Aalborg University
Department of Development and Planning
MSc (Eng) Sustainable Energy Planning and Management

Wind-to-Gas-to-Money?
Economics and Perspectives of the Power-to-Gas Technology

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Preface

This master thesis is the final thesis of the M.Sc. programme Sustainable Energy Planning and Management at Aalborg University. I guess it does not happen very often that students feel that they are struggling with the same questions like a whole nation. The questions can be condensed to the one big question: How is it prossible to convert from a nuclear and fossil fuel based system to an energy system based on renewables. Of course, the discussion is already going on for decades, but was quite intensive after the Fukushima catastrophe, when the conservative-liberal Merkel government changed its position on nuclear power over night and proclaimed the “energy-turnaround”.

Since then news coverage in Germany on the topic is stamped by the opinion that the next winter will be characterized by black-outs, extraorbitantly high electicity prices, imports of French and Swiss nuclear power etc. Whatever the solution will be, it has to be high-tech and big. Therefore, Power-to-Gas is one of the most promising candidates. The dimension of the natural gas grid seems big enough to satisfy even the most conservative journalists and planners, and the concept also sounds a bit high-tech. Of course this was polemic exaggeration, but it indicates the character of the debate.

I have to admit that I was pretty enthusiastic about the PtG solution as well, and I was convinced that such a smart concept will pay out by itself, or with little help of political support. So I started my thesis with the idea to find out how a smart public regulation could look like to make the technology attractive for investors.

Finding a scenario, done for the Federal Environmental Agency, a governmental agency, where PtG is the main balancing technology, confirmed my opinion, that PtG technology could be solution to all balancing and storage problems. I wanted to assess the hurddles for its necessary implementation. I spent some time reviewing the literature on the topic. My first finding already raised some doubts. It was simply not possible to find any fact-based and comprehensible analysis of prices or costs. The first title I found on the economics of different operational concepts for PtG plants was never published. Even after contacting the authors of the study, the answer was that it was a report done for the company which is promoting PtG plants and is not available. Another study was done by the institute that developed the PtG concept and the scenario. The study assumed electricity prices of 0-2 ct/kWh, prices that appear quite seldom.

It was finally my supervisor, Brian Vad Mathiesen, who admonished me, to be more critical towards the technology and the scenario. I did not understand his critics towards the technology, before I had the results of my calculations. This was when I lost my initial enthusiasm about the PtG technology. But I decided to follow the path I was on and assess the economics of the plant and show the “economic bowels” of the technology in order to bring a new perspective in the discussion about, what PtG can do and for what costs. Costs, that are paid by society in case of an implementation.

What I theoretically already knew from my lectures, I learned again in my thesis: The absence of an open, deliberative fact-based discussion about a technology, its business-economics and its costs for society already indicates, that there is a need for further research and alternatives - and there is always an alternative.

Therefore, the thing I regret the most is that I did not include other alternatives than electrolysers in my study. I first wanted to fully understand the technology, before comparing it to other technologies. I hope that I was able to built a bearing fundament and to provide a knowledge basis on which further students and researchers can build on and use it to compare PtG to other alternatives.

In this regard I would like to thank my supervisor Brian vad Mathiesen for the inspiration and his constructive critiques based on expertise and knowledge about the high costs of energy systems based on electrolysers. He gave an important guidance for my work. I also would like to thank all my professors at Aalborg University and the whole Development and Planning Department, especially my former supervisors Anders N. Andersen, who introduced me in market based, hourly models and Anna Carlson. Thanks to all my friends, group mates and colleagues from university and juwi for all their input, and all other persons who took their time answering my questions, among them: Ms. Jentsch (Frauenhofer IWES), Ms. Spielmann (SolarFuel), Mr. Härdtl (RES Projects), Mr. Jaggy (Biomethan Mühlacker) and Mr. Koustrup (nordic green). The most important thanks are due to my family for their love and support.

Report Guide

The report consists of 10 chapters. References to sources of information follow the Chicago style. If the reference is used for only one sentence, it is placed at the end of this sentence, however if the reference is used for the entire paragraph, it is placed at the end of the paragraph. A complete bibliography is found in the end of the report. References to chapters, figures, tables and appendixes are made as follows:

- References to chapters are indicated by chapter or section and the number (e.g. chapter 5 or section 5.3).
- Figure and table referencing are numbered throughout the report starting with 1.

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“You cannot endow even the best machine with initiative; the jolliest steam-roller will not plant flowers.” (Lippmann 1913:26)

1. Introduction

After the Fukushima catastrophe, Germany´s conservative-liberal government fundamentally changed its position on nuclear power and proclaimed the “Energiewende” (energy-turnaround)[1]. It inherits that until 2022 the last German nuclear power plant will stop to operate. This means that 18% of the German electricity production of 2011 has to be replaced within the next 10 years. In the same time carbon emission shall be reduced by 40% of the 1990 level and the amount of renewable electricity shall be doubled, from 17% to 35% until 2020 and further increased to 80% until 2050 (Bundesregierung 2011, BMWi 2012).

Onshore and offshore wind energy will represent the highest share under renewables then. Today over 27 GW wind capacity is installed in Germany which is expected to reach about 46 GW in 2020. For a 100% scenario 60 GW onhore and 45 GW offshore capacity seems to be necessary (Bundesregierung 2010, 2011, BMU 2010, FEA 2010). Demand side management and storage capacity for surplus electricity has to be increased in order to integrate this huge amount of fluctuating wind energy into the energy system.

Sterner et al. (2011) show that the Power to Gas (PtG) concept can manage this integration to a wide extent. The PtG technology converts electricity and water through electrolysis into hydrogen. Hydrogen is combined with CO_2 to methane, which is chemically almost similar to natural gas (Sterner 2009). Germany has a natural gas storage capacity of more than 200 TWh_{th}, enough to cover the electricity demand for more than three month, while the hydro pumping storage capacity of Germany is only 0,04-0,06 TWh_{el} (BMU 2010). Due to its multiple uses the importance of methane will rise in the future. It is a multiple purpose fuel, used inhouseholds and industry, for electricity generation, cooking, heating and as a fuel for transportation. Gas power

[1] The same government has just cancelled an old law for nuclear phase-out one year earlier, which was done by the social-democrat and green government in 2000.

plants will be necessary in order to balance the electricity system with their fast regulating ability. Apart from that methane is the cleanest fossil fuels, according to its CO_2 balance. The natural gas infrastructure is already fully developed. Today Germany is importing 87% of its natural gas supply. Most of it is coming from Russia, Norway and the Netherlands. According to the latest World Energy Outlook, European natural gas resources will be mostly exploited within the next 70 years (IEA 2012).

In this vein, Power-to-Gas could help to serve two purposes: Balancing the fluctuating electricity sources through a downward regulation and a long-term energy storage and help to switch from an imported fossil gas to a domestically produced renewable gas.

1.1 Problem Formulation and Research Question

In the latest 100% renewable energy scenario of the Federal Environmental Agency (FEA) PtG is the most important balancing and storage technology (FEA 2010). The scenario takes a system perspective and foresees a PtG capacity of 44 GW $_{\text{el input}}$ in order to balance the energy system. In the FEA scenario the plants then only operate in times of surplus electricity, mainly from wind energy (Sterner 2009, FEA 2010). Then the question remains open why anybody should invest 1750 €/kw$_{\text{el input}}$ in a power to gas utility and operate it in an intermittency mode, only in peak-wind hours. No study on the economics and the profitability of PtG plants under the current market and legal framework is published so far.

The finding, that it would be technically feasible to balance the system with PtG plants is undoubted, but is the economics of PtG really suited to be the main solution for the problem of balancing and storing excess electricity from fluctuating, renewable energy sources today and in the future? Giving an answer to this question is the main goal of this thesis.

In order to achieve this goal, the question is divided into three subquestions:

The first subquestion of this report asks for the economics of the plant: Is an investment in a power to gas plant profitable under current and future market and regulative framework conditions? In a market based energy system this question is crucial for the breakthrough of a technology. In the public discussion on the economics of the PtG concept was neglected so far, or not made public like the the work of Jentsch and Sterner (2010) on the economics of PtG in different operational concepts.

Only Trost et al. (2011) compare costs of renewable methane to other fuels for transportation, but under the doubtful assumption of very low electricity prices (0-2c/kWh).

Even though this question is among the most crucial question for the implementation of new technologies, it needs to be supplemented by the second subquestion: Does the economic characteristics suit to a balancing function?

Electrolysers are the main "competitor" of PtG as they offer the same functions at lower costs and higher efficiency and are therefore used as a "point of orientation" and comparisons with PtG[2] for this thesis. However, electrolysers are not the only alternative to balance fluctuating electricity production. There is no fixed pathway towards 100% renewable energy system.

PtG can be one among many possible technologies for the integration of renewable energy. Therefore, an introductive task for this thesis is it to show what other technologies could be considered. Here it is important to note the limitations of this thesis. Apart from electrolysers, the following thesis does not asses any alternatives to PtG. Alternatives are qualitatively described, but not directly compared to PtG. Therefore the following thesis cannot answer the question, how a renewable energy system in Germany should look like or what is the best technology to implement the most renewable energy at lowest cost for society into the system. Even though these questions will be touched, they are not in the focus of this thesis. The focus of this thesis is it to fully understand the economics of the PtG technology. If PtG is not a profitable investment, or if it is a profitable investment, but its economics contradicts an balancing operation, political incentives could be designed, in order to change this. Therefore, the last subquestion of the thesis is how political measures to foster PtG could be designed in a smart way, in order to make an investment in a power to gas plant and a balancing operation profitable from a business economic perspective. On the basis of these findings statements about the long- and short-term perspectives of PtG under current market conditions and in a future renewable energy system are made.

