 starts with more than 250 MW at the pos. PT SBM. The neg. balancing energy values are 6.9 starts, respectively, 1.5 starts per hour. The technical stress towards electrolyzes and electric components is investigated in the case study of this business case.

5.3.1.4 Additional Ancillary Services and Power Exchange

In addition to the balancing market, the grid operator has different other possibilities to stabilize and support the grid frequency. These additional ancillary services are called *redispatch*, *activated loads*, and *supply management of RE*. All these interventions are done to relieve the power grid. The redispatch, for example, is decreasing or increasing the power production of different power plants to relieve grid tension. In 2018,

redispatch actions were necessary for 354 days (out of 365 days) to stabilize the grid. So almost every day, the grid operator has to come into action. In total, 15,529 GWh of energy have been redistributed.[319] This is six times more than in 2014.[320] Most of the action takes place in the northern grid area, which highlights a relation to regions with a high share of renewable electricity generation.

However, not only the supply side can participate in ancillary services. Energy consumers with more than 50 MW can take part in a monthly tendered market of activated loads and can obtain capacity prices of 2,500 €/MW and commodity prices of 100 to 400 €/MWh.[321] Participants are, for example, plants of the chemical, steel or aluminum industry. However, due to the minimum capacity of 50 MW, no pooling options yet and a monthly steady readiness this ancillary service is impossible for small, decentralized PtG plants at the moment.

The supply management of RE as a third ancillary option is an important tool for German grid operators to control the fluctuating generation of wind and solar energy. Figure 50 shows the development of the curtailment costs and energy amount of supply management of RE. It indicates an increase of curtailments of renewable power generation. The energy amount, which has been cut off because of grid stress, is 5.4 TWh in 2018.[322] This is almost 1% of the total electricity generation in Germany. 72% of the curtailed RE was wind onshore and 25% wind offshore.[323] The costs have increased to €635 million, which is more than the total costs for balancing energy (€123 million) and redispatch actions (€352 million) together.[324] 74% of the supply management takes place at the distribution grid (20 kV), in which a PtG plant is assumed to be connected. More than half of the RE was curtailed in the northern federal state Schleswig-Holstein.[325] The German federal network agency identifies the RE expansion and delays of the grid expansion at the distribution grid as possible reasons.[326] In future the PtG technology could help to minimize the curtailment costs.

319 BNetzA (2019), p. 140 ff

320 BNetzA (2015), p. 100 ff

321 AbLaV (2016)

322 BNetzA (2019), p. 140

323 BNetzA (2019), p. 158

324 BNetzA (2016), p. 97 and p. 23

325 BNetzA (2019), p. 159

326 BNetzA (2015), p. 112

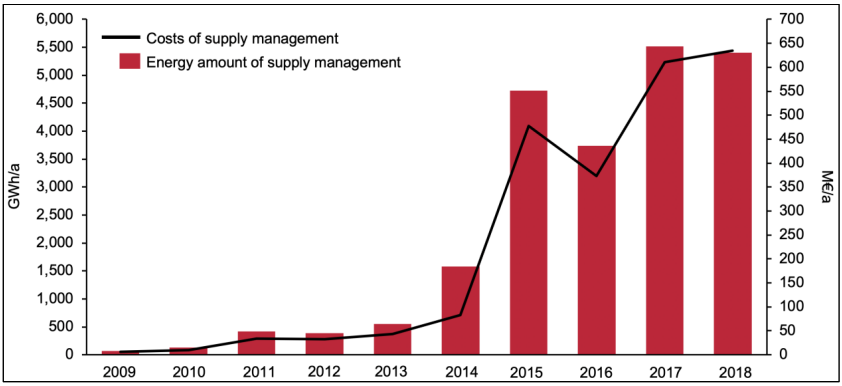


Figure 50: Costs and energy amount of supply management of RE[327]

Another interesting concept to obtain power for PtG plants is the internal balancing energy of energy suppliers. Energy companies must report their forecasted power generation or demand daily to the grid operator. Every time a company supplies or demands more energy than predicted, it has to pay so-called *internal balancing energy*. Especially with highly fluctuating RE, the internal balancing energy becomes an important topic for energy suppliers. According to the German federal network agency, the max. price of internal balancing energy has increased from 601 €/MWh in 2010 to 2,013 €/MWh in 2018. The average price was 81.28 €/MWh and is double as high as the spot market price in 2018.[328] Therefore, a business case for PtG plants can be to balance the internal energy management of a company. In the future, with a high share of RE, it can be possible that energy suppliers need PtG or other storage facilities to control the internal pool management. A further industrial case study analysis of these possible business cases is recommended in the conclusion (see chapter 7.3.2).

Another indicator of the highly stressed energy system is the amount and direction of international power exchange. The balance of export to import has changed from 21.5 TWh/a in 2012 to 52 TWh/a in 2018.[329] The federal network agency writes that the lower power prices cause this development due to the merit-order effect and RE expansion in Germany.[330] The average import power price has been 34.71 €/MWh and the average export power price 30.35 €/MWh in 2015.[331] This price difference indicates that energy is exported to a greater extent in hours with lower power prices, which are

327 BNetzA (2019), p. 157 ff

328 BNetzA (2019), p. 213 ff

329 BNetzA (2014b), p. 102 and BNetzA (2019), p. 233

330 BNetzA (2014b), p. 105

331 BNetzA (2016), p. 151

characterized by more RE production due to the merit-order effect (see chapter 5.3.1.1). Therefore, it can be concluded that more RE, which is subsidized by guaranteed feed-in tariffs from electricity consumers, is exported than imported. From a national macro-economic perspective, this highlights a systematic downside because German electricity consumers are supporting REs, which are exported to other countries for low prices.

However, this chapter concludes that RE has a strong influence on other ancillary services. In the future, different additional power supply concepts could be of importance. Hereby, PtG offers the ability to store energy in large quantities at temporal and regional dimensions.

5.3.1.5 Renewable Power Supply

For communicative, regulatory, and ecological reasons, the acquisition of green, renewable power is important for the operation of a PtG plant. The difficulty is that all power markets besides the OTC trade do not reveal the information about the origin of the energy. Therefore, the evidence of renewable power supply is missing. For that reason, Guarantees of Origin (GO) of energy exist, which can be traded in addition to the physical delivery. Different qualities of GO exist. For example, the simple yearly compensation with certificates of, for example, hydro energy from Norway or the complex in-time generation and consumption of RE (e.g., regional wind power generation). Norwegian hydropower GO have prices of 0.2 to 0.8 €/MWh.[332] Austrian hydropower is between 3 and 4 €/MWh.[333] In addition, different certification companies are offering different labels for green power. In 2011, most of the GO came from Scandinavian hydro plants (89%) because national RE plants, which receive the governmental feed-in tariffs, are not able to sell GO because the green ability has already been appointed to the quota of the feed-in-tariff, which is paid by the electricity consumer.[334]

GO have been controversy discussed if more GO come from those countries than physical delivery of electricity is possible. Therefore, GO have to be considered very carefully. GO of RE are the only way to participate in spot and balancing markets. In the case of GO, the physical delivery of energy and the green ability of the energy product are separated. The PtG plant can also be connected to a RE plant or power is directly purchased at the OTC market. In general, there are three different possibilities of renewable power acquisition in the German power market design:

332 Reichmuth et al. (2014), p. 142

333 Reichmuth et al. (2014), p. 143

334 Reichmuth et al. (2014), p. 5

1. Direct connection between the RE and the PtG plant: this results in 100% delivery of physically RE
2. Purchase of energy at spot and balancing markets combined with GO
3. Purchase of RE with bilateral trades at the OTC market, e.g., per PPA

Case 1 has advantages in terms of the credibility of green SNG production but the PtG plant, however, does not allow any participation at spot or balancing markets. Case 2 is questionable if low-quality GO are purchased, but the only way to benefit from low power prices at the spot or balancing markets. In addition, the ecological benefit stays questionable if the power supply takes temporary and geographically place at different times and regions than the generation of the GO. The participation at the balancing market has an important stabilization character for the electricity grid as explained in chapter 5.3.1.3. This grid-friendly operation should be considered if renewable power supply concepts of the PtG technology are evaluated. The third case offers the possibility of the proof of origin but again does not allow the participation at spot or balancing markets and could also be questionable in terms of temporary and geographical correlation.

To solve that issue and to find appropriate solutions for case two and three, the EU commission will develop a regulatory framework of power purchase concepts in the delegated act article 27 of the recast of the RED until December 2021.[335] In recital No. 90, the commission mentioned the following criteria: temporal and geographical correlation, the origin and the additionality of RE.[336] The economics of PtG highly depends on the outcome of the delegated act. First industrial associations and platforms, which support the development of the PtX technology, have proposed a pragmatic score-card model, which considers all four criteria[337]. Fast and pragmatic development of this delegated act is also part of the discussion of the potential technology pathway (see chapter 7.2).

By the end of this dissertation, the political position is not fixed. So far, the BM is calculated with case two. Therefore, a basic certificate price of 0.5 €/MWh is assumed. This position can be adjusted if different information is available. In addition, the target market *power-to-gas-to-power* and a constructed PtG plant in the MENA-region are calculated with case one.

In the case study, case two is further expanded with an additional reliable renewable power supply with regional wind power (see chapter 6.2.1).

335 European Parliament (2018c), p. 19

336 European Parliament (2018c), p. 95

337 PtX Allianz (2020)

5.3.1.6 Conclusion of the costs at the Power Markets

Different power purchase concepts have been discussed in this chapter. It highlights the complexity of the power market design in Germany. Many of the discussed power supply concepts can be integrated into the BM. In addition, different analyses have been undertaken to achieve the results of power prices and possible operation time. These parameters are defining the economic driver costs at power markets, which were detected in the system analysis. The average power prices at the day-ahead and intraday spot markets are calculated with 4,000 FLH that have been displayed in Table 9 and Table 10. This arbitrary assumption of operation time is discussed and justified in chapter 5.4.8.

The average operation time for the neg. SBM products are calculated with 936 FLH for PT and 1,692 FLH for ST if the PtG plant is within the first 150 MW of demanded balancing power. This results in a commodity price of -0.37 ct/kWh for ST, and a commodity price of 0.55 ct/kWh for PT. The average operation time for the pos. SBM products are estimated with 1,092 FLH for PT and 1,974 FLH for ST with a commodity price of -3.73 ct/kWh for ST and -3.74 ct/kWh for PT. As mentioned, for pos. balancing energy, a certain load has been purchased earlier. Therefore, the average cost of the base load must be added. The forecast error for both markets has to be added as well. The average capacity price has to be multiplied with operational availability. Due to maintenance periods, an availability of 48 weeks per year is assumed.

Although the power price development has been negative at different spot markets until 2017, different studies assume, and the latest price development depicts an increase in the power price. Nitsch et al. (2012) forecast 14.5 ct/kWh in 2050.[338] This is equivalent to a yearly increase of 2.8%. Latest comprehensive studies, like Gerhardt et al. (2018), also foresee a power price of around 13 ct/kWh in 2050. This price development is used for power supply in the BM calculation. As a mean forecast error at all power market, a power price increase of 11.83% is taken into account.

A mixture of different power purchase concepts is also conceivable. The consideration of other ancillary services like internal pool management is not made due to missing data. In total, different power purchase concepts are further calculated in the validation of the BM: the participation at the day-ahead and intraday spot market with asset-backed trading, the optimization of gas and power prices as well as the SBM with different products.

However, all parameters can be individually changed for their own BM calculations. The following table is summarizing the results of the important BM value *costs at power markets*.

[338] Nitsch et al. (2012), p. 219

Table 13: Price composition at the power markets

Type of charge	Value	Operation time
Cost of GO	0.05 ct/kWh	-
Mean forecast error at all power markets	11.83%	-
Average day-ahead hourly spot market (2016)	1.97 ct/kWh	4,000 FLH
Average Intraday spot market price (ID_3-price) 2016	1.73 ct/kWh	4,000 FLH
Possible additional value with asset-backed trading	1.96 ct/kWh	-
Possible commodity price at the neg. PT SBM (first 150 MW)	0.55 ct/kWh	936 FLH
Possible commodity price at the neg. ST SBM (first 150 MW)	-0.37 ct/kWh	1,692 FLH
Possible commodity price at the pos. PT SBM (first 150 MW)	-3.74 ct/kWh	1,092 FLH
Possible commodity price at the pos. ST SBM (first 150 MW)	-3.73 ct/kWh	1,974 FLH
Average capacity price at the neg. PT SBM	121.71 €/MW_{Week}	48 weeks
Average capacity price at the neg. ST SBM	322.59 €/MW_{Week}	48 weeks
Average capacity price at the pos. PT SBM	357.04 €/MW_{Week}	48 weeks
Average capacity price at the pos. ST SBM	603.80 €/MW_{Week}	48 weeks
Yearly price increase of costs at power markets	2.8%	-

5.3.2 Costs of Power Taxes and Grid Fees

As the next important economic parameter, the *costs of power taxes and grid fees* are analyzed. The German power price is influenced by the political regulations of the power market. Figure 51 is illustrating the development of price compositions of an industrial customer in different years.[339] This is in range of a 5 MW PtG plant with 4,000 FLH. It demonstrates that two-third of the power price consists of taxes, fees, and apportionments. The power production and distribution account for 33% and, therefore, can be influenced by power supply concepts (see chapter 5.3.1). In addition, the price development shows that the ratio of fees and taxes to the share of supply and distribution increased. Especially the EEG apportionment has been increased within the last years. The EEG regulation was subsidizing REs with €22.9 billion in Germany in 2015.[340] It guarantees specific feed-in tariffs. Due to the expansion of RE from 6% in 2000 to 31.5% in 2015 of the gross power generation, this apportionment inclined.[341]

339 Yearly consumption of 160 to 20,000 MWh and a medium voltage grid connection.

340 BDEW (2016), p. 36

341 BMWi (2020a)

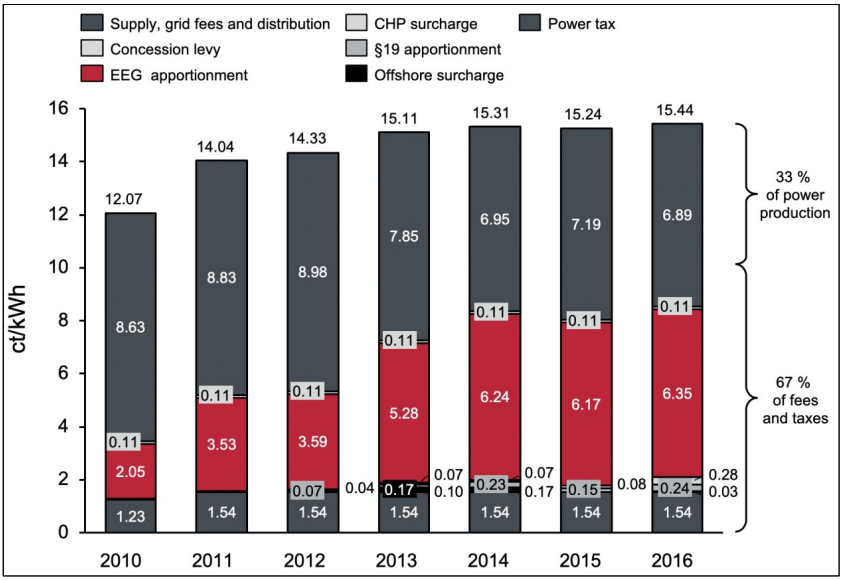


Figure 51: Development of different compositions of the German power price for an industrial consumer[342]

However, exemptions and reduction of those fees and taxes have to be considered. First, the EEG apportionment, as significant economic leverage, is politically exposed. Second, the power tax as the second biggest tax is analyzed, and third, the grid fees and different smaller dues like offshore surcharge, concession levy, and §19 apportionment are briefly explained. In the end, all PtG-relevant taxes and fees are summarized for business case calculations.

All power supply concepts, which are connected to the public electricity grid, are influenced by those taxes and fees. An exception of this situation is the direct connection of a RE source with a PtG plant. In this case, without the usage of the public power grid, the PtG plant can be exempted from all power taxes and fees.[343] According to section five and number 12 of the EEG (2014), the consumer is exempted if the produced power is not entering any public electricity grid. However, from a systemic perspective, the stabilization and storage of a grid region are rather important than a single wind park, as an example.

342 BDEW (2016), p. 25

343 Grimm et al. (2013), p. 18

EEG Apportionment

As mentioned above, the EEG apportionment is a key economic element. In 2016, the EEG apportionment had an amount of 6.35 ct/kWh. On the one hand, it is the driver of RE expansion in Germany, and on the other hand, it is three times higher than comparable spot market prices.

The EEG apportionment is paid with approx. 50% by private households and public institutions.[344] The industry, which is responsible for 37% of the power consumption, pays only 31% of the EEG costs.[345] The reason is that energy-intensive industries can be released from the EEG apportionment. In 2016, 45,253 companies received this benefit.[346] The EEG regulation is classifying energy-intensive companies if more than 1 GWh per year is consumed, and the power cost has a ratio of more than 16% to 20% of the overall gross value of the company. Different other terms and conditions have to be fulfilled, which are mentioned in section 56 and further of the EEG (2014). A significant component is a classification in an economic sector, which is defined by the federal statistical office in Germany. Economic sectors, which are announced in appendix four of the EEG (2014) regulation, can get a reduction of the EEG apportionment. These are mostly manufacturing sectors.

Two issues for the PtG technology are arising from the classification in economic sectors. First, energy suppliers, which are using public infrastructure like the gas grid, are not mentioned as one of the economic sectors eligible for reduction. PtG plants are energy suppliers because they are injecting SNG into the public gas grid. Second, if PtG plants have a negative overall gross value, in the beginning, these companies are classified as a research and development sector, which is again not able to be exempt from the EEG surcharge. Other economic sectors like oil refineries (also PtL plants), however, are eligible for exemption or reduction from the EEG apportionment.[347]

PtG plants can be classified as a manufacturing company if sales generate more than 50% of the revenue without the usage of the public gas grid. For example, the direct usage of hydrogen in the mobility sector per filling station or the transportation by trailers are opportunities to reduce the EEG surcharge.[348] Another possibility of avoiding the EEG surcharge is the direct combustion and power generation of SNG in a CHP plant. The economic value of this target market has been discussed in 5.2.1. The basic regulation is mentioned in section 60, sentence three of EEG (2014). However, it appears incomprehensible to allow the usage of energy storage and further utilization in

344 BDEW (2016), p. 36

345 BDEW (2016), p. 36

346 BDEW (2016), p. 37

347 No. 77 of the annexes four of EEG (2014)

348 For example, this is possible at the E.ON AG PtG plant in Hamburg-Reitbrook and at the PtG plant of the Stadtwerke Mainz.

the power sector but not in other energy sectors like the heat or transportation market. None of the existing PtG plants is using this approach in 2020.

Nevertheless, in 2020 there is no realistic way to exempt the EEG apportionment unless the PtG technology is not integrated into the RE system. Grid- and system-friendly operating units have to be defined as a part of the energy system, like transformers and not like end consumers. The energy in a PtG plant is not consumed but converted into another energy form.

Another cost driver of the EEG apportionment is the curtailment of RE production. As mentioned in 2018, 5.4 TWh of renewable power generation could not be fed in because of grid stress. This led to costs of €635 million in Germany.[349]

Future development of the EEG apportionment is foreseeable due to the expansion schedule of RE. Chrischilles (2016) is expecting an increase of up to 8.74 ct/kWh in 2025.[350] Nevertheless, the EEG apportionment is not considered as a dynamic economic driver because of a fixed price and no market fluctuations. Therefore, further price development is not taken into account as an assumption.

Power Tax

As shown in Figure 51, the power tax is an important surcharge on the overall power price of industrial clients. The shown price is already a 75%-reduced price for energy-intensive industrial companies. According to section 9a, sentence one, and number one of StromStG (2015), the power consumption of electrolyzes can be exempted from the power tax. In addition, the power tax of the peripheral devices like hydrogen compressor, cooling and pumping systems can also be reduced by introducing an energy management system like EN ISO 50001.[351]

The energy management certification, as well as the execution of the discharge, is leading to further transaction costs. Therefore, bureaucratic expenditures have to be included. A simple definition or categorization of energy storage systems can decrease these efforts and open the market for smaller, new companies. The energy management is also necessary for a potential reduction of the EEG apportionment. There is also a disaccord between the EEG apportionment and the power tax because in the power tax regulation, the PtG operating companies belong to the manufacturing trade, whereas the EEG regulation is classifying those companies as energy suppliers.[352]

349 BNetzA (2019), p. 87 and p. 140

350 Chrischilles (2016), p. 7

351 Section 10, number three and sentence one of the SromStG (2015)

352 Section 9a of StromStG (2015)

Grid Fee, Offshore Surcharge, CHP Surcharge, Concession Levy, §19 Apportionment and Reactive Energy

Smaller surcharges like the grid fee, offshore surcharge, concession levy and §19 apportionment have an overall ratio of less than 15% (see Figure 51). According to section 118 and sentence six of the energy industry act (EnWG) in Germany, hydrogen or SNG production is exempted from electricity grid fees for 20 years. Not included are the measurement and financial costs of the grid fees as well as other surcharges.[353] Actual average grid fees were about 2.06 ct/kWh in 2016.[354] PtG plants are possibly built in rural areas of northern or eastern Germany. In this case, grid fees can be lower, but it depends on the region. However, the practical discussion in the single case study is further investigating the costs of grid fees.

The offshore surcharge is subsidizing grid operators for compensation costs for delays of offshore wind park connections.[355] This surcharge can increase with the further installation of offshore wind capacity. The price is 0.025 ct/kWh for power-intensive companies, which are defined with power costs of more than 4% of the gross value.[356] The purpose of the CHP regulation is to increase the regional power and heat production with CHP stations up to 110 TWh in 2020.[357] The amount of the surcharge is yearly calculated, like the EEG apportionment. The price is 0.025 ct/kWh.[358] The concession levy is meant to compensate for the costs of energy suppliers or grid operating companies to use public road transport infrastructure.[359] The price for industrial clients is 0.11 ct/kWh.[360] The surcharge can be exempted if the yearly average power price is below the concession levy.[361] The §19 apportionment is compensating the losses of the grid operators of the exempted grid fees. For that purpose, the amount of all exemptions is divided by all consumers. In 2016, the §19 apportionment was 0.025 ct/kWh for the same target group as the CHP surcharge.[362] In addition, the grid operator can charge reactive energy if the factor of active and reactive power is less than 0.9. Reactive energy has caused €11 million of system costs in the power grid in 2018.[363] The price depends on the grid operator and is discussed in the single case

353 Section 118 and sentence six of EnWG (2016)

354 BNetzA (2016), p. 116

355 BNetzA (2016), p. 218

356 Netztransparenz (2016a)

357 Section one of KWKG (2015)

358 Netztransparenz (2014) and section 26, sentence 2 of KWKG (2015)

359 Section one, sentence two of KAV (2006)

360 Section two, sentence three of KAV (2006)

361 Section two, sentence four of KAV (2006)

362 Netztransparenz (2016b)

363 BNetzA (2019), p. 199

study as well. All mentioned surcharges and taxes can be exempt if the PtG plant is directly connected to the RE production.

Figure 52 illustrates the taxes, fees, and surcharges on the power price. In total, a surcharge of 10.57 ct/kWh has to be paid on top of the market power price for an industrial customer. Approx. 40% of the taxes can be released for a PtG plant (power taxes and grid fees). In sum, 6.54 ct/kWh has to be paid by the PtG plant operator in the year 2016. In this graph, the additional amount of power taxes for peripheral devices is not displayed because the amount depends on the plant configuration.

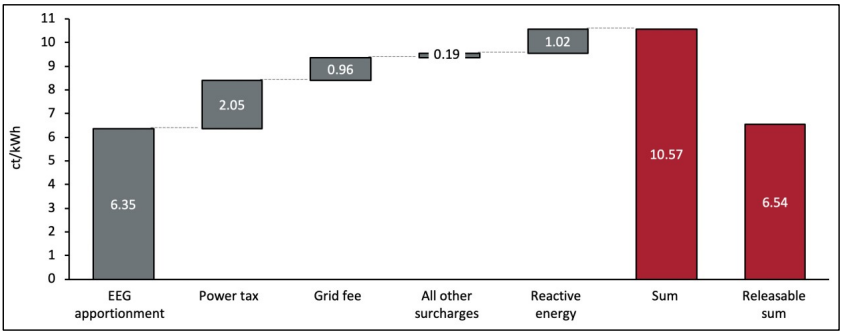


Figure 52: Taxes and surcharges on the power side

Table 14: Summarize of surcharges and taxes on the power side of the PtG technology

Surcharge or tax	Amount in 2016 [ct/kWh]	Possible exemption for PtG
EEG apportionment	6.35	No
Power tax	2.05	Yes, but only for the power consumption of the electrolyzer
Grid fee	2.06	Yes
Offshore surcharge	0.025	No
CHP surcharge	0.025	No
concession levy	0.11	No
§19 apportionment	0.025	No
Reactive energy[364]	1.02	Yes
Sum of all surcharges for PtG	6.54	-

364 Depends on the regional grid operator. This value is taken from the single case study (see chapter 6.2).

5.3.3 Capital and Maintenance Expenditures

This chapter analyzes the CAPEX or investment costs as well as the maintenance costs. Most of the data is achieved with a survey of electrolyzer and methanation producers, which has been undertaken from December 2015 to May 2016 during this research. In total, ten companies have participated. Because of the small market of water electrolysis, the participants wished to stay anonymous. The survey consists of different technical and economic parameters for different target years 2015, 2020 and 2025 and complete plant sizes of one, five and 20 MW. The costs are respectively given for the entire electrolyzer stack, including all engineering and installation costs. In the appendix, a representative survey is presented (see Figure 101). The mentioned numbers are – wherever possible – compared to the latest data from the literature.

Additional technical information according to different types of electrolyzers (alkaline electrolyzer (AEL) (see chapter A.4), polymer electrolyte membrane electrolyzer (PEM) (see chapter A.4.2), solid oxide electrolyzer cell (SOEC) (see chapter A.4.3)) and biological methanation (see chapter A.6) as well as chemical methanation (see chapter A.5) are displayed in the appendix. For example, the ramp-up time of electrolyzers or the dynamic range of methanation units is discussed there. Also, the lifetime of PtG components is described in the appendix.

5.3.3.1 CAPEX and Maintenance of Electrolyzer

According to the undertaken survey, the investment costs of AEL are between 1,036 and 2,000 €/kW in 2015 for a small 1 MW plant. They will decrease to a range of 660 and 974 €/kW in 2025. This is in line with different other studies, see Lehner et al. (2014) (1,000 to 1,300 €/kW)[365] and Sterner et al. (2015) (1,000 to 3,000 €/kW in 2015 and 300 to 800 €/kW in 2020).[366]

Following the own survey, the costs of PEM systems are between 1,500 to 1,655 €/kW in 2015 for a 1 MW plant and between 539 and 1,426 €/kW in 2025. It is interesting that one PEM producer is not expecting lower production costs of PEM in the future. Investment costs of a larger facility (20 MW) will decrease to 600 and 857 €/kW in 2025. According to Ayers et al. (2010), the capital costs are divided into 15% of power supply techniques, 32% of the balance of plant (BOP) and 53% of stack construction. Two-thirds of the stack costs are caused by flow shields, separators and the membrane electrode assembly.[367] Thereof roughly 60% of the membrane costs are caused by the membrane electrolyte and 40% of the platinum-based catalysts.[368] One of the leverages to reduce investment costs is, therefore, to replace platinum in PEM electrolyzers.

365 Lehner et al. (2014), p. 28

366 Sterner et al. (2015), p. 52

367 Ayers et al. (2010), p. 8

368 Lehner et al. (2014), p. 33

In 2015, the CAPEX of PEM electrolyzers appear to be 1.5 to 2 times higher than AEL electrolyzers. Further economies of scale effects and experience curve effects in production could reduce the costs and the two technologies could be even. Tremel (2018) has mentioned that the term *economies of scale* is wrong. *"An increase of the plant size is usually achieved by building several smaller modular systems ("economy of numbers") and connecting them to a larger electrolysis plant."*[369] In this work, *economies of scale* are meant for a number of modules, not for the individual stack. The maintenance cost of PEM is lower than the AEL electrolyzer.

The investment costs of SOEC as a third electrolyzer technology are between 1,504 and 1,106 €/kW for a range of 1 to 20 MW in 2020 and down to 664 and 885 €/kW in 2025. The investment costs are still higher than the AEL or PEM system. In 2025, producers of all electrolyzer systems are expecting the same capital costs. The maintenance cost of SOEC systems has not been mentioned by the producers due to less operational experience yet.

The CAPEX of electrolyzers are illustrated in Figure 53. The sizes of one, five and 20 MW as well as the target years 2015, 2020 and 2025 are shown for different kinds of electrolyzers in average. In sum, a decrease in investment costs is indicated. Whereas nowadays the investment costs of different electrolyzer technologies differ, in future, the costs will adjust to each other. The AEL has the lowest investment costs in all considered years. The development of the investment costs of electrolyzers depends on the amount of installed capacity as the system analysis has indicated. Only with a high number of installations a mass production, economies of scale and experience curves have an impact.

369 Tremel et al. (2018), p. 63

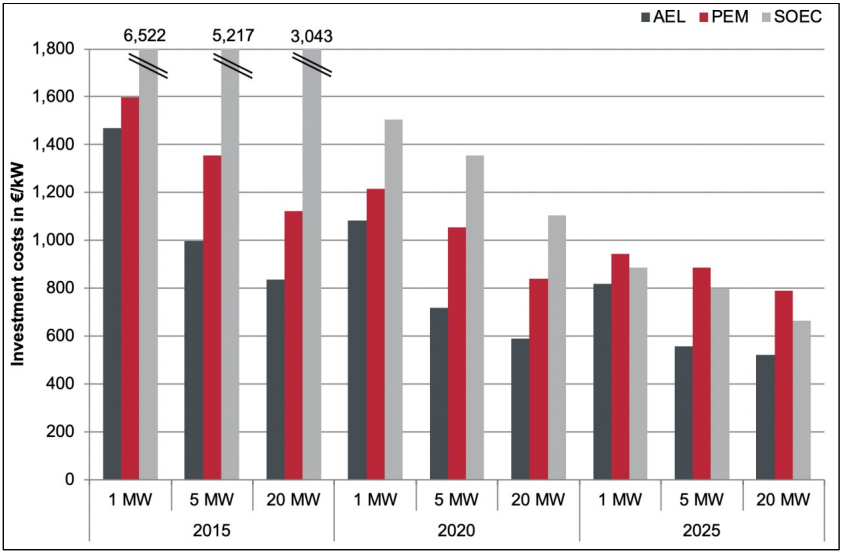


Figure 53: Investment cost development of electrolyzers

Table 15: Results of the survey towards electrolyzer in 2020

Plant size [MW]		1	5	20
AEL	CAPEX [€/kW]	1,082	717	590
	Maintenance [T€/a]	42	131	385
PEM	CAPEX [€/kW]	1,217	1,056	839
	Maintenance [T€/a]	38	56	303
SOEC	CAPEX [€/kW]	1,504	1,354	1,106
	Maintenance [T€/a]	3	5	51

Since the industrial survey has been executed at the beginning of the dissertation project, it is worthwhile to mention the latest publications on the development of investment costs of water electrolysis. Deutsch et al. (2018) have published an intensive literature review of different investment costs. The result is shown in the following figure. The single studies are not listed in the literature of this dissertation. However, it is demonstrated that the data from the own industrial survey is within the range of the literature. A more interesting fact is that scientists have decreased the CAPEX from 2011 to 2020 without any significant installment of new plants (see chapter A.4). Therefore, only the theoretical consideration of the production of electrolysis and the market potential has led to these reductions. Practical experience (e.g., the production of electrolysis in GW scale factories) is still missing in those assumptions. Due to the fast

development of CAPEX of electrolyzers, a repetition of the industrial survey is recommended at the end (see chapter 7.3.2).

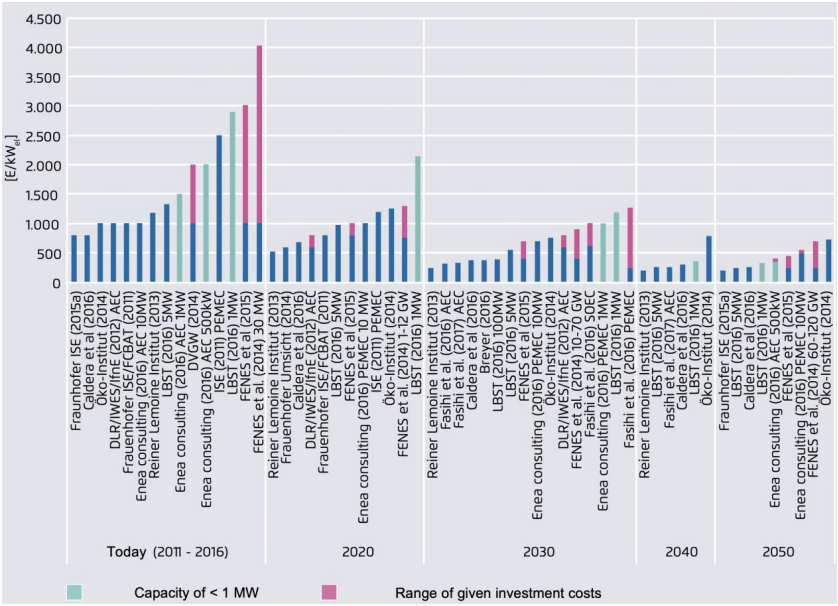


Figure 54: Development of different investment costs of water electrolysis until 2050[370]

5.3.3.2 CAPEX and Maintenance of Methanation

If hydrogen cannot be directly injected into the gas grid, the CAPEX and maintenance cost of the methanation unit have to be added. Four different companies have announced data. Two different technologies exist, the biological and the chemical methanation. Again, the study is divided into the same plant sizes and target years. The range of the CAPEX for a 1 MW chemical methanation is around 1,130 €/kW in 2020. The biological methanation is priced 1.6 times higher. The future development of CAPEX of different methanation reactors is illustrated in Figure 55. It shows that the chemical methanation has advantages regarding the investment costs. Only in future big plants, the CAPEX of biological and chemical methanation is converging. In 2015, none of the asked producers of biological methanation reactors could give information about a 20 MW plant due to missing technical experiences. The cost comparison is also showing that the difference from smaller to bigger plants is decreasing. Therefore, biological methanation could be appropriate for larger facilities.

[370] Deutsch et al. (2018), p. 63

The mentioned investment costs are in line with data from the literature. Sterner et al. (2015) claim costs of 1,000 €/kW in 2015 to 200 €/kW in 2023.[371] Grond et al. (2013) show future capital costs in a developed market of 300 to 500 €/kW for methanation units.

The mentioned maintenance costs in Table 16 are in a range from 1% to 3% of the CAPEX. The maintenance of biological methanation is lower than the chemical one, where catalyst material has to be replaced occasionally. Zwart et al. (2006) mentioned maintenance costs of 10% of the CAPEX of a methanation unit, which appears to be somewhat high. Usually, operational costs are between 3% and 7% of investment costs.[372] Tremel (2018) declares maintenance costs of 4% of the overall CAPEX.[373] Fasihi et al. (2016) have taken 3% maintenance costs into account.[374] However, the displayed data is offering firsthand information about the development of the costs of different methanation units.

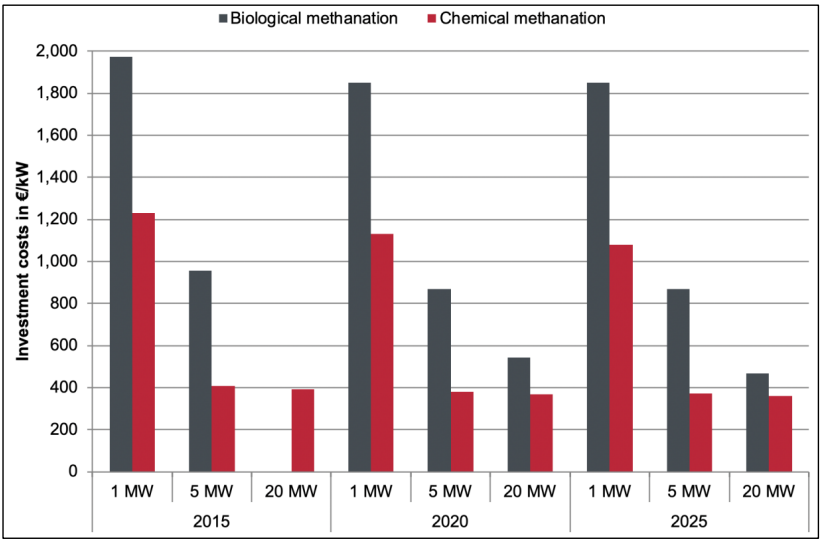


Figure 55: Investment cost development of methanation reactors

[371] Sterner et al. (2015), p. 20

[372] Lehner et al. (2014), p. 60

[373] Tremel (2018), p. 64

[374] Fasihi et al. (2016), p. 252

Table 16: Results of the survey towards methanation in 2020

Plant size [MW]		1	5	20
Chemical methanation	CAPEX [€/kW]	1,130	382	369
	Maintenance [T€/a]	39	75	270
Biological methanation	CAPEX [€/kW]	1,850	870	469
	Maintenance [T€/a]	35	66	115

5.3.3.3 CAPEX of PtG

According to the collected data, different kinds of combinations of electrolyzers and methanation reactors are possible. In addition, the BOP and peripheral devices of the whole PtG plant is missing. As an assumption, 10% of the investment costs of the entire PtG plant are taken in addition. This assumption is tested in a single case study later. The different combinations of PtG plants are illustrated in Figure 56.

The first possible PtG construction is the direct hydrogen injection. Therefore, the average data of the AEL and PEM system is added with the costs of the plant balancing. Technical restrictions of the direct hydrogen injection in terms of feed-in guidance are discussed in chapter 5.4.4.

The second combination is the average CAPEX of AEL and PEM system added with the chemical methanation, and the third combination is the average CAPEX of AEL and PEM system with biological methanation. As additional information, the combination of SOEC and chemical methanation is displayed. The advantage of this combination is discussed in heat management (see chapter 5.4.3). The evaluation demonstrates sharp cost reductions for future PtG constructions. In addition, the spread between direct injection of hydrogen and the additional methanation is decreasing in the future. In 2015, the hydrogen injection is half as expansive as the combination with chemical methanation in small plants. In 2025, the differences between the combinations become more similar. In conclusion, the survey indicates information about the development of investment costs of the PtG technology from the producers' perspective.

CAPEX costs usually are depreciated in a company's financial accounting. Therefore, additional information like depreciation rate and lifetime is necessary. The lifetime of different components is described in the appendix. The financial information is explained in the revenue stream (see chapter 5.5). In the BM calculations, the same target years can be set the same way as it is done in the industrial survey.

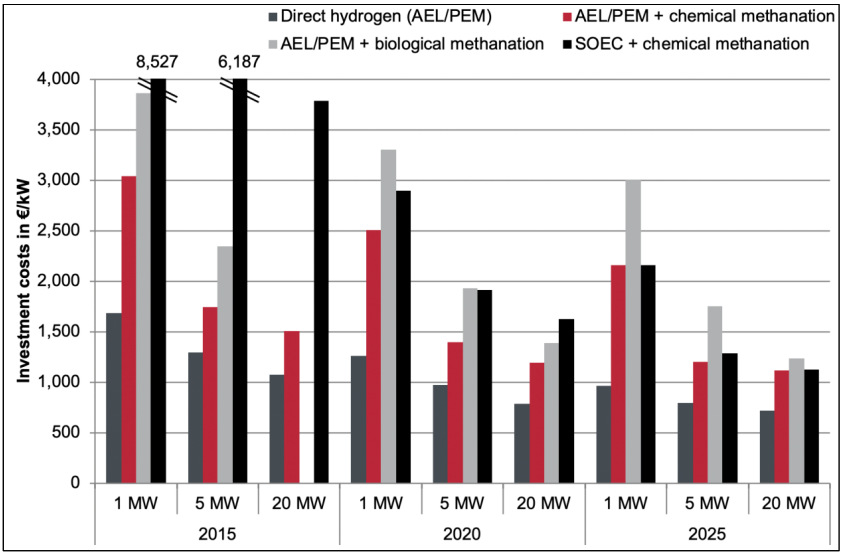


Figure 56: Investment cost development of different combinations of PtG plants

The CAPEX of electrolyzers and methanation units have seen a tremendous price reduction during this dissertation project. The own industrial survey has forecasted investment costs of around 500 €/kW in the best case in the year 2025. Fasihi et al. (2016) foresee the costs of AEL of 319 €/kW or of PEM of 250 €/kW in 2030.[375] In principle, the general BM can be fitted with different inputs of CAPEX.

5.3.4 Revenue of Oxygen Sale

When water is split to the hydrogen in the electrolyzer, also oxygen is produced. The oxygen usage showed economic leverage in many studies and was mentioned by the expert group in the system analysis. Different studies announce oxygen prices from 70 €/t[376] up to 210 €/t.[377] The oxygen has a purity of nearly 100% and can be used for medical or industrial applications, for example, in oxyfuel combustions or sewage plants. Other studies are mentioning an oxygen valorization price of 20 to 70 €/t in an optimistic scenario.[378] Fasihi et al. (2016) mentioned a market price of industrial oxygen of 80 €/t.[379] The same study announces the marginal costs of 20 €/t. From this

375 Fasihi et al. (2016), p. 249

376 Sterner (2009), p. 112

377 Mueller-Syring et al. (2013), p. 241

378 De Saint Jean et al. (2015), p. 6498

379 Fasihi et al. (2016), p. 250

level on, an oxygen separation is economically worthwhile and would decrease the final production costs of SNG by 8% in their analysis.[380] According to Hermann et al. (2014), the operational costs for absorption from ambient air are 6.2 €/t of oxygen.[381] Therefore, the discussed oxygen prices seem to be somewhat high. In 2020, none of the installed industrial scale PtG projects are using the oxygen output yet. The reasons could be further investment costs for compression and storage of oxygen and the management of a logistic supply chain. However, future oxygen usage at specific sites is possible and worth considering. Three different price categories are defined: a minimum oxygen sale price with 6.2 €/t, a medium sale price with 40 €/t and a max. sale price with 80 €/t. For the MC simulation, a random price volatility between the minimum and max. sale price is set.

The amount of oxygen production is calculated with the molar weight similar to the calculation of carbon dioxide (see chapter 5.4.6). According to the sum formula of the methanation (see chapter A.5), 8 g of hydrogen per mole is necessary to produce one molecule of methane (CH_4). Including the sum formula of the electrolysis (see chapter A.4), 64 g of oxygen is produced by generating the demanded amount of hydrogen. Overall, the mole ratio of oxygen to methane in the whole PtG process is 4:1. For example, to produce 1,000 t of methane, 4,000 t of oxygen is emitted. A 5 MW plant with 4,000 FLH and an efficiency of 53% (see chapter 5.3.5) produce 10,600 MWh of methane, which is proportional to 765 tons of methane. The produced amount of oxygen, in this case, is 3,061 t. Of course, this is an ideal number according to the theoretical chemical formula. The single case study will further investigate the oxygen capturing and their economic value.

The further price development of oxygen sales is assumed with 2% because conventional chemical oxygen production depends on fossil fuels, which have a similar price development (see chapter 5.2.2). However, first business cases can be drawn with these assumptions.

Table 17: Oxygen sale

Type of charge	Value
Minimum oxygen sale	6.2 €/t
Medium oxygen sale	40 €/t
Maximum oxygen sale	80 €/t
Volatility of oxygen price	6.2 to 80 €/t
Price development of oxygen sale	2%

380 Fasihi et al. (2016), p. 256

381 Hermann et al. (2014), p. 30

5.3.5 Efficiency of the PtG Process

The efficiency of the whole PtG process is an important economic driver because the amount of produced SNG or hydrogen has a direct influence on the important economic drivers like the gas and heat sale as well as the yields of the GHG reduction quota. The efficiency is defined as the quotient of injected SNG or hydrogen into the gas grid and the electricity input at the plant.

The process heat of exothermic components like the methanation can be sold to the heat market if the plant is connected to a district heating grid. Therefore, the heat management is analyzed in the value network because it depends on an existing infrastructure (see chapter 5.4.3).

Due to different combinations of PtG components like electrolyzer, methanation and CO_2 source as well as different applications at the target markets like combustion in NGVs, several different PtG efficiency levels exist. This complexity leads to ambiguous statements of the overall efficiency and becomes the main point of criticism about the PtG technology. For example, the assurance, tax, and business consulting company *PricewaterhouseCoopers GmbH* published an article, in which a vehicle with synthetic fuel needs 6.2 times more energy than an electric car.[382] The energy think-tank *Agora Energiewende* sees a proportion of 5.3 compare to the energy demand of electric mobility.[383] Whereas Sterner and Stadler (2015) analyzed an overall efficiency of up to 37% of the used energy in the mobility case with internal combustion engines, which is a ratio of less than two compare to Agoras efficiency of electric cars. One advantage of this general BM is that efficiencies can be exchanged, and therefore, different combinations can be tested. Because the efficiency is often the first point of criticism of the PtG technology, it is advisable to analyze the technical efficiency of the conversion process further and to discuss the importance of the efficiency in aspect to other economic drivers.

First, each component of a PtG plant is illustrated in Figure 57 to provide an overview. The input efficiencies are shown in Table 18. The efficiencies derive either from the industrial surveys of electrolyzer and methanation unit producers or from additional literature sources (mentioned in Table 18). The efficiencies are described here for a 5 MW power connection. The efficiency of the PEM electrolyzer is confirmed by the first industrialized PtG plant in Mainz.[384] The CO_2 capturing is increasing the necessary power input. The consumption of different CO_2 sources is discussed in chapter 5.4.6. The process heat can be internally used to decrease the energy use in stand-by or, for example, of CO_2 capturing.

382 Bollmann et al. (2017), p. 14

383 Deutsch et al. (2018), p. 12

384 Tremel (2018), p. 25

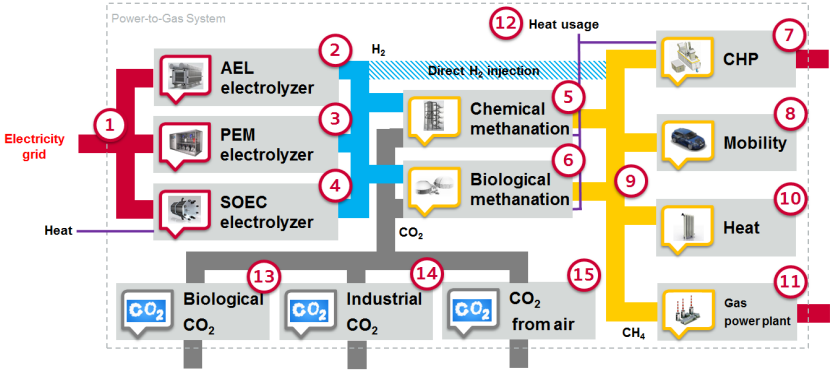


Figure 57: Overview of different efficiency paths of the PtG technology

Table 18: Description of different efficiency paths of the PtG technology

No. of component	Description of the efficiency path	Efficiency [%]	Source
1	AC/DC converter	90	Sterner and Stadler (2015)
2	AEL system	71	Survey see A.4.1
3	PEM system	66	Survey see A.4.2
4	SOEC system	64	Survey see A.4.3
5	Chemical methanation	83	Survey see A.5
6	Biological methanation	77	Survey see A.6
7	CHP plant	85	Sterner and Stadler (2015)
8	Mobility case (combustion engine)	35	Sterner and Stadler (2015)
9	Gas grid (transport and storage)	97	Sterner and Stadler (2015)
10	Heat market (condensing boiler)	105	Sterner and Stadler (2015)
11	Gas power plant	60	Sterner and Stadler (2015)
12a	Heat from biological methanation	113	Survey see A.6
12b	Heat from chemical methanation	114	Survey see A.5
13	Biological CO_2	100	Analysis see 5.4.6
14a	CO_2 from ammonia production	100	Analysis see 5.4.6
14b	CO_2 from iron and steel	99	Analysis see 5.4.6
14c	CO_2 from cement production	99	Analysis see 5.4.6
14d	CO_2 from coal-fired power plant	98	Analysis see 5.4.6
14e	CO_2 from gas-fired power plant	95	Analysis see 5.4.6
15	CO_2 from ambient air	76	Analysis see 5.4.6

The result of different efficiency calculations is presented in Figure 58 (the component number is placed in brackets). It shows that the necessary efficiency of the PtG process is about 50% while converting electric power to the chemical form of methane. The efficiency can be increased if the process heat is utilized. The third bar represents the most efficient pathway, which is the conversion of alternating current (AC) to direct current (DC), the AEL and chemical methanation with heat usage from the exothermic methanation as well as product gas cooling. Of course, a direct injection of hydrogen can be more efficient but these pathways consist primary of the electrolysis, whose efficiencies are described in the appendix (see chapter A.4). The usage in different target markets displays further losses due to the low efficiency of combustion engines, for example, in the mobility sector.

It has to be mentioned that these results are static. Power consumption during standby time or run up and down periods is not included, which would lead to further efficiency losses. This is partly considered in the single case study during the participation at the SBM (see chapter 6.2.2.2). But further research on that topic is recommended (see chapter 7.3.2).

An enormous efficiency reduction is indicated by comparison of CO_2 capturing from biological sources or from ambient air (see bar 3, 6 and 7 of Figure 58). The energy demand of the CO_2 capturing from ambient air is highly inefficient if the required energy comes from additional RE, which is further investigated in the value network in chapter 5.4.6. The bars 8, 9, 10 and 11 are comparing the overall efficiency of specific end consumer markets. The heat market with an efficient condensing boiler is representing the market use with the highest efficiency. The application of SNG in the mobility sector is representing the market with the lowest energy efficiency. The power generation of SNG in CHP plants (bar 8 and 12), as well as with efficient gas power plants (bar 11), has an efficiency range of 36% to 51%. In the end, bar 13 and 15 are demonstrating the case with the lowest efficiency. As a result of this, the combination of SOEC, biological methanation, gas grid usage, mobility, and CO_2 from ambient air is resulting in an efficiency of only 11%. These cases present an unrealistic pathway.

But energy efficiency is not the only decision criterion about the success of different business cases. In the end, the economic calculation is crucial, because efficiency losses are increasing the costs at power markets and the costs of power taxes and fees. But if renewable electricity is temporary and regionally available at low costs, the importance of efficiency declines. However, the efficiency of the PtG process is delivering important technical as well as economic information. The single case study is testing different efficiency paths later.

In the end, this consideration is declaring a discussion about the efficient use of energy. In some cases, the effective use of energy with a significant systemic character (stabilization of the energy system) has, in sum, more importance than the efficient use. Therefore, low-efficiency rates can be justified. The PtG process can be compared to

natural photosynthesis. CO_2 and energy in the form of solar radiation are converted to biomass and oxygen by splitting water. Biomass consists of long-chain hydrocarbons, which can also be used as a renewable fuel. However, this procedure has been succeeded in the natural, ecologic system on earth, although the overall efficiency of photosynthesis is quite low with a max. of 2.5%.[385] This demonstrates that natural systems seek more after ecologic effectiveness rather than technical efficiency. In addition, in the future energy system, it is likely that RE is produced in regions with low levelized costs of electricity generation and imported to the demand sector. For example, solar radiation in North Africa[386] with 2,410 kWh/m² per year is more than two times better than in Germany[387] (approx. 1,088 kWh/m² per year), which direct electric solution would have to use. For that reason, the possibility of global production and easy transportation of SNG and, therefore, by implication low power prices of RE is further reducing the importance of the efficiency factor and compensating efficiency losses in the application.

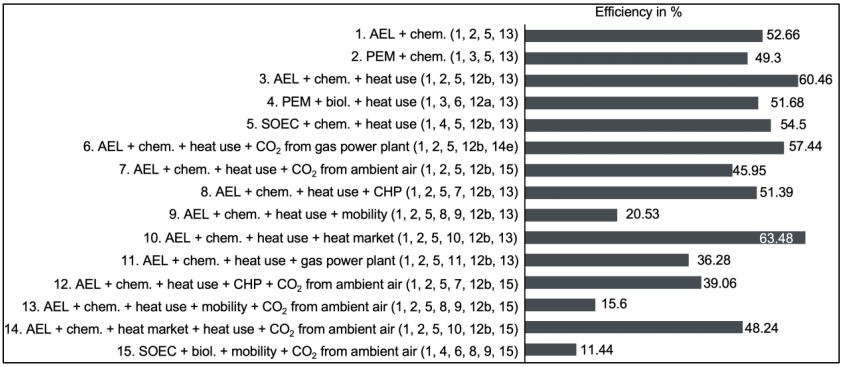


Figure 58: Comparison of different efficiency pathways

5.4 Value Network or Ecosystem

The key economic drivers along the value chain have been followed. In a holistic value network, different additional drivers exist, which must be considered in the BM. In the following section, other parameters of the value network or ecosystem are explained. These additional BM parameters were either deduced during the system analysis or discovered by the investigation of other economic drivers by literature review. For example, in the discussion of the efficiency of the PtG technology or heat sale, heat

385 Sterner and Stadler (2014), p. 8

386 Fasihi et al. (2016), p. 246

387 Wirth (2020), p. 25

management has been mentioned as a possibility to increase the overall efficiency or heat sale amount. Therefore, heat management is discussed in the value network.

First, critical financial parameters are discussed, which are also detected in the system analysis. Second, peripheral devices, which have an influence on the CAPEX, maintenance, and efficiency, are described. Third, heat management is explained. Fourth, the feed-in guidance of the public gas grid is explained to highlight the potential of direct hydrogen injection and necessary gas qualities. Fifth, the public gas grid is explained with the storage potential and future expansion schedules. Sixth, the carbon dioxide capturing is exposed, which is an important cost driver. In that case, also the political framework of that topic is briefly clarified. Eighth, ecological information of the PtG technology is given with a life cycle analysis comparison to other RE carriers. Lastly, the possible operation time of a PtG plant is discussed.

The ecosystem of the energy system, which belongs to the value network or ecosystem, was discussed in the system analysis (see chapter 4.1) and in the costs at power markets (see chapter 5.3.1.1).

5.4.1 Financial Parameters

There are many different financial parameters, which impact the economic performance of the business case. In the pre-industrial technology stage, the estimation of financial parameters is difficult. Due to different target markets, different interest rates on equity shares can exist. The weighted average cost of capital (WACC) displays the average interest rate on debt and equity capital that a company has to pay to finance its assets. In this case it is the CAPEX of the PtG plant. It can include different shares and interest rates of equity and debt capital. All parameters can be adjusted in the BM. The BM can be expanded with a tax shield, which is described at the end of this section. The following formula is showing the WACC with a tax rate.

Equation 5-2: WACC formula[388]

$$WACC = \frac{equity\ capital}{total\ capital} \times i_e + \frac{debt\ capital}{total\ capital} \times i_d \times (1 - t)$$

with:

- I_e = Interest rate on equity capital
- I_d = Interest rate on debt capital
- t = tax rate

The literature exposes different values of the WACC for the PtG technology. Fasihi et al. (2016) calculate with two different WACCs. On the one hand, 7% in the base

388 Farber et al. (2006), p. 215

scenario with a 5% interest rate on debt and 12% on equity and a debt to an equity share of 70:30. In a minimized risk scenario, they calculate with corresponding 4% on debt and 7% on equity, which results in a WACC of 5%. This is decreasing the production costs of renewable fuels by 14.5% in their analysis.[389] This shows the high impact of this financial parameter.

Tremel (2018) estimates a WACC of 8% as well as a financial lifetime of 20 years.[390] The undertaken survey with producers of electrolyzers and methanation reactors indicates shorter lifetimes for electrolyzer stacks (see chapter A.4 to A.6). But stack replacement costs are included in the maintenance expenditures. Brunner et al. (2015) have taken a WACC of 6% into account for PtG plants.[391] Hobohm et al. (2018) have analyzed different factors between 2% and 7%.[392] A low WACC of 2% or 3% can be justified if a subsidized BM is considered. For example, if feed-in tariffs are paid over a long period like in the EEG or financial aid is guaranteed (see chapter 5.3.2).

For the business modeling, this dissertation takes into account a corridor of WACC factors of 3% to 8%. The impact on the economic outcomes of different WACCs is analyzed in the BM calculations. The share of debt to equity is similar to Fasihi et al. (2016). Certainly, this assumption implies a positive economic performance. Debt to equity capital share of 70:30 is only possible under reliable economic conditions. In first installed facilities, the need for equity capital can be much higher, which results in a higher WACC if the interest rate of equity is higher than on debt capital. However, different WACCs are analyzed in the BM calculation. The financial lifetime and deprecation are following Tremel (2018).

Additional information is financial aid, for instance, from public funds and plant insurance and other taxes. These numbers can be added and are mentioned in the business case calculation if they are considered. In different studies additional 2% of the CAPEX is assumed for insurance costs and other taxes.[393]

The BM can calculate the economic result before and after the consideration of taxes. For the tax model, a linear depreciation of the CAPEX over the technical lifetime of the plant is considered. The deprecation is subtracted from the free cash flow and reduces the amount of taxes. In addition, losses of previous years can be carried forward and reduce the taxes in future years, in which the free cash flow is positive. The net operating losses can be carried forward without a time limit and up to €1 million. Past losses of more than €1 million can be subtracted from the positive cash flow by 60% in

389 Fasihi et al. (2016), p. 255

390 Tremel (2018), p. 64

391 Brunner et al. (2018), p. 277

392 Hobohm et al. (2018), p. 131

393 De Saint Jean et al. (2015), p. 6496 and Buchholz et al. (2014), p. 8007

Germany.[394] The tax rate in the model is the overall average corporate tax rate for Germany of 30%, according to the European statistical office.[395]

Table 19: Financial parameters

Type of charge	Value
WACC	3% to 8%
Share of debt to equity	70:30
Lifetime	20 years
Depreciation	20 years
Corporate tax rate	30%
Insurance costs and other taxes	2% of CAPEX
Financial aid	-

5.4.2 Peripheral Devices

Next to the electrolyzer and the methanation reactor, which have been described in the previous chapters, the surrounding components have an influence on economic drivers like efficiency or heat management. Upstream of the electrolyzer, the water treatment takes place (see Figure 34). Here, usually, tap water gets filtered, deionized, and demineralized. The water treatment prevents the contamination of the electrolyzer with toxic elements, reduces the degradation rate of electrolyzers and, therefore, increases the conductivity.[396] On the other side, at the electric input AC has to be converted to DC and the grid voltage has to be decreased to the operating voltage level of the electrolyzer.[397] After electrolysis, the hydrogen stream needs to clean and dry. Residual materials of potassium base, oxygen and water are separated if AEL is used. This stage is called hydrogen cleaning and drying.[398] Afterward, depending on the type of plant construction, the pure hydrogen must be compressed to the operating pressure level in the methanation unit or can be injected into the public gas grid.[399]

The water consumption is not mentioned as an important economic driver in the system analysis (see chapter 4). Therefore, the costs of water supply are not included in the BM. This assumption is tested in the single case study later. The literature sources confirm this assumption. Fasihi et al. (2016) calculate water costs of 0.04 €/MWh of

394 §10d EStG

395 Fantini et al. (2010), p. 199

396 Mueller-Syring et al. (2013), p. 113 ff

397 Mueller-Syring et al. (2013), p. 113

398 Mueller-Syring et al. (2013), p. 114

399 Lehner et al. (2014), p. 44 ff

renewable fuel. Therefore, they proclaim that the cost of water is almost negligible.[400] In remote areas, seawater can be desalinated by mechanical vapor techniques. This case would increase power consumption and decrease efficiency. Desalination of seawater is not considered in the BM yet but further recommended to add (see chapter 7.3.2).

At the methanation process, on the one hand, the compressed, pure hydrogen arrives, and on the other hand, as a second feed gas, carbon dioxide is demanded. The capturing of CO_2 depends on carbon dioxide sources (see chapter 5.4.6). The CO_2 stream needs to be compressed to the operating pressure level of the methanation unit as well.[401]

After the methanation process, the product gas has to be cooled down, dried and filtered. The cooling and drying process takes place in a separate unit and heat as well as water can be reused in the PtG plant.[402] By multiple usage of energetic and material efforts this is in line Vester's recommendations of superior system elements (see chapter 3.1).

The energy consumption of peripheral devices like compressors and pumps is increasing the overall power demand. As mentioned in the analysis of the efficiency (see chapter 5.3.5), the peripheral devices also consume power in standby time when the plant is not operating. Therefore, on average, 10% of the electrolysis power connection is taken into account for peripheral power input in operation and for standby time. These assumptions are tested in the case study in chapter 6.1.9.

Next to the operational costs of peripheral devices, additional investment or capital costs are generated for the balance of plant (BOP). Especially if a hydrogen storage capacity is necessary, CAPEX has to be expanded. Tremel (2018) has analyzed the BOP investments of different operational concepts. Hydrogen storage is needed if the ramp-up and downtime of the electrolyzer and the methanation unit are different. The technical discussion in the appendix of electrolysis technology (see chapter A.4) and chemical (see chapter A.5) as well as biological methanation (see chapter A.6) shows that flexibility differs. Therefore, a convenient storage capacity is needed. Tremel (2018) calculate with additional costs of 286 €/kg of hydrogen.[403] This results in BOP costs of 18% in a grid-connected 50 MW power-to-methanol plant in Germany.[404] Due to more flexibility of methanation unit (see chapter A.5) and smaller considered PtG plant, additional BOP costs of 10% of the overall CAPEX are considered.

400 Fasihi et al. (2016), p. 255

401 Lehner et al. (2014), p. 44 ff

402 Mueller-Syring et al. (2013), p. 131

403 Tremel (2018), p. 54

404 Tremel (2018), p. 81

Table 20: Peripheral devices

Type of charge	Value
Additional BOP power demand of peak capacity	10%
Additional BOP investment costs of overall CAPEX	10%
Water costs	Not considered

5.4.3 Heat Management

Heat management is an important technical option to increase the overall efficiency and also to participate in the heat market in addition to other target markets. Therefore, the amount and temperature level of different components of a PtG plant need to be mentioned and are later tested in the case study (see chapter 6.2.1). Here, the data is summarized from the undertaken survey of electrolyzer and methanation producers.

In sum, it has to be divided into heat management during operation and stand-by time of the PtG plant. In operation, the electrolysis and methanation are both heat sources. In addition, the mentioned peripheral device of product gas cooling is a heat source as well. The heat from the gas cooling, as well as the chemical methanation, is at high-temperature level (approx. 170°C), and the heat from the electrolysis and biological methanation is at low-temperature level (approx. 90°C), as was identified in industrial surveys. The produced heat can be used in different ways:

1. **District heating:** the heat amount can be sold to households and distributed via a district heating grid. The district heating grid has an average temperature level of typically 90°C to 120°C,[405] which can be provided with heat from the methanation and product gas cooling.
2. **Industrial processes:** heat can be used in connected industrial processes, in which heat is required, and, therefore, has a specific economic value of the avoided heating energy.
3. **Internal processes:** heat can be used in internal PtG processes, for example, with the SOEC system, upgrading input streams, regeneration of the catalyst of the direct air capturing, heat storage for standby time or gas liquefaction for further gas transportation.

The issue of the district heating and industrial application is that it is expected that the location of PtG plants is mostly in rural areas next to RE sources. The availability of district heating grids and connectable endothermic industries processes is low. A further study of these applications is recommended. The usage of heat in internal PtG processes increases the efficiency of the plant. The result of different heat usages for the overall efficiency is shown in chapter 5.3.5.

405 Maaß et al. (2015), p. 34

At standby time, the electrolysis and methanation are requiring heat to be able to start up quickly. All economic values of heat management are discussed in the economic information about the heat market (see chapter 5.2.3). According to the undertaken survey of electrolyzer and methanation producers, the following figure can be drawn from heat management. The heat amounts of peripheral devices like product gas cooling, biogas upgrade, and biogas disinfection are achieved according to Hammer (2014) and calculated to a 5 MW plant.[406] These first assumptions of possible heat sources and sinks are also checked in the single case study.

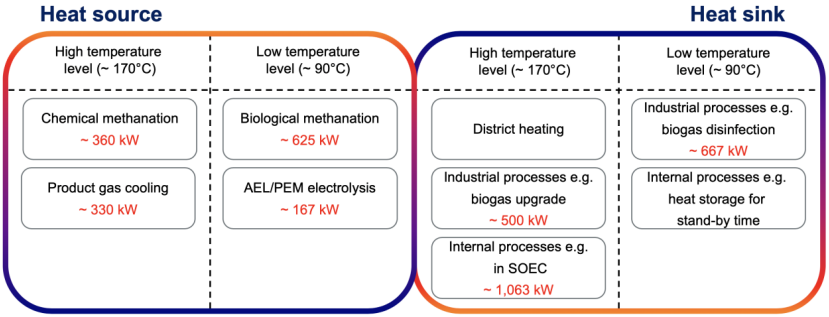


Figure 59: Exemplary heat sources and sinks in the operation of a 5 MW PtG plant

5.4.4 Feed-in Guidance

The injection of hydrogen or SNG into the public gas grid has to fulfill specific guidelines or rules of requirement. The German gas grid requirements are exposed because the focus of the BM consideration is on Germany. The requirements are following different guidelines: the DVGW-AB G 260 natural gas quality in Germany, the EASEE-gas for natural gas quality in Europe and the DIN 51624 for fuel quality in Germany. For example, the DVGW-AB G 260 is requiring a Wobbe-index, a measurement of the heating value with respect to the specific density, of 10.5 to 13 kWh/Nm³ in the German lower calorific gas grid.[407]

The DVGW-AB G 260 is tolerating hydrogen injection up to 12% of the gas volume. But in DIN 51624, the hydrogen admixture is limited to 2% of the gas volume due to technical issues (e.g., in NGVs).[408] The reason is the composition of the gas filling tank of NGVs. 95% of all existing NGV's are holding a full-steel tank, which is sensitive to

406 Meyer et al. (2016), p. 34 to 43

407 Mueller-Syring et al. (2013), p. 39

408 Mueller-Syring et al (2013), p. 38

high hydrogen concentrations.[409] Some NGV's have a composite gas filling tanks without any sensitivity to hydrogen.[410] Studies have detected that higher hydrogen concentrations are possible.[411] In future, higher hydrogen concentration at sensitive components in the public gas grid could be filtered by special membranes.[412] The direct hydrogen injection has economic advantages with respect to investment costs and efficiency. However, a specific site analysis is necessary to fulfill the feed-in criteria.

A further technical question is if gas feed-in stations can handle several starts and stops of injections per day because of the fluctuation of SNG production. This is investigated in the single case study and has an economic impact in the case of the efficiency of a PtG plant.

5.4.5 Gas Grid Infrastructure and Future Development

The utilization and storage of hydrogen and SNG in the existing public gas grid is one of the advantages of PtG as an energy storage unit. The infrastructure and distribution grid of this technology is built. Comparing to other energy storage technologies, this means that the battery or pump storage lake already exists. As already mentioned, Sterner and Stadler (2014) expose a storage capacity in the German gas grid of 217 TWh.[413] This number includes gas storage facilities like cavern and pore storages, as well as the possibility of direct hydrogen injection. The future storage potential of synthetic gas (hydrogen or methane) is numbered with 533 TWh.[414] The existing gas infrastructure is offering a temporal as well as a regional storage opportunity. For that reason, PtG technology is more flexible across different energy sectors (power, mobility, heat).

The German natural gas grid has a length of pipelines of 477,000 km and is well-expanded.[415] Almost every second household is connected to the gas grid as well as most of the approx. 900 gas filling stations of the mobility application.[416] Therefore, a distribution advantage compares to fuels like bioethanol, dimethyl ether, or hydrogen can be assumed. Figure 60 illustrates the national German gas grid. The dark blue lines are symbolizing the main distribution infrastructure with high-pressure pipelines. The gas quality in the grid is separated into low and high calorific valued gas. The low calorific gas comes from German and Dutch explorations and is marked with bright

409 Mueller-Syring et al (2013), p. 78 f

410 Mueller-Syring et al (2013), p. 80

411 Mueller-Syring et al (2013)

412 Lubenau and Kussin (2019)

413 Sterner and Stadler (2014), p. 423

414 Sterner and Stadler (2014), p. 379

415 BDEW (2019b)

416 BDEW (2019c)

blue lines in the Northwestern part of Germany. Until 2030, these natural resources will be run empty and replaced by high calorific gas.[417] It is also possible that parts of the low calorific grid are used for hydrogen transportation. In this case, the installation of PtG plants with direct hydrogen injection is advisable. The gas comes primarily from Russia (38%), the Netherlands (27%) and Norway (22%) in 2014. 10.3% of the German gas supply originates from its own exploration (9.6%) and biogas plants (0.7%).[418]

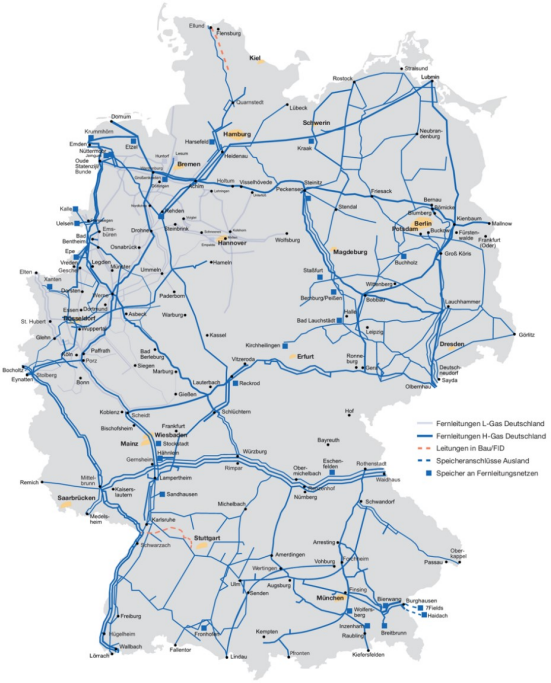


Figure 60: German gas infrastructure[419]

The future gas infrastructure development depends on the future utilization of target markets, which is influenced by the developments of CHP plants, gas and steam power plants, the demand of the heat sector, future potential of gas mobility and of course the usage as an energy storage utility in a future RE system. Except for the heat usage, all drivers have ascending trends, according to Nitsch et al. (2012). The world energy

417 NEP Gas (2014), p. 80 ff

418 BDEW (2019d)

419 NEP Gas (2014), p. 55

outlook from the international energy agency is forecasting an increase of 20% of the natural gas consumption in Europe from 2012 to 2040.[420] The gas demand in the power, heating and transportation sector arise, whereas the consumption of the industry sector is decreasing in Europe up to 2040.[421] For that reason, the German gas providers are investing €1.8 billion until 2019 and €3.1 billion until 2024 to improve the gas grid.[422]

5.4.6 Carbon Dioxide Capturing and Sources

This chapter exposes the methods of carbon dioxide capturing and possible amounts of carbon dioxide sources if a methanation is required. There are three significant techniques of carbon dioxide capturing: absorption from biomass, absorption from flue gas of industrial processes and fossil power plants and the capturing from ambient air. First, the different techniques and, second, the amount of CO_2 sources in Germany are declared. At the end of this section, the economic and ecological sense of different CO_2 sources and their regulative status are discussed.

The CO_2 capturing from biogas plants with the amine scrubber technology or the pressure swing adsorption is an efficient and technologically mature method. Both methods are commonly used in the biogas industry to upgrade the raw biogas to the required feed-in quality of the gas grid. Normal biogas stream consists of 40% CO_2 and 60% methane (CH_4), which depends on the input subtracts.[423] Biogas plants, which inject biomethane in the public grid, require a CO_2 removal. Schünemeyer et al. (2013) have investigated the advantages and disadvantages of the amine scrubber and the pressure swing method in combination with a PtG plant. The result is that the amine scrubber has an advantage in terms of purity of CO_2, methane slippage and heat usage if the degree of capacity utilization of the PtG plant is more than 4,000 FLH.[424] A further practical investigation of the pressure swing adsorption in combination with the biological methanation is missing yet and, therefore, recommended as further research.

The methods of a carbon dioxide capturing from industrial processes and fossil power plants can be further divided into pre- or post-combustion methods. Pre-combustion methods are separating carbon dioxide in front of the combustion process. Therefore, substantial technical changes have been implemented. An advantage is the usage of oxyfuel combustion methods with higher efficiencies.[425] Here, also the oxygen of the electrolysis can be used. Existing industrial facilities or fossil power plants prefer post-

420 IAE (2014), p. 139

421 IAE (2014), p. 144

422 NEP Gas (2014), p. 9

423 Trost et al. (2012), p. 179

424 Schünemeyer et al. (2013)

425 Steinmueller (2014), p. 88 ff

combustion techniques like amine scrubbers, other washing materials, or the calcium looping. The post-combustion absorption from flue gas, for example, has been successfully tested at the lignite power plant from RWE AG.[426] Because of the low CO_2 concentration in fossil power plants, the primary energy consumption increases with 20% to 44%.[427] For that reason, the economic aspect of such CO_2 source needs to be considered. But often, internal heat is available in fossil power plants and can be used in the capturing process.

An interesting upcoming but also energy-intensive technology of CO_2 capturing is the absorption from ambient air, which has a CO_2 concentration of only 0.04%,[428] by a special sorbent material. One of the first PtG plants (250 kW) from the research institute ZSW has used such a technology.[429] Another CO_2 capturing unit from the Swiss start-up Climeworks AG was installed and integrated at the Audi PtG site to produce up to 50 tons per year of CO_2 in 2016, using a catalytic-supported circular process.[430] The CO_2 absorption from ambient air has the advantage of offering a regionally independent CO_2 source. For example, in remote regions with high potential of RE but without any point source of CO_2. This opens an unlimited market potential in a long-term perspective of PtG technology.

As mentioned in the technical chapter of the chemical methanation (see chapter A.5), the purity of the CO_2 is important to avoid the degradation of the catalyst. Therefore, CO_2 capturing methods must fulfill certain requirements of purity. Most of the potential sources like flue gas absorption from combustion processes (cement plant, fossil power plants) or biomass take place at atmospheric pressure level. Therefore, also compressors to the pressure level of methanation reactors have to be installed, which increase the further power consumption of BOP (see chapter 5.4.2). In addition, most of the CO_2 capturing methods require heat input, which can arrive from exothermic PtG processes (see chapter 5.4.3).

Normally, carbon dioxide is a waste product. Therefore, it does not have a specific market price. The energy demand is the main driver of the operational expenditures (OPEX) of CO_2 capturing. The OPEX of amine scrubber units are announced with 25 to 60 €/t.[431] The cost of CO_2 capturing from ambient air is difficult to measure due to the early stages of technology development. Hermann et al. (2014) are describing operational costs of 46 €/t in a low power price scenario and investment costs of 150 to

426 RWE (2014)

427 Trost et al. (2012), p. 184

428 Denman et al. (2007), p. 512

429 ZSW (2014)

430 Sterner und Stadler (2015), p. 489

431 Lehner et al. (2014), p. 54

320 €/t of CO_2 capturing per year.[432] The investment costs of a 1,000 t/a Climeworks container is mentioned with 800 €/t. The operational costs are about 30 €/t. Investment costs could be decreased to 200 €/t in the future due to economies of scale and experience curve effects.[433] Tremel (2018) states capturing costs of 28 to 41 €/t of CO_2 from coal-fired power plants and 37 to 85 €/t from gas-fired power plants. He assumes that the costs of capturing from ambient air are in the range of 100 to 150 €/t of carbon dioxide.[434]

Fasihi et al. (2019) have conducted a techno-economic assessment of direct CO_2 air capture plants. They have analyzed different technology options like a high-temperature aqueous solution, a low-temperature solid sorbent as well as a scenario in which free waste heat is available (e.g., from the exothermic methanation process see chapter 5.4.3) for different operation times and years. The results are that for 4,000 FLH, CO_2 capturing costs of 226 €/t CO_2 (free waste heat) to 289 €/t CO_2 (solid sorbent) are calculated for the year 2020 for large scale applications. In 2050, the CO_2 costs can be reduced to 56 €/t (free waste heat) and 80 €/t.[435] Fasihi et al. (2019) have further reproduced industrial CO_2 capturing costs following Leeson et al. (2017). Industrial point sources are around 40 €/t CO_2 at iron and steel plants, 65 €/t at refineries, 35 €/t at pulp and paper facilities and 63 €/t at cement plants in 2020.[436] This shows that point sources are by far cheaper than the absorption from ambient air.

In the business modeling, the CO_2 costs of Fasihi et al. (2019) are taken into account due to the latest available set of data and the detailed comparison to other literature sources. The separation from biogas plants is not increasing the overall CAPEX because only biomethane plants are considered that already have an installed CO_2 treatment. Because Fasihi et al. (2019) calculated with levelized costs of heat and electricity generation over 20 years with a WACC of 7%, no further price development is assumed. The following table is summarizing the additional costs of CO_2 capturing.

432 Hermann et al. (2014), p. 21

433 Sterner and Stadler (2015), p. 418

434 Tremel (2018), p. 61

435 Fasihi (2019), p. 970

436 Fasihi (2019), p. 975

Table 21: Costs of CO_2 capturing in 2020[437]

Type of charge	Value in €/t CO2
Biogas plant	-
Bioethanol plant	7
Iron and steel plant	40
Refineries	65
Cement plant	63
Pulp and paper	35
From ambient air (free waste heat)	226
From ambient air (solid sorbent)	289

In the efficiency calculation (see chapter 5.3.5), just the additional energy consumption of the individual CO_2 source is taken into account. Hermann et al. (2014) published a table of power consumption per ton of CO_2. These additional consumptions are added to the power consumption of peripheral devices. For example, the CO_2 separation from cement production consumes 88 kWh/t, the separation from a gas-fired power plant 450 kWh/t and from ambient air 2,280 kWh/t.[438] The separation from biogas or ammonia plants is not increasing the overall power consumption. These amounts of additional power consumption are not in line with the cost of a separated ton of CO_2 of Fasihi et al. (2019) because different assumptions in terms of power price, plant size and the latest development of CAPEX and OPEX are considered. Due to the more updated publication, Fasihi et al. (2019) are chosen as the input data for the BM calculation.

The following section is discussing the amount of potential CO_2 sources. Some studies have comprehensively recapped the number of different sources. Again, the sources are separated in CO_2 from biomass, industrial processes, and ambient air. First, the potential of carbon dioxide from biomass is focused on biogas and bioethanol plants as well as sewage plants in Germany. The biogas plants, which are injecting into the gas grid and, therefore, already have a CO_2 absorption and biogas plants, which are using the biogas for power production, are considered. In Germany, 8,928 biogas plants are installed in 2015, from which 190 are upgrading the biogas and injecting into the public gas grid.[439] Most of these biogas plants are located in rural areas, in which also a high installation of RE exists and has a connection with the gas infrastructure.[440] In addition, if biomethane from manure is produced, it avoids methane emissions in comparison to the usage of manure as a fertilizer in agriculture. For that reason,

437 Fasihi et al. (2019)

438 Herman et al. (2014), p. 23

439 Fachverband Biogas (2015), p. 6

440 Trost et al. (2012), p. 186 to 189

biomethane from manure has an emission factor of -103 kg/GJ with close digestate and off-gas combustion in the regulatory framework of the RED II.[441] These ecological benefits can be even increased if the CO_2 from the raw biogas treatment is used for SNG production. More than 1,200 of approx. 10,000 sewage plants are producing sewage gas, in which CO_2 is included.[442] In addition, bioethanol production is emitting carbon dioxide. In 2011, 0.75 million Nm^3 of bioethanol had been produced.[443] A further increase of biofuels, which has not taken place until 2020 (see chapter 5.2.4.3), could also increase this CO_2 source for the PtG technology.