Of course, the more the economics of PtG contradict a balancing operation, the more expensive an implementation with the help of political measures will be. Therefore, it should be kept in mind that it cannot be a smart goal to implement such a technology immediately and at all costs. The public debate on PtG, is characterized by a

[2] In the following thesis the abbreviation "PtG" is exclusively used as a synonym for the conversion of electricity into methane. For the conversion of electricity into hydrogen, the term electrolysis is used.

enthusiastic optimism, based on the hope for a technical solution to all balancing and storage problems that comes along with a transformation of the energy system. The motivation for this thesis is the extension of the debate, in order to add the point of the economics of PtG and costs of an implementation to a discussion, which is so far heavily biased towards technical feasibility.

1.2 Thesis Structure

In order to answer the research questions, the thesis proceeds as follows:

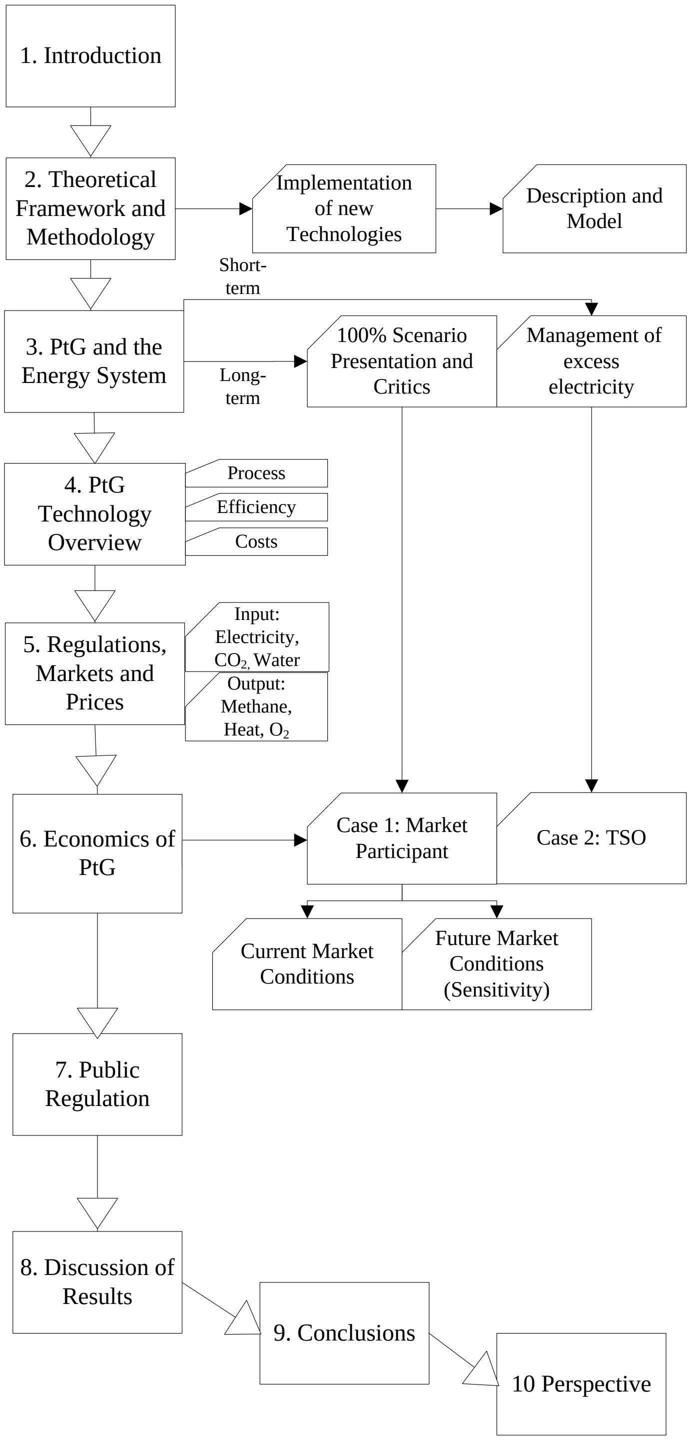

Figure 1: Thesis Structure

Firstly a chapter gives an overview of the theoretical framework and the methodology of the thesis. The thesis consists out of two main parts. Chapter 3 starts with a presentation the 100% scenario done on behalf of the FEA and explains the importance and the different functions PtG can fulfil in this scenario. The scenario is then critically compared to other scenarios and pathways to a 100% renewable energy system. This long-term perspective for PtG is complemented by a short-term perspective, dealing with local integration problem of wind energy, German TSOs are facing already today and how PtG could help to solve this problem.

Chapter 4 briefly explains the PtG technology, its investment and O&M costs, the technical process together with the most important performance data. The fifth chapter describes the framework for the not-technological measures. It describes the regulations, markets and prices of each variable concerning the PtG process from electricity, until the feed-in into gas grid.

After that chapter 6 performs an analysis of the economics of PtG. The profitability of an investment in a power to gas utility is evaluated for two business cases from different perspectives: The first case is an investment in a PtG plant made by a normal market participant. This case evaluates PtG under current and future market conditions. This a long-term perspective builts up on the framework of the 100%scenario, presented in chapter 3. A second case assesses the investment from a TSO´s perspective. This case gives an idea about a short-term perspective for PtG, as an temporary solution to the problems with excess electricity, described in chapter 3.

Chapter 7 evaluates several proposals for political measures, which enhances the feasibility of investment in a power-to-gas utility and place incentives to operate it in a balancing mode. Chapter 8 discusses the results and after that the thesis concludes with answers to the research question and other concluding remarks. The results of the thesis are perspeectivized through possible shortcomings of the research and open questions for further research are seen from the perspective of the results.

2. Theory and Methodology

This chapter presents a theoretical background and presents the methods used. The theoretical framework is based upon the work of Hvelplund, Lund and Sukkomnded (2007) and is settled within the field of the studies of feasibility and public regulation.

2.1 Theoretical Framework

European states have liberalized their power sector to a far extent over the past decades, in accordance with European law (Andersen 2010). This liberalization includes a market based electricity system in which electricity is sold over the counter and on spot markets. Investment into new production capacity should be profitable within a certain time frame, otherwise an investment will become unlikely in a neoclassical economy.

New technologies are very often more expensive than established technologies, making it very unlikely to be feasible from a business-economic point of view in a time frame usual in the market, leading to an investment bias towards existing technologies (Hvelplund 2001). Under pure market conditions new technologies in the electricity sector rarely get the chance to develop their full market potential.

Especially in the energy sector it is a well known phenomenon that new technologies struggle with high prices which decrease after a short time, due to cheaper production and innovative progress. Onshore wind energy and solar energy are examples of the past decades. Among other reasons, political measures have a huge influence for the breakthrough of these technologies. Most prominently fixed feed-in-tariffs provided stable financial framework conditions, minimizing risks for investors leading to a breakthrough of the technology.

However, the system is not independent from societal and political influence. Especially technologies, which are defined by society to be a desirable alternative, have been objects to specific political support measures, enhancing their business-economic feasibility already in an early stage of their technological development.

Hvelplund, Lund and Sukkomnded (2007) describe this dynamic in a relationship between business economy, socio economy and public regulation with two different situations:

1. A feasible technology from a societal point of view might be unfeasible from a business-economic point of view under existing market conditions and public regulations.

Public regulations and market conditions then should be adjusted through a democratic process which leads to the following situation:

2. A feasible technology from a societal point of view is now also feasible from a business-economic point of view under changed market conditions and public regulations.

A prominent example is the support for wind energy. Feed-in-tariffs triggered a financial breakthrough of the technology. Of course many other factors have influenced this breakthrough as well: The long fight of social movements against nuclear power and the rise of the green party and the Fukushima catastrophe lead to new public perception about the risks of nuclear power. These factors are part of the democratic process, which sometimes can be a long struggle. It is definitely interesting to analyse and understand how and why the public perception of technologies changes, but this question is out of the frame of this thesis.

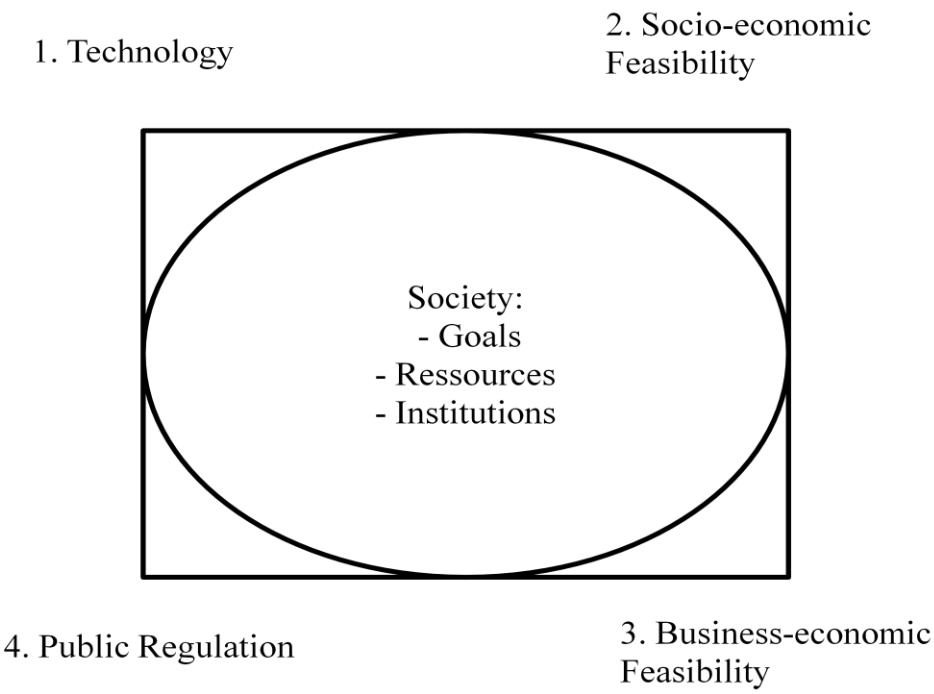

Figure 2: Squaring the technological-implementation-circle (own illustration, inspired by Hvelplund, Lund and Sukkomnded (2007)

Figure 2 helps to understand the theoretical macro-structure in which the thesis is embedded. It is the relationship between technology, socioeconomic feasibility, business-economic feasibility and public regulation, which needs to be understood and completed for the implementation of new technologies. It is called “squaring the technological-implementation-circle”. The circle represents the society with its goals, resources and institutions, which are defined and distributed in democracies through a democratic process. Each corner of the square represents one step that needs to be considered for the implementation of a new technology. The corners can be without any connection to the “society circle”, but if the circle is not squared, the implementation of a new technology is getting unlikely.