Trost et al. (2012) expose a biological CO_2 potential of 187 million Nm^3 or 370,000 t from biogas plants, which are injecting biogas in the public gas grid.[444] For a better comparison with the potential of PtG in the research status (see chapter 2.1), the amount of CO_2 is recalculated to the installed capacity of PtG. According to the chemical equation of the methanation (see chapter A.5), 2.75 mole of CO_2 is required to produce one mole of CH_4. This proportion indicates that 135 million kg of methane can be generated with 187 million Nm^3 of CO_2. According to the energy density of SNG of 13.85 kWh/kg,[445] an energy amount of 1,866 GWh is identical to the methane potential. With an operation time of 4,000 FLH (see chapter 5.4.8) and efficiency of approx. 50% (see chapter 5.3.5), an installed capacity of 0.93 GW of PtG is possible with that amount of CO_2.

In addition, from other biogas plants, which are generating power with CHP plants, a potential of 2,400 million Nm^3 CO_2 is specified.[446] This results in a further capacity of approx. 12 GW PtG plants. Both amounts are added in summary. Further on, 1.5 GW from bioethanol facilities and 1.26 GW from sewage plants are available in Germany.[447] In the future, a biological CO_2 potential of approx. 37.5 GW PtG is forecasted in 2050 due to national strategy programs of biogas and bioethanol production.[448] In addition, carbon dioxide emissions from breweries can be valued as a biological source as well. In Germany, approx. 100,000 tons of CO_2 are emitted by breweries.[449] These CO_2 amounts can supply 0.25 GW PtG. Table 22 is summarizing the potential amount of installed capacity of PtG plants.

441 European Parliament (2018c), p. 199

442 Blesl and Ohl (2010)

443 Trost et al. (2012), p. 182

444 Trost et al. (2012), p. 179

445 Gosda (2014), p. 44

446 Trost et al. (2012), p. 181

447 Trost et al. (2012), p. 181 to 182

448 Trost et al. (2012), p. 181

449 Gosda (2014), p. 93

Another more critical research from the institute for applied ecology is mentioning different numbers. Hereby the biological potential of carbon dioxide is calculated with existing biogas plants, which are injected into the gas grid, operational availability of 50% and without sewage plants. The potential is about one million tons CO_2 from bioethanol and 0.2 million tons CO_2 from biogas plants.[450] Due to insecurities about the further development of biofuels and biogas usage, Hermann et al. (2014) forecast a low future potential of carbon dioxide from biological processes. They announced a max. availability of one million tons from bioethanol production and 6.6 million tons from biogas plants in 2030.[451] According to the mentioned conversion calculation of CO_2 per installed capacity, the PtG potential is about 19.2 GW.

As a second potential source, the CO_2 amount of industrial processes that are responsible for 5% of the GHG emissions in Germany[452] and fossil power production are taken into account. Only the steel and cement industry have the capability of 65.15 GW installed PtG capacity in Germany, although the CO_2 absorption from the flue gas is highly cost-intensive.[453] In the chemical industry, ammonia, ethylene oxide, acrylonitrile and methanol production are emitting carbon dioxide in high concentrations. In total, the chemical industry had directly emitted 15.6 million tons of CO_2.[454] This is respectively to an installed capacity of PtG of 39.4 GW. The fossil energy production is accounting for a CO_2 amount of 21 million tons, or 53 GW installed PtG power in Germany.[455] Nevertheless, Hermann et al. (2014) are neglecting the usage of CO_2 from industrial and fossil combustion processes. On the one hand, they are citing a study from the institute of applied ecology and Fraunhofer Institute (ISI), in which the overall amount of CO_2 from industrial processes decrease from 53.46 million tons in 2010 to 2.21 million tons in 2050 due to climate targets.[456] On the other hand, they are exposing the ecological sense of usage of fossil CO_2. Also, Trost et al. (2012) are not mentioning the amount of CO_2 from industrial processes in the future. However, the amounts are available and should be discussed to produce SNG.

Third, the capturing of CO_2 from the ambient air needs to be considered. The potential of this source is nearly unlimited. The disadvantage of energy intensity and, therefore, highly cost insensitivity has been discussed. An important advantage, however, is the independence of location. The PtG site can be installed wherever a surplus of RE or low levelized costs of power generation exists. For that reason, the CO_2 capturing from

450 Hermann et al. (2014), p. 15 f

451 Hermann et al. (2014), p. 15 f

452 Hermann et al. (2014), p. 18

453 Trost et al. (2012), p. 182 f

454 Trost et al. (2012), p. 183

455 Kasten et al. (2013), p. 17

456 Repenning et al. (2014)

ambient air is an interesting aspect of future PtG development. The ecological perspective is controversial because the origin of each carbon dioxide molecule is unknown.

Table 22: Potential of CO_2 sources in Germany for 2011

Type	Origin of CO_2	Potential of installed PtG capacity in 2011 in GW
Biological CO_2	Bioethanol plants	1.5 to 2.52
	Biogas plants	0.5 to 12.93
	Sewage plants	0 to 1.26
	Breweries[457]	0.25
	Sum	3.27 to 13.43
Industrial and fossil CO_2	Steel and cement factories	0 to 65.15
	Chemical industry	0 to 39.4
	Fossil power production[458]	53
	Sum	53 to 157.55
CO2 from the air	Ambient air	Unlimited
	Overall sum without ambient air	56.27 to 170.98

Another interesting literature source of existing CO_2 feedstock in Europe is von der Assen et al. (2016). The following figure is showing the distribution of facilities that are emitting more than 0.1 megaton per year. The height of the scales displays the yearly emitting amount of carbon dioxide and the color highlights the source. As shown, huge emissions come from fossil power plants like coal or natural gas. These are mostly located in West Germany and East Germany as well as in Poland. Other more ecological sources like cement, refineries or pulp and paper production are well distributed. A comparison to possible generation sites of renewable electricity clarifies that interesting locations in South Europe and the United Kingdom exist.

457 Gosda (2014), p. 93

458 Kasten et al. (2013), p. 17

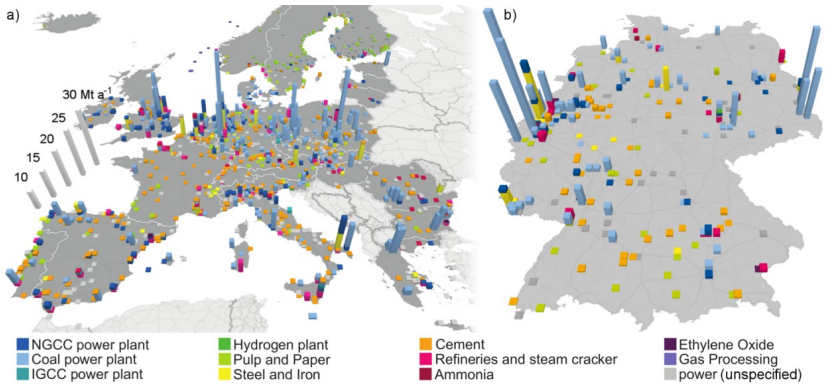


Figure 61: European distribution of CO_2 emitting facilities[459]

The capturing methods of carbon dioxide and possible sources have been explained above. Another important aspect is the ecological quality of the carbon dioxide source. Therefore, the carbon cycle must be mentioned. Carbon is stored in four different subsystems with different quantities, different chemical combinations, and different turnover rates. According to the report of the international panel of climate change (IPCC), the atmosphere contains 762 gigatons of carbon with a turnover rate of one year. Second, the biosphere, with approx. 2,300 gigatons of carbon and a turnover rate from months to one decade. Third, the hydrosphere with around 38,000 gigatons and a turnover rate of decades to one century. Last, the lithosphere with more than 77 million gigatons and a turnover rate of centuries to millions of years.[460]

Due to different turnover rates, there is a discussion about what kind of carbon dioxide source is ecologically worthwhile to use. On the one hand, it is argued that no anthropogenic carbon dioxide should be used for the PtG technology to avoid further justification of fossil combustions or industrial processes. Anthropogenic carbon dioxide, which means that human beings cause the emission, has short turnover rates and is only available in the atmosphere and biosphere but not in the lithosphere. On the other hand, the argumentation claims that every carbon dioxide capture and utilization is better than the usage of carbon from the lithosphere. And even with a complete energy transition, some industrial processes like cement, glass or the steel industry will continue to exist and emit CO_2. On the other hand, the energy-intensive sector is on a clear track to reach the Paris climate goals due to the ETS mechanism, which is explained in chapter 5.2.2. As long as these sources are available and limited in the ETS, it should also be considered to use for CO_2 utilization.

459 Von der Assen et al. (2016), p. 1096

460 Denman et al. (2007), p. 515

This discussion also has an economic impact. The German energy industry act (EnWG (2016)) describes in section three (glossary) in number 10c the equalization of SNG and biogas if the carbon dioxide comes predominantly (usually 80%) from renewable sources. The definition of renewable sources refers to the RED (2009/28/EG ABl. L 140), in which just biomass as a possible CO_2 source is mentioned. This has an impact on the investment costs of the feed-in station and the yield of the avoided gas grid fees (see chapter 5.2.1). CO_2 from the ambient air or industrial processes is not included in this law and is losing the *biogas status*. In cases of CO_2 usage in fossil plants or industries, who trade CO_2 certificates (ETS), it must be clarified which party is allowed to receive the CO_2 credits. Double counting of carbon dioxide credits should be avoided.

A change of this political framework to include all sustainable CO_2 sources is recommend in the conclusion (see chapter 7.3.2).

5.4.7 Ecological Information

This chapter gives further ecological information, which, for instance, explains the GHG reduction quota of SNG compared to other fuels in the mobility market.

The ecological footprint of different energy carriers in different energy sectors is illustrated in Figure 62. Therefore, a life cycle analysis of the different applications of SNG is necessary to make statements about the ecological impact of this technology. This approach considers all emissions along the value chain of PtG. It includes the power generation as well as the transport and consumption of synthetic fuel. For example, the compression to a pressure level of 200 bar at the gas filling station is taken into account. Sterner and Stadler (2015) have calculated the ecological footprint of different applications of SNG. It indicates an ecological advantage of SNG compared to fossil and biofuels in all energy sectors.

The reason for these ecological benefits is the recycling of CO_2 and the use of RE only. The same amount of CO_2 is bounded during the methanation that is emitting by combustion in the power, heat or mobility sector. Direct injection of hydrogen is avoiding the usage of fossil natural gas and, therefore, the emission of further carbon dioxide. SNG can help to decarbonize the power, heat, and mobility sector by using existing infrastructures (pipelines, CHPs or gas-fired power plants, heating systems, applications in the industry, NGVs and their filling stations). However, the ecological consideration obtains that the political goals of CO_2 reduction can be achieved by integrating the PtG technology into a RE system.

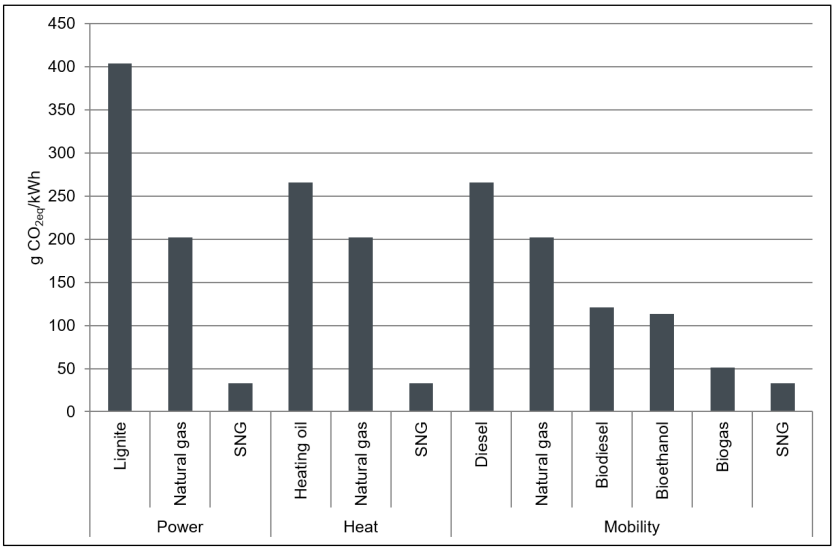


Figure 62: Ecological footprint of different PtG applications[461]

An ecological point of criticism of gaseous fuels in different markets is often the possible methane slippage. Methane has a much higher GHG potential than carbon dioxide. According to the fifth IPCC report the factor is 34 times higher than the GHG factor of CO_2.[462] But most of the methane emissions take place by the gas exploration in Russia or other countries[463]. Therefore, this is mainly an issue for fossil, natural gas and not for biogas or SNG. But it should be considered in a holistic analysis of the GHG footprint of SNG.

As mentioned in the description of the target market, *power-to-gas-to-mobility*, multiple uses of the green ability of SNG has to be discussed. Double counting of the green ability is forbidden in the RED of the EU-27: "*however, with a view to ensuring that a unit of renewable energy is disclosed to a customer only once, double counting and double disclosure of guarantees of origin should be avoided.*"[464] Following that statement, this research study is avoiding double-counting of RE. For example, if SNG is sold to the mobility market, and the GHG reduction quota is yielded a further sold of the green ability to the customer is forbidden. A combination of biogas sale, GHG reduction quota, and eco-premium to the customer is not allowed in the business model.

461 Sterner and Stadler (2015), p. 426 and BLE (2015)

462 Mueller-Syring et al. (2016), p. 40

463 Mueller-Syring et al. (2016)

464 European Parliament (2017), p. 40 and 41

5.4.8 Operation Time and Concepts

Another parameter, which is used in the business modeling, is the operation time of PtG plants. The importance of the operation time of a PtG plant is also shown in other studies of an economic consideration of the PtG technology.[465] The operation time depends on both input streams' power supply and CO_2 availability if methanation is required.

The overall operation time has a significant impact on the BM. If the cash flow is positive and the power price constant, a higher yearly operation time would increase the economic result. The possible operation time depends on the operational concept. If the PtG site is only operating with a single power purchase concept like at the balancing market or is directly connected to the RE source, the operation time is limited by the market or hours of operation of the RE unit. If the facility is grid-connected and participates at various power markets, the theoretical yearly operation time is not limited. However, if the capacity factor, which is defined as the share of yearly operation, increases higher power price hours have to be taken into account during a year. In addition, a gird- and system-friendly operation is questionable with a high capacity factor because the hours of RE feed-in are limited. Therefore, due to economic and ecological reasons, a limitation of the capacity factor has to be considered. For the spot markets, an operation time of 4,000 FLH is assumed. This is justified as, on the one hand, preferred wind energy locations like offshore wind power can achieve similar operation times[466]. On the other hand, simulations of the future energy system are presenting a surplus of power generation with that number.[467]

Brunner et al. (2015) distinguished between centralized grid-connected and decentralized off-grid PtG facilities. They calculated an economic-optimized operation time of 4,073 equivalent FLH in a low RE scenario and 4,483 hours in a high RE scenario for hydrogen injection into the gas grid in Germany. Methane injection would decrease the amount of FLH to 4,040, respectively 4,441.[468] For decentralized PtG plants, the operation time highly depends on the connected RE source. The combination with onshore wind accounts for 3,377 and 2,968 FLH between the investigated scenarios in Germany. Offshore wind connection results in 4,206 and 4,166 FLH and photovoltaic in 1,756 and 1,625 FLH.[469] Due to different levelized costs of electricity generation, the lowest gas production costs are achieved in combination with onshore wind. Another interesting fact of this study is that the installed peak capacity of the power plant is twice in respect to the PtG plant for the combination with wind onshore and

465 Brynolf et al. (2017), p. 22; Zapf (2017), p. 232; Parra and Patel (2016), p. 3748

466 Stadler and Sterner (2014), p. 81

467 Klaus et al. (2010), p. 92

468 Brunner et al. (2015), p. 289

469 Brunner et al. (2015), p. 287

photovoltaic. For wind offshore, nearly the full RE peak power can be used in the PtG facility.[470] Therefore, in the case of onshore wind and photovoltaic additional renewable power generation is available because it is not economically worthwhile to feed all the energy in the PtG plant. Especially for developing countries, this is an additional advantage of PtX production because additional RE can be used in local grids.

Tremel (2018) has further investigated worldwide operational concepts. He mentioned a wind capacity factor of 43% (approx. 3,750 FLH) in Morocco, 50% capacity factor with offshore wind in Chile, 1,730 FLH photovoltaic in the United Arab Emirates and combined onshore wind and a solar capacity factor of 40% in Australia.[471]

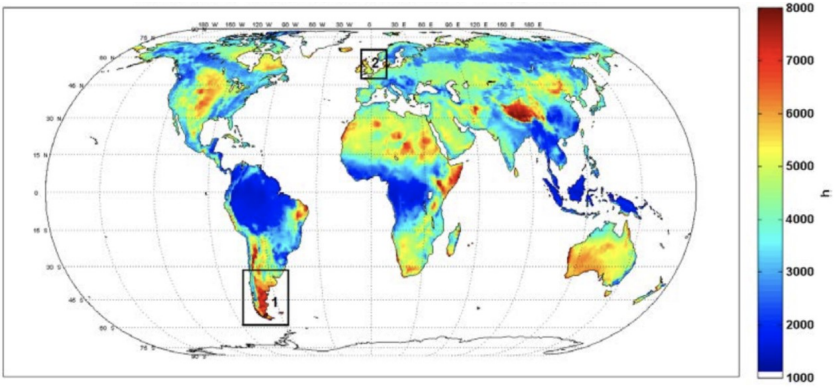


Figure 63: Map of FLH in a hybrid wind onshore and PV operational mode[472]

Another international study regarding the FLH has been done by Fasihi et al. (2016) and was presented at the 10th international RE storage conference in Düsseldorf in 2016. A worldwide consideration of solar radiation and wind speed leads to a map of potential FLH in a combined wind onshore and solar operational mode. It indicates regions with almost 8,000 FLH like Patagonia, Somalia, and China.[473] SNG can be liquified and easily transported from there to the target markets.

In the end, it is a mixture of economic and ecological considerations for the operation time of a PtG plant. Considering the curtailment of renewable power production operation within only a few hours cannot be economically feasible because of high

470 Brunner et al. (2015), p. 287

471 Tremel (2018), p. 68 ff

472 Fasihi et al. (2016), p. 247

473 Fasihi et al. (2016), p. 246

CAPEX.[474] However, this dissertation is using an operation time limitation of 4,000 hours for grid-connected instances except for the balancing energy concept. As shown, this amount is appropriate in a RE system as well as in a direct connection to an offshore wind park in Germany. However, the number can be adjusted in the BM for future research activities. A sensitivity analysis is recommended to analyze the impact of the operation time on the business cases (see chapter 7.3.2).

5.5 Revenue Mechanism

The analysis of different economic parameters along the value chain and the network has indicated first quantitative numbers of an emerging PtG BM. In a next step, a revenue model is built by taking into account the results of the system analysis (see chapter 4) as well as findings of the value chain and network analysis. This proceeding results in a basic matrix of the general BM.

In Figure 64, a brief revenue model of PtG technology is displayed. The center shows the value chain. In red, the cost and green, the income parameters are illustrated. The cost parameters have a negative sign. Different parameters are influenced by external drivers. The revenues of the *CAPEX* and *OPEX* depend on the chosen plant construction. The *costs at the power markets* (R_{PC}), for example, depend on the chosen power supply concept, which has been discussed in chapter 5.3.1. The *costs of power taxes and fees* (R_{PT}) depend on the operation time (O) of the chosen power supply concept. Exemptions from taxes and fees are discussed in chapter 5.3.2. The decision of the CO_2 source impacts the *costs of CO_2 capturing* (R_{CO2}) and the income of the avoided gas grid fees. The efficiency of the specific plant construction lead to the amount of produced SNG. After this step, the production cost of SNG is known and is presented as *gas production costs* in the business case calculations later. Now the possible yields are added with respect to the chosen target market. For example, the GHG reduction quota as an eco-premium can only generate proceeds if SNG is sold to the mobility market. In the end, the yearly cash flow is analyzed.

Equation 5-3: Revenue formula

$$Cash\ flow\ (R) = R_{CAPEX} + R_{OPEX} + (R_{PC} + R_{PT}) \times O + R_{CO2} + R_O + R_H + R_G + R_{ECO} + R_{AGGF}$$

In the average cash flow formula, R_{CAPEX} is the yearly revenue of the CAPEX divided through the lifetime, R_{OPEX} is the yearly revenue of the operational and maintenance expenditures without power costs, R_O and R_H are the yearly revenues of oxygen and heat sale if possible, R_G, R_{ECO}, and R_{AGGF} are the yearly revenues of gas sale yields, the eco-premium, which depends on the target market, and income of the avoided gas grid fees. This revenue model is not fixed. It displays the market situation after a system analysis and the consideration of the value chain and network in Germany in 2020. In

474 Brunner et al. (2015), p. 284

the future, the revenue model can be changed, for example, if additional power purchase concepts appear or if the eco-premium can be accountable to the CO_2 fleet regulation of automotive companies (see chapter 7.2).

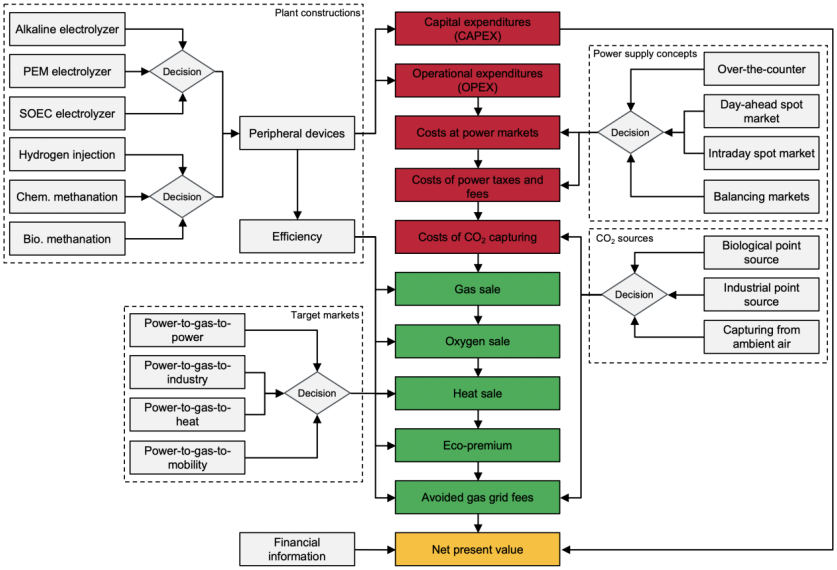


Figure 64: Revenue model of the PtG technology

The yearly discounted cash flow analysis is a suitable financial tool to investigate the status of a business case. It indicates the most crucial cash flows and, therefore, allows statements about the economic feasibility. The economic viability is presented in three numbers. First, the net present value (NPV) over the lifetime of the PtG plant is calculated. The NPV is a useful measurement for the profitability of an investment. Therefore, the yearly net cash flow (R*) without R_{CAPEX} is discounted over lifetime with the interest rate back to the present value. As the interest rate (i), the WACC is taken into account as additional financial information (see chapter 5.4.1). If the NPV after taxes is calculated, the interest of the debt capital is reduced by the tax rate (t), and the net cash flow is reduced by taxes, depreciation and forward losses (see chapter 5.4.1). The NPV allows a statement about a long-term financial project. The NPV formula is as follows:

Equation 5-4: NPV formula[475]

$$NPV\ (i,n)\ =\ -\ \mathrm{CAPEX} + \sum_{t=0}^{n} \left(\frac{R^*_t}{(1+i)^t} \right)$$

In addition, the return on investment (ROI) can be calculated with the net operating profits, which is the average cash flow over lifetime, divided by the overall CAPEX. Thus, this financial parameter indicates the efficiency of investment by relating profits to capital. The ROI is stated in percentage and a high ROI displays high economic feasibility of a project. In comparison to the NPV, the time value of an investment and cost of capital are ignored. The ROI is appropriate to compare investments to their capital. If the tax model is activated, the average cash flow with depreciation, forward losses, and taxes is considered.

Equation 5-5: ROI formula[476]

$$ROI\ =\ \frac{R \times lifetime}{\mathrm{CAPEX}}$$

Another useful financial parameter is the internal rate of return (IRR). This calculation method sets the NPV formula equal to zero and solves the equation for *i*. This parameter displays the rate of return of an investment. The IRR needs to be higher than the WACC if the project is economically feasible. The formula is as follows:

Equation 5-6: IRR formula[477]

$$\sum_{t=0}^{n} \left(\frac{R_t}{(1+i)^t} \right) = 0$$

In total, three different financial parameters are given in the BM. This allows different statements about the value, efficiency, and rate of an investment. The revenue model is applied in the business case calculations (see chapter 6.1) and practically tested in the single case study (see chapter 6.1.9).

The data sourcing is an important step of DSR to apply the developed artefact. For that reason, possible data origins and the collection method is briefly discussed for all input parameter along the value chain. This proceeding has been done in chapter 5 in this work. The plant related data like the CAPEX, OPEX and efficiency can be collected by literature review and technical analysis. Due to the small market size industrial surveys

475 Berk et al. (2015), p. 64

476 Coenenberg et al. (2007), p. 762

477 Berk et al. (2015), p. 64

and expert interviews are further useful. In this early stage of technological development, technical leaps and innovations are possible and have to be detected. It is the same proceeding for possible CO_2 sources. This market is neither matured and, therefore, requires detailed investigations. Case studies of first project like the direct air capturing are suitable as well. The costs of existing power markets can be detected by quantitative analysis of electricity markets. This is exemplary done in chapter 5.3.1. The cost of power taxes and fees can be achieved with the literature analysis of regulations. The data collection of revenue streams at target markets needs a mix of data collection, which depends on the maturity of the markets. If sufficient market data is available the income parameters at different target markets can be quantitively sourced. This is the case for example for the ETS price as the eco-premium at the power-to-gas-to-industry market. New target markets requires further detailed investigations with more qualitative methods like expert interviews and case studies to collect the data. For the transparency and reproducibility, it is recommended to display the sources of data in a table in front of each calculation of the revenue model. This is done in chapter 6.

Due to the high price fluctuation of different economic parameters, also the distribution of the outcomes is essential to consider the bandwidth of results. Therefore, a MC simulation and a bootstrapping method are chosen.

The MC simulation generates a probability distribution by random sampling. Some of the economic parameters like the gas or power price correlate to each other. In this case, random sampling is done by using a multivariate bootstrapping method. This expansion of the BM allows potential stakeholders of the PtG-technology to estimate the risk of their investments. In the next sections, the basics of the MC simulation and bootstrapping methods are briefly explained.

MC is a numerical technique to solve a problem by using random replications. If physical experiments are not possible, multiple theoretical simulations can help to gain results. For this reason, the first large-scale MC work was carried out by Stanislav Ulam, John von Neumann, and Nicholas Metropolis. They worked upon other terms on neutron multiplications at the Los Alamos Scientific Laboratory.[478] Nicholas Metropolis named the simulation “Monte Carlo,” which refers to the Monte Carlo Casino in Monaco.[479] First applications in finance are published by David B. Hertz in his Harvard Business Review article “Risk Analysis in Capital Investment” in 1964.[480] Here, MC methods are used to value and analyze complex portfolios and investments. For example, Holtan (2002) is using MC simulations to calculate the NPV and average cash flow of a project. He uses a discounted cash flow model as well. The results are given

478 Murthy (2003), p. 4

479 Metropolis (1987), p. 127

480 Hertz (1964)

in histograms to show the probability distribution in a fixed range as well as the volatility of the project.[481]

Following these examples, the BM is expanded with a MC simulation. All dynamic economic drivers have historical data, which are analyzed along the value chain in the previous chapters. The MC method is used to generate randomly new samples out of the existing data with replacements.

As mentioned before, a correlation between the gas and power price exists. For example, the 2016 intraday power prices and the 2016 daily gas prices have a Pearson correlation coefficient of -0.35. That indicates a slight negative linear correlation between the power and gas price at spot markets this year. However, a simple random sampling would destroy the correlation and would negate the dependencies of both drivers. Therefore, a multivariate bootstrap method is further integrated to respect the correlation.

Bootstrapping is a special method of resampling. It was first published by Bradley Efron in “Bootstrap Methods: Another Look at the Jackknife" in 1979.[482] The basic idea is that existing observed data can be resampled to get a broader sample, in which, for example, the distribution or standard error can be analyzed. The original data is sampled in a randomized way again and placed back. Bootstrapping raises scientific interest because modern computers can apply these methods flexibly, quickly, and easily.[483]

For that case, each calculation generates new yearly power and gas price samples out of the existing data with replacement. The correlation of depending parameters is kept by clustering the samples in blocks. For each bootstrap, the gas and power prices are simultaneously drawn and replaced. With that proceeding, similar Pearson correlation coefficients is achieved compared to the original data source.

The construction of the BM allows the single activation of the MC simulation of economic parameters to analyze the impact of specific drivers in detail. In the input table of the BM, each dynamic parameter can be set to *random*, and then specific analysis can be made. For the MC simulations, 10,000 repetitions are calculated to receive clear results but also considering the calculation time. In addition, a confidence interval of 90% is taken into account for the histogram of the NPV, as recommended in a later publication of Bradley Efron.[484]

481 Holtan (2002)

482 Efron (1979)

483 Efron and Tibshirani (1993), p. 2

484 Efron (2003), p. 137

5.6 Conclusion of the Business Modeling

So far, the BM of the PtG technology has been developed following, first, system analysis to announce necessary economic parameter and their relation and, second, an investigation of the target markets, value chain, revenue streams and ecosystem following the technology-driven school of business model innovation. As a conclusion of this chapter, Chesbrough's six functions of business model innovation is comprehensively displayed in Figure 65. In this dissertation, the analysis of the value network has been done before the revenue mechanism is drawn because different parameters of the value network play a certain role in the revenue mechanism in the end. Therefore, function five is done before function four. Function six, *competitive strategy*, is described in the overall conclusion in chapter seven.

In addition to the construction of the general BM of the PtG technology, the quantification of important cost and income parameters took place through a literature review, detailed market analyses, and industrial surveys. These numbers are used in the validation of the general BM. Therefore, main empirical work is executed by following Teece (2010), who quotes that *"a business model articulates the logic, the data and other evidence that support a value proposition for the customer, and a viable structure of revenues and costs for the enterprise delivering that value."*[485]

The focus of the business modeling chapter has been on the target market analysis and the prices of different power supply concepts. Both subchapters demonstrate the complex revenue structure of PtG technology. More than 30 parameters can influence the BM of the PtG technology, depending on plant constructions, power supply concepts and target markets.

The BM structure can be used in continuative studies for different locations or timeframes. Therefore, the quantification of the deduced parameters has to be analyzed for the investigated purpose. Also, other storage or demand side-oriented technologies can use parts of the PtG BM.

485 Teece (2010), p. 179

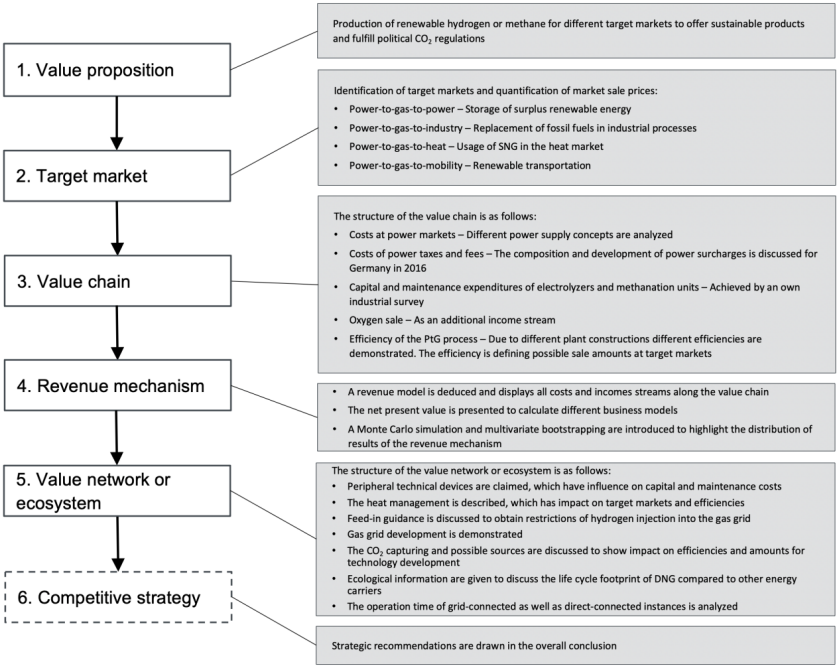


Figure 65: Structure of the PtG BM following the technology-driven school of business model innovation

6 Validation of the General Business Model

The validation of the business modeling takes place, first, by reproducible business case calculations and, second, by a single case study. The business case calculations are highlighting the theoretical relevance, and the case study is demonstrating the practical adaptability of the BM. However, as mentioned in the scientific framework (see chapter 2.5), the induced theoretical BM has to be empirically tested whether it works or not. In addition, important information about the BM and the PtG technology can be achieved. For example, key economic drivers, which are hindering the market ramp-up of the PtG technology. The findings of the business case calculations are also the input for the analysis of the potential technology roadmap.

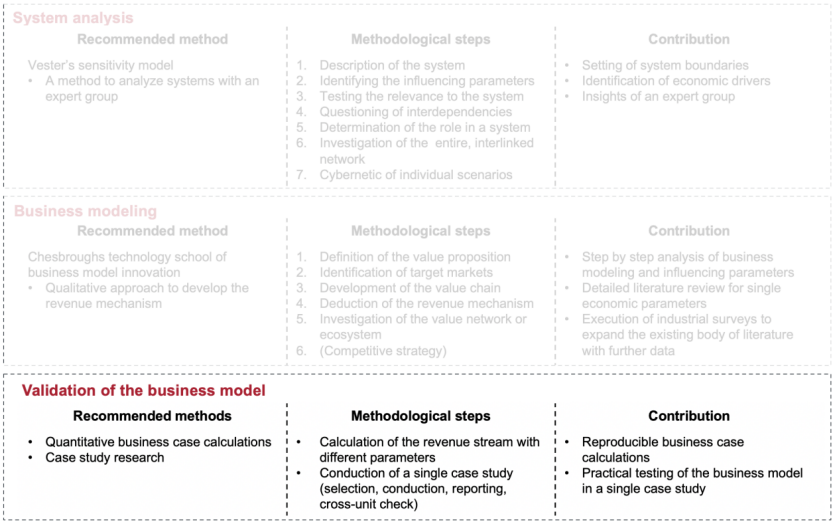


Figure 66: Validation of the BM

6.1 Calculations of the Business Model

This chapter summarizes the given detailed information about the PtG technology by calculating single business cases. First, case calculations are divided into the application in different target markets. The revenue mechanism of chapter 5.5 is followed. As a software tool, Microsoft Excel is chosen. On the one hand, Excel is universally available and user-friendly. Different cases can be reproduced for validation or expanded, e.g., for different regions. Third parties can adjust the BM and develop further insights. On the other hand, Excel allows all the implementation of all statistical methods like MC simulation or multivariate bootstrapping.

The business case calculation of the target market *power-to-gas-to-mobility* (see chapter 6.1.4) is then chosen as the basic scenario, on which different sensitivities are analyzed like different power purchase concepts (chapter 6.1.5), different plant designs (chapter 6.1.6), different CO_2 sources (chapter 6.1.7) and one specific case in the MENA-region (chapter 6.1.8). After these single scenario investigations, the distribution of the economic results is tested with all dynamic market parameters at once on the basic scenario following the MC simulation and multi-variate bootstrapping (chapter 6.1.9). In the end, the BM is empirically tested in different ways, and economic statements can be achieved.

The information about plant engineering, power purchase concepts and others are given at the beginning of each subchapter. All information is derived from previous research, which is done by analyzing the target markets (see chapter 5.2), value chain (see chapter 5.3) and value network (see chapter 5.4) by following the technology-driven way of business modeling. Further, necessary assumptions of all BM calculations are summarized in the following table.

Table 23: Further assumptions of the business case calculation

Economic parameter	Description	Value
CAPEX	10% of the investment costs of the electrolysis and possible methanation unit is added for the installation of peripheral devices like pumps and compressors	+ 10%
Operation time	The business cases are calculated with FLH. An investigation of partial loads is recommended	-
Lifetime	The lifetime is expected to be 20 years as the discussion in chapter 5.4.1 shows	20 a
Financial parameter: insurance costs	General BM can include insurance costs. If nothing else is mentioned the insurance costs are off	-
Financial parameter: financial aid	The general BM allows the use of financial aid. If nothing else is mentioned the financial aid is off	-
Financial parameter: deprecation	The deprecation is expected to be equal to the lifetime of the plant	20 a
Power price: cost of green power certificates	The power price is added with green certificate prices (see 5.3.1.5)	+ 0.05 ct/kWh
Power price: forecast error	The average power price is increased by a standard forecast error (see 5.3.1.1)	+ 11.83%
Balance of plant	The power consumption during stand-by time and additional power consumption of peripheral devices like compressors or pumps is added by 10% of the overall power input (see 5.4.2)	+ 10%

All calculations of the PtG technology take place under the German legislation. For that reason, the taxes and fees, which are explained in chapter 5.3.2, are taken into account. The future price development at different markets is an important topic of long-term business modeling. Different starting years can be set. In this case, the price

development to the starting year is already considered and displayed in front of each business case calculation. The future price development has been mentioned in each previous chapter if available and is comprehensively summed up as follows.

Table 24: Future price development

Parameter	Value	Source
Gas sale price as natural gas	2.01%	5.2.1
Heat sale price	2.53%	5.2.3
Oxygen sale	2.01%	5.3.4
Eco-premium (industrial CO_2 prices)	4.23%	5.2.1
GHG reduction quota	4.23%	5.2.4.4
OPEX	3%	5.3.3
Power price	2.8%	5.3.1.6
Capacity price at the SBM	2.8%	5.3.1.6

All other parameters are steady and have no further price development. The individual input parameters are mentioned in the description of each calculation. The following chapter describes the result of different business case calculations.

In total, the general model allows the calculation of 45 different plant constructions with different starting years, eight different CO_2 sources and direct hydrogen injection, 20 power purchase concepts, four target markets as well as the option to switch on and off the oxygen and process heat sale. In addition, different financial conditions can be calculated, and different dynamic economic parameters can be set to random to consider the distribution of the outcomes. In conclusion, around 100,000 different business cases can be calculated with the provided general BM of the PtG technology.

6.1.1 Business Case 1: Power-to-Gas-to-Power

The first calculation is done for the target market *power-to-gas-to-power* and is presenting the storage case in a future RE system. As explained in chapter 5.2.1, this case needs a direct connection to the RE unit. Zapf (2017) mentioned levelized costs of energy (LCOE) of wind onshore of 57.8 €/MWh.[486] This actual price has no further market price development because, in general, the price development is included in these lifetime costs. In addition, a forecast error, GO and power taxes and fees are not needed. But power taxes and fees for standby-time and peripheral devices are taken into account. The operation time depends on the location of the wind park. In this case, the operation time of Brunner et al. (2015) of a PtG plant with a connection to an onshore wind park is taken into account, which has been discussed in chapter 5.4.8. The produced SNG can be sold to a CHP plant. The generated electricity in the CHP has

[486] Zapf (2017), p. 83

the same guaranteed power price than the LCOE of the primary power source. For that reason, the efficiency is further multiplied with the efficiency of the CHP plant. For the gas sale price, the primary LCOE is retaken into account without a future price development. The efficiency includes the power demand of peripheral devices and the CHP plant. All individual input parameters are displayed in the following table.

Table 25: Input parameters of the business case 1: power-to-gas-to-power

Parameter	Value (2020)	Source
Plant description	5 MW AEL + chemical methanation	
Power purchase concept	Direct connection to RE (Germany)	
Target market	Power market (biogas)	
Operation time	2,968 h/a	Brunner et al. (2015)
CAPEX	€6.05 million	5.3.3
Power price	5.78 ct/kWh	Zapf (2017)
Power taxes and fees	0.19 ct/kWh	5.3.2
OPEX	206 T€/a	5.3.3
Efficiency (Power-to-gas-to-power)	44%	5.3.5
Power sale price at CHP	5.78 ct/kWh	5.2.1
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale price	40 €/t	5.3.4
Eco-premium (ETS CO_2 price)	25 €/t	5.2.2
Heat sale price (only process heat)	6.1 ct/kWh	5.2.3
CO_2 source	Biogas plant	5.4.6
Financial parameter: WACC	5%	5.4.1

The following figure shows the average cash flows of the first case calculation over the lifetime.

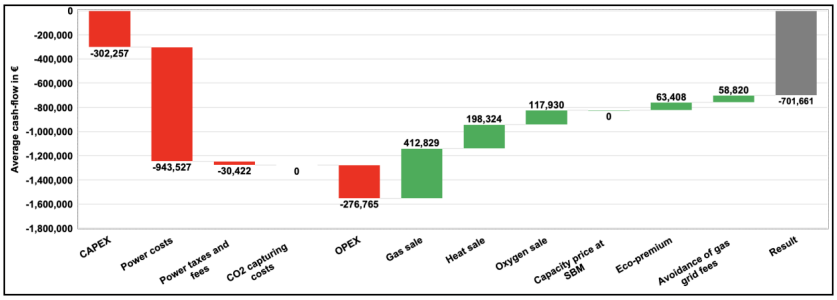


Figure 67: Business case 1: power-to-gas-to-power, 5 MW AEL/chem. Meth. 2020

The cash flow analysis shows a negative business case, as already assumed in the chapter of the description of the target market. The biggest cost driver is the power price and CAPEX. However, the most significant advantage of this target market is the exemption from almost all power taxes and fees of the electrolysis due to the direct connection to the RE plant. The process heat of the methanation is sold at the heat market as direct heating and displays the second biggest income driver next to the gas sale. The oxygen sale results in an average yearly revenue of approx. €120,000. In comparison to the combustion of fossil natural gas in a CHP plant, an eco-premium with a ETS price of 25 €/t of CO_2 gains approx. €63,000 per year. The avoidance of gas grid fees yields an income of around €60,000 per year because a biological CO_2 source is applied. All in all, with all possible income streams, the electricity costs cannot be compensated. The capital and operational expenditures lead further to a negative overall business case. This demonstrates that the energy storage case is not economically feasible if high renewable electricity costs, for example, in Germany hit on low ETS and fossil fuel prices.

It has to be mentioned that a WACC of 5% with a debt to equity share of 70:30 is not realistic for an uneconomic business case. In this case, no lender would be willing to supply debt. Different WACCs and an all-equity case are later calculated with positive cash flow because discounting all negative cash flows lead to different results. However, different financial parameters can be set in the general BM. For better comparison to later case calculations, the debt to share ratio stays.

The following table demonstrates the financial results of the first investigated case. The gas production price includes all cost drivers like CAPEX, OPEX as well as power price and taxes divided by the amount of produced SNG. Because of the overall negative cash flow, an IRR cannot be calculated. The NPV with losses of €11.3 million is highly negative. In total, the implementation of such a case is not recommended.

Table 26: Results of the business case 1: power-to-gas-to-power

Parameter	Value
Gas production costs	18.48 ct/kWh
Net present value after taxes	-€11,329,959
Return on invest after taxes	-221%
Internal rate of return after taxes	-

6.1.2 Business Case 2: Power-to-Gas-to-Industry

The second scenario is the application of PtG in the industry sector. SNG can replace natural gas in the industry and can reduce the carbon footprint of different industrial productions. Power is purchased at the day-ahead spot market in 2016, which allows a limited operation time of 4,000 h (see chapter 5.4.7). The year 2016 is taken because of a better comparison to other analyses of power markets, for example, the intraday

market with asset-backed trading, which is only analyzed for the year 2016. The power price includes GO, a forecast error, and the above-mentioned future price development, which has a major influence on the economic result. The price development to the starting year 2020 is already included in the numbers in Table 27. At this stage, the temporal purchase of electricity and the sale of SNG are not optimized yet. This case is analyzed later.

The efficiency, CAPEX and OPEX are calculated with a plant engineering of a 5 MW AEL and chemical methanation, which is identical to case one for a better comparison. The SNG is sold as natural gas at the gas market. Additional yields can be generated with the avoidance of gas grid fees and an eco-premium for CO_2, which displays an ETS price of CO_2 certificates in 2020. All input parameters are displayed in the following table.

Table 27: Input parameters of the business case 2: power-to-gas-to-industry

Parameter	Value (2020)	Source
Plant description	5 MW AEL + chemical methanation	
Power purchase concept	Day-ahead spot market 2016	
Target market	Industry (natural gas)	
Operation time	4,000 h/a	5.4.7
CAPEX	€6.05 million	5.3.3
Power price	2.31 ct/kWh	5.3.1.1
Power taxes and fees	6.72 ct/kWh	5.3.2
OPEX	206 T€/a	5.3.3
Efficiency (Power-to-gas)	51%	5.3.5
Gas sale price	1.45 ct/kWh	5.2.2
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale price	40 €/t	5.3.4
Eco-premium (ETS CO_2 price)	25 €/t	5.2.2
Heat sale price (only process heat)	6.1 ct/kWh	5.2.3
CO_2 source	Biogas plant	5.4.6
Financial parameter: WACC	5%	5.4.1

The following figure demonstrates the average cash flows of the second calculation.

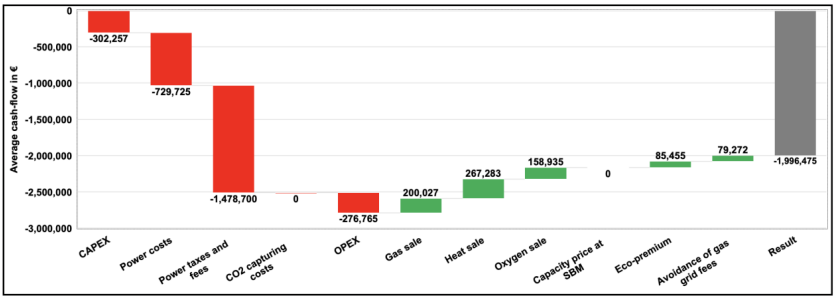


Figure 68: Business case 2: power-to-gas-to-industry, 5 MW AEL/chem. Meth. 2020

The cash flow analysis results in a strongly negative business case for over 20 years. The power taxes and fees have a major influence on this business case if the plant is connected to the public electricity grid. Especially the EEG apportionment in the power taxes and fees is causing negative cash flows of approx. €1.4 million each year. Also, the income situation at the natural gas market and low CO_2 certificate prices render this case highly uneconomical. Under these conditions, the application of SNG in the industry is no choice. Benefits for sustainable products or CO_2 penalties are not promoting the use of RE carriers. The process heat sale becomes as important as the SNG sale. Due to more hours of operation, the heat, oxygen and eco-premium sale increase compared to case one.

The following table demonstrates the financial results of the second case calculation. Because of the constant negative cash flow, the IRR cannot be calculated. The gas production price via PtG technology is more than 18 times higher than natural gas (see chapter 5.2.2), or three to four times higher than biomethane (see chapter 5.2.3). The NPV after taxes has a deficit of almost €27 million demonstrates an economically unfeasible target market.

Table 28: Results of the business case 2: power-to-gas-to-industry

Parameter	Value
Gas production costs	24.61 ct/kWh
Net present value after taxes	-€28,131,451
Return on invest after taxes	-629%
Internal rate of return after taxes	-

6.1.3 Business Case 3: Power-to-Gas-to-heat

The third case is analyzing the application of PtG in the heat sector. SNG can be sold as biogas to end customer, who uses renewable fuel in a balancing concept in their gas heating system. Power is again purchased at the day-ahead spot market 2016 and

further translated to the starting year to provide comparable results. The other input parameters have not changed and are displayed in the following table.

Table 29: Input parameters of the business case 3: power-to-gas-to-heat

Parameter	Value (2020)	Source
Plant description	5 MW AEL + chemical methanation	
Power purchase concept	Day-ahead spot market 2016	
Target market	Heat (biogas)	
Operation time	4,000 h/a	5.4.7
CAPEX	€6.05 million	5.3.3
Power price	2.31 ct/kWh	5.3.1.1
Power taxes and fees	6.72 ct/kWh	5.3.2
OPEX	206 T€/a	5.3.3
Efficiency (Power-to-Gas)	51%	5.3.5
Gas sale profit (biogas)	6.64 ct/kWh	5.2.3
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale profit	40 €/t	5.3.4
Eco-premium (CO_2 price)	-	-
Heat sale profit (only process heat)	6.1 ct/kWh	5.2.3
CO_2 source	Biogas plant	5.4.6
Financial parameter: WACC	5%	5.4.1

The following figure shows the average cash flows of the third calculation.

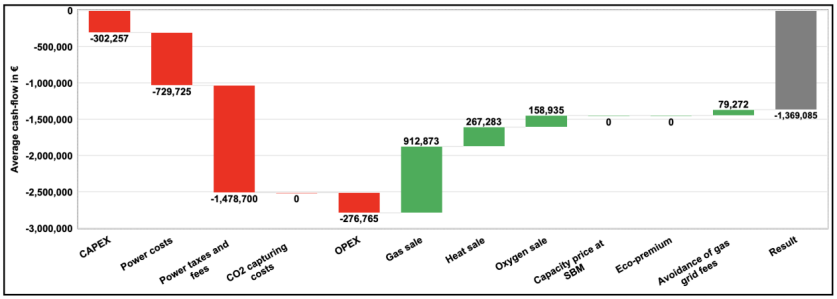


Figure 69: Business case 3: power-to-gas-to-heat, 5 MW AEL/chem. Meth. 2020

Again, the cash flow analysis delivers a strongly negative business case over 20 years. The result is slightly better than the target market *power-to-gas-to-industry* due to higher gas prices at the heat market. The power taxes and fees are the cost driver with a major influence on the business case. Especially the EEG apportionment is causing

negative cash flows of approx. €1.4 million each year. Without the EEG apportionment, the average cash flow can be positive and results in an IRR of 0.86% before taxes. This IRR is still lower than the WACC and displays an uneconomic case. However, with full power taxes and fees, the application of SNG in the heat sector is not economically feasible either.

The following table demonstrates the financial results. Because of the always negative cash flow, the IRR cannot be calculated. The NPV losses are reduced by approx. €8 million due to the higher gas price at the heat market compared to the industry case. Nevertheless, with these input data the heat market is not an economically worthwhile target market.

Table 30: Results of the business case 3: power-to-gas-to-heat

Parameter	Value
Gas production costs	24.61 ct/kWh
Net present value after taxes	-€20,072,962
Return on invest after taxes	-431%
Internal rate of return after taxes	-

6.1.4 Business Case 4: Power-to-Gas-to-Mobility

The fourth case is analyzing the application in the mobility sector. SNG can be sold to gas filling stations and therefore used in the transportation sector, for example, in NGVs. Power is purchased at the day-ahead spot market 2016 again. An additional yield can be generated for the eco-premium as a GHG reduction quota, which is the regulatory CO_2 price in the fuel sector. All input parameters are displayed in the following table for the starting year 2020. The gas sale price is only the natural gas price, like in the industry case. All other parameters have not changed to the previous target market analysis.

Table 31: Input parameters of the business case 4: power-to-gas-to-mobility

Parameter	Value (2020)	Source
Plant description	5 MW AEL + chemical methanation	
Power purchase concept	Day-ahead spot market 2016	
Target market	Mobility	
Operation time	4,000 h/a	5.4.7
CAPEX	€6.05 million	5.3.3
Power price	2.31 ct/kWh	5.3.1.1
Power taxes and fees	6.67 ct/kWh	5.3.2
OPEX	206 T€/a	5.3.3
Efficiency (Power-to-Gas)	51%	5.3.5
Gas sale profit	1.45 ct/kWh	5.2.2
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale profit	40 €/t	5.3.4
Eco-premium (GHG reduction quota)	6.65 ct/kWh	5.2.4
Heat sale profit (only process heat)	6.1 ct/kWh	5.2.3
CO_2 source	Biogas plant	5.4.6
Financial parameter: WACC	5%	5.4.1

The following figure highlights the average cash flows of the fourth calculation.

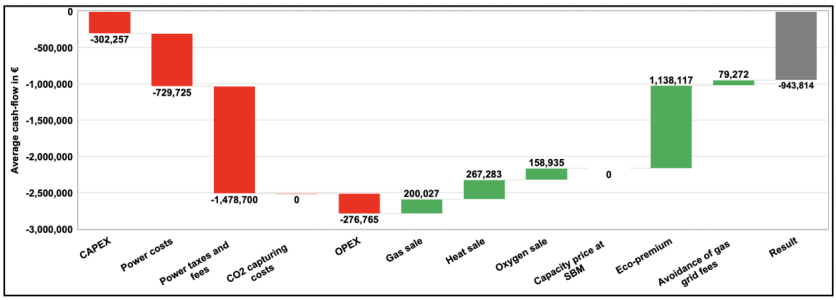


Figure 70: Business case 4: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020

Again, the cash flow results in a strongly negative business case over 20 years. But without EEG payments for PtG plants, a positive business case would be possible. The income situation is better compared to other target markets. The GHG reduction quota, which the oil industry is subject to, with approx. €1.14 million per year, has a substantial influence on the economic situation. In the second last year, the GHG quota reached the price level of the penalty. This shows that the target market analysis and the selection are important. Nevertheless, the application of SNG in the mobility is not

economically viable as long as the EEG apportionment has to be fully paid on the electricity used.

The following table highlights the financial results. Because of the always negative cash flow, the IRR cannot be calculated. The gas production costs are identical to the industry and heat market due to the same CAPEX, OPEX and power costs conditions. The NPV is slightly better than in the industry and heat market. But the business case is still economically inefficient.

Table 32: Results of the business case 4: power-to-gas-to-mobility

Parameter	Value
Gas production costs	24.61 ct/kWh
Net present value after taxes	-€15,040,098
Return on invest after taxes	-297%
Internal rate of return after taxes	-

In total, four different target markets have been analyzed with the constructed BM. Under the defined conditions, the storage and repowering case has the best financial results. The mobility case indicates the highest income streams. The use of SNG in the heat market or in the industry is not economically feasible due to low CO_2-prices in the target market. However, as discussed in the analysis of the German power market (see chapter 5.3.1), different power purchase concepts can further decrease the power costs. Therefore, in a next step, the impact of different power purchase markets on the economic result is investigated. The analysis of different power purchase concepts requires a grid connected PtG plant. Therefore, the target market *power-to-gas-to-mobility* is chosen as the basic case for further investigation, also due to a better comparison to the single case study later.

6.1.5 Business Case 5-9: Comparison of Power Purchase Concepts for Power-to-Gas-to-Mobility

The next research goal is to compare different power purchase concepts. The power purchase concept at the day-ahead market has been previously analyzed and indicated a negative NPV after taxes of approx. €15 million. In total, five additional power purchase concepts are examined. First, the situation at the negative and positive secondary balancing market is put on focus. Second, next to the previously analyzed day-ahead market, the intraday market is in interest. Also, different operational modes in the intraday market are tested. First, the combination with asset-backed trading and, second, the optimization to the day-ahead gas prices. The power prices and operation time of these concepts have been explained in the analysis of the economic driver *costs at power markets* (see chapter 5.3.1). The power prices always include GO, a forecast error, and the price development to the starting year. All input parameters are displayed in the following table.

Table 33: Input parameters of the business case 5-9: comparison of power purchase concepts for power-to-gas-to-mobility

Parameter	Value (2020)	Source
Plant description	5 MW AEL + chemical methanation	
Target market	Mobility	
Power purchase concept BC 5	Neg. SBM 2015	
Power purchase concept BC 6	Pos. SBM 2015	
Power purchase concept BC 7	Intraday spot market 2016	
Power purchase concept BC 8	Intraday spot market 2016 with asset-backed trading	
Power purchase concept BC 9	Optimization of intraday spot market 2016 and day-ahead gas prices	
Operation time BC 5	2,628 h/a	5.3.1.3
Operation time BC 6	5,694 h/a	5.3.1.3
Operation time BC 7	4,000 h/a	5.4.7
Operation time BC 8	4,000 h/a	5.4.7
Operation time BC 9	4,000 h/a	5.4.7
Average power price BC 5	0.14 ct/kWh	5.3.1.3
Average power price BC 6	2.16 ct/kWh	5.3.1.1
Average power price BC 7	2.22 ct/kWh	5.3.1.1
Average power price BC 8	0.28 ct/kWh	5.3.1.1
Average power price BC 9	2.24 ct/kWh	5.3.1.1
Capacity price SBM BC 5 (48 weeks)	122,420 €/a	5.3.1.3
Capacity price SBM BC 6 (48 weeks)	264,746 €/a	5.3.1.3
Power taxes and fees	6.72 ct/kWh	5.3.2
CAPEX	€6.05 million	5.3.3
OPEX	206 T€/a	5.3.3
Efficiency (Power-to-Gas)	51%	5.3.5
Gas sale profit	1.45 ct/kWh	5.3.1.1
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale profit	40 €/t	5.3.4
Eco-premium (GHG reduction quota)	6.65 ct/kWh	5.2.4
Heat sale profit (only process heat)	6.1 ct/kWh	5.2.3
CO_2 source	Biogas plant	5.4.6
Financial parameter: WACC	5%	5.4.1

The following figure demonstrates the average cash flows of the target market *power-to-gas-to-mobility* with a power purchase concept at the neg. SBM 2015.

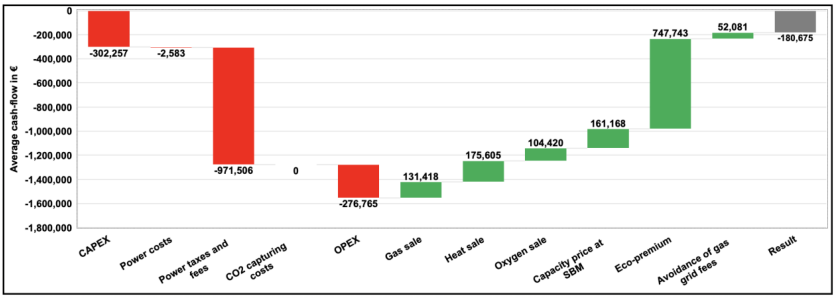


Figure 71: Business case 5: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020 with power purchase at the neg. SBM

The cash flow analysis displays an average cash burn of €180,675 per year. The commodity price is 0.14 ct/kWh in 2020, which already includes forecast error, price of GO, and price development. The power taxes and fees influence the business case significantly. Due to fewer hours of operation, the EEG apportionment is causing a negative cash flow of only €0.9 million each year. The capacity price is calculated for 48 weeks. An additional oxygen sale would generate up to €100,000 per year. Due to the different price developments, the cash flow turns positive after seven years. Because of the depreciation of the CAPEX and the losses that be carried forward, taxes have to be paid from 2036 onwards. With a longer technical lifetime, the business case would become economically feasible.

However, the balancing market is an interesting power purchase concept for PtG plants and decreases the overall power costs. As mentioned in the analysis of the balancing market (see chapter 5.3.1.3), only a few PtG plants can operate with that power supply strategy due to the limited demand for balancing energy in the German electricity grid. In addition, the numbers of starts of the electrolyzer display technical challenges. The technical stress to different components and the impact on the overall efficiency is analyzed in the single case study later. If more and more flexible loads participate here, the operation time and capacity price would decrease, and the commodity price would increase. Therefore, this concept is only possible for the first 100 to 200 MW of installed PtG in Germany.

In the following figure, the average cash flows of the pos. SBM are displayed.

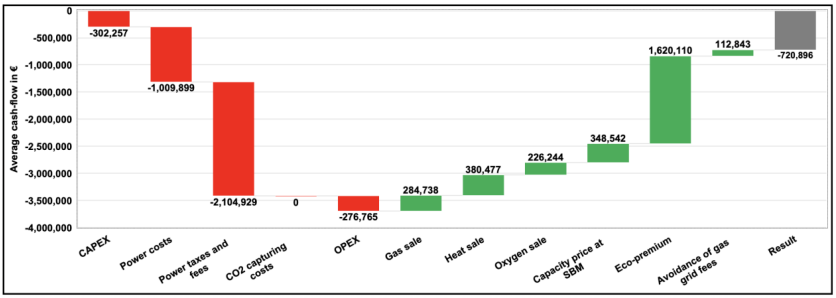


Figure 72: Business case 6: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020 with power purchase at the pos. SBM

The higher possible operation time of almost 5,700 FLH leads to higher incomes at the pos. balancing market. Ecological operation time of more than 5,700 FLH can be justified with the grid-friendly operation at the balancing market. This has been explained in the description of renewable power supply concepts in chapter 5.3.1.5. In this case, a base load has to be purchased for the operation time. In the calculation the average yearly day-ahead spot market price 2015 with a constant power price development is considered. However, due to the proportional increase of power taxes and fees, the BM is not economically feasible either. In addition, compared to the neg. balancing market, the capacity price is higher and displays the third biggest income parameter. The influence of the cost driver on the result with respect to the operation time is higher than on the income driver. However, the financial result is similar to the power purchase at the day-ahead market.

The cash flow analysis of the power purchase at the intraday market 2016 is slightly better than the day-ahead market 2016 in the fourth business case calculation. The intraday market improves the average cash flow with approx. €90,000 per year due to lower power prices. The operation schedule, as well as the number of start-ups of the electrolysis of this power purchase concept, has been explained in chapter 5.3.1.1.

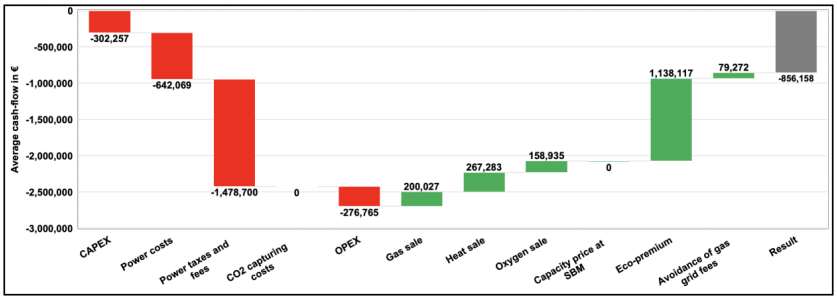


Figure 73: Business case 7: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020 with power purchase at the intraday market 2016

Due to the continuous trading and price fluctuation at the intraday market, asset-backed trading is possible (see chapter 5.3.1.1). In that case, option trading yields of around 1.96 ct/kWh can be added as forecasted by the Black-Scholes model. In comparison to the power purchase concept without asset-backed trading, approx. €630,000 per year can be yielded in addition. This additional trading value almost compensates for the power costs. This is possible due to the availability and short ramp-up time of PtG plants. The average cash flow is similar to the neg. SBM, but probably more PtG plants can operate with this concept. Without the EEG apportionment as the biggest surcharge in power taxes and fees, a positive business case is possible. The cash flow turns positive after eight years.

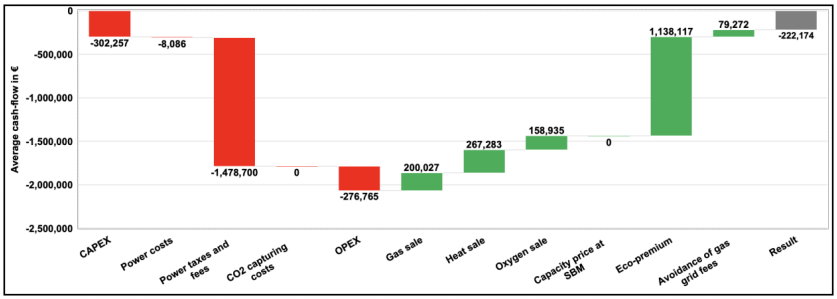


Figure 74: Business case 8: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020 with power purchase at the intraday market with asset-backed trading

The last power purchase concept considers an economic optimization of the hourly power and gas prices. Instead of considering the 4,000 FLH with the lowest power cost, the 4,000 hours with the lowest overall power cost plus gas sale profit per hour are picked. As mentioned in the analysis of the power market (see chapter 5.3.1.1), the average power price slightly increases as well as the average gas sale price, which

results in additional yields of €670 in the starting year in case of a 5 MW PtG plant. But due to the higher price increase at the power markets instead of the price at gas markets, the overall economic result over 20 years is worse than the intraday market without optimization to the gas market. It can be different in more volatile years.

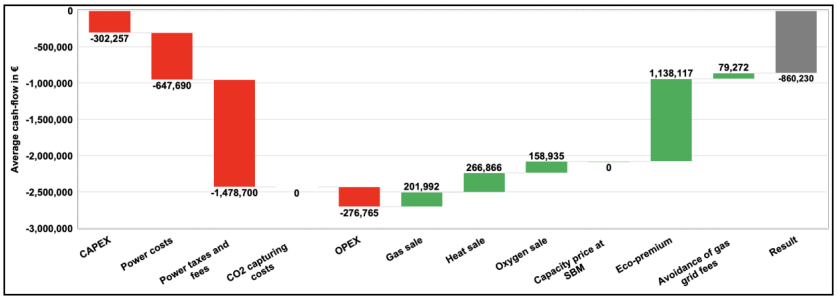


Figure 75: Business case 9: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020 with optimization of the intraday spot market and day-ahead gas prices 2016

The power purchase of the day-ahead market has been examined in the previous chapter. All analyzed power purchase concepts result in negative average cash flows and negative NPVs. The participation at the neg. SBM with low operation time shows the best financial results. However, the constructed BM allows the analysis of different power purchase concepts. This has demonstrated that the choice of power supply concept has a major impact on the overall business case. A wrong decision can triple the yearly average losses. But further research is required to analyze, for example, the combination of different power supply concepts or test it in practice, which is explained in the research recommendation (see chapter 7.3.2). For example, the combination of pos. and neg. balancing energy could be of interest. In addition, a PtG plant has to prove in practice that asset-backed trading at the intraday market works and gains the analyzed income streams.

All power markets are dynamic and need to be constantly observed. Power supply strategies can change from day to day or from year to year. The general BM can be used to calculate the economic outcome of different modes of operation by using forecast data of different power markets. The following table is demonstrating some financial results of different power purchase concepts. It shows the gas production price, which includes the costs of CAPEX, OPEX, power price and taxes and fees, and the NPV after taxes. This sensitivity analysis highlights substantial differences due to the chosen power supply concept. The NPV can be quadrupled if the wrong concept is selected.

Table 34: Results of the business case: comparison of power purchase concepts for power-to-gas-to-mobility

BC	Parameter	Gas production price in ct/kWh	Net present value after taxes in €
4	Day-ahead market 2016	24.61	-15,040,098
5	Neg. secondary balancing market 2015	20.87	-5,139,738
6	Pos. secondary balancing market 2015	22.91	-12,595,777
7	Intraday spot market 2016	23.84	-13,931,098
8	Intraday spot market 2016 with asset-backed trading	18.24	-6,026,902
9	Optimization of the intraday spot market and day-ahead gas prices 2016	23.89	-13,982,369

6.1.6 Business Case 10-12: Comparison of Plant Designs for Power-to-Gas-to-Mobility

The last calculations have investigated the impact of different power purchase concepts. Now the investigation of different plant designs is on focus. Therefore, different plants are constructed. First, a 5 MW PEM and chemical methanation is chosen , which is comparable to previous calculations. Second, the plant is calculated with a future, larger plant design for the starting year 2025. Third, only the SOEC electrolysis with direct injection of hydrogen is displayed. As a suitable power purchase concept, the intraday spot market 2016 with asset-backed trading is picked because it delivers the best financial results if PtG plants are broadly implemented. In the following table, an overview of the necessary input parameters is provided.

Table 35: Input parameters of the business case 10-12

Parameter	Value	Source
Plant design BC 10	5 MW PEM + chemical methanation (2020)	
Plant design BC 11	20 MW PEM + biological methanation (2025)	
Plant design BC 12	20 MW SOEC (2025)	
Power purchase concept	Intraday spot market 2016 with asset backed trading	
Target market	Mobility	
Operation time	4,000 h/a	5.4.7
CAPEX BC 10	€7.91 million	5.3.3
CAPEX BC 11	€27.7 million	5.3.3
CAPEX BC 12	€14.6 million	5.3.3
OPEX BC 10	131 T€/a	5.3.3
OPEX BC 11	418 T€/a	5.3.3
OPEX BC 12	30 T€/a	5.3.3
Efficiency BC 10 (Power-to-Gas)	45%	5.3.5
Efficiency BC 11 (Power-to-Gas)	43%	5.3.5
Efficiency BC 12 (Power-to-Gas)	71%	5.3.5
Power price (2016)	0.02 ct/kWh	5.3.1.1
Power taxes and fees	6.72 ct/kWh	5.3.2
Gas sale profit (natural gas in 2016)	1.34 ct/kWh	5.2.1
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale profit	40 €/t	5.3.4
Eco-premium (GHG reduction quota 2016)	5.64 ct/kWh	5.2.2
Heat sale profit (only process heat 2016)	5.53 ct/kWh	5.2.3
CO_2 source	Biogas plant	5.4.6
Financial parameter: WACC	5%	5.4.1

The following figure demonstrates the average cash flows of a PtG plant with PEM instead of alkaline electrolyzer. The CAPEX and OPEX is reduced, whereas the efficiency with only 45% from electric power to SNG is lower, as the industrial survey has pointed out (see chapter 5.3.3). The CAPEX is increased by almost €2 million compared to AEL, but €100,000 per year decreases the OPEX in comparison. Without or less payment of static power taxes and fees, this case has a strong positive NPV. In present settings, the NPV after taxes has a deficit of €8.9 million and, therefore, is a bit higher than the comparable case with AEL. The cash flow turns positive in the year 2031.

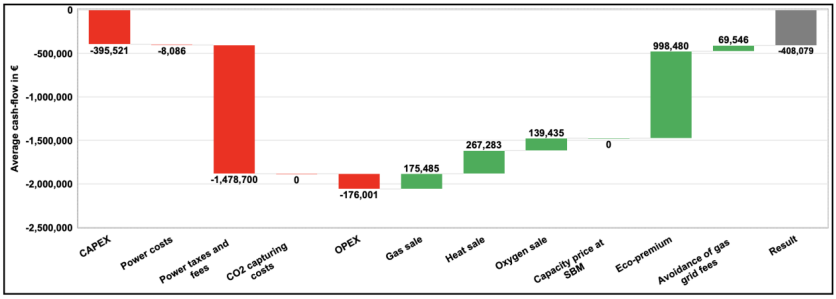


Figure 76: Business case 10: power-to-gas-to-mobility, 5 MW PEM/chem. Meth. 2020

The cash flow analysis of a future larger plant identifies the most important economic drivers of the PtG technology more accurately. On the cost side, the power taxes and fees are responsible for almost €6 million of losses per year. On the income side, the GHG reduction quota is by far the main income driver. The process heat sale is bigger than the SNG sale. The efficiency of 43% is a bit lower than the efficiency of the combination of AEL or PEM with chemical methanation. Again, the economic result is negative due to the regulative situation of PtG technology in the electricity market. This demonstrates that the economic results of the BM cases depend on certain political regulations like power taxes and yields of eco-premium in target markets.

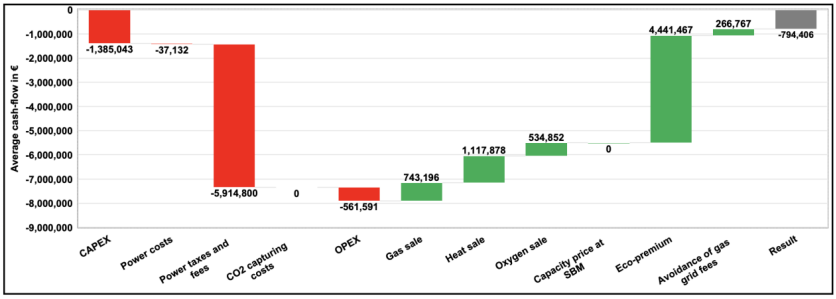


Figure 77: Business case 11: power-to-gas-to-mobility, 20 MW PEM/biol. Meth. 2025

Another future case is calculated with the SOEC electrolysis and the direct injection of hydrogen into the gas grid. This plant design demonstrates the highest overall efficiency, with 71% from power to gas without any further energy demand of CO_2 capturing because of the direct injection of hydrogen. Therefore, the gas and oxygen sale and eco-premium are much higher than for the comparable previous plant designs. The process heat sale is less due to the missing exothermic methanation. OPEX, with only €40,000 per year, is relatively small. For that case, a further industrial survey is

required to collect more data. However, novel research data can be integrated into the general BM, and even those future business cases could be tested.

The analysis furthermore shows that even more than €5.9 million of power taxes and fees are compensated by estimated market price developments of the GHG reduction quota in the fuel sector and oxygen sale with high efficiency. In the year 2038, the penalty costs of the GHG quota are achieved. Because of the direct injection of hydrogen without the necessity of any CO_2 source, the avoided gas grid fees cannot be yielded. As discussed in chapter 5.4.6, SNG is only defined as *biomethane* if a biological CO_2 source is applied. This case requires further regulatory research.

Due to the innovative power purchase concept of asset-backed trading at the intraday market and high predictions of GHG quota prices, this future case delivers the first economic situation. The cash flow is positive from the beginning. Due to the depreciation and forward carried losses, taxes only have to be paid after eight years. This results in an IRR of 16% before taxes and 13% after taxes under these assumptions. This is higher than the WACC of 5%. For that reason, the NPV with capital costs is a strong positive.

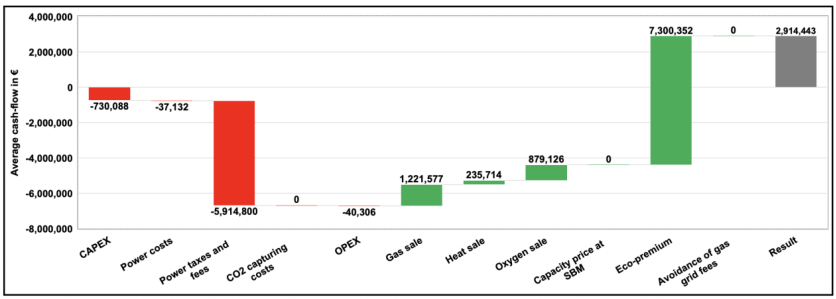


Figure 78: Business case 12: power-to-gas-to-mobility, 20 MW SOEC 2025

As mentioned in the first business case calculation, different financial parameters should be analyzed in the first positive business case. First, an all-equity case with an interest rate of 10% on the equity capital would reduce the NPV to €4.9 million after taxes. Whereas a WACC of 3% with equity to debt share of 70:30 results in an NPM after taxes of €25 million. That shows that investment highly depends on capital costs.

The following table shows the gas production price and NPVs after taxes of different plant designs.

Table 36: Results of the business cases: comparison of plant designs for power-to-gas-to-mobility

BC	Parameter	Gas production price in ct/kWh	Net present value after taxes in €
8	5 MW AEL + chemical methanation (2020) see 6.1.5	18.24	-6,026,902
10	5 MW PEM + chemical methanation (2020)	20.72	-8,934,749
11	20 MW PEM + biological methanation (2025)	20.73	-23,134,537
12	20 MW SOEC (2025)	10.73	18,535,373

6.1.7 Business Case 13-15: Comparison of Different CO_2 Sources for Power-to-Gas-to-Mobility

In the following comparison, business cases with different CO_2 sources are calculated. In total, three different sources are considered: CO_2 from a biogas plant from previous calculations, CO_2 from a pulp and paper factory, a refinery, and CO_2 from ambient air. Each CO_2 source has different capturing costs, which are including the capital as well as OPEX and price developments of each specific CO_2 sources, as explained in chapter 5.4.6. In addition, as mentioned in the last case calculation, if it is not a biological CO_2 source, the avoidance of gas grid fees cannot be yielded.

Table 37: Input parameters of the business case 13-15: power-to-gas-to-mobility

Parameter	Value (2020)	Source
Plant design	5 MW AEL + chemical methanation	
Power purchase concept	Intraday spot market 2016 with asset-backed trading	
Target market	Mobility	
Operation time	4,000 h/a	5.4.7
CAPEX	€6.05 million	5.3.3
OPEX	206 T€/a	5.3.3
Efficiency (Power-to-Gas without CO_2 source)	51%	5.3.5
Gas sale profit (natural gas)	1.45 ct/kWh	5.2.1
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale profit	40 €/t	5.3.4
Eco-premium (GHG reduction quota)	6.65 ct/kWh	5.2.2
Heat sale profit (only process heat)	6.1 ct/kWh	5.2.3
CO_2 source BC 13	Pulp and paper	5.4.6
CO_2 source BC 14	Refinery	5.4.6
CO_2 source BC 15	CO_2 from ambient air (solid sorbent)	5.4.6
Financial parameter: WACC	5%	5.4.1

The first calculation is almost similar to the basic case with CO_2 from a biogas plant. The CO_2 from a pulp and paper factory costs approx. 35 €/t. Therefore, the average cash flow is €157,971 inferior to the CO_2 from biogas, in which an installed CO_2 separation is assumed.

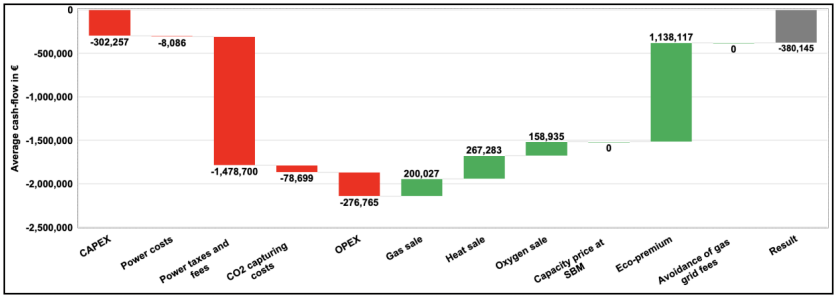


Figure 79: Business case 13: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020, CO_2 from pulp and paper plant

In the next case calculation, CO_2 from a refinery is considered. According to literature, this source costs 65 €/t of CO_2. In this comparable small PtG plant, additional costs of almost €150,000 arise from this CO_2 source. In comparison to the previous case, the gas production costs rise from 18.93 to 19.53 ct/kWh.