Point 1 is the technology itself. Point 2 is the socio-economic feasibility study, which proofs that the technology “is feasible from a societal point of view” (Lund 2008:67). For PtG this was already done to some extent by other studies (see Sterner 2009 and Sterner et al. 2011). What is missing in the public discussion about PtG so far, and is therefore missing to complete the “implementation square” is the connection between point 3 and 4. Point 3 is a business-economic feasibility study „where the purpose is to examine whether a project is economical from the point of view of a specific company” (Lund 2008: 67). Very often it turns out, that new and green technologies, especially in the energy sector “are good for society but not good for business” (Lund 2008:68). If this is the case, then a change of point 4 “public regulation” becomes necessary. If the technology is in line with the goals of society, then institutions and resource distribution should be adjusted in a changed public regulation in order to implement a desirable technology. This thesis can be settled within point 3 and 4 of this macro-structure.

This does not mean that PtG should be immediately implemented. There might be other and better technological solution for the integration of renewable energy, but this study is mostly limited to PtG and its perspectives. Therefore, the following thesis is not a feasibility study, although it has some point of contact: It deals with a newcomer technology and analysis its economics within a given market and public regulation structure and gives an idea under what conditions it could be profitable. What distinguishes from a classical feasibility studies is the fact, that it does not observe several alternatives for an investment. It can be described as a “single technology, business-ecoconomic feasibility/public regulation study”, or simply a study of the economics and perspectives of PtG.

2.2 Methodology

In order to find an answer to the question if the economics of PtG is really suited to be the main solution for the problem of balancing and storing electricity of today and in the future, the study starts with a close description of two possible application perspectives for PtG, one in a long-term perspective and one in a short-term perspective. The long-term perspective is based on a description of the recently published FEA 100% scenario, the first scenario that considers PtG for a large scale integration of renewable energy. It comes to the conclusion that a PtG capacity of 44 $GW_{el\ input}$ will be necessary to cover storage demand until 2050 and absorb the intermittent production of renewable energy sources. After that the scenario is critically reflected and compared to other scenarios and pathways towards a 100% renewable energy system.

While the 2050 scenario gives an idea about the long-term perspective for PtG, it is complemented by a short-term perspective. The framework for the short-term perspective is the problems German TSOs are already facing today with the local integration of wind energy into the grids. It is based on the latest data for disconnection of wind turbines for the sake of grid stability and gives an outlook for this problem in the next years, with a special focus on the problems of high voltage grid development and the connection of near future offshore wind farms and the resulting problems for the responsible TSO. This first “introductive” part is purely descriptive and built up on existing literature and reports.

After that the PtG technology, the process and the most important key figures and performance characteristics are gathered through a close literature review or expert statements. The current markets and public regulation conditions are outlined in order to give an overview of the framework for the further analysis.

The main analysis is done in two steps and aims on answering two questions: Is an investment in a power to gas plant profitable under current and future market and regulative framework conditions? And: Does the economic characteristics suit to a balancing function?

Therefore, In a first step, the economics of the PtG is depicted, with a special emphasis on the cost structure of the produced gas and the dynamics between electricity prices and full load hours for the cost level of the gas.

In a second step the economics of a PtG plant operating under current market and public regulation conditions will be analyzed from two different perspectives, developed in the first part of the thesis:

1. In case 1, the investment is made by a “normal market participant”, operating on different markets and market conditions. This is rather a long-term perspective, as market conditions need a long period until they change. The 100% scenario gives a loose scenario frame for this perspective.

2. In case 2, the investment is made by a TSO and the plant is using only excess electricity from offshore wind turbines. The current problems of the TSO and the disconnection of wind turbines from the grid give the scenario frame for this case. For PtG it offers a short-term perspective, as it deals with today´s problems of TSOs.

In case 1 the performance characteristics of PtG plant is feed into an hourly model. Price input data for electricity comes from the German spot market (EPEX), the Danish Elspot-market and the Danish balancing power market. The gas price is set externally. All variables, market conditions and influential public regulations which need to be set externally for the model are discussed and presented.
In case 1 the investment is done by a private market participant. In this case four scenarios are calculated. Each scenario consists of the plant working on each market and a combination of Elspot and the balancing market. Profit the plant can make on each market is of a special interest. Profit is calculated for each electricity market over one year (market data from 2011) on an hourly basis in an excel spreadsheet model. Every hour the plant only operates if marginal production costs can be covered by the income. The following figure shows exemplary the most important input and operational output data of the model for each hour of January 8^{th} . In this scenario the plant operates on the Danish spot and downward regulation market, respectively the market with the lower prices:

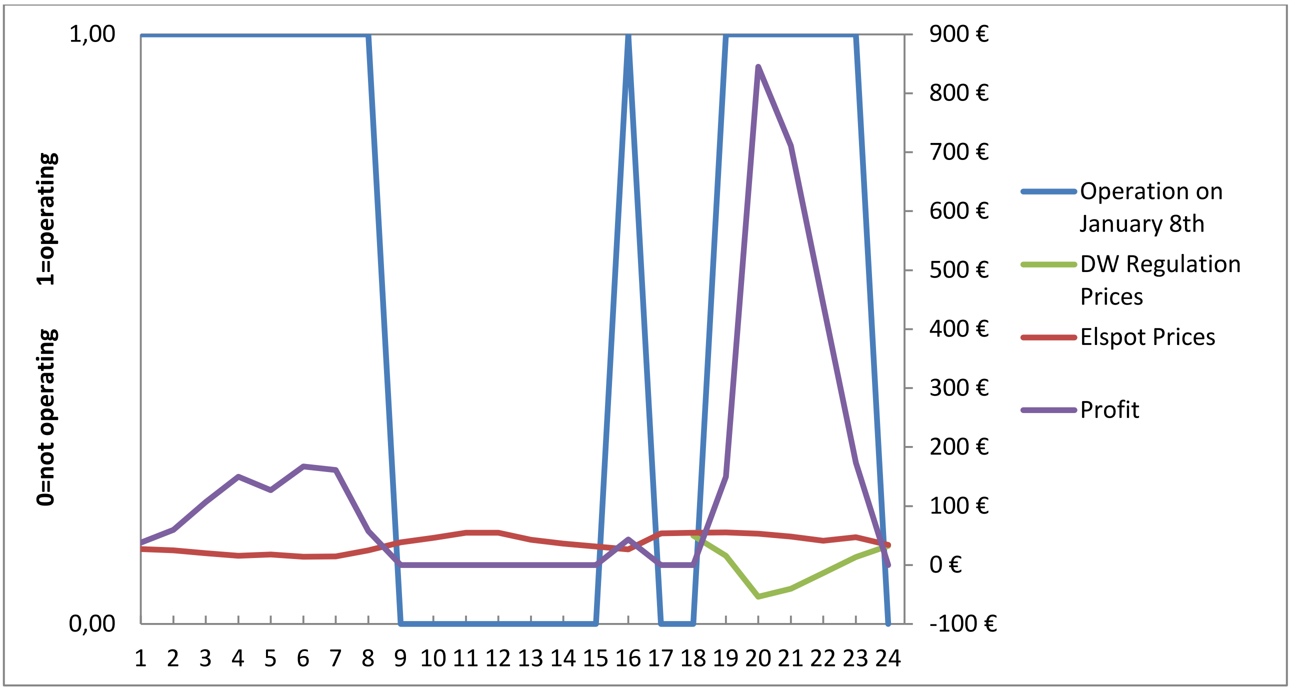

Figure 3: Important in- and output data of the excel model for January, 8th

The plant only operates, when it makes profit. Working hours are shown by the blue line and reefer to the left axis. On this day there where negative prices for downward regulation occured, what leads to a very high profit of the plant.

The market scenario in which the plant achieves the highest profit is used as basis for further sensitivity analysis. The sensitivity analysis aim to assess the profitability of the plant under possible future market conditions (changed electricity and gas prices), but also under changed investors expectations (lower discount rates). Special emphasis is given to the amount of full load hours, as an indicator for balancing characteristic. This analysis of the profitability is seen as a long-term perspective, because it will take a certain time frame, until the price assumptions of the sensitivity analysis become reality.