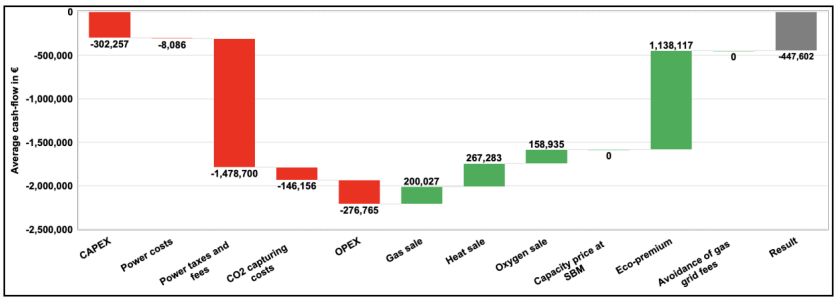


Figure 80: Business case 14: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020, CO_2 from a refinery

The CO_2 from ambient air is increasing the overall production costs. The average cash flow is more than four times worse than installed biological CO_2 sources. The costs of CO_2 capturing are higher than the CAPEX and OPEX together. The gas production costs increase by 5.74 ct/kWh in comparison to the CO_2 from a biogas plant. The NPV of this case is more than double as worse than the installed biological CO_2 source.

This demonstrates that the choice of CO_2 source matters. Therefore, concentrated CO_2 sources should be used wherever available.

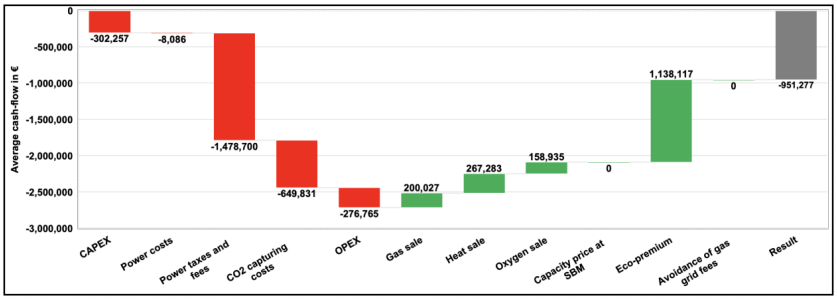


Figure 81: Business case 15: power-to-gas-to-mobility, 5 MW AEL/chem. Meth. 2020, CO_2 from ambient air (solid sorbent)

The overall economic results are shown in the following table. The high costs of CO_2 from ambient air are increasing the negative NPV up to more than €17.3 million, which is approx. twice as much as concentrated CO_2 sources at these conditions. The bigger the PtG plant, the higher the impact of the CO_2 source will be.

Table 38: Results of the BC: comparison of different CO_2 sources for power-to-gas-to-mobility

BC	Parameter	Gas production price in ct/kWh	Net present value after taxes in €
8	CO_2 from biogas plant (see 6.1.5)	18.24	-6,026,902
13	CO_2 from pulp and paper facility	18.94	-8,009,489
14	CO_2 from a refinery	19.53	-8,877,296
15	CO_2 from ambient air (solid sorbent)	23.98	-15,501,965

6.1.8 Business Case 16: Power-to-Gas-to-Mobility in MENA-Region

Different studies show that significant amounts of renewable fuels are produced in the regions, in which the costs of RE are low, for example, in the MENA-region.[487] Therefore, this case calculation tests if the constructed general model can be used under these conditions. As a basic assumption, the CAPEX, OPEX, and efficiency are taken from a 20 MW plant for the starting year 2025. The power price displays the levelized costs of renewable electricity in these regions. Therefore, the investments in RE plants are included, and no further price development, purchase of GOs, or forecast error is

[487] Hobohm et al. (2018), Hecking et al. (2018), Siegemund et al. (2017)

assumed. That means that this business case automatically leads to the further installation of RE plants, which covers the whole energy demand of the PtG plant. Especially in comparison to other solutions of climate-friendly mobility like electric mobility, this must be carefully considered if different technologies are benchmarked to each other. The operation time is also adjusted.

CO_2 absorption from ambient air (free waste heat) is taken into account. The overall efficiency without CO_2 capturing is 48%. Additional logistic costs are not considered, because the transportation of SNG in existing pipelines or as LNG is negligible in comparison to other cost drivers. Fasihi et al. (2016) calculate that the liquified shipping of synthetic fuels has a share of 1.35% of the total cost at the destination.[488] It is assumed that SNG can be injected in existing gas pipelines.

The process heat of the high-temperature electrolysis is not further sold but used to regenerate the catalyst that captures CO_2 from ambient air. Low power taxes and fees have to be paid for power consumption during standby and for peripheral devices. In this case, a medium oxygen sales price of 40 €/t is assumed. Avoided gas grid fees cannot be yielded because the plant is not located in Germany. Financial aid of €5 million is added. This can be justified, for example, to support industrial investments in developing countries like Morocco, Algeria, or Tunisia. In return for the financial aid, a specific amount of jobs needs to be generated, or a certain amount of RE needs to be provided to the local electricity grid. This is normally the case because the capacity of the RE plant needs to be approx. 25% higher than the capacity of the PtX plant, as discussed in the chapter of the operation time (see chapter 5.4.8). Many innovative, ecological-friendly technologies will need such financial support to overcome high costs at the beginning of the industrialization of that technology. The assumption is that due to the financial aid and, therefore, guaranteed payment, the WACC is still 5% even in a developing country.

[488] Fasihi et al. (2016), p. 254

Table 39: Input parameters of the business case 16: power-to-gas-to-mobility in MENA-region

Parameter	Value	Source
Plant design	20 MW SOEC + biological methanation (2025)	
Power purchase concept	Direct connection to RE plant	
Target market	Mobility	
Operation time	3,750 h/a (Morocco)	5.4.8
CAPEX	€24.9 million	5.3.3
Power price (2015)	2.3 ct/kWh	Fasihi et al. (2016)
Power taxes and fees	0.19 ct/kWh	5.3.2
OPEX	145 T€/a	5.3.3
Efficiency (Power-to-Gas)	56%	5.3.5
Gas sale profit (2016)	1.34 ct/kWh	5.2.1
Avoidance of gas grid fees	-	5.2.1
Oxygen sale profit	40 €/t	5.3.4
Eco-premium (GHG reduction quota 2016)	5.64 ct/kWh	5.2.2
Heat sale profit (only process heat)	-	-
CO_2 source	CO_2 from ambient air (free waste heat)	5.4.6
Financial aid	€5 million	-
Financial parameter: WACC	5%	5.4.1

The cash flow analysis shows that a positive business case is possible in 2025. The financial aid is reducing the CAPEX in this case. The CO_2 capturing displays the highest cost driver, even if free waste heat is assumed. The cash flow is positive from the beginning. Taxes have to be paid in the third year. Here the same corporate taxes like in Germany are assumed. In the year 2038, the GHG quota reaches the penalty costs of 13.65 ct/kWh SNG (see chapter 5.2.4.3). However, with the financial aid, the WACC and high GHG quota it is quite an optimistic case, but it demonstrates that the general BM can also be applied outside of Germany.

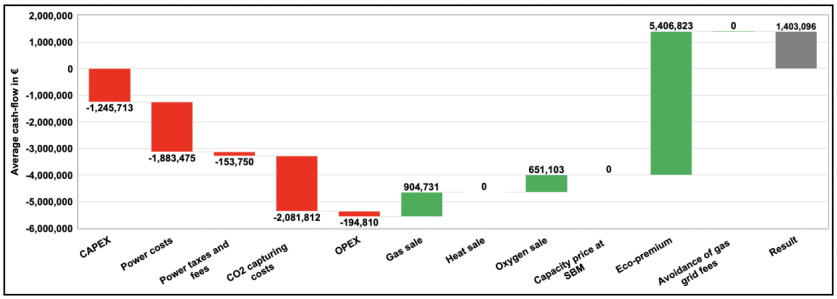


Figure 82: Business case 16: power-to-gas-to-mobility in MENA-region, 20 MW SOEC/bio. Meth. 2025, CO_2 from ambient air (free waste heat)

The financial results are highlighted in the following table. The average cash flow is about €1.65 million in 20 years of operation. The NPV of this investment is positive because the IRR is higher than the WACC.

Table 40: Results of the business case 16: power-to-gas-to-mobility in MENA-region

Parameter	Value after taxes
Gas production price	11.98 ct/kWh
Net present value	€1,855,204
Return on invest after taxes	74%
Internal rate of return after taxes	5.05%

6.1.9 Business case 17: distribution of results based on MC simulation and multivariate bootstrapping

In the previous calculations, single scenarios have been investigated and compared. These considered different plant configurations, power purchase concepts, or CO_2 sources. All the analyses have their basis on historical market data with assumed price developments. Due to a lot of dynamic and fluctuating economic parameters, the probability of different results is the focus of this analysis. This further investigation highlights the influence of different drivers and points out a risk analysis for potential investors.

The constructed BM allows the setting of random parameters. For example, the financial parameter WACC has a theoretical spread of 3% to 8% (see chapter 5.4.1), or the oxygen sale has a volatility of 6.2 to 80 €/t based on the literature review (see chapter 5.3.4). For that reason, the uncertainty of an investment is high, and further risk analysis is recommended. In this analysis, only market-driven parameters like power costs, gas, heat, and oxygen sale, as well as GHG quota revenues, are taken into account. It is assumed that the plant configuration, CO_2 source, and financial

parameters are known from the beginning and, therefore, static. In a MC simulation, the BM randomly applied a number within the defined interval. The BM calculations are repeated 10,000 times, which allows statistical statements about the distribution of results. For the power and gas prices, a random selection is not appropriate because a correlation between the power and gas price exists, which would be ignored in a simple MC simulation (see chapter 5.5). Therefore, a multivariate bootstrapping is generating a new time series of the power and gas price and is considering the correlation of both parameters.

Table 41: Input parameters of the business case 17: power-to-gas-to-mobility

Parameter	Value	Source
Plant design	20 MW PEM + biological methanation (2025)	
Power purchase concept	Bootstrapping of intraday spot market 2016 with asset-backed trading	
Target market	Mobility	
Operation time	4,000 h/a	5.4.7
CAPEX	€27.7 million	5.3.3
OPEX	418 T€/a	5.3.3
Efficiency	43%	5.3.5
Gas sale profit (natural gas)	Bootstrapping of day-ahead market prices 2016	5.2.1
Avoidance of gas grid fees	0.7 ct/kWh	5.2.1
Oxygen sale profit	6.2 to 80 €/t	5.3.4
Eco-premium (GHG reduction quota)	3.3 to 7.1 ct/kWh	5.2.2
Heat sale profit (only process heat)	5.1 to 5.9 ct/kWh	5.2.3
CO_2 source	Biological	5.4.6
Financial parameter: WACC	5%	5.4.1

The average cash flow amounts with 10,000 repetitions are displayed in the waterfall diagram below. Compared to the BM calculation in Figure 77 with static market parameters, the average outcomes of economic parameters, which have been set to *random*, do not differ considerably. The gas and oxygen sale revenue slightly increases, and heat sale has almost the same volume. However, the overall cash flow is approx. €80,000 per year better than the static case but still negative due to the power taxes and fees. The average gas production price is 20.73 ct/kWh. The average NPV after 10,000 repetitions and taxes is minus €21.3 million. The average IRR is -4.33%. Therefore, this business case with the consideration of dynamic parameters is still not viable. If the exemption of power taxes and fees is achieved or with a more efficient plant construction, the case can be positive.

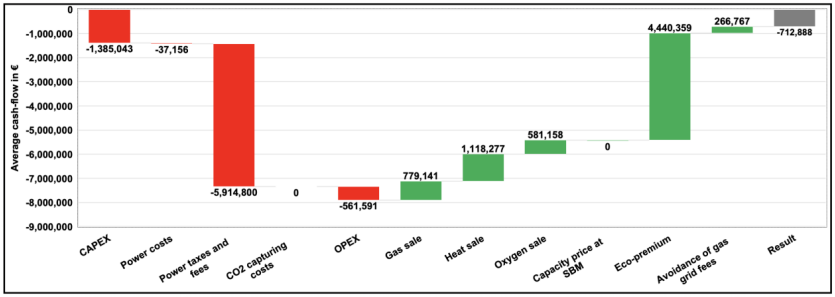


Figure 83: Business case 17: power-to-gas-to-mobility, 20 MW PEM/bio. Meth. 2025, MC simulation

The financial results differ due to several dynamic parameters. NPV after taxes has a huge range of losses of €13.9 to €28.5 million. The IRR from -0.98% to -8.27%, which demonstrates a wide range of possible results. A negative IRR is possible. It is checked that there is only one sign change in the cash flow to avoid multiple IRRs. However, the minimum and maximum values allow no statement about the distribution of the outcomes. Therefore, further analyses are necessary.

Table 42: Results of the business case 17: power-to-gas-to-mobility distribution of results based on MC simulation and multivariate bootstrapping

Parameter	Value after taxes
Gas production price	20.54 ct/kWh to 20.91 ct/kWh
Net present value after taxes	-€14,879,968 to -€29,767,915
Return on invest after taxes	-14% to -91%
Internal rate of return after taxes	-1.09% to -8.42%

As a next analysis, a histogram of the NPV after taxes obtains the distribution of all the business cases. As mentioned in chapter 5.5, a confidence interval of 90% is chosen. This means that the 5% lowest and 5% highest NPVs after taxes are not considered. The following figure highlights the number of results in an evenly distributed range in the form of a wide-spread histogram. The results are broadly distributed without any peak. Therefore, the probability of results is in a wide range. For an investor, this translates into a high risk because the yearly outcome can differ and is uncertain.

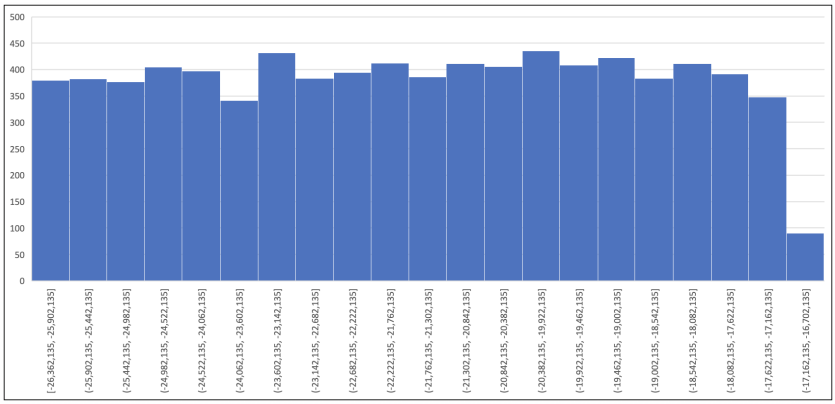


Figure 84: Histogram of the NPV of business case 17

A more detailed investigation is done to discover the influence of specific dynamic parameters. For that case, a box plot diagram is drawn to highlight different statistical indicators. The box plot starts and ends with the minimum and max. value of each dynamic parameter in the above-mentioned confidence interval. In addition, a box is drawn from the first quantile till the third quantile. This range indicates the area where 50% of all results are located. Further, the median is displayed with a line in the box and the mean with a cross.

Figure 85 shows all dynamic parameters of the BM. The range of oxygen sale profits is the largest of all single economic parameters. The absolute minimum is an extra income of €187,000 per year, and the absolute max. is about €1.07 million per year with this plant configuration. The box range is from €508,000 to €842,000 per year. The mean is about €682,000 per year. This indicates, on the one hand, that the oxygen sale can play a major general of the PtG technology, but on the other hand, further research and practical implementation is necessary to achieve a smaller range of possible oxygen sale prices. The literature range from 6.2 €/t to 80 €/t delivers a dynamic economic parameter.

The parameter with the second most distributed results is the eco-premium. In this case, this is the GHG reduction quota, which can be sold like CO_2 certificates to market participants in the fuel sector. The random choice of historic parameters leads to yearly results between €4.32 and €4.56 million. The mean is at €4.44 million. This is by far the highest income stream and could further increase if climate goals for the fuel industry are intensified. The heat sale price is randomly chosen between 5.07 and 5.88 ct/kWh. This results in an additional income stream of €1.04 to €1.17 million.

It appears surprising that the fluctuation of the power and gas price is quite low. The simultaneous bootstrapping of one set of power and gas price out of 35,040 options

(quarter hours of the year 2016) with replacement depicts only relatively small changes in the overall business case. The range of the power costs with asset-backed trading is between negative €102,000 and positive €35,000 yields. The gas sale profits vary only between €776,000 and €782,000, which results in a difference of approx. €6,000. Compared to a range of almost €1 million per year of the oxygen sale, these fluctuations are insignificant. This could change if different power purchase concepts are chosen for that analysis.

All in all, the different uncertainties lead to a widespread of the yearly average cash flow. The range of the average annual cash flow losses goes from €1.17 to €0.71 million. That means that the yearly losses are nearly doubled with uncertainties in the same configuration.

However, the analysis of the distribution of the results is important and should be undertaken if business cases of the PtG technology are investigated. The analysis shows the first risk considerations. Further analysis should be done with different base years of the power and gas price, target markets, and more accurate data in terms of oxygen sales. The constructed BM allows this analysis and deduced statements.

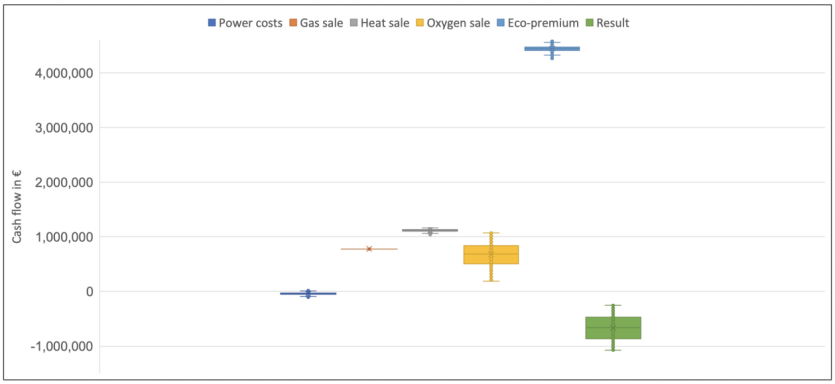


Figure 85: Box plot of dynamic parameters of business case 17

6.2 Case Study of Power-to-Gas

Next to the theoretical validation with reproducible business case calculations, a practical example shall test the general BM of the PtG technology in a case study. Chapter 3.3 has described the theoretical background of the case study research. Following this methodology, a single case study is executed. First, the PtG plant is described to highlight all necessary background information. Second, different business cases, which have been calculated in the previous chapter, are tested at this plant. Hereby, if possible, further practical insights are mentioned. Again, it has to be declared that a

single case study cannot validate the BM under all conditions. It can only show how effective the theoretical model works under single conditions like geographical location and current political framework. However, a real case analysis is significantly increasing the practical relevance (see chapter 2.3) and is strengthening the strategic recommendations.

As mentioned, due to a limited number of installed PtG plants, this case study is limited to a single plant. Therefore, the deduced BM is only tested on relevance under specific conditions in terms of time, region, and technical specifications. These conditions are explained in the first subchapter 6.2.1. Nevertheless, the selected case has different advantages. First, the plant has an industrial scale of 6 MW power input. Second, the target market of that plant is the mobility, and different power supply concepts are testable due to the prequalification of that plant at the SBM. For that reason, different, previously constructed business cases can be tested. Third, a public-funded research program has been executed from 2013 to 2016 at this plant. This research program is called WOMBAT, which is explained in chapter 2.1. Different research facilities and industrial companies have participated. In addition to expert interviews, the final reports of the WOMBAT project partners are included. This comprehensive data collection gives valuable insights into a multi-years' operating industrial scale PtG plant. Due to those reasons, this plant has been chosen following the case selection of Yin (1994).

In this single case study, different multi-unit analyses are conducted. These units can be seen as different business cases. For example, one unit is a case with a power supply at the day-ahead spot market, and another case has a power supply concept at the balancing market. In addition, the multi-unit analysis is achieving additional insights into the PtG technology like operation time or practical experiences in terms of feed-in guidance into the public gas grid. However, this practical information is important for business model innovation and should be considered in further adoptions of the general BM of the PtG technology.

The data collection takes place as follows. Necessary BM information is taken from the final reports of the WOMBAT project.[489] If data is missing, additional expert interviews with the operating company of the site are conducted. Here, this dissertation could use preliminary work of partners of the research project and from the operating company itself.

Again, a comprehensive table for each BM test displays the source of each information. In the end, a cross-unit conclusion is drawn to highlight the main results of the case study research.

[489] Meyer et al. (2016), Rieke and Waldstein (2016), Otten et al. (2016), Schuenemeyer (2016), Zuberbuehler et al. (2016)

6.2.1 Case Description

This chapter delivers further insight into the PtG technology and provides the necessary input parameter of the multi-unit analysis, in which business cases are calculated. This chapter is divided into general and economic information of the single case. Therefore, the target market, value proposition, value chain, and value network are described following the methodology of technology-driven business model innovation (see chapter 3.2). Next to the economic information, the technical data is of interest. For that reason, the carbon dioxide source and capturing methods are explained. Also, the hydrogen stream from power input over production to upgrade, and further treatment is followed. The methanation as the conversion of hydrogen and carbon dioxide to SNG is described as well. In the end, peripheral information like gas feed-in, heat management and operation modes are discussed, which belongs to the value network or ecosystem.

The PtG plant has an electrical input of 6 MW and has been installed in 2013 in Lower Saxony in northern Germany.[490] The construction consists of three times 2 MW alkaline electrolyzers and catalytic, chemical methanation. The site has been financed and is still operated by a sub-company of an automotive manufacturer. Therefore, the *target market* is *power-to-gas-to-mobility*. The plant is producing SNG to reduce the CO_2 footprint of NGVs. According to the staff of the provider company, the only sale price is the natural gas price because the green ability is promised to the customer. Therefore, the eco-premium is neither sold by CO_2 certificates via ETS to the industry nor to the fuel industry via GHG reduction quota. The natural gas prices are like the analyzed prices in chapter 5.2.2. Additional income streams are explained in the value chain.

The *value proposition* has a communication or marketing purpose with the claim of almost climate-neutral mobility. The automotive company is reducing the environmental footprint of their NGVs by at least 80% with the SNG produced on that site. It is assumed that this argument increases the sales numbers and attracts sustainable new customers to the brand. In addition, according to the staff of the provider company, the plant demonstrates different strategic aspects of the relevance of PtG in a RE system. First, the technical feasibility of an industrial PtG plant is proven. Second, during the WOMBAT research project, the energy storage potential and systemic integration are highlighted. And third, an increase of awareness toward renewable fuels can be observed, which should convince political decision-makers to improve the regulations of that technology. In total, this PtG case has multiple communicative, technical, and strategic value propositions but does not focus on economic optimization. However, the constructed general BM of the PtG technology can be applied for that case.

Following the *value chain* of chapter 5.3, the *costs at power markets* are on focus at the beginning. The investigated case has tested several power supply concepts.

490 Meyer et al. (2016), p. 11

During the instruction period, a constant load has been purchased with OTC trades from a hydropower plant. According to the operating company, the average power price has been 5 ct/kWh without any power taxes and fees. As a next supply concept, the day-ahead spot market has been considered because of the low power prices in the night and weekend shifts (see chapter 5.3.1.1). The main challenge of the spot market supply has been the constant technical availability of the PtG plant. During the first few years, a shift schedule has been developed to provide the physical presence at the site. This has increased personal operational costs, which is discussed later. However, automatic and autonomous operation of this plant is possible since the beginning of 2018. Since then, continuous participation in the spot market is possible without further personal costs. A third power supply concept was achieved in summer 2016. Here the prequalification at the SBM took place.[491] Both concepts, the day-ahead spot market as well as the SBM, are tested in the multi-unit analysis later. Then, power prices, operation times and further information are mentioned. More power supply concepts like an intraday market or TBM are not tested so far and recommended as supplementary research in the conclusion.

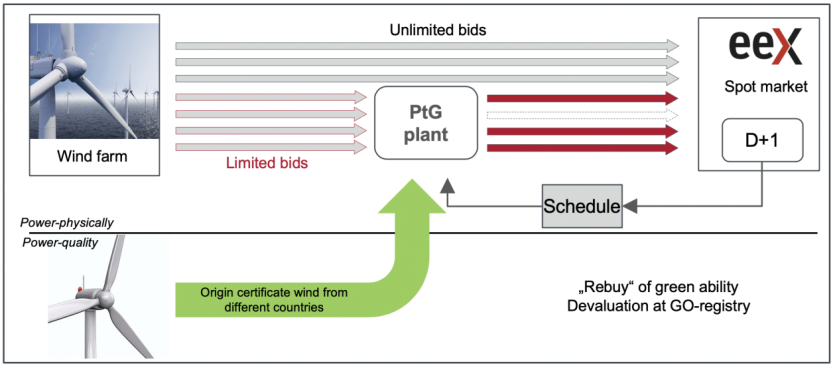


Figure 86: Regional renewable power supply concept[492]

The renewable power supply is guaranteed by GO and an additional regional power supply concept. The GO price is 0.05 ct/kWh and GO are purchased for the whole yearly energy amount, which includes the energy demand of peripheral devices as well. The regional renewable power supply concept has been developed with an energy supply company, which has several wind generators in direct marketing within 200 km around the PtG plant. Every time the PtG instance plans to bid energy at spot markets, the energy company checks whether their regional wind generators are

491 TeneT (2015)

492 Otten et al. (2016), p. 39

forecasted to generate electricity or not. If the RE is generated, the energy is not sold at the spot market but to the PtG plant for spot market prices. This unique concept integrates a regional and temporal aspect but allows the participation at spot markets and improves the systemic convenience. Figure 86 describes the regional renewable power supply concept.

The costs of *power taxes and grid fees* have been reviewed in chapter 5.3.2. The investigated industrial scale PtG plant is exempted from several surcharges. As mentioned, the grid fees differ for households and industrial clients in Germany. The grid fee of the medium voltage grid for industrial clients is about 0.51 ct/kWh for 20 kV and more than 2,500 FLH in the region of the case study.[493] As one of the first PtG plants, this site has received a confirmation of the federal grid agency that it is exempted from grid fees.[494] If the reactive energy is higher than a specific value, the provider must pay 1.02 ct/kWh in the specific region.[495] Taking into account the energy bills of 2015, which are provided by the operating company, in total, €65,080 reactive energy has been paid. The reactive energy improvement has been part of the WOMBAT project.[496] In 2017, the cost of reactive energy was below €2,000. Therefore, this cost driver can be corrected and is not further considered in the business modeling. Smaller surcharges like the concession levy, offshore surcharge, CHP surcharge, or §19 apportionment are paid by the provider company. In the case study interview, the provider company mentioned that the power tax can be released for the power consumption of the electrolyzers. For the power consumption of peripheral devices, the power tax must be paid. Additional certification of energy management can lead to further refunds. With these approaches, it was possible to release 95% of the power tax in 2013.[497]

Also, the biggest surcharge, the EEG apportionment, has to be fully paid. The provider company declares different unsuccessful approaches to release the EEG apportionment. But because of the injection of SNG into the national gas grid, the company is classified as an energy supplier and cannot be released (see chapter 5.3.2). Due to the massive cost driver, the provider company plans to install a hydrogen and LNG filling station to generate more than 50% revenue with hydrogen and LNG sales instead of SNG injection. That leads to a classification of a producer of industrial gases and the possibility to reduce the EEG apportionment. However, the staff points out that an economical operation is not possible with the payment of the EEG apportionment. In total, the costs of power taxes and grid fees are like assumed in chapter 5.3.2. In sum, the provider company must pay 6.62 ct/kWh of power taxes and fees in 2015.

493 EWE (2015a), p. 2

494 EWE (2015b), p. 28

495 EWE (2015a), p. 2

496 See Rieke and Waldstein (2016), p. 66

497 Otten et al. (2016), p. 24

The *capital expenditure* of the investigated PtG plant was €17.3 million in total. That price excludes later installments of optimizations during the WOMBAT research project as well as the investment of the amine scrubber to increase the carbon dioxide quality coming from a biogas plant. These additional investments are about €2 million, according to the staff of the provider company. Therefore, the assumption of approx. 10% additional costs of peripheral devices is justifiable. The carbon dioxide source is discussed in the value network of the BM. A cost per installed capacity of 2,883 €/kW is stated. That is approx. 20% higher than the investment costs of the same constellation, which are mentioned in the undertaken industrial survey in chapter 5.3.3.3. The lifetime of the site is assumed for 20 years.

Maintenance costs include external assignments and personal costs. During the WOMBAT project three internal and one external employee guarantee continuous technical availability to participate in different power markets. The staff of the provider company specifies maintenance costs of €988,000 in 2016 and €765,000 in 2017. This also includes materials as water (see value network), nitrogen, amine, and carbon dioxide as well as insurances and plant security. Therefore, the total maintenance costs are two to four times higher than mentioned in the industrial survey in chapter 5.3.3.1. In 2017, the costs make up about 4.4% of the investment costs. However, the OPEX decrease from 2016 to 2017 shows further potential with more automatic operation.

At the moment, *oxygen sale* is not considered at the site. The staff quote that they have calculated the possible oxygen sale, but the storage, filling, and transportation costs are higher than a potential additional income.

The provider company confirms the yield of *avoided gas grid fees* of 0.7 ct/kWh in Germany during the WOMBAT project.

The *efficiency* of the PtG plant has been investigated during the WOMBAT research project. The result is a stationary efficiency of 54.1% from received power to injected methane.[498] The dynamic efficiency is measured in weeks and depends on the power purchase concept. Therefore, dynamic efficiency is explained in the multi-unit analysis. The efficiency can be increased to 65.8% if heat production is included.[499] The heat management of the investigated PtG plant is discussed in the value network. In total, the efficiencies are comparable to the industrial survey of the business modeling.

The *value network* consists of the power consumption of peripheral devices, water management, efficiency increase with heat management, issues of SNG feed-in and carbon dioxide capturing. At the investigated site, several additional electric devices are installed next to the 6 MW electrolyzer. These are, for example, compressors for hydrogen or carbon dioxide or pumps of cooling water. In full load, the average power

498 Meyer et al. (2016), p. 8

499 Meyer et al. (2016), p. 9

input of peripheral devices is 516 kW and, therefore, approx. 8% of the total power consumption. The average power input in partial load is still 439 kW.[500] The partial load differs between the main components. The electrolyzers have a dynamic range of 8% to 100% after optimization during the research project.[501] The methanation is less dynamic and requires a constant input stream of at least 910 Nm^3/h of hydrogen.[502] Therefore, the dynamic range of the methanation unit was between 70% to 100% in the beginning. During the WOMBAT project the minimum load is reduced to 50%. The results of the industrial survey indicate similar values for the electrolyzer but more dynamic capability for catalytical methanation units. These results are displayed in the appendix. Between both main components of the investigated PtG case, a hydrogen storage of 1,300 Nm^3 is installed to uncouple both units and increase the number of operation modes.[503] Therefore, a buffering time of approx. one hour is available. The WOMBAT project has detected that particularly peripheral devices have technical issues in partial load. Most of the components are constructed to operate on full load, for example, the hydrogen compressor or the hydrogen cleaning and drying unit. The impact of the dynamic behavior on the weekly efficiency rates is questioned in the multi-unit analysis due to the dependency on power supply concepts. The assumption of the business modeling that peripheral devices lead to approx. 10% of additional power consumption can be almost confirmed for that case.

The water management of the PtG site with methanation has a nearly closed water circle. The site has an overall tap water demand of 1,820 kg/h in full load.[504] After the water treatment, 1,300 kg/h of deionized water is utilized in the electrolyzers. 500 kg/h can be reused from the methanation process.[505] Therefore, 800 kg/h of deionized water or 1,120 kg/h of tap water are required. At 4,000 FLH, the yearly water consumption is about 4,482 m^3. According to the German environmental agency, this is a bit more than the average yearly individual water footprint with 3,676 m^3 in 2016.[506] For that reason, an economic consideration of water consumption can be ignored with respect to other cost units, which confirms the assumption of the BM.

The heat management of the PtG site is complex due to the connection with a neighboring biogas plant and different operation modes. During the WOMBAT project, the focus of efficiency improvement has been the combination of PtG and biogas plants. Here the heat management plays a major factor. Two different kinds of heat cycles are

500 Rieke and Waldstein (2016), p. 35

501 Rieke and Waldstein (2016), p. 32

502 Rieke and Waldstein (2016), p. 30

503 Rieke and Waldstein (2016), p. 108

504 Rieke and Waldstein (2016), p. 83

505 Rieke and Waldstein (2016), p. 79

506 UBA (2020c)

installed. The high-temperature heat cycle has a temperature level of 170°C. It is mostly fed by the exothermic methanation process with a heat power of up to 700 kW in a full load. This heat cycle supplies the amine scrubber. In this unit, the amine is regenerated by heating to capture carbon dioxide from the raw biogas stream. The heating energy comes from the high-temperature heat cycle. If the PtG plant is on standby, the heat is provided by a biogas boiler.[507] This indicates a further synergy of the combination of PtG and biogas plants because biogas can be upgraded without the combustion of raw biogas if the PtG plant is operational. This increases the bio-methane injection into the gas grid.

The second heating cycling has a temperature level of 90°C. It is fed by the product gas cooling, which has a heat output of up to 400 kW.[508] This low-temperature cycle supplies the disinfection of the biogas plant with heat if the PtG plant is running. Additional heat comes from the electrolyzer cooling. In stand-by time, the heat comes from the high-temperature cycle. Both temperature cycles are connected with heat exchanging devices. As mentioned above, the efficiency can be increased up to 65.8% if the heat energy in full operation mode of the PtG plant is included in the calculation. The following figure is explaining both heating cycles of the single case. The numbers are like the theoretical consideration of the heat management in chapter 5.4.3.

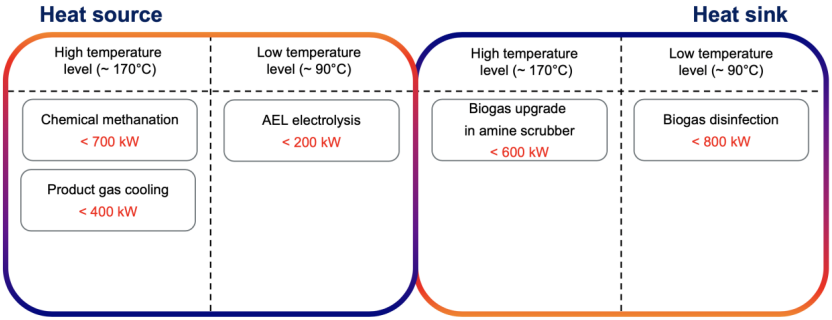


Figure 87: Heat management of the single case

In addition, a cooling system is installed if heat is not taken off. Also, during the optimization of the WOMBAT project, a heating storage unit has been integrated.[509]

The hydrogen further reacts with carbon dioxide to SNG. The CO_2 is absorbed from the raw biogas stream by an amine scrubber. Before the PtG plant has been installed, the biogas was upgraded with a pressure swing adsorption unit. According to the staff

507 Meyer et al. (2016), p. 40 ff

508 Meyer et al. (2016), p. 41

509 Meyer et al. (2016), p. 43

of the provider company, the purity of carbon dioxide is higher with the amine scrubbing technology. Different toxic elements in the CO_2 stream can degrade the catalyst in the methanation, which would increase the maintenance costs. Therefore, the amine scrubber unit has been installed. These additional investment costs are not included in the BM because it depends on the kind of CO_2 source. In full load, the methanation unit requires a CO_2 stream of 325 Nm^3/h.[510] The biogas plant has a max. production rate of 1,000 Nm^3/h raw biogas.[511] In 2012, the CO_2 concentration of the raw biogas had been about 30.42%.[512] Therefore, the max. production of SNG was not possible. Three different approaches have optimized CO_2 management during the WOMBAT research project. First, different input substrates have been used. This raised the average CO_2 concentration up to 35.73% in 2015.[513] Second, the roofs of the biogas plant are changed to a more flexible construction. This results in CO_2 storage of up to seven hours if the biogas plant is not producing, and the PtG site operates on a 70% partial load.[514] Third, liquid CO_2 storage is installed to provide carbon dioxide even if the biogas plant does not operate for a specific time period. Here the CO_2 comes from another biogas plant, which is also using only waste materials. According to the staff of the provider company, the origin of CO_2 is important. The automotive company wants to avoid any kind of ecological discussion about the origin of CO_2. Therefore, only biological CO_2 from waste materials is considered.

A further technical challenge has been the gas feed-in station. According to Rieke and Waldstein (2016), these feed-in units are made for constant gas injection and are not appropriate for several starts and stops of injections per day. Although the injection process has been optimized during WOMBAT, the measurement of the gas quality took several minutes, in which the product gas has to be flared. The injection criteria are a hydrogen limit of 5% and a carbon dioxide limit of 6%.[515] During the ramp-up and ramp-down of the methanation unit, SNG with higher H_2 and CO_2 concentration is produced, which also has to be flared. In total, each start of methanation and injection consumed approx. 100 Nm^3 of hydrogen.[516] Therefore, the avoidance of starting processes of the methanation unit is the main driver of efficiency improvements and choices of power supply concepts in this case.

The SNG of the case plant, which is located at the lower calorific grid, with a gas component concentration of approx. 94% methane, 3% hydrogen, and 3% carbon dioxide

510 Schuenemeyer (2016), p. 111

511 Schuenemeyer (2016), p. 111

512 Meyer et al. (2016), p. 64

513 Meyer et al. (2016), p. 64

514 Schuenemeyer (2016), p. 111

515 Zuberbuehler et al. (2016), p. 51

516 Rieke and Waldstein (2016), p. 101

has a Wobbe-index of 13.59 kWh/Nm³ according to the staff of the provider company. Therefore, the grid requirements are overperformed and the calorific value must be downgraded with an admixture of biomethane from the biogas plant.

In conclusion, the case analysis has already detected different important facts of PtG business modeling. Some economic parameters, like target market prices, costs of power taxes and grid fees, CAPEX, and heat management, is confirmed. Further economic drivers such as costs at power markets and efficiency are tested in a multi-unit analysis. Important technical issues in terms of CO_2 management and gas feed-in are addressed.

6.2.2 Multi-Unit analysis

In the single case, different units in the form of business cases are further tested. These cases differ in types of power supply concepts. So far, the data of two different power supply concepts are available. First, the purchase at the *day-ahead spot market* and, second, the participation at the *secondary balancing market*. As discussed in the business case calculation of chapter 6.1, the basic assumptions are mentioned first. The data is provided by the operating company.

Table 43: Input parameters of the multi-unit analysis

Parameter	Value (2015)
Plant description	6 MW AEL + chemical methanation and 516 kW peripheral load
Target market	Mobility market (natural gas)
CAPEX	€17.3 million
Power taxes and fees	6.62 ct/kWh
OPEX	765,000 €/a
Gas sale profit	2.1 ct/kWh
Avoidance of gas grid fees	0.7 ct/kWh
Oxygen sale profit	-
Eco-premium (CO_2 price)	Customer value
Heat sale profit (only process heat)	-
WACC	5%

Table 43 shows the basic assumption of the case study's business case calculation. The values are described in the previous chapter. The natural gas price displays the average spot market price between 2008 and 2016, as analyzed in chapter 5.2.2. As mentioned, the oxygen sale, eco-premium and heat sale are not monetized. The eco-premium is used as an additional customer value of almost climate-neutral mobility. The process heat is increasing the efficiency in combination with the biogas plant without any additional economic value.

During the research project, the economic performance is measured in weeks. Different power supply concepts are tested and analyzed in the same way. The main numbers are the required electric power at a specific price and the injected amount of SNG. With these values, different business cases can be calculated. For that reason, the weekly performance is upscaled to a yearly performance and calculated for the whole lifetime. It is assumed that the performance per week is also achievable per year. Unfortunately, a yearly and comparable performance of each power supply concept is not available. In the following subchapters, two different power supply concepts are applied with the general BM of the PtG technology in the described way.

6.2.2.1 Business Case 18: Case Study Unit 1

First, the business case at the day-ahead spot market is analyzed. Otten et al. (2016) have published different weekly performances. For example, in CW 14 in 2015, 89.3 MWh power has been demanded at the day-ahead spot market price of 0.92 ct/kWh, and 39.5 MWh of SNG has been injected. Therefore, a weekly efficiency of 44.3% is achieved. The low purchase price was possible during night and weekend hours.[517] In CW 19 in the same year, 211.1 MWh power has been needed at a spot market price of 2.1 ct/kWh to produce 103.8 MWh of SNG. In conclusion, a weekly efficiency of 49.2% is realized.[518] The CW 21 was similar to a requirement of 203.5 MWh electricity and an injection of 99.6 MWh of SNG.[519]

The analysis of specific weeks shows that the power supply concept at the day-ahead spot market is possible, and the dynamic efficiency over time is approx. 7% lower than the static efficiency of 54.1%, which has been mentioned above. The reasons for the difference between both efficiencies are the combustion of low-quality gas during run ups and downs and technical issues, for example, with the gas injection system. Therefore, the avoidance of starting processes of the catalytic, chemical methanation is identified as a key technical and economic issue. In total, the spot market power price of chapter 5.3.1.1 can be used for 4,000 FLH. The efficiency should be reduced to a realistic, dynamic efficiency. In this case, the average of the three published calendar weeks is taken into account. The following table summarized parameters, which depend on the power supply concept.

[517] Otten et al. (2016), p. 28

[518] Otten et al. (2016), p. 29

[519] Otten et al. (2016), p. 30

Table 44: Input parameter of the business case 18

Parameter	Value (2015)
Power purchase concept	Day-ahead spot market
Operation time	4,000 h/a
Power price	2.14 ct/kWh
Green power certificates	0.05 ct/kWh
Efficiency (Power-to-gas)	47.5%

The general BM of PtG technology is calculating the business case and key economic information. The result is displayed in an average cash flow analysis to show the impact of different economic drivers and to be comparable to the theoretical business case calculations in chapter 6.1. The financial information and future price developments are also identical to the previous case calculations.

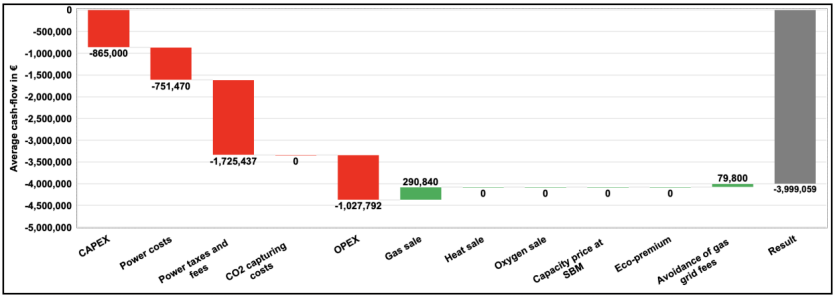


Figure 88: Business case 18: single case study unit 1 Day-ahead spot market

It obtains a highly negative business case with an average cash-burn of approx. €4 million per year. Compared to the business case *power-to-gas-to-mobility* of chapter 6.1.4, different parameters are responsible. First, the practical efficiency is worse than the theoretical efficiency of the industrial surveys. This leads to lower gas production and, therefore, less income with the gas sales and avoidance of gas grid fees. Second, the personal and maintenance costs (OPEX) are three times higher than figured out with an industrial survey (see chapter 6.1.4). Third, also CAPEX is two to three times higher due to the *first-of-its-kind* character of the case plant. Fourth, the eco-premium is not used directly in the business case. As mentioned, instead of demonstrating the economic feasibility, the plant should show the technical approvability and highlight strategic advice.

The single case validation indicates that the general BM can be used in practice and that the main cost driver of the PtG technology is power taxes and fees with almost €1.73 million per year. An IRR or a ROI is not possible to determine under these circumstances. In addition, even without power taxes and fees, additional income

streams in terms of credits of CO_2 reduction, heat or oxygen sale are necessary to make PtG economically feasible. The price of SNG in this business case is about 39 ct/kWh.

Table 45: Results of the business case 18: single case study unit 1 Day-ahead spot market

Parameter	Value
Gas production price	38.53 ct/kWh
Net present value after taxes	-€58,058,410
Return on invest after taxes	-443%
Internal rate of return after taxes	-

6.2.2.2 Business Case 19: Case Study Unit 2

Next to the power supply concept at the day-ahead spot market, also the SBM is on investigation. Also, Otten et al. (2016) have published first experiences during the research project. Again, the performance is measured in weeks. The mechanism of the balancing market is explained in chapter 5.3.1.3. The operation time highly depends on bidding behavior. First, a capacity price within the range of the required balancing energy is necessary. Second, the commodity price decides the number of calls of the grid operator. This single case unit analysis has been observed for several weeks at the end of 2015 and at the beginning of 2016 with different bidding strategies.

First, neg. SBM has been tested. But the count of calls was too low for a constant and efficient operation due to the gas injection system and low-quality gas during run ups and downs.[520] Second, a mixed strategy of positive and negative balancing energy has been chosen at the beginning of 2016. Therefore, a baseload has been purchased to provide positive balancing energy.

In CW four of 2016, 2 MW of positive and 4 MW of negative balancing energy has been provided during prime time (PT). In total, 519 MWh of power has been consumed, and 188 MWh SNG has been injected into the gas grid during that week. Therefore, the weekly efficiency was 36.2%. The costs of the baseload at the OTC market was €4,224 and earnings at the balancing market was €1,045 with capacity and commodity prices. Therefore, the average power supply price was only 0.61 ct/kWh. In CW five, the same bidding strategy was applied, but only 102 MWh of SNG are injected with the supply of 308 MWh of electricity. The differences to the previous week could be different commodity prices, different durations of calls of the grid operator due to different grid situations, or different bidding strategies of competitors at the SBM. The efficiency was 33.12%. The costs have been €3,720, and the incomes have been €2,499 in CW five. Therefore, the power price was 0.4 ct/kWh. The comparison of CW four and five shows

520 Otten et al. (2016), p. 31

high fluctuations in terms of SNG production and efficiency with the same bidding strategy. As mentioned, different reasons could be possible.[521]

In the CWs seven and eight, also the operation during the secondary timeslot (ST) has been investigated. In both periods, two MW positive and negative balancing service has been provided. In CW seven, 442 MWh power has been supplied to produce 160 MWh of SNG with a weekly efficiency of 36.2%. The costs of the baseload have been comparable high with €9,190. Yields are generated with €1,382 at that time. In sum, the power price was 1.77 ct/kWh. In CW eight, only 84 MWh of SNG is produced by using 220 MWh of electricity, which makes the efficiency of 38.18%. The costs have been €7,946, but the earnings of €9,013 are achieved. Therefore, the negative power prices of -0.49 ct/kWh have been observed.[522] A long-term investigation is recommended. According to Otten et al. (2016), in the first quarter of 2016, power purchase prices of only 1 ct/kWh have been achieved. Again, the differences between those weeks are difficult to explain due to many possible reasons.

This unit analysis shows potential low power prices with a mixed strategy at the SBM with disadvantages in terms of efficiency although the pos. balancing energy provides an almost constant load. The staff of the provider company has provided the following example of a mixed strategy at the secondary balancing market, which is shown in Figure 89. It displays the number and duration of calls for 12 hours. The black line is the signal from the grid operator, and the red line is the power consumption of the PtG plant. It shows how flexible PtG plants can operate and that it is possible to follow fluctuating price signals at the secondary balancing market. With such a power supply concept, the plant is stressed due to many single calls with a short duration. Technical challenges have not been observed during that time, but the ramp-ups of the electrolyzer and methanation unit lead to efficiency losses.

521 Otten et al. (2016), p. 31 f

522 Otten et al. (2016), p. 31 f

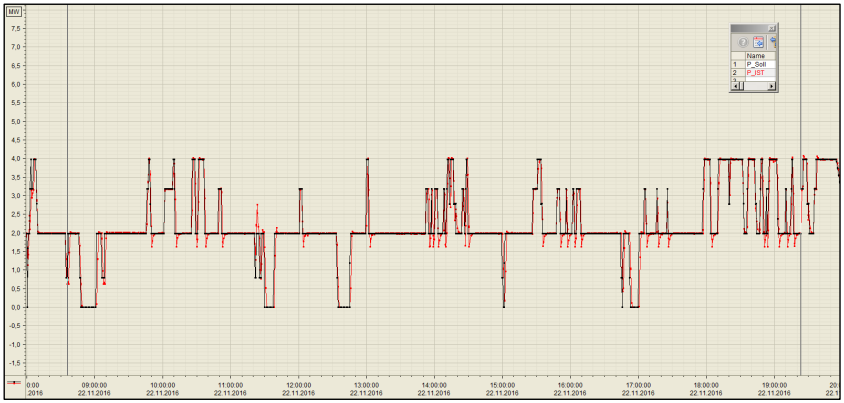


Figure 89: Practical drive schedule at the secondary balancing market

The observed weekly performances are used in the case calculation of PtG technology. Therefore, the power price of the first quarter of 2016 and the efficiency during the investigated time periods are taken into account. The yearly operation time mentioned in chapter 6.1.5 is used.

Table 46: Input parameter of the business case 19

Parameter	Value (2016)
Power purchase concept	Secondary balancing market
Operation time	3,066 h/a
Power price	1 ct/kWh
Efficiency	35.93%

The result of business modeling is as follows. Due to the lower power price and less operation time, the overall losses are smaller than with the power supply concept at the day-ahead spot market. But even without power taxes and fees, a positive business case is not possible because of the bad efficiency. Additional income streams like the GHG reduction quota or heat sale would be necessary. The incomes of the capacity price are included in the power price in this example due to the availability of data. However, it has been practically shown that participation in balancing markets with relatively low power prices is possible. As already mentioned in chapter 5.3.1.3, the number of participants at the balancing market is limited to a few hundred PtG plants due to the amount of required balancing energy per period. Therefore, this is an additional business case, for example, for early market entries.

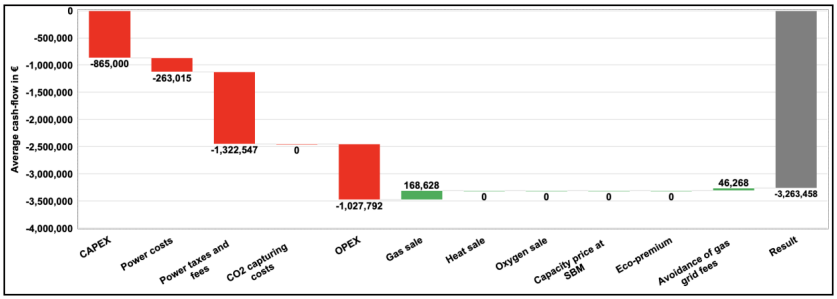


Figure 90: Business case 19: single case study unit 2 Secondary balancing market

Table 47: Results of the business case 19: single case study unit 2 Secondary balancing market

Parameter	Value
Gas production price	52.62 ct/kWh
Net present value after taxes	-€48,267,504
Return on invest after taxes	-360%
Internal rate of return after taxes	-

6.2.3 Cross-Unit Conclusion

The comparison of the two investigated power supply concepts is part of the cross-unit conclusion. As demonstrated, both business cases are uneconomical under the current market and regulatory situation. The first business case with power supply at the day-ahead spot market has advantages in terms of operation time and efficiency. The plant primarily runs during the night shift and at weekends. Therefore, precise operation schedules are available. Maintenance takes place during the day shift. In addition, due to less start-ups and downs, a constant operation is possible, which is increasing efficiency. However, due to enormous cost drivers like power taxes and fees and CAPEX, the average yearly cash burn is approx. €4 million.

The second analyzed unit has an advantage in terms of power price. The average yearly power purchase cost is reduced to €263,015 by participation at the SBM with a mixed strategy of pos. and neg. balancing energy. A disadvantage is the lower overall efficiency of 36%. The average cash flow burn is decreased by €735,601 per year in comparison to the first analyzed unit at this plant. But as investigated in chapter 5.3.1.3, the operation at the SBM with the appropriate number of FLH is only possible for the first few hundred installed PtG cases. Afterward, the market for necessary balancing energy is saturated.

In sum, in the current power market design and regulatory system, both practical business cases are highly uneconomical in Germany. If the plant is always available and

able to operate autonomously, then the participation at the SBM is recommended as long as the market is not saturated and issues of SNG injection are solved from an economic perspective. The practical case study investigation of further power supply concepts like the participation at the intraday market with asset-backed trading or a combination of different markets appears useful.

6.3 Conclusion of the Validation of the Business Model

The constructed theoretical general BM of the PtG technology is first calculated at different examples with literature data, spot market analyses, and own surveys, which has been examined in the analysis of the target markets (see chapter 5.2), value chain (see chapter 5.3) and value network (see chapter 5.4) following the technology-driven approach of business modeling, and second practical application explored in a single case and multi-unit analysis. The insights of the validation are as follows.

First, the application of the general BM is tested in different theoretical and practical ways, which demonstrate, on the one hand, the adaptability and, on the other hand, the scientific rigorousness due to multiple validations. Second, the results of different business cases can be compared to analyze probable first business cases. As shown, the mobility market with yields of the GHG reduction quota appears as a possible first target market. In addition, future business cases are also tested, which show economic potential. Third, the comparison of the theoretical business case calculation with an existing plant in a case study delivers insights about differences between theory and practice in terms of important economic drivers like OPEX or efficiency. Otherwise, it demonstrates that the general model works in a real-world environment. The main results are summarized in chapter 7.1.

It shall be reiterated that a comprehensive and final validation is not possible. Necessary further validations are recommended in the critical evaluation in chapter 7.3. But the existing research design delivers a first confirmation about the functionality of the general BM of the PtG technology.

7 Conclusion

This chapter summarizes the main propositions of the dissertation. In addition, the last RQ (*What are the final, strategic recommendations? How could a possible technology pathway look like?*) is answered with a potential technology pathway of the PtG technology and strategic recommendations. Therefore, first, the results of the empirical section are summed up. Second, a possible technology pathway is drawn. Third, the outcomes are critically evaluated. With this, limitations of the dissertation are announced, and further scientific, industrial, and political recommendations are given. In the end, the potential theoretical and practical impact is discussed.

7.1 Results

In the empirical section, the general business model (BM) is constructed as an artefact of the design science research approach (DSR) by following the six steps of Peffers et al. (2007). As an intermediate result of the *design and development phase*, a revenue model with different economic drivers was developed. The proposition is that this general BM can be used to calculate different business cases for the PtG technology. The proposition is tested by different BM calculations for different target markets, power purchase concepts, plant designs and CO_2 sources. Next to the confirmation of the adaptability of the artefact, the practical improvement and usage is verified by a single case study.

The first result is a well-described proceeding of how to develop a configuration model that can be used to assess business models in the deployment of the PtG technology. The advantage of the constructed model is the understandable course of action and a structured template for further research. In next steps, the configuration model can be transmitted to other regions or applications and updated with latest data. This is further discussed in the chapter of research recommendations (see 7.3.2).

The system analysis has identified main important economic parameters of the PtG technology. An expert group with high knowledge about PtG has detected additional parameters like the *GHG reduction quota* or the *avoided gas grid fees*, which could stay unknown if only a literature review along the value chain is executed. In addition, relations between these parameters have demonstrated that the PtG technology is mostly driven by parameters, which are part of the energy system like *regulations* or *infrastructure costs*.

The general BM is constructed with these identified parameters and further literature research as well as quantitative analysis of target markets. The general model and revenue streams are graphically shown in Figure 64. This model is built along the value chain and network, and several parameters can be adjusted like target markets, power purchase concepts or different plant designs. Theoretically, the calculation of around *100,000 different BM cases* is possible. For example, 45 different plant constructions

with different starting years, eight different CO_2 sources and direct hydrogen injection, 20 power purchase concepts, four target markets, as well as the option to switch on and off the oxygen and process heat sale. In addition, different financial conditions can be calculated, and different dynamic economic parameters can be set to random to consider the distribution of outcomes. The general BM is available as a well-arranged Excel tool, and outcomes are shown as a financial parameter like net present value (NPV), return on investment (ROI), internal rate of return (IRR), and the yearly average cash flow.

The application of the general BM under different conditions delivers further individual results, which depends on the input data. For different market participants, the results of the first BM calculations are of interest. Therefore, the scientific findings of different economic parameters are briefly summarized in the following sections. First, the gas production prices and the NPVs of all calculated cases are displayed in the following table. Cases four to 19 are calculated for the target market *Power-to-gas-to-mobility*. In the following section, the results of the different BM calculations are discussed.

Table 48: Results of the business case calculations

BC	Business case description	Gas production price in ct/kWh	NPV after taxes in million €	Chapter
1	Target market: power-to-gas-to-power	18.48	-11.3	6.1.1
2	Target market: power-to-gas-to-industry	24.61	-28.13	6.1.2
3	Target market: power-to-gas-to-heat	24.61	-20.07	6.1.3
4	Target market: power-to-gas-to-mobility	24.61	-15.04	6.1.4
5	Power purchase concept: neg. SBM	20.87	-5.14	6.1.5
6	Power purchase concept: pos. SBM	22.91	-12.6	6.1.5
7	Power purchase concept: intraday spot market 2016	23.84	-13.93	6.1.5
8	Power purchase concept: intraday spot market 2016 with asset backed trading	18.24	-6.03	6.1.5
9	Power purchase concept: optimization of intraday spot market and day-ahead gas prices 2016	23.89	-13.98	6.1.5
10	Plant design: 5 MW PEM + chemical methanation (2020)	20.72	-8.93	6.1.6
11	Plant design: 20 MW PEM + biological methanation (2025)	20.73	-23.13	6.1.6
12	Plant design: 20 MW SOEC (2025)	10.73	18.54	6.1.6
13	CO_2 source: pulp and paper factory	18.94	-8	6.1.7
14	CO_2 source: refinery	19.53	-8.88	6.1.7
15	CO_2 source: ambient air (solid sorbent)	23.98	-15.5	6.1.7
16	MENA-region (2025)	11.98	1.86	6.1.8

17	Distribution of results based on MC simulation and multi-variate bootstrapping	20.55 to 20.92	-30.42 to -41.86	6.1.9
18	Case study unit 1: day-ahead market	38.53	-58.06	6.2.2.1
19	Case study unit 2: balancing market	52.62	-48.28	6.2.2.2

The comparison of different BM results shows that, the PtG technology is not economically feasible with actual market data except for two constructed future cases with the SOEC technology, which is an efficient electrolysis technology, and in the MENA-region with financial aid. The target market *power-to-gas-to-power* displays the lowest losses (€11,47 million) of all target markets (BC one to four) due to a direct connection to a RE unit and, therefore, no payments of *power taxes and fees* – in particular the EEG apportionment. In this case, synthetic natural gas (SNG) is used in CHP plants for power generation. The industrial application of SNG, for example, the production of chemical raw materials, indicates the highest losses due to – by status quo – less willingness to pay extra for green products because of regulations with low CO_2 emission prices (ETS).

The comparison of different power purchase concepts (BC four to nine) demonstrates that the secondary balancing market is a potential first market for PtG plants using the example of the target market mobility. However, a detailed analysis of the operation time shows that this case is only feasible for a few hundred MW of installed plants in Germany (see chapter 5.3.1.3). Next to the balancing market, the spot markets (intraday and day-ahead) have been analyzed. At the intraday market, an average power price of 1.73 ct/kWh for 4,000 hours has been possible in 2016. Due to the continuous trading at the intraday market, a further option value of asset-backed trading can be added. This innovative power supply concept includes yields of continuous trading during the bidding period and, therefore, almost decreases the *costs at power markets* completely. The usage of the asset-backed trading at the intraday market, is not proven yet in its practicality for a PtG plant. In addition, further analysis shows that the operational optimization with day-ahead power and gas prices leads to less than 1,000 € of additional income per year in case of a 5 MW plant. Therefore, the economic impact of this optimization is low in comparison to other power purchase concepts.

The analysis of different plant designs (BC four and 10 to 12) with industrial surveys depicts the benefits of larger plants in terms of CAPEX and OPEX due to expected economies of scale. But because of the negative overall cash flow of those cases, the NPVs are more unlikely. One exception is a 20 MW SOEC plant with direct hydrogen injection and starting year in 2025. Even with all power taxes and fees, this business case is positive due to high expected incomes of the future *GHG reduction quota* and the high *efficiency* of the plant construction. The calculation of different CO_2 sources (BC four and 13 to 15) highlights that first concentrated point sources from biogas or industrial plants should be used due to the high costs of CO_2 from ambient air. The calculation in the MENA-region (BC 16) highlights that the general BM can be used

even to declare the business results of the PtG technology in different regions. In total, 19 different BM cases have been investigated.

Next to the financial results, the distribution of the results is on focus due to many dynamic, fluctuating parameters (BC 17). Therefore, a MC simulation and bootstrap methods are taken into account, as explained in chapter 5.5. This analysis demonstrates that economic outcomes are broadly distributed. The histogram of the NPVs (see Figure 84) illustrates this statement, and it allows further statements about the probability of results, which is an important instrument of financial investors. The distribution of the outcomes is highlighted in the business case calculation in chapter 6.1.9. Most dynamic parameters are the *oxygen sale* and *GHG reduction quota* due to a bandwidth of literature and historical data.

The business case calculations with input data from an existing industrial scale PtG plant (BC 18 and 19) demonstrates that first instances are not economical feasible. The gas production price is up to 53 ct/kWh. However, important insights could be achieved by these case considerations.

Next to the main results, the investigation of single economic parameters are further briefly embraced. The choice of *target markets* has a major impact on economics. Here, the NPV differs between losses of €11 and €28 million. Different sales prices lead to different results. In addition, most of the BM cases are influenced by the political framework like releases of power taxes and fees or additional yields from eco-premiums like GHG reduction quota or CO_2-certificates. *This result highlights that the political regulation of the target markets is one of the main driver of economic performance.*

The *capital expenditures* (CAPEX) have been analyzed with an own industrial survey (see chapter 5.3.3). All different electrolyzer and methanation technologies are expected to have enormous cost reductions according to the survey. In 2025, the CAPEX is striving a cost corridor of 720 and 1,250 €/kW for a PtG plant. The investment cost of chemical methanation is approx. 40% lower than the biological methanation. In addition, the industrial survey delivers insights on *efficiency* development, usage of *process heat*, maintenance costs (*OPEX*), reaction time and partial load, which is important to participate in balancing markets. Another research result, which is discussed in the appendix (see chapter A.5 and A.6), is that in comparison to the chemical methanation, the biological methanation offers solutions in terms of fast start-up time and dynamic range. The heat usage of the exothermic, chemical methanation process is an important parameter to achieve further incomes at the heat market. The costs of CO_2 capturing are included, and the potential of different CO_2 sources has been discussed (see chapter 5.4.6).

The *power price* differs highly between the chosen power purchase concepts, which are in detail discussed in chapter 5.3.1. For that case, the NPV is between deficits of €5 million at the negative secondary balancing market and €15 million at the day-ahead

spot market. The possible operation time of each supply concept has been considered in detail. The operation time of a spot market power purchase concept is higher during the weekend and night hours. The operation time of spot market concepts is limited to about 4,000 hours due to ecological and economic reasons (see chapter 5.4.8). With innovative power purchase concepts like the asset-backed trading at the intraday market, the average power price is reduced to 0.02 ct/kWh, which includes costs of GO and an average forecast error. The operational optimization by taking into account the forecasted power and gas prices has not detected huge economic advantages but needs further investigations.

The *power taxes and fees* are the biggest cost factor in most of the BM calculations, although an exemption from different power taxes and fees is possible. This topic is comprehensively discussed in chapter 5.3.2 and is validated in a single case study for PtG plants in Germany. For example, the target market *power-to-gas-to-mobility* would be economically feasible if also the EEG apportionment is releasable for PtG plants. Power taxes and fees are responsible for up to 70% of the cash flow costs at the intraday market with asset-backed trading. This underlines once again that the PtG technology highly depends on the regulatory framework.

The income through *gas sales* differs between the target markets. If an additional *eco-premium* is yielded because of the regulatory accounting of the CO_2 reduction in different target markets, for example, with the GHG reduction quota, the gas can only be sold as a fossil, natural gas to avoid any kind of double counting. At the target market *power-to-gas-to-power*, the guaranteed feed-in tariff of the RE source can be included in the calculation. At the target market *power-to-gas-to-heat*, a biomethane price can be considered. The GHG reduction quota displays the highest income stream and is, therefore, an important economic driver for the mobility case, which is discussed in chapter 5.2.4.

Heat and *oxygen sales*, as well as the *avoided gas grid fees*, are additional yields, which can be generated wherever possible. The BM calculations identify that these economic drivers can have an impact in sum, but this depends on the value network or ecosystem. For example, heat sale is only possible if a heat source is available. The investigation of the distribution of the outcomes shows that, in particular, the oxygen sale price leads to yearly average cash flow uncertainties of about €1 million per year.

Next to the theoretical BM calculations, a single case study is executed to test the general BM in practice and to explore further practical knowledge of business modeling (see chapter 6.1.9). In this case, two different power purchase concepts are compared. First, the participation at the hourly day-ahead spot market and, second, a mixed strategy of positive and negative balancing energy at the SBM. The single case study concludes that the structure of the general BM can be confirmed for this event. The power taxes and fees resemble the main cost driver. The single case study contributes that efficiency losses due to many start-ups must be added and issues with a fluctuating

SNG injection into the gas grid exist. With an average yearly cash flow loss of €4 and €3.3 million, it demonstrates that first PtG projects are not economically feasible. However, these results represent one of the first published, practical financial outcomes of a PtG plant.

The second result of the dissertation is that the constructed configuration model can be applied to calculate different BM cases in theory and practice. The different outcome of the calculations furthermore shows that the PtG technology is not economically feasible under analyzed market conditions in Germany in 2020. Operators of PtG plants must pay end consumer fees like the EEG apportionment and, in turn, have issues to yield a sustainable bonus for SNG. This dilemma results in highly negative average cash flows and NPVs. Most of the cost factors thereby depend on the regulatory framework like the GHG reduction quota. Innovative power purchase concepts show that PtG can be economically feasible even in Germany if the EEG apportionment would be waived. In addition, a statistical investigation using bootstrapping methods indicates the impact of dynamic parameters on the overall business case. It shows that the outcomes are well-distributed, which increases the risk of potential investors due to different financial predictions.

The following table presents additional contributions of the dissertation in comparison to the existing body of literature from the author's perspective. During the research process, valuable insights are achieved that will expand the theoretical and practical knowledge of PtG technology.

Table 49: Additional contributions of the dissertation project in comparison to the existing literature about the PtG technology

No.	Additional contribution	Chapter
1	Development of a design science research process configuration model for the assessment of business models in the deployment of the PtG technology	2.4.1
2	Use of system analysis to identify less investigated economic parameters (e.g., GHG reduction quota) and the role of the PtG technology in the energy system	4
3	Quantitative analysis and comparison of four target markets is conducted	5.2
4	Quantification of new power supply concepts and their operation time e.g., the SBM or the asset-backed trading at the intraday market. In total, 20 different power supply concepts can be set in the general BM	5.3.1.1 and 5.3.1.3
5	An industrial survey with manufactures of electrolyzers and methanation reactors is performed to gain new insights of capital and maintenance costs, efficiencies, heat management as well as dynamic ranges. Especially the insights of the biological methanation contributes new value	5.3.3
6	The discounted cash flow model is expanded with a tax model and dynamic parameters are investigated by a MC simulation and multivariate bootstrapping	5.5
7	Calculation of 16 business cases with further insights by comparing different target markets, plant constructions, power supply concepts, CO_2 sources and an additional case in the MENA-region	6.1

8	Use of MC simulation and bootstrapping methods to analyze the distribution of economic results of the BM of the PtG technology	6.1.9
9	Practical insights of an existing industrial PtG plant by the execution of a single case study are provided. This includes first publications of economic results of an operating industrial scale PtG plant	6.2
10	Detailed political recommendations of necessary regulatory bridges to scale up the PtG-technology including an approach to account SNG in the CO_2 standards of the automotive industry are given	7.2

PtG plants can play a major role in a RE system as the literature review (see chapter 2.1), system analysis (see chapter 4) and discussion of a future energy system (see chapter A.1) indicate. However, further technology development is hampered by too many different regulatory systems. Therefore, a technology pathway with clear political recommendations is necessary. For that reason, a technology roadmap is drawn in the following chapter on the surrounding regulations and political goodwill.

7.2 Potential Technology Pathway

The business case calculations have analyzed the economic situation of the PtG technology. It demonstrates that a business case only exists under future boundary conditions or with financial support. Different stakeholders, like target market participants, technology developers, politicians, energy suppliers, and financial companies, demand an appropriate and solid strategy on how to handle this new technology. Therefore, the achieved results are evaluated, and an outlook is created.

The PtG technology is still in a pre-industrial phase in 2020. The technology maturity is almost finally developed as the technical discussion along the value chain and network has depicted (see chapter 5.3). Different pilot plants exist, as mentioned in the introduction (see chapter 2.3). They have demonstrated the basic technical feasibility. Further development of the PtG technology requires upscaling and the realization of economies of experience. For the required upscaling, certain economic conditions are needed. The economic analysis of different cases shows that these conditions are nearly nonexistent. But the dissertation also highlights which adjustments of economic drivers could change the economic situation. In conclusion, if the eco-premium of SNG is increasing due to its CO_2 reduction potential in different target markets and otherwise power taxes and fees are decreasing, an economically feasible business case appears more likely. Both economic drivers depend on the development of political regulations. A robust, long-term political framework is needed to scale up the PtG technology and decrease production costs with economies of scale.

Only political changes can lead to competitive costs compared to fossil fuel prices. Figure 91 draws a potential cost corridor of SNG, considering the results of the business case calculations and the forecasted outcomes of Hecking et al. (2017) for the year 2030 and 2050. The increase of the natural gas price is following Nitsch et al. (2012), which is discussed in chapter 6.1.2. A period until 2025 to 2035 needs to pass

until SNG can be cost-competitive compared to fossil equivalents. This period needs a robust political framework to support the technological development. The situation of PtG is comparable to the situation of REs like wind or photovoltaic before guaranteed feed-in tariffs have been introduced with the EEG in Germany. A long-term investment security is missing. A technology pathway of PtG is interlinked with the development of climate regulations in Europe. For that reason, in the next section, these regulations are discussed.

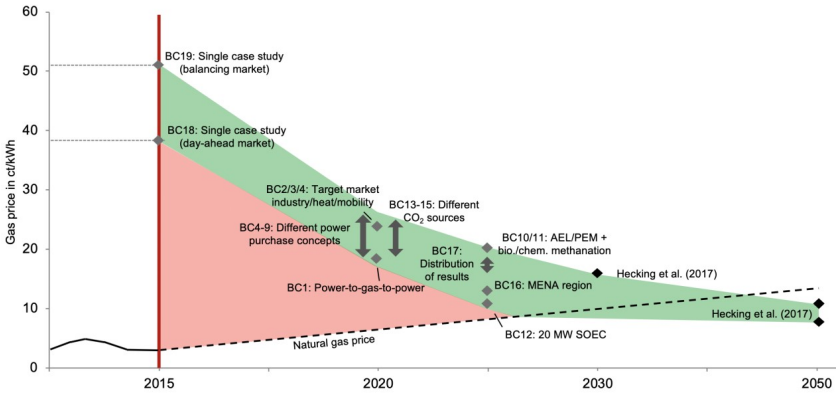


Figure 91: Potential cost corridor of SNG

The validation of the BM by various case calculations has depicted that the main economic parameters are power taxes and fees (in particular the EEG apportionment see chapter 5.3.2) and the eco-premium in the target market *power-to-gas-to-mobility*. If both parameters are adjusted by regulative changes, an industrial scale-up of the PtG technology can be initiated. Therefore, in the following section, first, the exemption of the EEG apportionment and second, future development of the eco-premium in the transportation sector are discussed. In the end, additional instruments like a market introduction program, energy taxation, and the definition of sustainable CO_2 sources are described.

In principle, two ways exist to boost technology development with an exemption of the EEG apportionment. In the short-term, the government can *withdrawal the necessary re-electrification of SNG* in section 60, sentence three of EEG (2014). This sentence is limiting the exemption of the EEG apportionment to the target market *power-to-gas-to-power*. But it has to be checked if this withdrawal is compliant with the EU-27 framework for state-aid. However, from a long-term perspective, a clear classification of the PtG technology in a specific economic sector is necessary, as discussed in chapter 5.3.2. The United Nations have started the revision of the *International Standard*

Industrial Classification of All Economic Activities (ISIC Rev.4) in 2019.[523] If PtG plants belong to manufacturing companies (e.g., the production of industrial gases in the economic class 19.11.), an exemption or at least reduction of the EEG apportionment is possible if more than 50% of the revenue makes up power costs, which is the case (see chapter 6.1). Due to the worldwide homologation of the ISIC Rev.4, this process is expected to take several years.

As mentioned before, according to the calculations undertaken, power taxes and fees are responsible for up to 70% of the cash flow costs. There are other initiatives addressing this issue: a joint position paper from different industrial associations in Germany suggests an extensive reduction of power levies and fees for a limited ramp-up phase.[524] This would be especially eligible if the plant operates grid-friendly in regions with a temporal surplus of renewable power generation, which would justify a reduction of power taxes and fees. For the German regulatory framework, there are some more proposals like the exemption of power taxes and fees of PtG plants in the so-called *real laboratories*.

The future development of the regulatory design of power markets could change the economic situation of PtG rapidly and thereby set the trend towards a more resilient RE system. For example, in March 2016, the German federal state Schleswig-Holstein has introduced a proposal to allow PtG plants as shiftable, regional loads, which are released off all taxes and fees on the power price.[525] Another interesting approach would be the dynamic share of taxes and fees on the power price, which has been brought up by the think-tank *Agora Energiewende*. The share of taxes and surcharges would be aggregated with the spot market price. The advantage is that hours with a low spot market price would have lower overall power prices and vice versa. For that reason, the spread between the cheapest and most expensive hours would increase. Energy storage systems and demand-side management instances would profit from this market behavior.[526] Inflexible loads would, by the trend, pay higher power prices, which is an indirect penalty for the stress put on a RE system. The impact of such serious changes in the power system on the business case of PtG is not foreseeable yet and, therefore, not further analyzed. An additional political and scientific investigation is recommended in chapter 7.3.2.

On the 4th of June 2020 the German government has presented their economic stimulus package to recover the economy after the COVID-19 pandemic. In that package also details of the national hydrogen strategy are announced. The German government plans to install 5 GW of electrolyzer capacity in Germany until 2030. But the most

523 Kronimus (2019)

524 Nießen and Richter (2018)

525 Antoni et al. (2016)

526 Nabe and Bons (2014)

important detail of the stimulus package is the exemption of the EEG apportionment for the power supply of PtX instances.[527] Therefore, one of the main leverages of a market ramp-up of the PtG technology is almost realized.

The eco-premium of different target markets displays the second leverage on how to make PtG economically feasible. The highest eco-premium is possible in the mobility case as the comparison of different target markets demonstrates. This eco-premium is regulated in the European RE directive (RED).[528] Here, SNG is defined as *renewable fuel from the non-biological origin*. In the German implementation of the RED, SNG is further defined with a specific GHG reduction quota as described in chapter 5.2.4.3. Due to these definitions, SNG can yield an average of 5.64 ct/kWh on top of the fossil fuel price in Germany by taking into account the historical data from 2015 to 2017. But the negative business results at the target market *power-to-gas-to-mobility* shows that the CO_2 price of the RED is still too low. Since 2006 the amount of renewable fuels is constant in the German transportation sector (see Figure 32).

This could change with the next regulation (RED II), which described the political framework from 2020 to 2030. The RED II was finalized in 2018. In this, the overall targets are increased to a 14% share of RE in the transportation sector in 2030.[529] Although conventional biofuels are limited by 7% from 2021 onwards, a market push for SNG is not certain. Different multipliers of specific fuels are reducing the necessary amount of renewable fuels physically applied. For example, the charging power of electric vehicles is quadruple counted for the RE share, which is justified in the regulation by the higher efficiency of electric compared to internal combustion engines. For the same reason, hydrogen in fuel cells benefits from double counting. Advanced biofuels like biomethane from waste materials are counted twice and renewable fuels, which are used in the aviation or shipping sector[530], are also counted several times.[531] However, SNG from renewable electricity is only counted once. According to these different conditions, it is economically foreseeable that first charging power and advanced biofuels are used to fulfill the climate goals of the RED II. In line with a likewise foreseeable market upscale of electric vehicles, triggered by the passenger car fleet target regulation, the necessity of SNG in the RED II framework – and therefore the price of the GHG reduction quote – is very uncertain until 2030. However, the RED II still must be implemented in national regulations, which leaves the possibility for more rigorous application into national law. More ambitious targets and multipliers for SNG can be developed for each member state. Positive elements of the RED II regulation

527 Wiedemann (2020)

528 European parliament (2009a), p. 8

529 European Parliament (2018c), p. 44

530 SNG can be used in liquid form as synthetic LNG in the shipping sector but due to the international competition an appropriate eco-premium is not foreseeable in this target market.

531 European Parliament (2018c), p. 46

in terms of the PtG technology is the clear goal setting to the EU commission to define possible power purchase concepts in the delegated act article 27 until December 2021.[532]

Another delegated act of the RED II is similarly important. As analyzed in the business case investigation of different CO_2 sources (see chapter 6.1.7), the definition of a sustainable CO_2 source is unclear and leads to economic uncertainties. Article 25 of the RED II claims that the EU commission has to evaluate until January 2021 through life cycle analysis the GHG reduction of synthetic fuels.[533] In this process, also different CO_2 sources have to be considered, which should solve the issue of an ecologically acceptable CO_2 source (see chapter 5.4.6).

An industrialization of the PtG technology requires more ambitious RED II targets like a minimum quota of synthetic fuels like SNG and fast development of the outstanding delegated acts in the national implementation of the RED II, as well as on European level in the *Green Deal* (June 2021). A minimum quota like the existing minimum quota of advanced biofuels would increase the security of investment by setting a minimum demand until 2030. With these political changes, a market ramp-up of the PtG technology is possible.

Next to the development of synthetic fuels in the RED II, an additional target market can appear in the mobility sector. The integration of innovative renewable fuels into the CO_2 standards for the automotive industry can be a powerful instrument to achieve a market-based ramp-up of the PtG technology. The EU regulation for the CO_2 emissions of passenger cars, light and heavy-duty trucks is solely based on the tailpipe emissions of the vehicles in 2020.[534] The draft of the EU Commission for the passenger car post 2020 period, which was issued in November 2017, does not consider possible GHG reductions by means of renewable fuels like SNG or other synthetic fuels.[535] In addition, the commission draft for heavy-duty trucks does not include such a possibility either.[536]

However, there is a certain political will: the voting of the EU parliament demonstrates an openness to the inclusion of CO_2 reduction from fuels in these regulations. In the voting upon the passenger car regulation, which took place on October 3, 2018, the accounting of renewable fuels was refused – but only seven votes were missing.[537] The situation is more promising in the field of heavy-duty mobility, where the

532 European Parliament (2018c), p. 128

533 European Parliament (2018c), p. 126

534 European Parliament (2009b)

535 European Commission (2017)

536 European Commission (2018)

537 European Parliament (2018a), Amendment 79

parliamentary vote has approved the integration of renewable gas on November 14, 2018.[538] The EU parliament proposed to develop a methodology of accounting renewable gas shall until 2021. During the legislative process of the EU the parliament and council, in which all member states are represented, reached the arrangement to recheck the accounting of renewable fuels in the revision of the heavy-duty regulation, which is advanced to June 2021 due to the *Green Deal* of the new EU commission.[539] For the passenger regulation, the commission must check the necessity of accounting of renewable fuels like SNG in the review process in 2023.[540] Within the process of the European *Green Deal*, the commission has announced to pre-draw the passenger car regulation also to June 2021.[541] Therefore, a new political process can be started to initiate a new target market for the PtG technology.