In a second case the profitability of an investment in a PtG plant is assessed from a TSO´s perspective. Especially opportunity costs of no investment are taken into account, because TSOs will be responsible for excess electricity that needs to be disconnected from the grid. They have to refund the full feed-in tariff, for the unused electricity. Because of deferments in the grid development and acceleration in the deployment of wind energy, this perspective is a short-term perspective. In this case calculations are not done in a hourly model, as the prices for offshore wind energy are assumed constant, according to feed-in tariffs.

In both cases profitability is assessed following the logic of Net Present Value (NPV) and accordingly Dynamic Payback Times. This is done in order to achieve a “rational” decision if the investment is feasible from an investor perspective. If the NPV is positive and Dynamic Payback time shows a break even within the plant´s lifetime an investment in a PtG is profitable (Serup 1998).
The last part of the thesis aims on answering the last research question question which public regulation could place incentives to invest in a PtG plant and operate it in a predominantly balancing mode in hours of downward regulations. In order to do so the model of both cases are adjusted to the new measures and the profitability is evaluated under the changed conditions. Because the perspective is different in both cases, some policies are only calculated for case 1, others for case 2, using exactly the same tools and logic as in the first part to evaluate the profitability under the current public regulation. On the basis of this analysis proposals are made how public regulation can foster the profitability of PtG plants, while offering incentives for a balancing operation.

According to European law transparency of the electricity markets should be assured by the spot market and the TSOs (Andersen 2010). During the data gathering for this thesis it turned out that transparency policy is interpreted differently by the German and the Danish TSOs. While the Danish TSO energinet.dk offers a complete hourly based data set of the amounts and prices for the regulating power markets, it was not possible to get the same data quality for the German regulating power markets. Data is available, but only in its “rawest” possible version, without any supporting information. This means that data about the reserve markets includes all offers, even unsuccessful offers were listed on a fifteen minutes bases in monthly documents. Finding out the marginal prices and transforming it on an hourly basis would have been a very high workload. Energinet.dk offers this data on its homepage. For this reasons prices for the regulating power market correspond to Danish market data.

2.3 Methodological Problems and limitations

Such an approach suffers from several methodological shortcomings and necessary limitations. The most fundamental point is coming from the research design itself. The profitability is calculated on the basis of existing markets conditions. This already sets a tight framework for possible conclusions and policy proposals. They will be based on the profitability within the given market and therefore follow the logics of these markets. Such a design a priori has path dependency towards the integration of the technology into the market. There is no reason to believe, that the existing markets, or electricity markets in general are the best possible solution for the integration of renewable energy. They might even be part of a problem, when it comes to the point of giving incentives for investments in regulating technologies.

Another problem is the estimation of income for next 20 years by a deterministic hourly model based of last year´s market data. The first problem is that developments of markets are not taken into consideration. The sensitivity analysis only deals this problem partly. Market changes are calculated statically, meaning e.g. a reduction of 30% in electricity prices brings a reduction from the first year onwards, while in reality this may rather be a dynamical step-by-step development.

A third problem resulting from such an approach is that the model offers full information of market data, which is not true in reality. The spot markets in the model are day ahead markets, this means that in reality the plant operator has to anticipate when it is better to buy electricity from the market and when it is better to offer downward regulation and which price he will achieve. There is a highly probabilistic element in this decision. In the model it is a simple “if;than” formula. Therefore the model income is a maximum income, which in real life depends on the quality of market prognosis, knowledge of the operator and fortune.

3. Power to gas and the energy system

All energy systems based on unsteady energy sources, like most of renewable energy has to deal with the issue of surplus electricity and residual load. In a 100% renewable energy scenario, elaborated for the FEA, Germany´s energy system will depend strongly on on- and offshore wind energy. Wind energy has the largest potential of all renewable energy sources in Germany, estimated capacity is around 60 GW onshore and 45 GW offshore (FEA 2010). Photovoltaic will play an important role with a potential for 275 GW capacity, which will be important, especially with its peak production hours during midday, meeting the peak demand hours.

This chapter consists of two parts. The first part presents a 100% renewable energy scenario for Germany. It is the FEA (2010) scenario, the first scenario that includes PtG on a large scale for Germany. The results and consequences for the role of PtG in a future energy system of the existing studies are discussed in here. The scenario is done on behalf of the FEA by the Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES) on the basis of an hourly model with the SimEE tool (FEA 2010). After the presentation of the scenario, with a special focus of the role of PtG plants, the scenario is critically reflected and other pathways towards a renewable energy system are presented.

The second part deals with the difficulties German TSOs are already facing today with the integration of large amount of wind energy into the grid. It presents the latest figures for the so-called feed-in management. Feed-in management means that in emergency cases for grid stability, TSOs can disconnect turbines from the grid, but they have to fully refund the lost electricity (EEG §11,12). Both parts show the need for further balancing and storage technologies, a role PtG could technically fulfil.

3.1 FEA 100% scenario

In the FEA scenario the full potential for wind energy is exploited, while only half of the photovoltaic potential is used, as the following table 1 shows.

The following table shows the key input data for the year 2050 used in the FEA scenario and the estimated potential according to the FEA scenario:

Renewable Energy Source	**Capacity**	**Production**	**Potential Capacity**	**Potential Production**
Wind onshore	60 GW	170 TWh_{el}	60 GW	180 TWh_{el}
Wind offshore	45 GW	177 TWh_{el}	45 GW	180 TWh_{el}
Photivoltaic	120 GW	104 TWh_{el}	275 GW	248 TWh_{el}
River Hydro	5,2 GW	22 TWh_{el}	5,2 GW	23 TWh_{el}
Geothermal Power	6,4 GW	50 TWh_{el}	6,4 GW	50 TWh_{el}
Biomass and -gas	23,3 GW	11 TWh_{el}		Biomass 162TWh_{th}/Biogas 40 TWh_{th}
Storages	**Capacity**	**Storage**		
Hydro Pumping	8,6 GW	0,059 TWh_{el}		
PtG	44 $GW_{el\ input}$	75 TWh_{el}		
e mobility	250 GW	0,18 TWh_{el} (only gtv)		
	Capacity	**Demand**		
Electricity Demand		401 TWh		
e mobility	250 GW	50 TWh		
Heat demand household		141,8 TWh		
industry and Commerce		40,2 TWh		

Table 1: Key input data for the year 2050 and potential used for the FEA scenario (FEA 2010)

A yearly model on a hourly basis shows the need of electricity storage in The FEA scenario. The hydro pumping plants, heat pumps and e-mobility are not sufficient to balance the system. Figure 4 shows on an hourly over a whole year that the system produces in total 78,5 TWh excess electricity (blue and negative in the the graphic), while a deficit of 82,6 TWh cannot be covered due to a lack of productive capacity (red and positive in the graphic). Hydro pumping plants, heat pumps, e-mobility and flexible demand and production are already considered (FEA 2010).

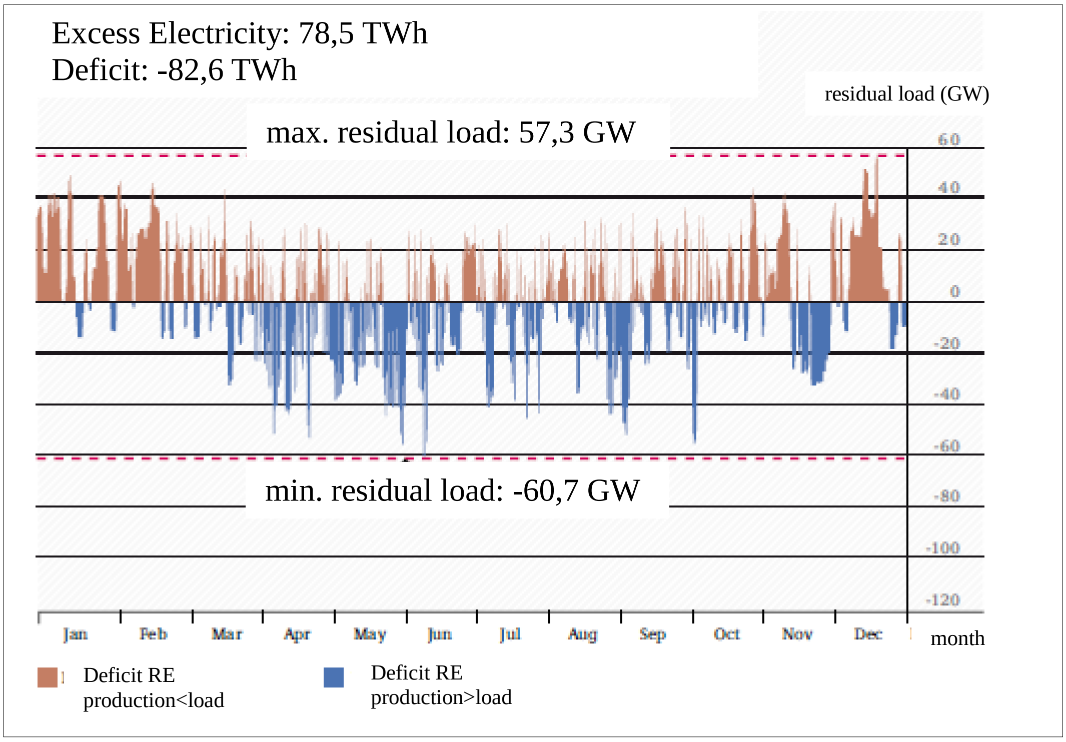

Figure 4: Residual load on an hourly basis in the FEA 100% Scenario (FEA 2010: 87)

It can be seen, that especially between December and February the demand cannot be met, while hours with excess electricity dominate the summer months. Balancing influence of hydro pumping storages and heat pumps is already considered in this model – all the heat for industry and private households is provided with heat pumps. The fundamental challenge is to balance surplus and deficits so that supply covers demand.

While “pure” electricity saving technologies are rare and their storage capacity is extremely limited and/or expensive, the conversion of electricity into hydrogen and methane seems to be a very promising solution, like the following graphic shows:

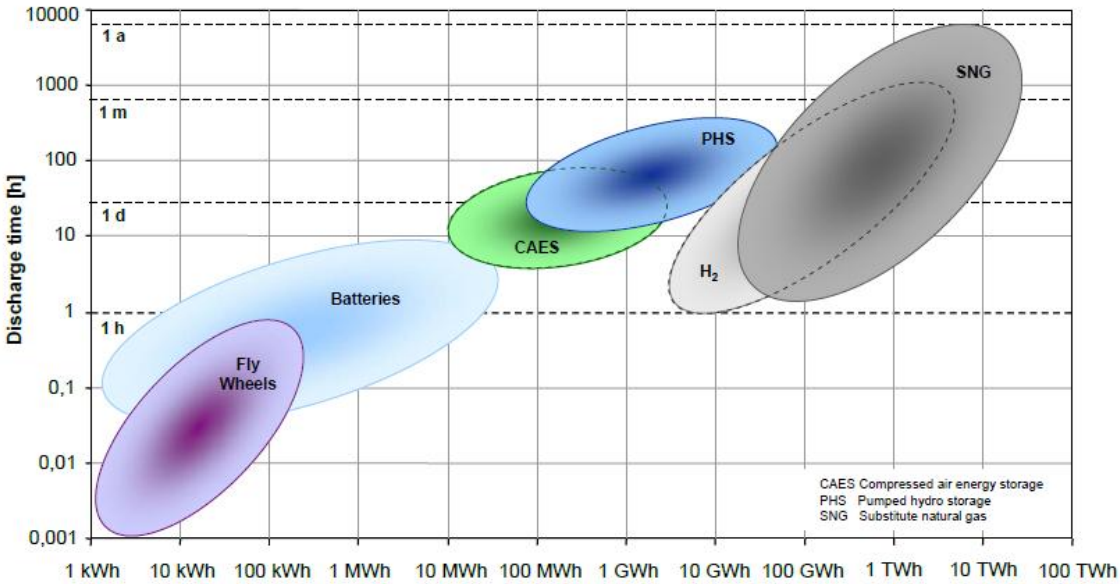

Figure 5: Storage capacity and Discharge Times (Specht et al. 2009:70)

While the pure hydrogen storage facilities are restricted, they could take up to 8 TWh only methane offers a storage capacity that can take up the 80 TWh excess electricity in a long term storage. Although the numbers might not be completely accurate, they give a indication of the large electricity storage potential of PtG and Electrolysis.

Of course, the expression “Electricity storage” is not accurate. It is a conversion of electricity into methane, a multifunctional energy source. It is therefore rather an “energy storage through conversion” technology.

Methane can be used to produce electricity and heat, as a fuel for transportation and it can be stored. The same functions can be fulfilled by H2 as well (ForskeEL 2009). The production of H2 through electrolysis is even more efficient, than PtG process, because the step methanation, is an additional step, which lowers the efficiency of the process.

However, distribution and storage of H2 is still a hurdle for the technology to fulfil its potential (ForskEL 2009). Looking at the infrastructural system CH_4 has a clear advantage: an international pipe infrastructure, including the largest energy storage facilities in Germany. The natural gas infrastructure already exists on all levels, even to the level of individual households, connecting borehole and consumers within one system. The “lock-in effect” of methane is obviously an advantage. Further methane has an energy density three times higher than Hydrogen, reducing the necessary storage capacity by factor three (FEA 2010). However, the natural gas grid can take up a certain share of hydrogen, without any problems, what is neglected in the FEA scenario.

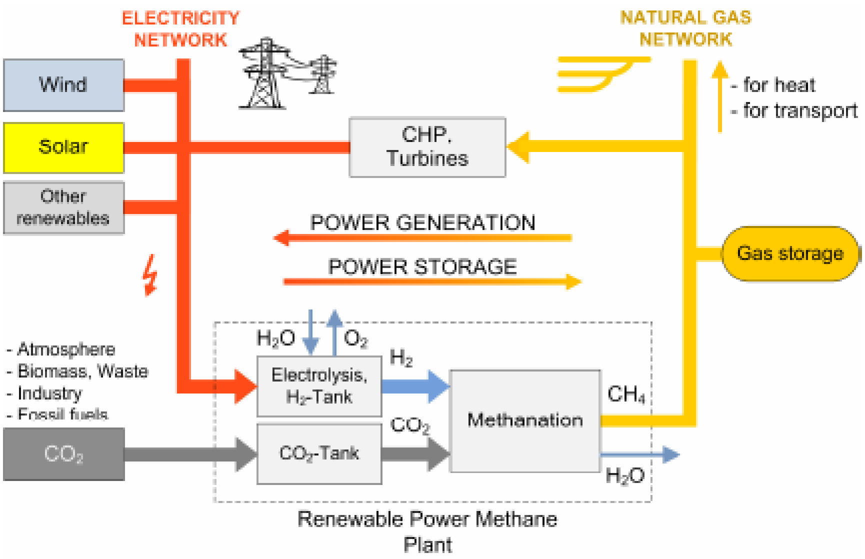

Figure 6: The role of PtG plants in an energy system (Sterner 2009:106)

The FEA scenario foresees PtG plants with an overall capacity of 44 $GW_{el\ input}$ in order to handle this conversion. The following graphic shows the amount of working hours for selected regulating technologies. The working hour of PtG is shown in purple. The majority of PtG capacity is operating in less than 2000 hours. Between 2000 and 3000 hours are rare, while only a minority of capacity is used for more than 3000 hours. This is a decisive point for the calculation of the profitability and potential political incentives to support it. Public Regulation will have to deal with that and consider that a plant that only operates less than 4000 hours is difficult to run profitable. Combined cicle gas turbine plants (CCGT) for upward regulation are facing the same problems. PtG capacity in combination with CCGT provide the lion´s share of balancing electricity:

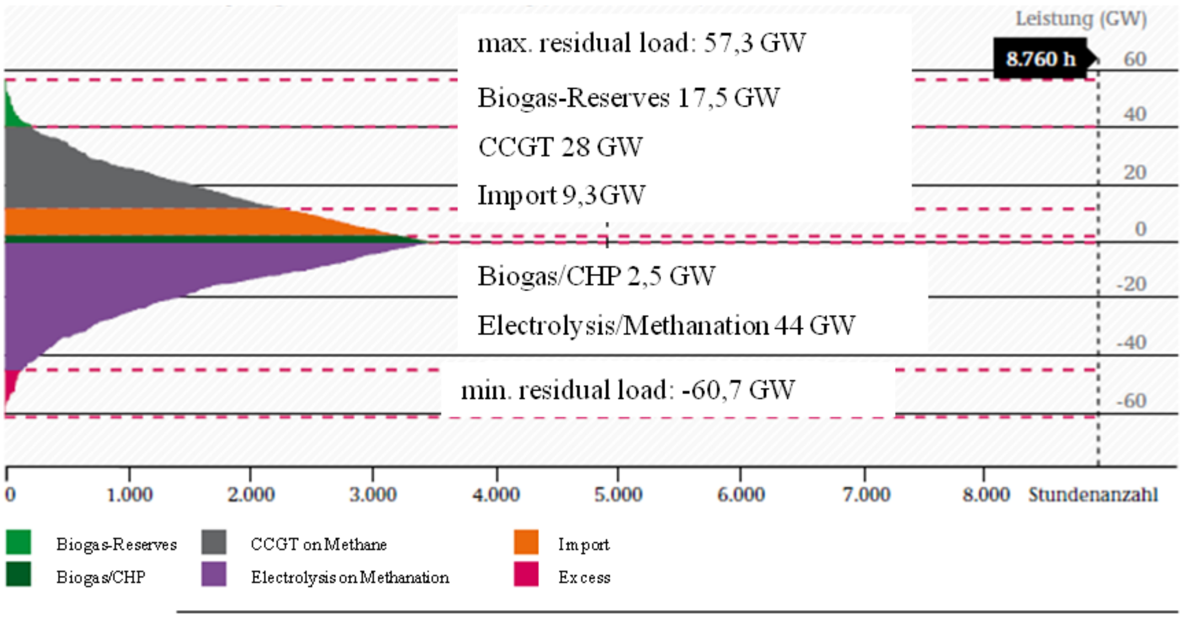

Figure 7: Working hours of long term storages in the 100% scenario (FEA 2010:94 (translated by the author))

3.2 Critical Notes on the FEA scenario and alternatives to PtG

It is obvious, that a perspective towards a 100% renewable energy supply and a time frame until the year 2050 is clearly a long-term perspective. Unfortunately the scenario does not offer a roadmap towards the scenario. It is important to keep in mind that the conversion of the energy system can only be achieved stepwise. Apart from that there is no official 100% policy of the German government. But under the given legal framework, especially the EEG, it is likely that the further development of on- and offshore wind energy will continue. Until a certain point fluctuating wind energy can be balanced by the existing flexible production and interconnectors.

The main point of critique on the FEA scenario is, that alternatives to PtG are not considered, costs of PtG and other alternatives are not compared. Denmark, the country with the highest share of wind energy in the electricity mix worldwide, manages it to cover almost 25% of its electricity consumption by wind power, 15% more than Germany (EWEA 2011). The important thing is that the integration of this percentage can be achieved easily, without huge storage capacities, by a flexible regulation of production of central and decentralised power plants. Even more wind energy can be integrated if demand is made more flexible not necessarily with gigantic electricity storages but with a flexible electricity conversion from electricity to heat via heat pumps in connection with a functioning district heating system and heat storages (Lund 2005). CHP plants in combination with heat storages also guarantee a possible energy efficient CHP production in times of low heat demand. (Lund and Andersen 2005).