The accounting of renewable fuels in the fleet regulation is economically attractive due to the highest CO_2 costs of all climate regulations in the EU-27.[542] The penalty costs of the automotive industry are 95 €/g/km per car as part of the passenger car regulation until 2030. This penalty applies in case the fleet target of 95 g/km is not reached from 2020 onwards, while for the year 2020, some exceptions apply which are phased-out henceforth.[543] It is supposed that many automotive companies would not be able to achieve that target in Europe. Schiller et al. (2020) calculate penalties of €3.3 billion for the European automotive manufacturers in the year 2021. The consultancy *PA Consulting* expects overall penalties of more than €14 billion from the car industry in 2021.[544] The biggest manufacturer, Volkswagen AG, with the largest fleet of NGVs in the EU-27, would have to pay approx. €4.5 billion in 2021, which equates to 32.4% of the earnings before interests and taxes in 2018. In case the regulation was to be opened towards the accounting of renewable fuels on the fleet target values, this possibly cheaper option to fulfill the climate goals would be of high interest for the European automotive industry. Such an approach would allow implementing several advantages for the industry: not only could it lower the cost of conformity, but it would also enable the industry to safeguard precious know-how and maintain value creation in the field of the internal combustion engine. It is important to note that this complementary approach would also be of benefit for the attainment of the transition towards RE since it enhances the resilience of the power system, as discussed in the system analysis (see chapter 4.1). Last but not least, there is also an ecological benefit: the adoption of renewable fuels allows for additional GHG savings in applications and

538 European Parliament (2018b), Amendment 76

539 European Commission (2019b), p. 19

540 European Council (2019), p. 70

541 European Commission (2019c)

542 Bardt and Schaefer (2018)

543 European Parliament (2013)

544 PA Consulting (2020)

regions where the existing regulatory approach does not lead to holistic GHG mitigation because for example the ecological footprint of the battery production or the electricity mix of electric mobility are not included.

The key to such an accounting approach is economic attractiveness. In an exemplary calculation, which has been presented at an international automotive conference, a proposed mechanism is shown on how to integrate synthetic fuels like SNG in the CO_2 fleet regulation.[545] The car manufacturer must verify upon the registration of a new vehicle, that the overall CO_2 footprint of the respective car is reduced. Therefore, the company can purchase certificates of renewable fuels for the entire vehicle lifetime (e.g., 160,000 km, according to the EU commission[546]). An official authority would have to assure to check these certificates and would guarantee that a double counting in different climate regulation like the RED is prevented. The amount of renewable fuels compared to a fossil reference, which is defined in the RED, leads to clear and accountable CO_2 savings. These savings can be divided by the number of newly registered cars over their lifetime. This would result in a reduction in the fleet target value of an automotive company.

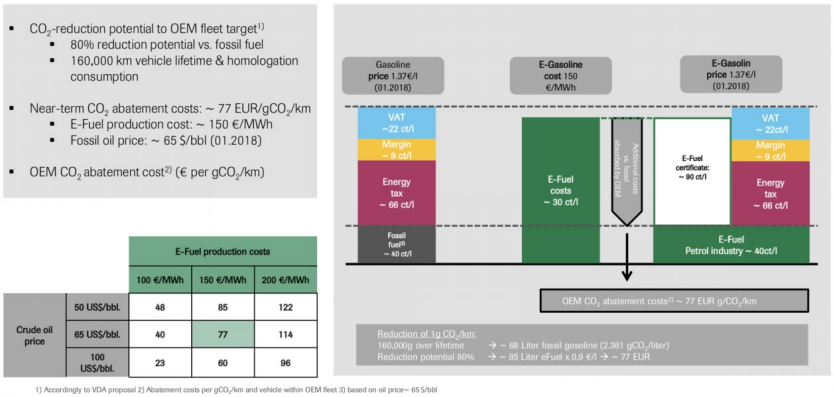


Figure 92: Exemplary calculation of CO_2 costs in the passenger fleet regulation[547]

Figure 92 shows the results from the perspective of an automotive company. For easier and more intuitive understanding, this case is calculated for liquid renewable fuels, however, the same logic can be applied for gaseous fuels. The example shows the CO_2 avoidance costs at different renewable fuel production costs and future crude oil prices. This example calculates CO_2 avoidance costs of 77 €/g/km with certificate costs

545 Block (2018), p. 10

546 European Commission (2008), p. 75

547 Block (2018), p. 11

of 90 ct/l and crude oil prices of $65 per barrel. Noticeably, this is already lower than the penalty costs of 95 €/g/km. In this case, a vehicle producer pays up to 150 €/MWh or 15 ct/kWh to compensate the elsewise incurring CO_2 penalty costs. If this eco-premium is included in the previous BM case calculations from the starting year on, several business cases would suddenly become economically feasible, which changes the perspective of attractiveness completely. Because of the already high level of avoidance cost, the car industry can instantly be the locomotion for the proliferation of advanced low carbon fuels based on sustainable energy. The only precondition would be the accounting of renewable fuels in the respective fleet regulations.

The same approach of accounting renewable fuels is possible for the heavy-duty fleet regulations. In this regulation, penalties are starting from 2025 onwards with 4,250 €/g/tkm per vehicle and increasing to 6,800 €/g/tkm in the year 2030.[548] The difference to the passenger car regulation is the much higher mileage of heavy-duty vehicles. Considering an analysis of the sales volumes per vehicle subgroup from the European automobile manufacturers association (ACEA), taking into account the payload and mileage factors of the fleet regulation and assuming a truck lifetime of 12 years, the average mileage is 15,396,641 tkm.[549] Therefore, the CO_2 avoidance cost is 276 €/t in 2025, which is less than half of the cost of the passenger car regulation (594 €/t with 160,000 km), and 442 €/t in 2030. Hence, less willingness to pay for the CO_2 reduction exist. An accounting of renewable fuels for heavy-duty truck manufacturers appears only economically feasible in combination with further promotion of renewable fuels (e.g., exemption of power taxes and fees) or additional CO_2 prices on fossil fuels. For example, the German government has already decided on a CO_2 price of up to 60 €/t in 2026.[550] It is highly probable that this price turns the accounting of renewable fuels in a worthwhile economic option for truck manufacturers.

Figure 92 also displays the energy tax as an important price component. In 2020, fossil and renewable fuels have the same energy tax. Although natural gas benefits from a reduced energy tax compared to liquid fuels (see chapter 5.2.4.1), the complete reduction of the energy tax for climate-neutral gases can further incentivize the market development of the PtG technology. SNG would become more economically feasible in the target market *power-to-gas-to-mobility* (RED as well as CO_2 standards). The new EU-27 commission has announced to revise the European energy taxation in the new *Green Deal* again by June 2021.[551] But changes in tax regulation have to be decided unanimously in the EU-27. Therefore, the political feasibility of this regulatory option is highly questionable.

548 European Commission (2019b), p. 214

549 ACEA (2020)

550 BEHG (2019)

551 European Commission (2019c)

A legislative approach to integrate synthetic fuels into the fleet target regulations has already been implemented in Switzerland. Figure 93 highlights the most important steps in that legislative process. A draft law has been approved by the council and the parliament.[552] This means that the consideration of renewable fuels will be implemented in Switzerland. The consequence of the legislation on the fleet parameter can be a reduction of 75% to 100% of the vehicle tailpipe emissions. NGVs, for example, have a CO_2 tailpipe reduction of 10% because of the high share of biomethane at gas filling stations throughout the country as explained in chapter 5.2.4.1. This mechanism can be expanded for SNG, likewise, offering even higher GHG avoidance potential.

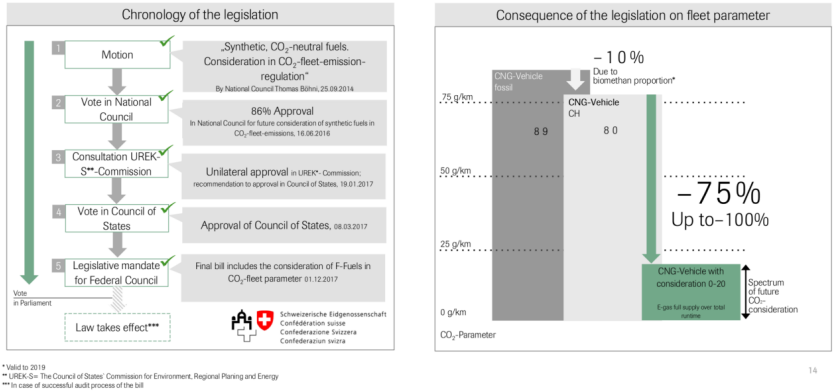


Figure 93: Legislative approach of synthetic fuels integration in Switzerland[553]

The past sections have pointed out that different climate regulations in the transportation sector exist and some of them are crucial for a future business case of the PtG technology. A market push of the PtG technology in the fuels sector, which until now is regulated by the RED, is improbable due to less expensive and politically preferred opportunities to reach the climate goals, for example, the quadruple accounting of charging power for electric cars. However, various vehicle regulations (passenger and heavy-duty) in the EU-27 and Switzerland can serve as first target markets with the high willingness of payment for CO_2 reduction. Further target markets like aviation, shipping, heat market, the chemical industry, or the energy sector require much lower production costs of synthetic fuels to be competitive compared to fossil fuels. Most of these markets are in global competition and do not have high CO_2 prices yet. To achieve these cost reductions, and therewith develop sustainable solutions for these sectors, a technology kick-off needs to start as soon as possible. After economies of

552 Swiss Parliament (2018)

553 Block (2018), 14

scale and experience have been achieved in the mobility sector, synthetic fuels from RE could also be used in these sectors.

If target markets are attractive, but German power taxes stay at current levels, the ramp-up of PtG sites will take place in other regions with more favorable regulatory frameworks. In addition, the German industrial position paper proposes a market incentive program to reduce investment costs. This program foresees a call for tenders to install up to 5 GW of PtX facilities until 2026 and the funding of the operating costs for 12 years in Germany.[554] That program would reduce the high investment costs in the early stage of technology development.

Table 50: Necessary regulatory changes to scale-up the PtG technology

No.	Regulatory changes	Due date
1	EEG apportionment: exemption by withdrawing the need of re-electrification of SNG	Immediate
2	RED II: more ambitious targets, a minimum quota for synthetic fuels like SNG and fast development of the delegated acts (article 27 and article 25)	June 2021 (Green Deal)
3	CO_2 standards: accounting the CO_2 reduction of SNG in the passenger as well as heavy-duty regulation	June 2021 (Green Deal)
4	Energy taxation: complete reduction for climate neutral SNG	June 2021 (Green Deal)
5	Market incentive program of 5 GW installed capacity until 2026	Immediate

Figure 94 shows a qualitative way of the market development of PtG technology according to the regulatory framework of different target markets in the EU-27 from the author's perspective. A market pull can be achieved if the regulations concerning individual mobility would include the use of synthetic fuels like SNG as a GHG mitigation option. At a later stage, other mobility markets like heavy-duty or shipping will raise demand, given that production costs are decreased. In the end, target markets like *power-to-gas-to-power* or *power-to-gas-to-industry* will lead to further market potential.

Finally, if the described economic parameters are adjusted by effective regulations, a scale-up can be possible, and fossil fuels can finally be replaced.

554 Bovi et al. (2019)

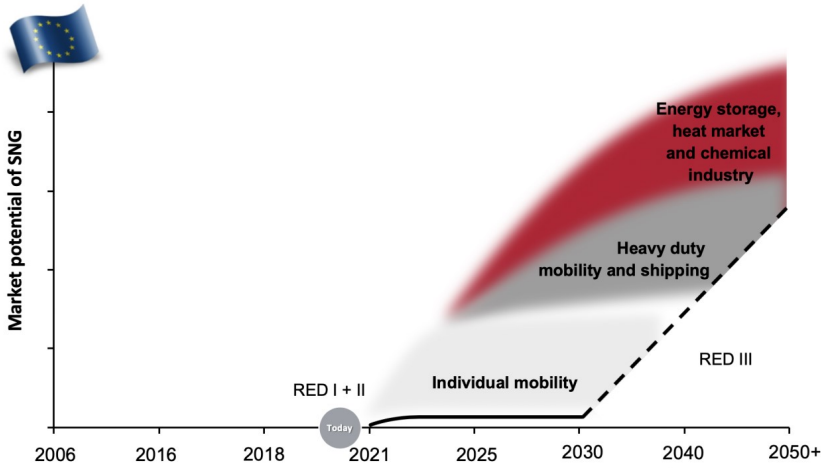


Figure 94: Possible technology pathway of the PtG technology

7.3 Evaluation

This chapter critically evaluates the dissertation. It is ensuring that all RQs are answered and that the research gaps are successfully closed. Therefore, the basic principles of scientific rigorousness, which have been defined in chapter two, are followed. In addition, limitations next to theoretical (scientific) and practical (industrial) impact are discussed to increase the value of this dissertation.

As an important critical consideration, the elaborated response to the RQs has to be checked. The first RQ (*What are the drivers of the economic situation of the Power-to-Gas technology and what is the relation between those drivers?*) is answered in chapter four with a system analysis of the PtG technology. An expert group has announced the economic drivers and has tested their relation to each other in a detailed methodology. In the end, a network of important parameters is drawn and deals as an additional input for the business modeling. Likely, of course, a different constellation of expert groups or experts from other countries could give different answers, which could result in different outcomes. But the further analysis of the value chain and network by literature review and further investigations in the following chapter, as well as the testing at the single case study, shows that the expert group has mentioned the main economic drivers. Therefore, the result of the expert group is positively tested. In addition, many studies have focused on similar economic drivers.[555] The same result could be achieved with an intensive literature review or an observation of an existing case, but relations between the economic drivers would be difficult to detect, and new

555 See literature review in 2.1

economic parameters like the *GHG reduction quota* or *avoided gas grid fees* would probably not be discovered. The system analysis allows investigating objects in a systemic way within an existing environment. Therefore, it is possible to detect the necessary external and internal parameters. The answer to RQ one sets the necessary basic framework of the business modeling.

The second RQ (*What is a general business model of the Power-to-Gas technology and what are most promising business cases?*) is answered in the fifth chapter with the construction of a general BM and their calculations in chapter six. This empirical section is the focus of the research. All derived economic drivers along the value chain and in the value network are analyzed in detail, like target markets or power purchase concepts. The quantitative data is sourced from literature, spot market analyses, or own surveys with industrial companies for the case of investment and maintenance costs. Due to a small and relatively young market, only a selected number of literary works and participating companies are available. Therefore, no claim of complete data exists. In addition, it has to be mentioned that due to the long period of research, some data is not up to date. For example, the industrial survey has been done in 2015 and 2016. Access to spot market data (e.g., day-ahead, intraday, or balancing market) has only been available until end of 2017. But wherever possible, the data is checked with latest publications and added with a reasonable price development. The validation – to a degree as far as possible – of the BM takes place in chapter six. Here, different calculations confirm the applicability and practical usage. Different BM cases for different target markets, technical constructions and power purchase concepts are developed. The most promising business cases are displayed in the results to answer the RQ and close the research gap (see chapter 7.1).

The single case study is used to answer the third RQ: *how do business models of the PtG technology work in practice?* The data from a single plant cannot validate the RQs two and three completely under all possible circumstances. But the combination of a system analysis, constructed general BM, theoretical calculations, and practical testing leads to a traceable scientific process. The dissertation is logical and top-down, constructed from system analysis to a single case study. Therefore, scientific rigor is reached. However, further theoretical and practical research is advised in the next subchapters.

The last RQ (*What are the final, strategic recommendations? How could a possible technology pathway look like?*) is considered in the conclusion. Based on the most impactful economic parameter, a strategic roadmap is built by considering possible developments of the political framework. Due to the dependency on the political framework, the answers to this RQ are formulated in the form of political recommendations. A qualitative picture is drawn as a conclusion. The answer of this RQ bases on logical steps from previous outcomes of the business case calculations and literature review.

7.3.1 Limitations

The present dissertation is limited concerning some aspects. These aspects represent further research objectives in the described proceeding of the DSR approach. It is important that the constructed configuration model for the assessment of BMs of the PtG technology is frequently expanded and updated to overcome the limitations and to further improve its performance.

The analysis focused only on the investigation of the PtG technology. For that reason, business cases of other renewable fuel forms like biofuels or synthetic liquid fuels are not considered. The most important limitation of this scientific work is the experimental validation of the constructed BM with only one investigated practical case, as mentioned above. For that reason, it is advisable to undertake further case studies to provide more validated information under different conditions, such as on larger scale plants. For example, the analysis of different power purchase concepts, carbon dioxide sources, or regulatory frameworks in different countries can supplementarily verify and adjust the general BM. The number of case studies of the PtG technology indeed depends on the number of installed PtG plants. Proceeding technology development and upscaling will automatically lead to more scientific activity and probably to more research about BM of the PtG technology.

In addition, some input data of the business case calculations, like capital and operational expenditures, come from own industrial surveys, which have been conducted during this research project. These surveys were conducted at the beginning of the dissertation project, and the number of participating companies was relatively small due to an early technology phase and a small market. Price development, for example, at spot markets, could have changed since finishing the analysis phase of this dissertation. Thus, the dissertation is limited in terms of timelines and the quantity of data. The universal design of the BM allows the adoption of updated data, and new business cases can be calculated in a further theoretical research or practical applications. Therefore, quantitative calculations might change with updated data or different regions, but the qualitative economic model of the PtG technology is applicable.

Another research constraint, which is in line with both previous limitations, is the focus on market conditions in Germany (except for the MENA-case). The calculations of different business cases are affected by this limitation. But again, the general BM has to be adjusted in specific cases if individual power market mechanisms exist or if CO_2 credits are considered in a different way. Therefore, further research activity is recommended to analyze the economic situation of the PtG technology in specific countries. An example is Switzerland, where different target markets like the mobility sector are possible (see chapter 7.2) under specific conditions. Therefore, before transferring the general BM to another region, a system analysis (see chapter 4) is recommended to detect all new economic drivers and their relation to each other, for example, other power taxes or fees or eco-premiums.

The system analysis has been conducted with a small group of experts from specific industries and subjective opinions. Therefore, the research has no claim to achieve complete knowledge of the role of PtG in the energy system. But important economic parameters and their relation to each other are identified. The detailed analysis of the value chain and value network of the PtG technology by literature review, market analyses, and surveys is further compensating the weakness of the system analysis.

In total, the dissertation has its focus more on the holistic construction of the general model of the PtG technology than on the partial considerations of single parameters, for example, single spot markets. The research aim is the economic consideration of specific business cases and not a detailed analysis of individual parameters e.g., the correlation of the power and gas market. Therefore, an additional limitation exists regarding the level of detail of the analysis of single input parameters.

Table 51: Limitations of the dissertation

No.	Limitation	Research recommendation
1	Most of the economic parameters are limited to the market or regulatory conditions in Germany	The research methodology should be applied in other regions
2	Practical validation of the constructed BM on only one case study due to few installed PtG plants	Further case studies on the PtG technology
3	Quality of data: due to many temporary parameters (e.g., CAPEX, power price) the currentness of all data is a limitation. Access to data is sometimes also a limitation (e.g., GHG reduction quota). Therefore, some data could be more analyzed than others	Constant updates of the market data of all economic parameters
4	System analysis: small group of experts from specific industries and regions	Repetition of the system analysis in a broader context

7.3.2 Further Research Recommendations

According to the mentioned limitations, further research is suggested. This chapter is divided into research recommendations from the perspective of science, industry and politics. These market participants are representing the most involved stakeholders.

From a scientific perspective, several recommendations appeared during the research period. In the value chain investigation, different innovative and technical RQs arose. These continuative topics are grouped by their BM input parameter.

From a scientific perspective, a further development of the configuration model is highly recommended. The model can be transmitted to other regions or applications. The model can be further expanded with new economic drivers, for example, new target markets if political regulations changes or new power purchase concepts. In addition, it is suggested to frequently update the data. This is in line with the DSR approach, in which the artefact (in this case the BM) is challenged by scientific scholars to improve its performance. Therefore, the researcher goes back to stage 2 of the DSR approach

and defines new objectives (see chapter 2.4.1). These objectives have to be integrated in the configuration model, which of course needs new verifications afterwards. This chapter describes possible further research objectives to improve the performance of the developed DSR model. For further research, the model is public available on inquiry.

Further research objectives are, for example, the target market *power-to-gas-to-heat* or the usage of process heat often depends on the availability of an appropriate infrastructure. However, district heating grids generally exist in metropolitan regions and not in rural areas, in which PtG plants would preferably be built, because of the better availability of renewable power generation. Therefore, a study is recommended to estimate the number of locations for the business case *power-to-gas-to-heat* (see chapter 6.1.3). Incomes of heat sales are, therefore, not always possible. In addition, extra costs for heat usage, for example, the implementation of heat exchanging devices, are not included in the CAPEX and OPEX of the present business case calculations. Also, combinations with industrial plants, for example, cement or steel production, can lead to different outcomes and should be investigated.

Many studies have been done regarding *CO_2 sources* and their potential amount, which is discussed in chapter 5.4.6. There are several innovative technologies with less available data in terms of economic parameters like efficiency, CAPEX and OPEX. On the one hand, for example, the necessary CO_2 quality of the biological methanation is less known to the public. This dissertation calculates with identical costs of CO_2 separation, like the chemical methanation. But less cost-intensive installations could be possible in the future, as mentioned in the appendix (see chapter A.6). On the other hand, data for the CO_2 capture from ambient air arrives from single sources. Therefore, a huge range of capital and operational expenditures exist. Certainly, additional technical and economic research is advised in this area.

This work calculates with average forecast errors of *power prices* for all markets. In reality, the forecast error differs between short- and long-term markets. The impact of the forecast error with approx. 11% of additional power costs is quite high and demands further research in combination with PtG plants. In addition, the forecast error is only implemented for power markets. A forecast error for other market-driven economic parameters like gas and heat sale profits or the GHG reduction quota is not included yet.

In addition, further research is required for the *price development* of different economic parameters. Especially if future business cases are calculated, the price development has a major impact. This dissertation assumed linear increasing price developments regarding single studies. Further detailed scientific research should verify this assumption or expand the BM with more accurate price and maybe non-linear developments.

Regarding CAPEX of peripheral devices, the need for hydrogen or carbon dioxide storage facilities is not sufficient considered yet. Additional costs of 10% for the balance of plant are added and verified in the single case study. Different power purchase concepts and operation modes can require gas reservoirs for hydrogen, carbon dioxide or SNG. It can be economically worthwhile to install gas storage units and operate the PtG plant in partial load to avoid losses of start-ups of the electrolyzer or methanation. The case study (see chapter 6.2) has shown that partial load is possible. Therefore, the general BM would need to be expanded in the case of CAPEX and OPEX expansion of storage units and economic advantages of operation in partial load. Also, a comparison of the necessarily used area of PtG and other production plants of RE carriers is missing. If SNG is imported from regions with water shortage the economic effect of installments of water desalination units needs to be analyzed as well.

As mentioned in the appendix while discussing the transition of the energy system (see chapter A.2), the question arises if the investment in hydrogen infrastructure and installations of new techniques like fuel cell vehicles or heating systems is macroeconomically more favorable than the efficiency losses of the old infrastructure and techniques like the combustion engine. Although some macroeconomic studies are addressing this issue, a detailed comparison is recommended by taking into account the economic insights of this work.

Overall, the further investigation of the application of the general BM in other countries, under different conditions and the examination of other case studies is a general research recommendation. In that case, the BM can be expanded, for example, with additional power purchase concepts or different regulatory cost parameters. Also, the system analysis should be constantly updated and conducted with a broader and more international group of experts.

From an industrial perspective, the following recommendations have been identified: first, the upscaling potential of the biological methanation is unknown at the moment. Only a few datasets from manufacturers exist, and there is no valid case study. Therefore, BM parameters like efficiency, CAPEX, OPEX, start-up time and dynamic range should be explored in further research. Also, the industrial implementation of the SOEC electrolyzer technology has not taken place until now. For that instance, the future potential of SOEC with an existing exothermic process heat source requires further research. The industrial survey with manufacturers of electrolyzers and methanation units should be repeated with the latest market information.

An interesting industrial case study can be the internal pool management of an energy supplier as an additional power purchase concept. As mentioned in chapter 5.3.1, energy providers have to fulfill their forecasted energy schedule. If less energy is consumed or more power is generated than forecasted, the company must pay penalties to the grid operator. In that case, the operation of a PtG plant can be of interest to balance the internal pool energy. This case can be an additional power supply concept,

which is not analyzed in the present investigation of the value chain. The newly exposed data can be integrated into the general BM and the economic result can be theoretically calculated. This demonstrates the flexibility and potential of expansion of the constructed general BM.

From a political perspective, different recommendations are derived from this research. The results of the theoretical, as well as practical investigation, highlight that the political framework hinders an economically feasible business case. Therefore, the technology pathway in chapter 7.2 includes several political recommendations.

Another political definition is required in the aspect of ecological carbon dioxide sources, as mentioned in chapter 5.4.6. Next to biological CO_2 sources, unavoidable emissions, for example, from cement plants and CO_2 from ambient air, should be included. A scientific study should quantify the ecological and economic impacts of each CO_2 source. This is also addressed in a delegated act of the RED II.

On the one hand, an attractive target market can be generated if the European CO_2 fleet regulations for cars were changed from a pure *tank-to-wheel*, which is only considering the vehicle, to a more holistic *well-to-wheel* approach, which also includes the fuel production. This political action would generate the first demand for PtG products. On the other hand, energy storage facilities must be integrated into the power market design. If plants, which are converting energy from one form to another, are treated like end-consumers and have to pay all power taxes and fees, an economically feasible business case of the PtG technology is not foreseeable. Regions have to be defined, in which the EEG apportionment is reduced for demand-side and grid-friendly operating plants. Additional political recommendations regarding energy taxes or the national implementation of the RED II are mentioned in the previous chapter.

In sum, the critical evaluation has depicted different limitations, which result in further research recommendations in perspective from scientific, industrial, and political stakeholder perspectives. However, it is intended to expand and assemble the present basic model with further research activities. This dissertation is providing the basic guideline and structure of how to handle business modeling of carbon capture and utilization technologies like PtG.

7.3.3 Theoretical and Practical Impact

The contributed theoretical impact is a general model for a comprehensive technology benchmark, including a systemic approach, in-depth analysis of the value chain and validation with existing data. In addition, new economic knowledge of this innovative technology is supporting further research in case of investment costs, power purchase concepts, operation time and in general business modeling of energy storage innovations. Business case calculations of PtG could be expanded e.g., with methods like bootstrapping to highlights the distribution of the outcomes.

From a research perspective, the combination of system analysis (see chapter 4) with the technology school of business modeling is an innovative approach to analyze the economic state of new technologies. A comprehensive research methodology with a construction of a general BM and a theoretical as well as practical testing of the theory develops a coherent and rigorous scientific work, which can be applied for further research. This is in line with the theory development and construction of hypotheses and empirical testing and falsification. The positive testing of the general BM demonstrates the functionality and applicability under the present circumstances. It is also in line with the research goal to shed light on the economic situation of PtG from different perspectives.

Next to the theoretical impact, the possible practical impact is important in terms of scientific work (see chapter 2.3). The practical impact is the achievement of detailed knowledge about the economic situation of the PtG technology. With this knowledge, interested players from the energy, fuel or automotive industry, as well as financial companies, can gain insights in case of future investment decisions. The detailed cases show opportunities and risks of the PtG technology. Interested stakeholders can develop strategic roadmaps of how to handle this technology. The existing calculation and distribution model can be used to analyze single scenarios. However, if the political framework or single economic parameters will change in the future, the general BM can be adjusted and can supply outcomes.

As the research recommendations have shown in the previous chapter, the practical interest from different stakeholders can be considered. Even operators of PtG plants can adopt new business cases with innovative power purchase concepts or calculate the participation at different target markets.

The single case study (see chapter 6.1.9) displays a practical approach to validate the general BM at one event. In addition, it presents the first technical and economic documentation of an operating, industrial scale PtG plant. Important practical experiences derive from this investigation. Both the theoretical and practical outcomes can be used to improve the technology development of PtG.

In the end, the results have confirmed the personal motivation and interest of the dissertation. The PtG technology can solve multiple challenges for different sectors in a RE system if political modifications open a pathway to an industrialization and, therefore, further decrease the production costs due to economies of scale and experience effects. The political recommendations have been developed for Germany. A first attractive target market has been identified with the transportation sector. SNG from renewable sources can offer climate-neutral mobility for passenger as well as heavy-duty vehicles. Business cases of other target markets have also been considered. In the long-term perspective, SNG can additionally contribute to climate-friendly solutions in the power, industry, and heat sector. The developed general BM and its testing on different applications leads to various insights: new power purchase concepts like the

asset-backed trading at the intraday market, efficiency losses due to many start-ups of the methanation unit at different power markets or possible political implementation like the accounting of SNG in the CO_2 fleet regulation are just a few examples. From greater considerations (system analysis or business model innovation) to detailed investigations (single case study at an existing instance or the operational behavior of PtG plants at the secondary balancing market) this dissertation covers different levels of an economic analysis and, therefore, accomplishes the research goal of a comprehensive, economic benchmark of the PtG technology.

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I heard about PtG for the first time during my master study program in energy- and environmental management at the University of Flensburg. I have been astonished and wondered whether this simple principle can really solve so many problems of the energy transition across different sectors. But where is the catch? What are the main obstacles of the PtG technology? I decided to put further effort on that topic and joined the car manufacturer AUDI AG, who has installed the world first, industrial scale PtG plant in 2013.[556] I wrote my master thesis about different power purchase concepts of the PtG technology.[557] Our team has solved technical issues, realized new, innovative power purchase concepts (first PtG plant with prequalification at the secondary balancing market[558]) and brought necessary public and scientific attention on this technology. We have still developed the most sustainable mobility concept and brought it successfully on the market and to the customer. I would like to thank my colleagues Dr. Hermann Pengg, Reiner Mangold, Reinhard Otten and Daniel Böhner for all the support, friend- and leadership that still inspires me.

After five valuable years I noticed that a market ramp-up of the PtG is only possible if the political framework changes. For that reason, I decided to work for the German association of the automotive industry (VDA) to activate an economic attractive first target market for PtG. Here, I wish to thank my colleague Philipp Ellett, who had the pleasure to proofread this dissertation. In addition, I would like to thank Korbinian Lang for the explanation of all the secrets of finance and investment management.

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In the end, my acknowledgement goes to my friends and family, who I have spent less time with during that time. But their sympathy and patience helped me to finish this work. Especially, my love Lena Schiller has to be mentioned here. Thus, I dedicate my dissertation to her.

556 Audi (2014)

557 Block (2013)

558 TenneT (2015)

Appendix

A.1 The Road to a Future Energy System

It is difficult to identify a starting point of the transformation of the energy system from the fossil to the renewable age. First social trends towards environmental awareness have been detected during the first and second oil crisis in the 1970s. The political dependency on fossil resources has arisen as a main argument to develop alternative energy sources across different energy sectors. In addition, fossil fuels are limited in their natural resources. The following figure illustrates the enormous increase of fossil energy production and the limitation of these resources. Different studies have exposed a peak of oil production during the first half of the 21st century.[559] Lovins (2011) declares "defossilizing fuels" as the main task of the energy economics in this century. However, the end of the fossil energy system is broadly accepted as climate agreement proves.[560]

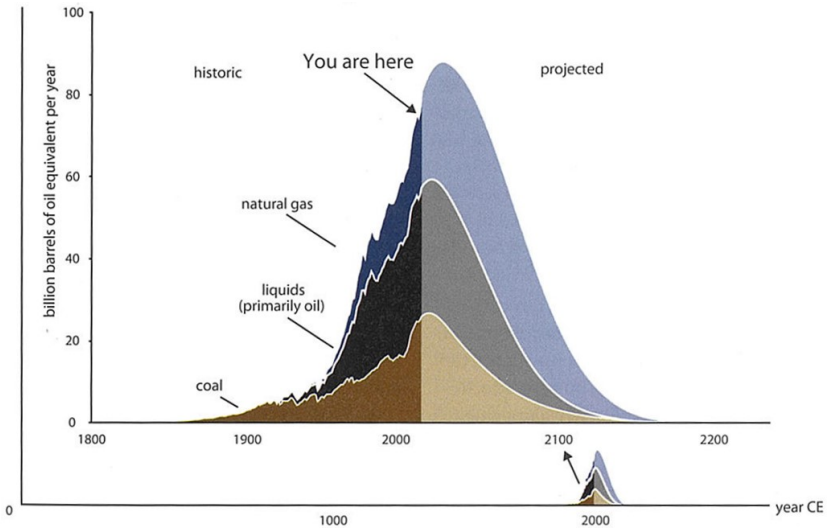


Figure 95: Global fossil fuel production[561]

559 Hirsch et al. (2005), Brockmann et al. (2012), p. 93

560 UNFCCC (2019)

561 Lovins (2011), p. 7

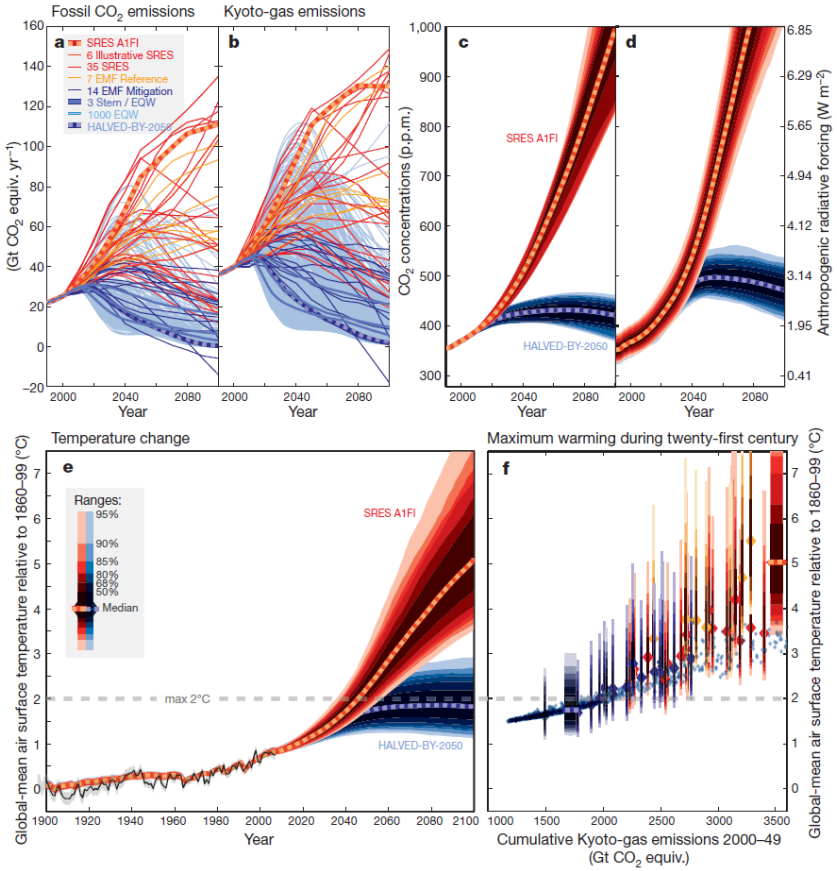


Figure 96: Correlation of the CO_2 concentration and the global temperature[562]

The global production and consumption of fossil fuels lead to a sudden combustion of million-year bounded hydrocarbons and enlarge the carbon dioxide concentration in the atmosphere, which leads to global warming effects.[563] The awareness of the climate change has been increased since first reports from the intergovernmental panel on climate change in 1990 and is nowadays broadly accepted as well. Figure 96 draws a picture of the correlation of the increase of CO_2 concentration and the global mean temperature. It can be identified that the starting point of the increase of atmospheric

562 Meinshausen et al. (2009), p. 1160

563 Meinshausen et al. (2009)

CO_2 concentration and temperature raise is equal. Therefore, the fossil energy system with his enormous anthropogenic CO_2 emissions is driving the global climate. The theory of the anthropogenic global warming effect has been tested and discussed until a measurable majority of 97% of researchers agreed.[564]

Both observations have led the society and therewith the politicians to rethink the energy system. The energy economy can be divided into three different end-consumer sectors: the electricity, heat and mobility demand. The development of RE in different sectors is illustrated in Figure 97.

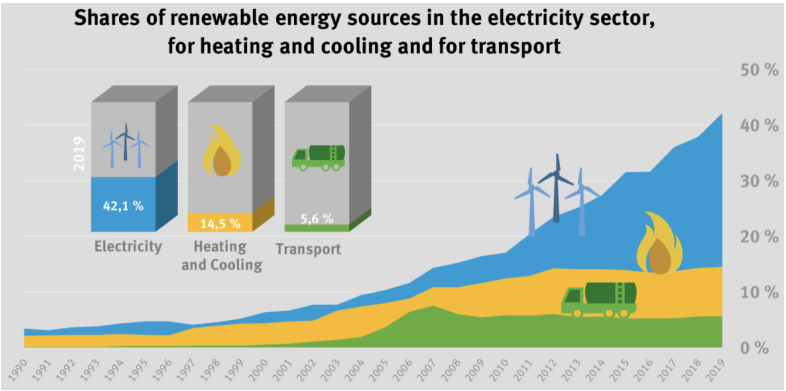


Figure 97: Development of renewable energies in Germany[565]

As a starting point of the transition in the power sector in Germany the introduction of the RE law (EEG) can be considered in April 2000. Due to fixed energy feed-in tariffs the share of RE in electricity generation rose to 42.1% in 2019.[566] These promotions for wind- and solar energy as well as biomass usage have supported technology development, activated economies of scale and achieved almost equal power production costs than the fossil industry.[567] In the heat sector similar regulation has sustained environmental-friendly inventions like biomass heating systems, improved heat insulation and solar as well as geothermal energy and heating pumps.[568] The mobility sector is influenced by different sustainable regulations (see chapter 7.2). On the one hand the petroleum industry is forced to achieve a RE share of 14% in 2030.[569] On the other

564 Anderegg et al. (2010)

565 UBA (2020a)

566 UBA (2020a)

567 IEA (2015), p. 4 f

568 EEWärmeG (2015)

569 European parliament (2019c)

hand, automotive companies have to decrease their average tailpipe emission of passenger cars to 95 g/km in 2021.[570]

Figure 97 also shows that the development of RE across the energy sectors differs. While the increases of RE in the power sector is quite impressive, the heat and mobility sector are lagging. Therefore, only a total share of 15% RE of the primary energy has been achieved in 2019. Germany's energy system still depends on mineral oil (35%), coal (18%), natural gas (25%) and nuclear power (6%).[571]

Technologies, which are offering sustainable solutions for the mobility and heat sector, are needed. Today's energy system is not a closed cycle and, therefore, it is ecologically harmful. Reduction of fossil fuel consumption as well as the recycling of carbon dioxide in a closed loop system helps to reduce the level of climate-relevant emissions. These important *system characteristics* have been described in the system analysis (see chapter 4). PtG can play a major general to improve the combination of fluctuating RE across all energy sectors. A consequent expansion of RE is necessary to avoid global warming and dependency on fossil fuels.

A.2 Transition of the Energy System

As highlighted in the previous chapter, the energy system is in transition from a fossil energy system to a RE system. This transition includes changes of technologies, business models, infrastructures, political regulations, social acceptance and so on. Many of these changes are disruptive. For example, some new technologies or business models are completely different from the previous ones. This disruptive change opens room for new innovations and destroys old economy models. The different stages of energy systems are analyzed by own observation from the author's perspective and from literature sources. Partly the transition has been discussed with the expert group during the system analysis.