In the FEA scenario methane from PtG is repowered in highly efficient gas plants (CCGT). The repowering of methane in CHP plants is not considered. This alternative should be considered. Especially when looking at figure 4 it gets obvious, that these plants will mainly run in winter, the time with the highest heating demand, which is covered now in the scenario mainly by electricity consuming individual heat pumps. Repowering the methane in CHP plants can help to reduce electricity demand from heat pumps in winter and therefore balancing the system, especially in combination with heat storages. The necessary PtG capacity can be reduced. This can be seen on a biogas basis for instance in the Danish energy system already today (Lund 2009).

Another important point is the roadmap to this conversion. In another 100% scenario for Germany, the BMU "lead scenario" (2010) electrolysers are not implemented before 2030 and only to cover transport demands. In the IDA 2050 (Mathiesen et.al. 2009) scenario electrolysers are not introduced before 2050. Other technologies are simply more cost efficient for the integration of renewable energy, among them electrical decentralised CHP plants, electrical boilers, heat pumps and electronic vehicles (Mathiesen and Lund 2009). Nevertheless, in a 100% renewable energy system Electrolysers and PtG could play an important role (Mathiesen and Lund 2009:202):

> [...] Although these analyses conclude that other technologies should be implemented first, the electrolyser technologies may prove important in 100% renewable energy systems with large amounts of intermittent renewable energy and in which biomass is a limited resource.

The gasification and fermentation of biomass should be first exploited to its full potential, what is not the case in the FEA scenario, from a potential of 23 TWh only 11 TWh are utilized. The 23 TWh are exclusively coming from waste-biomass, in the form of biogas combusted in CCGT plants, while a remaining potential of 162 TWh from biomass is not further considered in the scenario, almost twice as much electricity as the "deficit" of 82,6 TWh, described in the previous section 3.1. The remaining surplus electricity could be stored and utilized in the form of heat in decentralise district heating systems and storages with the use of heat pumps, which operated in a smart way can offer a high integration potential at low costs (Lund 2009).

It also needs to be emphasized, that the first step into a PtG system will be electrolysers. Methanation is an additional process step, implying conversion losses. The main advantage of methanation is the existing infrastructure. However, it is an official standard, that the natural gas infrastructure can take up to 5 vol % of hydrogen, without any modifications (DVGW G 260 2008). It is obvious that from a socio-economical point of view these 5% should be fully exploited by electrolysers, before an additional process step to methanation is used. Recent studies come to the conclusion that the natural gas infrastructure and consumers even can tolerate a hydrogen share in the gas mix up to 20 vol % or even more (DBI GUT 2010, Hüttenrauch and Müller-Syring 2010).

3.3 Feed-in Management

The overall reduction of excess electricity in the national grid is not the only hurdle PtG could help to overcome. The second important issue on the way to more than 100 GW of wind energy is the problem of integration of wind energy into the grid on a local level. Already today the integration of wind energy is a problem for TSOs in northern and eastern Germany.

According the EEG renewable energy has a feed-in priority. TSOs are only allowed to disconnect turbines from the grid in times of the risk of grid shortages, according to article 11 of the EEG. Between 2009 and 2010 the use of the so called "Einspeisemanagement" (feed-in management) raised by 69% (Ecofys 2011). Exclusively in northern and eastern parts of Germany, where the medium voltage grid is not yet adjusted to the high loads of electricity production in times of strong winds and the enforcement of high voltage transmission has not yet been fully accomplished. Areas affected by feed in management are shown in grey on the following map:

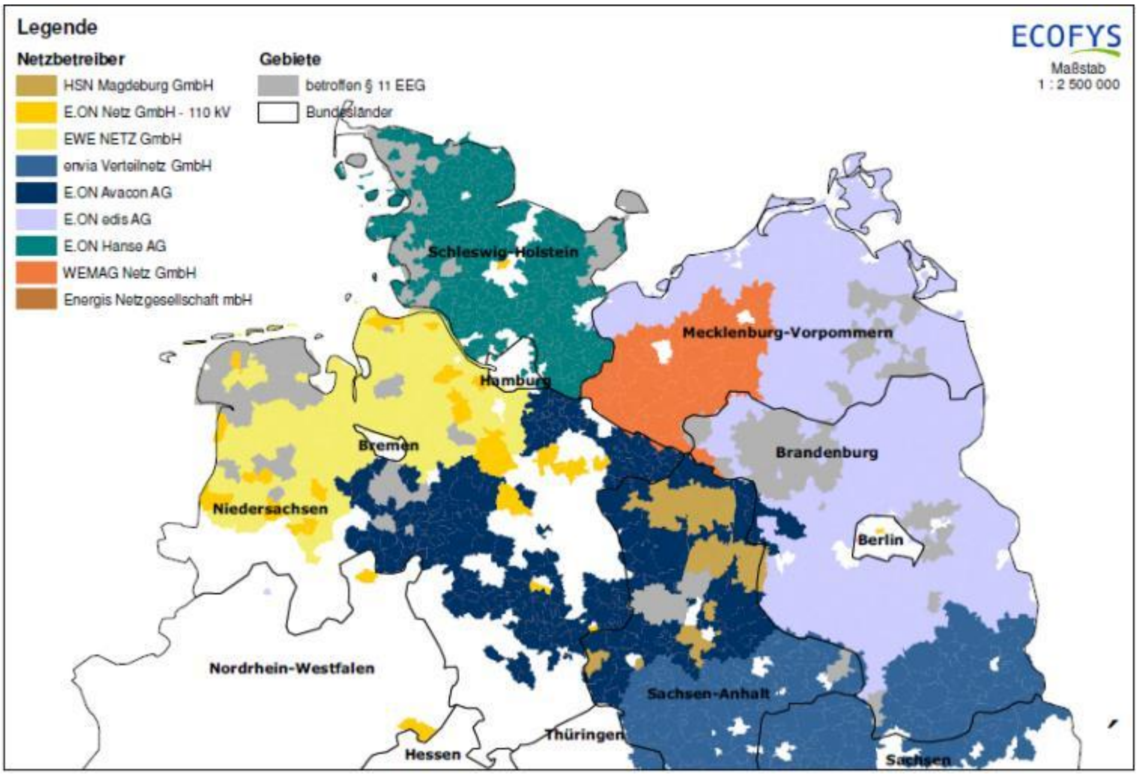

Figure 8: Areas tackled by Feed-in Management in 2010 (ecofys 2011:8)

In most national overall calculations of electricity demand and supply these local shortages are not taken into consideration. Most models disregard where electricity production is located. For the case of Germany this is an essential point, due to a delay of grid deployment in laggard regions, paradoxically these regions are almost identical with the areas of highest wind potential. Of course, an application of feed-in management prevails in areas of high deployment of wind energy. This technical problem leads to severe consequences for the electricity market. Instead of more times with very low market prices, the electricity never is traded on the market. The TSO and in the end the end-users have to pay for this unused electricity.

By consuming the wind energy directly from nearby turbines, especially offshore turbines in the north sea, the loading to the grid can be significantly lowered. The use of the excess electricity is economically highly interesting for the TSOs, because they have to refund the disconnected electricity production. According to the latest data, only in 2010, 3,4 GW of wind turbines or 13% of the installed wind capacity was tackled by feed-in management. The lost electricity production is estimated to be between 72 GWh and 150 GWh (ecofys 2011), which would mean TSOs had to pay between 4 and 9 million € for unused electricity.

If no immediate measures are taken, the numbers for feed-in management will grow extensively over the next years. Only in the North Sea area offshore wind farms with a capacity of more than 7 GW have permission and could be theoretically built today (dena 2012):

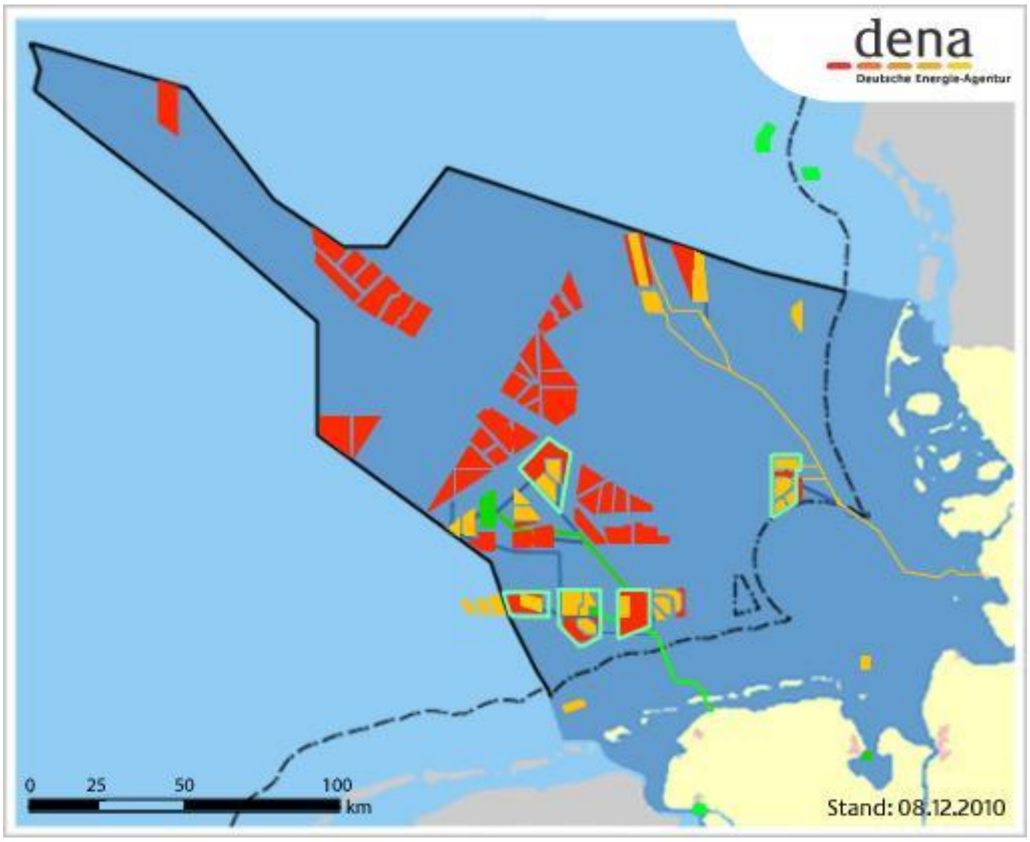

Figure 9: Overview of planned (red), permitted (yellow) and operating (green) North Sea offshore wind farms and cables (dena 2012).

The majority of produced offshore elctricity will go onshore within the area of TenneT, one out of four German TSOs. It will be within the responsibility of TenneT to integrate this huge amount of fluctuating energy into the grid. It is planned to built high voltage transmission lines to transport the electricity south to the densely populated areas of the Ruhr area (shown in red):

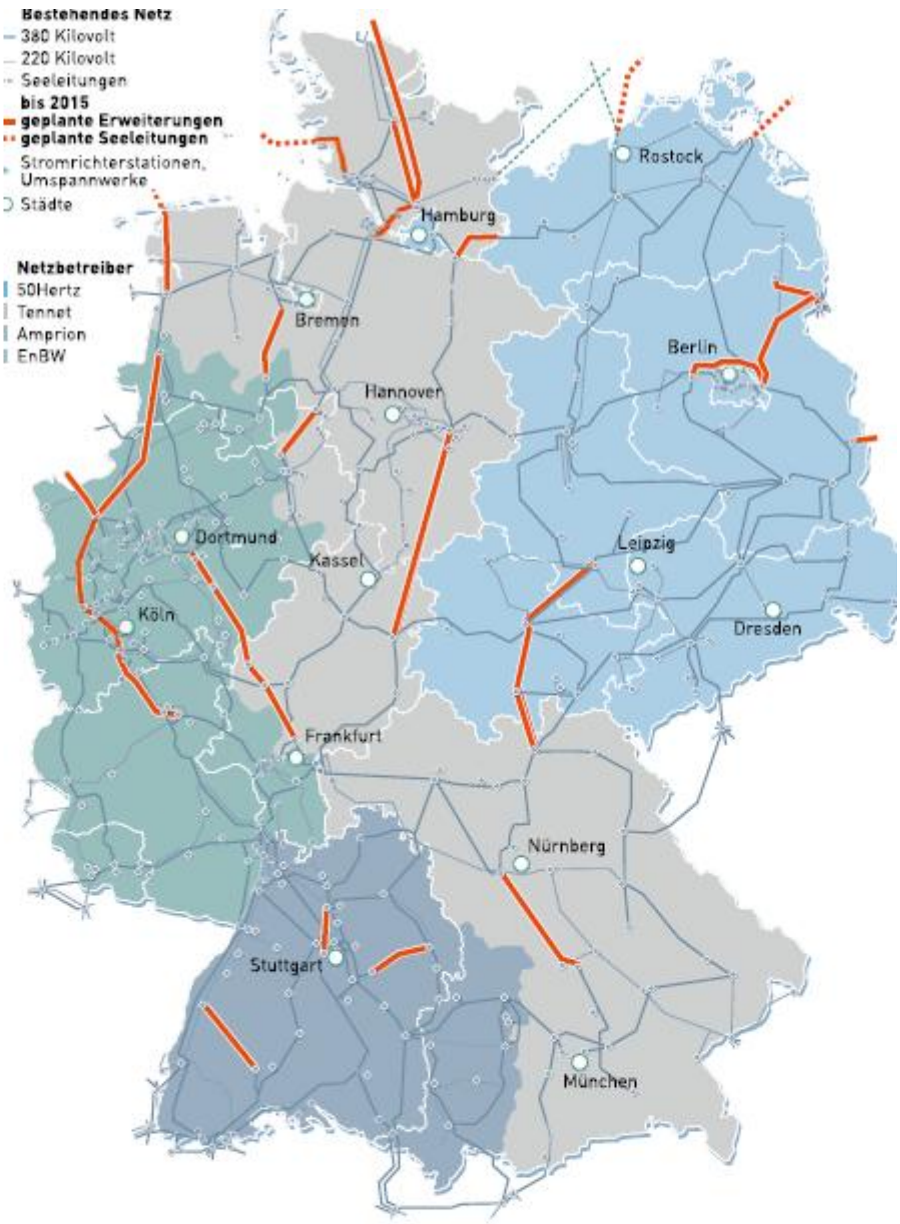

Figure 10: Urgent High Voltage Transmission Lines according to ABETL (Kunz (2011:7)

The further development of the high voltage grid is outlined in the "Energieleitungsbaugesetz" (act for the building of energy transmission line (ABETL) of 2009. Almost all of the 24 part projects identified as "urgent" are already delayed (Bischoff 2011).

If the 7GW offshore capacity in the North Sea will be connected to the grid, before the high voltage grids are ready, the costs coming from feed-in management refunds could increase drastically. Strategically placed PtG could offer a transitional short term solution to the problem: Electricity coming from offshore wind turbines can be converted into methane and transported or stored in the gas grid.

3.4 Summary

This chapter presented two perspectives for the application of PtG. The latest 100% scenario of the FEA showed a long-term perspective, in which PtG is an important technology for the integration of large amount of unsteady wind and solar energy into the energy system. A qualitative discussion on the FEA scenario in comparison to other studies unveiled, that biomass potential is used very restrictively in the FEA scenario. From the study of other scenarios and technology reviews for a integration of renewable energy, it turned out that with a further use of biomass and heat pumps in combination with a further use of district heating, the amount of hours with excess and deficit electricity could be reduced, what would reduce the need for PtG. In this vein the implementation of PtG would only become necessary in a long-term perspective, when other alternatives are exploited

In a short term perspective PtG can help the TSO to minimize the costs coming from the feed-in management regulations and the delayed extension of necessary high voltage transmission lines as an temporarily solution.

4. State of the art technology

4.1 The Power-to-gas Process

The process consists out of two steps: First step is the electrolysis of water and second the methanation of hydrogen. Both steps for their own are neither new nor innovative. Electrolysis is used for more than 200 years (DEA and Energinet.dk 201) and methanation of hydrogen, also known as Sabatier reaction after Paul Sabatier, a French chemist and noble price winner of the early 20th century. It is the combination of both steps and the integration into the energy system which is the innovative element. This combination is the result of a cooperation of the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) and the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) and is a registered patent since 09.04.2009 (Sterner 2009). The patent was bought by SolarFuel, a start-up company, aiming for a commercial use of the technology until 2015 (Specht et al. 2012).

Figure 11 depicts the process. The process will only be described shortly in the following chapter and some chemical side reactions which do not play an important role as an outcome are totally ignored. The description will mainly focus on the state-of-the art technology and the efficiencies (Jentsch et al 2011).

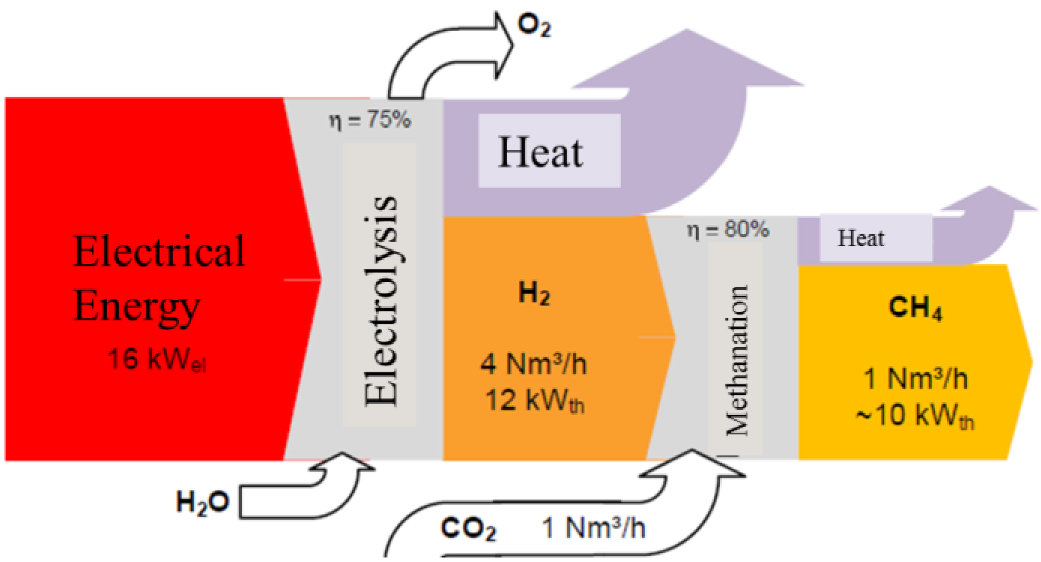

Figure 11: The Power to Gas process (Jentsch et al 2011:6)

Until today (march 2012) two PtG utilities are operating and one is under realization: The first 25 kW pilot utility was developed and set up at the ZSW in Stuttgart in 2009, showing the technical feasibility of the technology. It can produce up to 25m^3 methane per day. It was tested on different places, also at the juwi “energy landscape” in Morbach, operating together with a biogas plant as a CO_2 source. The second demonstration plant with an electrical input capacity of 250 kW was brought into service in 2012. It can produce up to 300 m^3 of renewable methane per day. A third plant is under construction for the AUDI AG in a corporation with EWE, a north German distribution system operator, it has a electrical input capacity of 6 MW and will produce 4000 m3 per day in an intemittency mode in 2013. SolarFuel plans to build commercial 20 MW plants until 2015 (Specht 2011, Specht et al. 2012, Sterner et al. 2011).