First, the energy system is analyzed to achieve a full understanding of systemic elements of the fossil-based energy system and their interactions. A systemic picture of the fossil energy system is drawn in Figure 98. The outer circle displays the usual dominating fossil energy sources, the middle circle shows the available infrastructure and the inner circle illustrates the demand sectors and the technologies involved. All possible intersections are charted. Different technologies allow combination of demand and supply. Fossil sources to the power grid are coal, oil and nuclear energy in Germany. A first intersection is identified by generating power from natural gas in gas power or combined heat and power plants (CHP). The CHP and fossil power plants are producing heat and, therefore, combining the power and heat sector. The heat

570 European Parliament (2013)

571 UBA (2020b)

sector is mainly supplied by heating oil and gas heating systems. Gas storage units in the gas grid are balancing the seasonal demand of the heat sector.

The energy demand of the transportation sector is satisfied by gasoline or diesel, which are derivatives of the crude oil refinery. In small scale also NGVs exist. In addition, alternative technologies could be used in the fossil energy system but are not economically competitive. PtH or heat boilers are coupling the power grid and the heat sector and PtG is the only technology, which is converting energy from the power to the gas grid. But however, why should energy be converted if it can be directly used in the power, heat or mobility sector? There is no necessity for cross-sectorial technologies in the fossil energy system. Also, battery storage systems are not needed because energy is produced in time of consumption. Supply and demand are regional and temporal synchronized. Therefore, energy storage, except of strategic storage, is not needed as production follows demand exactly.

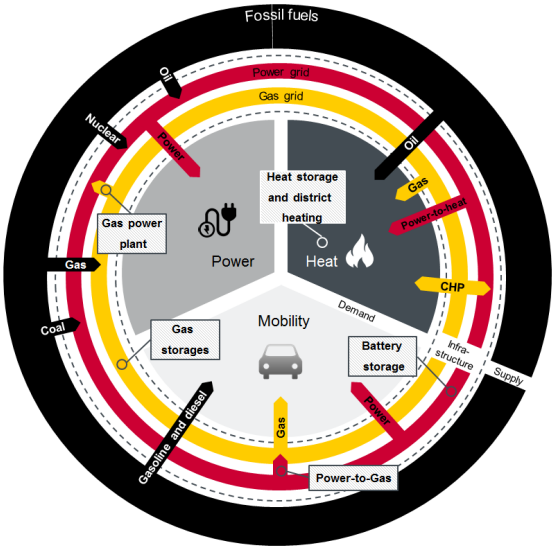


Figure 98: Schematic illustration of the fossil energy system

Due to social and political changes the energy system is transformed from the fossil to the renewable age. The reasons and drivers for this change have been explained in chapter A.1. The intermediate state of the fossil to the RE system is shown in the following illustration. Renewable technologies grow, while the fossil technologies are still present. The complexity of such a *double* energy system is higher than that of the fossil energy system. Next to the fossil fuels the renewable sources are added. New energy sources are wind, solar, biomass, hydro and geothermal energy. Hydro energy often

already exists in the fossil energy system but is more important in the renewable era. Most of the renewable sources are directly converted to electric power. Biomass can be used in the heating sector, for example, as pellet heating or can be gasified in a biogas plant. The biogas or biomethane, if it is upgraded and injected into the public gas grid, presents a RE source of the gas grid. Especially in combination with CHP plants biogas gets an important option for decentralized energy supply. In the mobility sector also biofuels from biomass and direct power for BEVs can be used. The intermediate energy system is marked by a high competition of existing and new, penetrating technologies.

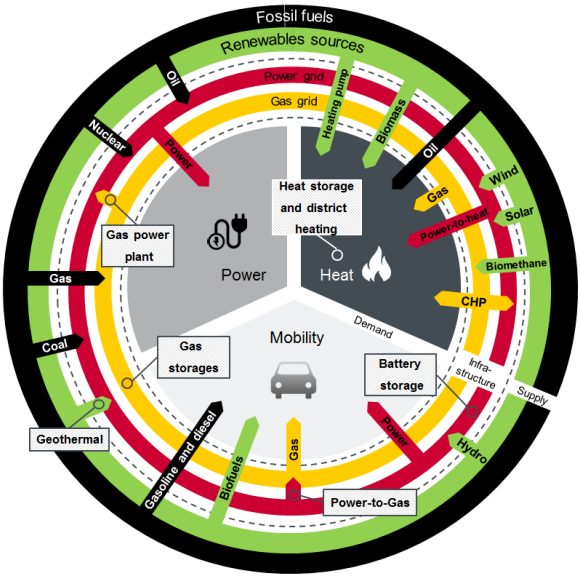


Figure 99: Schematic illustration of the intermediate energy system

This transition period identifies arising issues of the RE system. Whereas during the fossil energy system the demand and supply has been synchronized, the energy production in the renewable system depends on weather conditions. Demand and supply are separated regionally and temporally. Consequently, in times with a lot of wind and sunshine the renewable power production increases. The demand stays constant and periods exist with more supply than demand of energy. As a result, the power price at spot markets or other platforms decrease significantly to a specific amount as discussed in chapter 5.3.1.1. Normal market mechanism of demand and bid does not work because REs do not have operational costs. The investment costs are covered by guaranteed feed-in tariffs. Therefore, they can offer energy with low energy prices

and replacing fossil energy sources. Otherwise in times without wind and solar power, power prices are increasing, and storage solutions are becoming important.

The fluctuating power generation is enabling new technologies that can be operated intermittently and corresponding business models. In the heat sector for example, cheap electricity can be used in water boilers as PtH technology or biomethane can fuel the gas heating system. In addition, political regulations are supporting the application of heating pumps or solar heating. In the mobility sector, biofuels and direct power utilization in BEV are subsidized and, therefore, are opening new business areas for the petroleum and automotive industry.

As mentioned, storage opportunities become more important to stabilize the fluctuating REs. Battery systems allow short term energy storage due to the limit capacity.[572] The enormous storage capacity of the PtG technology is discussed in the following chapter. PtG is connecting the power and the gas grid and can, therefore, store RE in the gas grid, which can be used in all demand sectors.

The third diagram represents the future energy system without any fossil sources due to social and political preferences and has been discussed in the system analysis. Here also the figure is displayed (see Figure 17). In such a system, demand is satisfied by fluctuating renewable sources. Therefore, especially the storage facilities must be expanded to guarantee a constant energy delivery in the power sector. In the heat and mobility sector three renewable sources are competing: the direct use of electricity with PtH or BEV, the use of bio- or synthetic methane (SNG) or the use of biomass as fuel for cars and heating systems. Each different use case is satisfying different requirements. The direct electric usage is offering an efficient and emission-free option and should be used wherever possible. The biomass use is limited due to ecological issues, which are discussed in chapter 5.4.7. The missing gap – if electric use does not fit the consumer needs and biofuels are saturated – can be filled with renewable fuels like SNG.

For the gas grid only SNG and biomethane remains as energy sources. Therefore, the gas infrastructure can only be used if these technologies are further developed. The advantages of the coupling of two already existing infrastructures are discussed in the description of the target markets (see chapter 5.2). However, it is also possible that a third infrastructure is constructed. An often-discussed option is the hydrogen economy. A hydrogen infrastructure can replace or upgrade the gas grid[573]. Hydrogen can be also produced with the PtG technology with higher efficiency than the methane production (see chapter 5.3.5). Hydrogen can be repowered in fuel cells for power, heat, and mobility demands. An important question of the energy transition is if the

572 Sterner and Stadler (2014), p. 36

573 In some cases, the direct injection of hydrogen in the gas grid is possible (see chapter 5.4.4). Therefore, also a reconstruction of the gas grid is foreseeable.

investment in a hydrogen infrastructure and installations of new techniques like fuel cell vehicles is macroeconomic cheaper than the efficiency losses of the existing infrastructure and techniques like the methanation and internal combustion engine. This further research is recommended in the conclusion (see chapter 7.3.2). A full decarbonation or better *defossilization* stays questionable because hydrocarbons are required for different purposes like industrial processes or mobility like aviation or shipping. Nevertheless, PtG as a chemical energy storage for both infrastructures gas and hydrogen is needed in a future, RE system.

In sum, the analysis of different states of the energy systems clarifies possible business cases of PtG in the future. It all depends on the paste of renewable transformation and on the development of competitive technologies. A basic understanding of the transformation of the energy system and depending circumstances has been achieved. Important, competing technologies have been mentioned and discussed.

A.3 System Analysis

System	Parameter Influence from ↓ to →	Amount of fluctuating renewable energy	Installed capacity of PtG	Installed capacity of other storage technologies	Availability of fossil energy resources	Infrastructure costs	Economy of PtG plants	CAPEX	Costs at power markets	Costs of power taxes and grid fees	Gas sale	Heat sale	Oxygen sale	GHG quota	Avoided gas grid fees	Efficiency	Maintenance	Financial information	Lifetime	Active sum	Passive Sum	Product	Quotient
Energy system	Amount of fluctuating renewable energy		0	0	3	2	0	0	3	3	0	0	0	0	0	0	0	0	0	11	5	55	2.20
	Installed capacity of PtG	0		3	0	1	0	3	0	0	0	0	0	0	0	3	3	0	3	16	7	112	2.29
	Installed capacity of other storage technologies	0	3		0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	6	4	24	1.50
	Availability of fossil energy resources	3	0	0		1	0	0	2	1	0	3	3	1	0	0	0	0	0	14	4	56	3.50
	Infrastructure costs	2	1	1	1		0	0	2	3	1	1	0	0	3	0	0	0	0	15	5	75	3.00
PtG technology	Economy of PtG plants	0	3	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	3	16	48	0.19
	CAPEX	0	0	0	0	0	2		0	0	0	0	0	0	0	0	0	0	0	2	9	18	0.22
	Costs at power markets	0	0	0	0	0	2	0		0	0	0	0	0	0	0	0	0	0	2	7	14	0.29
	Costs of power taxes and grid fees	0	0	0	0	0	3	0	0		0	0	0	0	0	0	0	0	0	3	7	21	0.43
	Gas sale	0	0	0	0	0	1	0	0	0		0	0	3	3	0	0	0	0	7	4	28	1.75
	Heat sale	0	0	0	0	0	1	0	0	0	0		0	0	0	0	0	0	0	1	9	9	0.11
	Oxygen sale	0	0	0	0	0	1	0	0	0	0	0		0	0	0	0	0	0	1	6	6	0.17
	GHG quota	0	0	0	0	0	3	0	0	0	0	0	0		0	0	0	0	0	3	4	12	0.75
	Avoided gas grid fees	0	0	0	0	0	1	0	0	0	0	0	0	0		0	0	0	0	1	6	6	0.17
	Efficiency	0	0	0	0	0	0	0	0	0	3	3	3	0	0		0	0	0	9	3	27	3.00
	Maintenance	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0		0	0	2	3	6	0.67
	Financial information	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0		0	3	0	0	0.00
	Lifetime	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0		3	3	9	1.00
Sum		5	7	4	4	5	16	9	7	7	4	9	6	4	6	3	3	0	3	102			

Figure 100: Cross-impact matrix of the system analysis

		2015			2020			2025		
		1 MW	5 MW	20 MW	1 MW	5 MW	20 MW	1 MW	5 MW	20 MW
Technology (PEM, AL, HT)										
Manufacturer										
Model Name/Type/Series										
Total System Peak Power	kW									
Peak H2 Output	Nm^3/h									
Total System 100% Power	kW									
100% H2 Output	Nm^3/h									
Total System Cost	000 Euros									
O&M Cost (Excluding Electricity)	000 Euros/a									
HHV Efficiency at100% Power	%									
Heat Requirement Operation	kW									
Heat Requirement Standby	kW									
Electrolyser Module Temperature	°C									
Product Gas Temperature	°C									
Electrolyser Module Pressure	barg									
Product Gas Pressure	barg									
Stack Design Life	a									
Hot Start Time to Peak Output	s									
Dynamic Operating Range	%									
Gas Quality	in %: H_2; O_2; H_2O									
Standard Warranty Period	a									
Remarks										

What kind of installed capacity is necessary for the investment costs in 2016, 2020 and 2025?

year	Installled in MW
2016	10 for example
2020	100 for example
2025	1000 for example

For data protection regulations please mark with a cross:

☐ Data is allowed to be published ☐ Anonymized data is allowed to be published ☐ Data is not allowed to be published

Date, Signature

Figure 101: Exemplary data sheet of the electrolysis survey

Manufacturer					
Technology					
Construction Type					
H2-Input	Nm³/h		200	1000	4000
Amortization Period	a				
Power Consumption Standby	kW	2016			
		2020			
		2025			
Power Consumption Operation	kW	2016			
		2020			
		2025			
Heat Consumption Standby	kW	2016			
		2020			
		2025			
Heat Consumption Operation	kW	2016			
		2020			
		2025			
Investment Costs	I	2016			
		2020			
		2025			
Maintenance Costs	I/a	2016			
		2020			
		2025			
Efficiency	%	2016			
		2020			
		2025			
Capacity (CH4)	Nm³/h	2016			
		2020			
		2025			
Input Gases Concentration	in %: CH4; H2; CO2; H2O	2016			
		2020			
		2025			
Input Pressure	bar	2016			
		2020			
		2025			
Output Gases Concentration	in %: CH4; H2; CO2; H2O	2016			
		2020			
		2025			
Output Pressure	bar	2016			
		2020			
		2025			
Technical Lifetime to Reinvest	a	2016			
		2020			
		2025			
Start-Up Time to Full Load	Sec.	2016			
		2020			
		2025			
Dynamic Range	%	2016			
		2020			
		2025			
Degration Rate Catalyst Nutrient Solution	h	2016			
		2020			
		2025			
Warranty	a	2016			
		2020			
		2025			
Remarks					

What kind of installed capacity is necessary for the investment costs in 2016, 2020 and 2025?

year	Installled in MW	
2016	10	for example
2020	100	for example
2025	1000	for example

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Date, Signature

Figure 102: Exemplary data sheet of the methanation survey

A.4 Water Electrolysis

The water electrolysis is one of most important technical components in the process chain of the PtG technology from an economic perspective[574]. Water electrolysis means splitting water in hydrogen and oxygen with electric energy. Although water electrolysis has been invented for more than 200 years, it is not commonly used for hydrogen production in the chemical industry yet.[575] The most practiced technique of hydrogen production is the reformation of fossil hydrocarbons (natural gas) due to low fossil energy prices.[576] This situation can change by the energy transition from fossil to RE. Fluctuating RE can decrease the power price in certain hours and the price of fossil fuel can increase because of climate regulations. However, the water electrolysis is a necessary technology to store large amounts of surplus of electric energy.

Hydrogen is mostly used in the production of fertilizer (45%) and in fossil fuel refineries (46%).[577] Especially the usage in the refinery opens a potential business case of renewable hydrogen because it displays a direct blending of fossil fuels with RE and is promoted in the RED II.[578] The overall chemical equation of the water electrolysis is shown below. The water molecule consists of two hydrogens and one oxygen atom. The separation is an endothermic reaction. Therefore, energy is demanded to start and execute the process.

Equation 0-1: Reaction of water electrolysis[579]

$$H_2O \rightarrow H_2 + 1/2O \qquad \Delta H_R: 286\ kJ/mole$$

In the following part, three different kinds of electrolysis are described. First, the alkaline electrolyzer (AEL) as the most established technology is explained. Second, the polymer electrolyte membrane electrolyzer (PEM) as an upcoming alternative technology is briefly explicated. At last, an outlook on the solid oxide electrolysis cell (SOEC) under specific conditions is exposed.

Figure 103 is showing the development of installed power of the different technologies of electrolysis for PtG in Germany. Two different major events have marked this development: the installation of the Audi e-gas plant in December 2013 with a 6 MW alkaline electrolysis and the opening of 6 MW PEM electrolysis of Stadtwerke Mainz AG together with industrial companies like Siemens AG and Linde AG in 2015. In the latest years a development towards PEM systems is observable.

574 See analysis of the value chain 5.3

575 Geitmann (2002)

576 Sterner and Stadler (2014), p. 300

577 Gardiner (2012)

578 European Parliament (2018c)

579 Mergel et al. (2012)

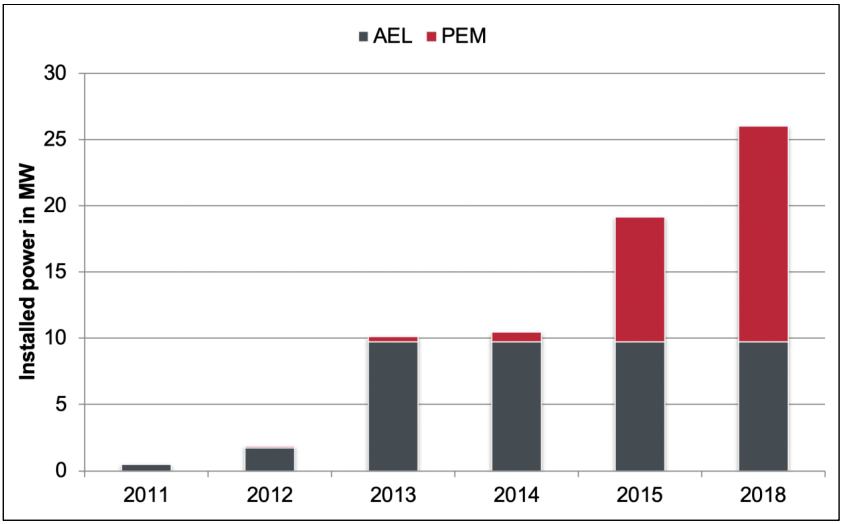


Figure 103: Cumulative development of installed power of electrolysis in Germany[580]

As mentioned, water electrolysis plays a certain role in PtG systems. The most important technical properties of electrolyzers are dynamic mode of operation, wide partial load ranges, efficiency, gas purity, compact stack design, high unit power densities, reliability, production capacities as well as low investments (CAPEX) and operational costs (OPEX).[581] The results of the economic data are presented in the chapter 5.3.3.

The water electrolysis is often surrounded by other components. In the beginning the water treatment is necessary to clean the tap water by filtration and demineralization. After electrolysis, the hydrogen stream consists of humidity and possible parts of potassium hydroxide (KOH), if AEL is used, and oxygen. Therefore, a further cleaning and drying process is necessary. Other additional components are explained in the chapter of peripheral devices (see chapter 5.4.2).

A.4.1 Alkaline Electrolysis

AELs are representing the most developed and matured kind of electrolysis.[582] Basically the installation is built as follows and is illustrated in Figure 104 below: two electrodes, which stand in an aqueous conducting fluid, are connected to direct current and separated by a diaphragm. The fluid or electrolyte consists of 20% to 40% of KOH.

580 Dena (2015) and TÜV Süd (2020)

581 Lehner et al. (2014), p. 20

582 Sterner and Stadler (2014), p. 320

This base is transporting the hydroxide ions from the cathode to the anode through the separator. Therefore, following reaction takes place in the cell of an electrolyzer.[583]

Equation 0-2: Reaction at the cathode of AEL

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Equation 0-3: Reaction at the anode of AEL

$$2OH^- \rightarrow 1/2O_2 + 2H_2O + 2e^-$$

At the cathode hydrogen and at the anode oxygen is produced in gaseous form. Water is continuously consumed whereas KOH stays in the system. A further parallel combination of multiple electrolyzer cells is called stack. Conventional electrolyzer stacks are commonly composed of 30 to 200 cells.[584] A modern development of the AEL is the pressurized alkaline system. The advantage is a smaller design of the electrolyzer and a pressured product gas, which can be used for example in the methanation sector without further compressions.

According to the own undertaken survey the lifetime of a stack is specified with ten to 15 years. The ramp-up time to full load differs between 20 and 300 seconds of a 1 MW electrolyzer. The dynamic range of the electrolyzer is between 10% and 200% of the full load (1 MW electrolyzer). The efficiency is ranged between 62.5% and 80% in 2015 and 73.1% and 82% in 2025. This technical data shows that modern AEL system can be operated fluctuating and start-up fast. The efficiency is expected to be at 70% in 2015 and around 77% in 2025 in average. These factors are important for an economic analysis. In the following table, the range of results of the electrolysis survey for 2020 and 2025 are demonstrated.

Table 52: Results of the survey towards alkaline electrolysis

Year	2020			2025		
Plant size [MW]	1	5	20	1	5	20
Efficiency [%]	71.4 to 81	71.4 to 81	71.4 to 81	73.1 to 82	73.1 to 82	73.1 to 82
Stack lifetime [a]	10 to 15	10 to 15	10 to 15	10 to 15	10 to 15	10 to 15
Hot start-up time to full load [s]	2 to 300	2 to 300	2 to 300	1 to 300	1 to 300	1 to 300
Dynamic range [%]	10 to 200	10 to 300	10 to 300	10 to 200	10 to 300	10 to 300

583 Smolinka et al. (2011), p. 7

584 Lehner et al. (2014), p. 25

A.4.2 Polymer Electrolyte Membrane Electrolysis

The difference between AEL and PEM electrolysis is characterized by the electrolyte membrane. Instead of hydroxide ions hydrogen protons are diffusing through the system. Hence, following reactions take place at the electrodes:[585]

Equation 0-4: Reaction at the cathode of PEM

$$2H^+ + 2e^- \rightarrow H_2$$

Equation 0-5: Reaction at the anode of PEM

$$H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$$

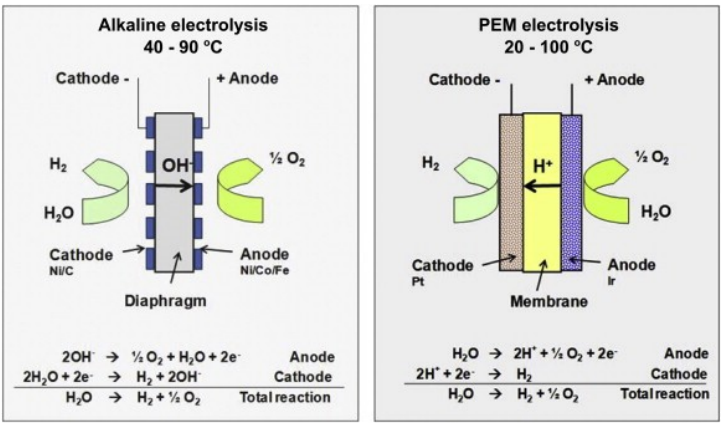


Figure 104: Schematic of an alkaline and PEM water electrolysis cell[586]

The PEM technology originates from the inverse process of the fuel cell technology.[587] PEM has been developed to overcome the issues of partial load, low current density and low-pressure operation that are plaguing the AEL.[588] Considering the undertaken study, the partial load is between 10% and 100% for smaller installations. This is in the same range as AEL producers are announcing. The ramp up time is between 1 and 120 seconds. This is important for the participation at the primary balancing markets (see chapter 5.3.1.3). For example, the PEM electrolyzer of the PtG plant from the

585 Lehner et al. (2014), p. 29

586 Carmo et al. (2013), p. 4903

587 Sterner and Stadler (2014), p. 322

588 Carmo et al. (2013), p. 4903

Viessmann GmbH in Allendorf is qualified to participate at the balancing markets.[589] The forecasted lifetime of the stack is the same as AEL electrolyzer. Larger plants have more efficiency, a longer stack lifetime, shorter start-up time and more dynamic range. The result of the own survey indicates that technical advantages of the PEM system can be equalized in comparison to the AEL system.

In the end, the differences between PEM and AEL electrolyzers are marginal. PEM electrolyzers have advantages in ramp up time and can follow power fluctuations within milliseconds. But however, the market designs in the power business are neglecting these advantages (see chapter 5.3.1). The competition between those technologies could be decided by the ability of industrial production and, therefore, economies of scale and experience curves to reduce the investment costs. The following table shows the range of results of the own industrial survey towards PEM producer.

Table 53: Results of the survey towards polymer electrolysis

Year	2020			2025		
Plant size [MW]	1	5	20	1	5	20
Efficiency [%]	68.5 to 70	68.5 to 70	69 to 75	74.7 to 77	74.7 to 77	75 to 77
Stack lifetime [a]	15	15	15 to 20	15	15	15 to 20
Hot start-up time to full load [s]	1 to 120	1 to 120	1 to 10	1 to 120	1 to 120	1 to 10
Dynamic range [%]	10 to 100	10 to 100	0 to 160	10 to 100	10 to 100	0 to 160

A.4.3 Solid Oxide Electrolysis Cell

The last technology of electrolysis is the SOEC. It is also called high temperature steam electrolysis. It is the least developed technique yet. A multi-MW installation is missed yet as mentioned as an industrial research recommendation in chapter 7.3.2. Neither hydroxide ions nor hydrogen protons are diffusing through a membrane. In this case, oxygen ions are responsible for the energy exchange. The endothermic reaction takes place under high temperatures. Lehner et al. (2014) expose temperatures of 500°C to 700°C and further that "*such high temperatures are beneficial for thermodynamic (low electrolysis voltage) as well as for kinetic (no platinum-base materials, low overvoltage) reasons*". In sum the stack efficiency can be raised up to 90% (not including the necessary previous heat for steam production).[590] Basically, the reaction at the electrodes is as follows:[591]

589 Viessmann (2016)

590 Lehner et al. (2014), p. 34

591 Lehner et al. (2014), p. 33

Equation 0-6: Reaction at the cathode of SOEC

$$H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

Equation 0-7: Reaction at the anode of SOEC

$$O^{2-} \rightarrow 1/2O_2 + 2e^-$$

A huge potential of SOEC is the installation in sites, in which a surplus of heat or water steam exists. This is for example given in combination with a chemical methanation in a PtG plant, industrial processes like in the cement, steel or glass industry or renewable processes like solar heating or geothermal sources. The demanded heat can be supplied by the exothermic process reaction and the overall efficiency can increase (see chapter 5.4.3). Another advantage is the reversible usage. Depending on the stack design, the reaction in a SOEC can be reversed. Therefore, the SOEC can be also seen as a fuel cell.[592] This potential can be used to stabilize fluctuations of RE in both directions.

According to the own survey of electrolyzer producers the SOEC has an efficiency of 85% to 87% at temperature level of 150°C. The start-up time is about 15 min in 2015 and 5 min in the next generation electrolyzers. The dynamic range is between zero and 150% in next generation plants. The heat requirement is exposed in addition. The required heat would reduce the efficiency of high temperature to levels of AEL or PEM systems.

Beside the investment costs, which are discussed in chapter 5.3.3, the construction design and the high degradation due to the material stress at high temperatures are still challenging. A stack replacement after 3 years demonstrates a short lifetime. Further technical and scientific research and development for all kind of electrolyzers is recommendable. The following table is showing the range of results of the survey towards SOEC producer.

Table 54: Results of the survey towards solid oxide electrolysis

Year	2020			2025		
Plant size [MW]	1	5	20	1	5	20
Efficiency [%]	87	87	87	87	87	87
Heat requirement in operation [kW]	213	1,063	4,252	213	1,063	4,252
Heat requirement in stand-by [kW]	43	213	850	43	213	850
Stack lifetime [a]	3	3	3	3	3	3
Hot start-up time to full load [s]	300	300	300	300	300	300
Dynamic range [%]	0 to 150	0 to 150	0 to 150	0 to 150	0 to 150	0 to 150

592 Ruiz-Morales et al. (2011)

A.5 Chemical Methanation

The methanation is the second process step of a PtG plant. It describes the further reaction of hydrogen and carbon dioxide to SNG. This process step is optional, because in some cases direct hydrogen injection is possible. This topic is discussed in the chapter of the feed-in guidance of the gas market (see chapter 5.4.4). The methanation can be divided into the chemical methanation, which takes place in a catalytic process, and the biological methanation, which uses microorganism. Both technical processes are explained to achieve basic understanding about advantages of each technology for economic drivers like efficiency, operational costs and heat sale.

First, the chemical methanation is explained briefly. The chemical methanation has been invented by Paul Sabatier, who received the Nobel Prize in 1912, in 1902.[593] The overall exothermic chemical reaction is as follows:[594]

Equation 0-8: Methanation reaction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad \Delta H_R: -165\ kJ/mole$$

As shown in the chemical equation above carbon dioxide and hydrogen are reacted to methane and water. The energy output, therefore, is 165 kJ/mol. This is an exothermic process and heat energy is produced.

State of art for the construction design of the chemical methanation is the fixed bed reactor, hereby two different kinds of constructions exists: the tubular and the plate reactor.[595] The construction of a fixed bed reactor is shown in Figure 105. At the top, the two input streams hydrogen and carbon dioxide are mixed. The fixed bed is filled with catalyst. Molten salt is conveyed the heat away. At the bottom SNG and water are the output streams.

593 Sterner and Stadler (2014), p. 338

594 Van Basshuysen et al. (2016), p. 143

595 Lehner et al. (2014), p. 44

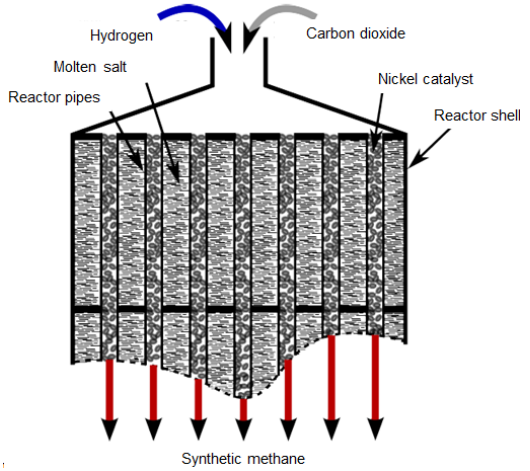


Figure 105: Schematic cross section of the methanation reactor[596]

Lehner et al. (2014) has compared different studies about industrial methanation processes. They exposed that the methanation takes place at a temperature level of 300°C to 700°C.[597] Rieke and Waldstein (2016) identify temperature levels of 250°C to 500°C in the methanation process, depending on the location of the hot spot. This high-quality heat can be used in different connected processes (see chapter 5.4.3). The purity of the input streams is important for the chemical conventional methanation. Waste and toxic materials in the hydrogen or carbon dioxide stream can lead to higher degradation rates and could destroy the catalyst. According to Bartholomew (2001) typical catalyst poisons are heavy metals, sulfur, or oxygen compounds. As catalyst, which is activating the reaction, often nickel-bases are utilized for the methanation process.[598] Therefore, the cleaning and filtration process of both input streams must be accurate.

Another point of consideration is the operation of methanation plants. Usually, the production of hydrogen is fluctuating depending on the power purchase concept (see chapter 5.3.1). Load changes of the methanation reactor are less sensitivity compare to electrolyzers.[599] Therefore, storage units must be installed between the electrolyzer and the methanation process. In addition, compression units are necessary for the hydrogen (if an AEL is installed) and carbon dioxide, because the reaction takes place

596 Hammer (2014), p. 31

597 Lehner et al. (2014), p. 44 f

598 Lehner et al. (2014), p. 42

599 Lehner et al. (2014), p. 51

at approx. 10 bar.[600] For the availability of carbon dioxide sources see chapter 5.4.6. The product gas is usually a mixture of methane (>90%), hydrogen and carbon dioxide (both <5%). The feed-in criterion is discussed in the chapter of peripheral devices (see chapter 5.4.4).

Similar to the survey of electrolyzer producers a survey towards producer of methanation units has been undertaken. An exemplary questionnaire is illustrated in Figure 102. The plant size fits to the electrolyzer survey of one, five and 20 MW installed capacity. In total four different companies have participated. Again, due to the small market the companies wish to stay anonymous. The rejected heat can be increased if the product gas is further cooled down. The start-up time is mentioned in a range of 5 min to 8 min. This can be a crucial technical issue and is investigated in the case study. The survey demonstrates that future catalytic methanation plants can decease the start-up time to less than five minutes. The dynamic range can be reduced to 30% in 2025. The following table is showing the range of results of the chemical methanation.

Table 55: Results of the survey towards chemical methanation

Year	2020			2025		
Plant size [Nm^3 of H_2 input]	200	1,000	4,000	200	1,000	4,000
Efficiency [%]	83	83	83	83	83	83
Rejected heat in operation [kW]	72	360	1,440	72	360	1,440
Start-up time to full load [s]	300 to 480	300 to 480	300 to 480	<300	<300	<300
Lifetime [a]	20	20	20	20	20	20

600 Zuberbuehler et al. (2016)

A.6 Biological Methanation

Next to the described chemical methanation the biological methanation is an upcoming and promising way of carbonizing hydrogen. Microorganisms of the category of Archaea are used as a catalyst. This species has been discovered by Carl Woese in the end of 1970s and was one of the first animates being on earth.[601] The Archaea normally exists in anaerobe conditions. Under these circumstances they are tolerant in face of toxic elements as well as heat, acidity or basicity and pressure.[602] The chemical reaction and energy equation are identical to the chemical methanation. The Archaea organism is producing methane by using hydrogen and CO_2. Studies have shown that the biological methanation is reaching all necessary feed-in qualities.[603] Another possible combination is the direct injection of hydrogen in the biogas plant. The methanation takes place inside of the biogas container. The advantages are that no further peripheral devices are needed like a CO_2 separation, H_2 compression or a secondary feed-in units.[604]

An advantage is that the input streams of hydrogen and CO_2 does not request any further treatment or preparation, which is reducing investment costs and plant complexity. In return, the biological culture necessitates electrolytes and minerals. For that reason, the first existing, industrial scale biological PtG plant in Allendorf from the Viessmann GmbH is using sewage sludge, which must be provided constantly. This obtains an ideal combination of PtG and sewage plants as a CO_2 and electrolyte provider.

A further advantage is the inertia of the biological system. Therefore, load changes of fluctuating REs are less vulnerable for the system and the flush of nitrogen is inapplicable. Probably no hydrogen or SNG storage capacity is required, which saves again CAPEX. This is increasing the efficiency and is compensating disadvantages of the chemical methanation. On the contrary the negative points are the constant feeding of the microorganism and the missing upscaling of the biological methanation yet.[605] To overcome the second reason the start-up Electrochaea GmbH plan to install a 1 MW plant in Copenhagen.[606]

In line with the industrial survey of electrolysis and chemical methanation a similar approach has been undertaken with companies in field of biological methanation. The survey results that efficiency without heat usage is lower than in the chemical

601 Sterner and Stadler (2014), p. 346

602 Sterner and Stadler (2014), p. 347

603 Reuter (2013)

604 Pecka (2014)

605 Sterner and Stadler (2014), p. 347

606 Electrochaea (2014)

methanation with about 76.5%. The rejected heat has an additional value of 12% in average in operation times. The ramp up time to full load is stated within seconds and the dynamic range is within the full scale. The investment costs are discussed in the business modeling (see chapter 5.3.3). The survey demonstrates the major advantages of the biological methanation and displays key values for efficiency, waste heat and operation modes. The following table is showing the range of results of the survey of the participating companies. In sum, the biological methanation is offering an interesting alternative to the chemical solution.

Table 56: Results of the survey towards biological methanation

Year	2020			2025		
Plant size [Nm^3 of H_2 input]	200	1,000	4,000	200	1,000	4,000
Efficiency [%]	76 to 77	76 to 77	76 to 77	79	79	79
Rejected heat in operation [kW]	140 to 200	550 to 700	1,500 to 2,800	170	625	2,150
Start-up time to full load [s]	3 to 40	3 to 60	3 to 90	3 to 40	3 to 40	3 to 40
Lifetime [a]	10 to 20	10 to 20	10 to 20	10 to 20	10 to 20	10 to 20
Dynamic range [%]	0 to 100	0 to 100	0 to 100	0 to 100	0 to 100	0 to 100

A.7 Secondary Balancing Market

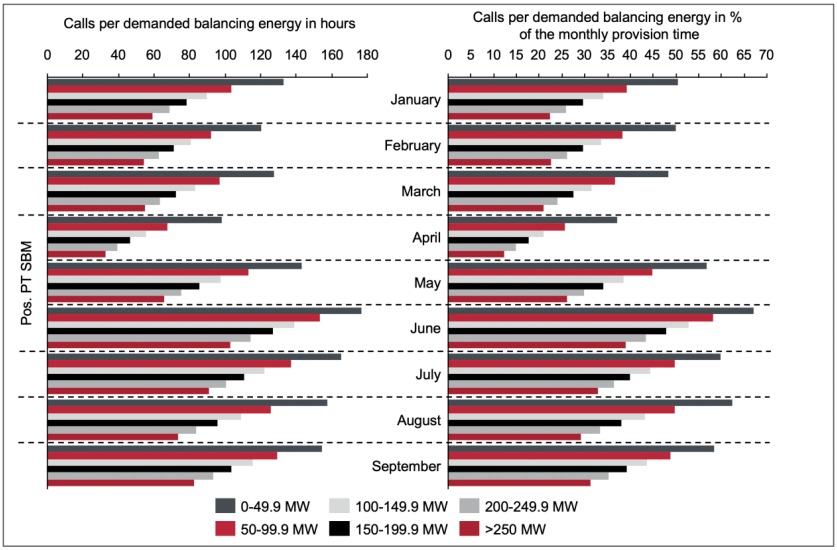


Figure 106: Calls per demanded balancing service at pos. PT SBM in 2015

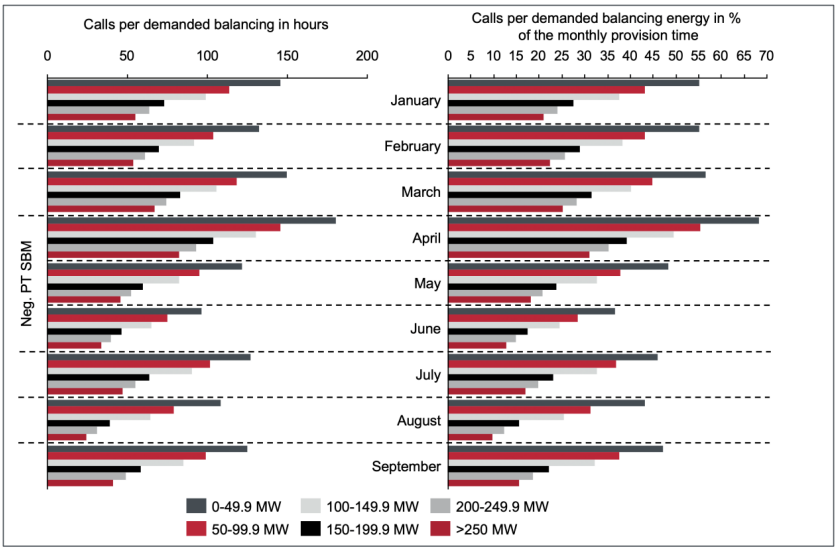


Figure 107: Calls per demanded balancing service at neg. PT SBM in 2015

Curriculum vitae

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05/2019	Co-Author: „Zukünftige Kraftstoffe (Future fuels)“ from Wolfgang Maus, Springer Vieweg, Berlin, Heidelberg
02/2016	Co-Author: „Natural Gas and Renewable Methane for Powertrains“ from Richard van Basshuysen, Springer Fachmedien, Wiesbaden
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04/2013 – 12/2016	Project management of the Audi e-gas Project at AUDI AG, Ingolstadt, Germany
08/2012 – 10/2012	Internship at Self Help Foundation Uganda in Cooperation with the Uganda Youth Network, Kampala, Uganda
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Other Qualifications

Languages	German, native speaker
	English, business fluent
Software	Office 365, Adobe Photoshop, Adobe Premiere, C++, Java, HTML

Interests

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American Football (Brussel Tigers)

Skiing

Running

Hofstetten, 15th of November 2020