The first step of the PtG process is an electrolysis of water. Three different technologies for electrolysers are existing, but at the moment alkaline water electrolyses is the state-of-the art and a well known and commercially used technology (DEA and Energinet.dk 2010). Through an electromechanical process water is separated into hydrogen and oxygen. The formal reaction is:

$$2\ H_20 \rightarrow 2\ H_2 + O_2$$

The second step, methanation, follows the Sabatier reaction in which CO_2 is added to the hydrogen in order to produce CH_4. The formal equation is:

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

The result of this reaction is synthetical methane, having almost identical properties like natural gas, which means that it can be fully integrated into the national gas grid.

4.2 Energy Conversion Efficiency

A crucial point for energy-transformation technologies is their efficiency. The efficiency data for the two steps are alternating between different sources. The following table gives an overview off efficiencies given in different studies for the PTG process: The overall efficiency depends on the efficiency of the alkaline electrolysis and the methanation efficiency. The range goes from an efficiency of 0,52 up to 0,625. Different state of the art efficiencies are reported for the overall efficiency of the PtG process:

Source	Overall efficiency
Jentsch et al 2011	0,625
Specht 2011	0,616
Trost et al 2011	0,52 - 0,6

Table 2: Different efficiencies found in the literature

Such high efficiencies can be doubted. DEA and Energinet.dk (2010) speaks of a 58% efficiency only for electrolysis, while Jentsch et al. (2011) and Trost et al. (2011) report efficiencies up to 75% referring to the lower heating value of hydrogen. The often quoted, but older FVS (2004) report speaks of 70% efficiencies for electrolysis, but refers to the higher heating value of hydrogen, the BMU (2010:38) reports speaks of 70% efficiency, referring to the lower heating value (3 kWh/Nm^3). SolarFuel confirmed to the values from 4,7-4,1 kWh input electricity per Nm^3 hydrogen and even higher efficiencies for very low loads (SolarFuel 2012). However, it seems more likely, that such high efficiencies refer to the near future development goals for electrolysis, as reported in another report, done by the same institute (BMU 2010).

All reports agree that with a partially load efficiencies go up: “Because the tension of electrolyseurs and accordingly the efficiency depend directly on the density (and accordingly on the load of electrolysers), the efficiency rises in partial load, the same effect is characteristically for fuel cells.” (FVS 2004:53):

Large scale alkaline pressure electrolysers are reported to have efficiencies up to 82% at a minimum partial load referring to the lower heating value of hydrogen (3 kWh/m^3):

plant load (referring to maximum capacity)	Efficiency (referring on a heating value of 3 kWh/m3)
25%	82,0%
50%	78,6%
75%	76,10%
100%	73,50%

Table 3: Loads and efficiencies of alkaline electrolysers (FEA 2010:80)

Methanation efficiency basically depends on the consistence of input gas (Sterner 2009, Specht 2011) Two basic variants are possible. Firstly an injection of pure CO_2, secondly an injection of “raw” biogas, which is basically a mixture of CH_4 and CO_2. Of course the second variant results in higher methanation efficiencies (Specht 2011). Because the methanation takes place at temperatures between 250 and 550 °C the second step has a high output of heat. Some of it can be used further (Specht 2011, Trost et al 2011). In a combination of with a biogas plant high efficiencies can be achieved:

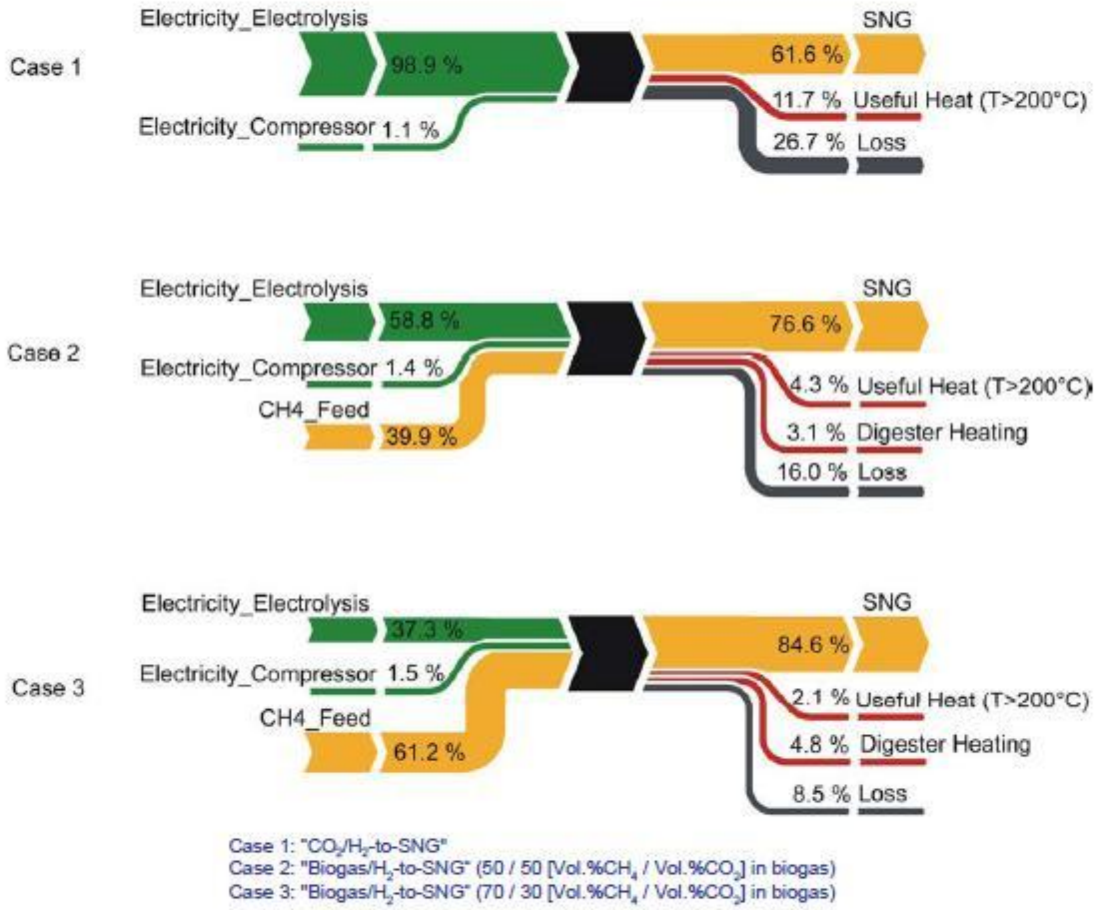

Figure 12: Different operation modes and efficiencies (Specht 2011:32)

However, in the core of this thesis is the question of the profitability of the PtG technology as an “independent” working unit (case 1). Of course, every unit participating in an energy system is interdependent with every other unit, especially when it comes to so-called smart or flexible energy systems. Operating a PtG plant in combination with a biogas plant would create new dependencies e.g. a CHP plant must be considered, meaning that the PtG plant would only operate in times of low heat demand, low electricity prices, but high biogas production. It would shift the intentional idea away from PtG as a balancing technology for the electricity system to a balancing technology for biogas production. Then the PtG technology would compete with other biogas upgrading technologies, which is definitely a highly interesting approach, but is not further investigated within the frame of this thesis.

Almost all literature indicates that a spatial combination of a PtG plant, either with a biogas plant, or both a biogas plant and a plant for upgrading biogas would result in positive synergies (Specht 2011):

1. Existing gas feed-in infrastructure
2. Use of waste heat from the PtG process
3. Use of waste CO_2 from biogas upgrading in PtG plant
4. Direct use of biogas

CO_2 is also a waste product in the biogas upgrading process. Especially this CO_2 source is optimal, as it is "impure" CO_2, having a low percentage of methane in it, which cannot be filtered (Jaggy 2012). With the use of waste CO_2 from the upgrading process of biogas, the efficiency is the highest for a "stand alone" plant, justifying the decision to assume an overall efficiency from electricity to methane of 62% for all following calculations for the PtG process.

4.3 Investment and O&M Costs

This chapter discusses the actual costs of the technology on the basis of available data and expert opinions. Because it is a maturing technology on a large scale level (even though the process is well known for over hundred years) the expected development of costs in the future is discussed as well.

Investment €/kW$_{el\ input}$		**OM €/kW$_{el\ input}$**	**Source**
2500	1250 (2030)	3% of inv costs	Trost et al. (2011)
2000	1000 (2020)	3% of inv costs	Sterner (2009)

Table 4: Different current and future Investment costs found in the literature

Table 4 already shows that the range between the assumed costs is large and that there is no accordance about the development of the technology costs. First of all it has to be mentioned that the cost estimations for today's cost level reefers in both studies to a demo scale level. Both authors also agree, that the investment cost will decrease over time and with the upscaling to a commercial scale.

However it is very difficult to estimate commercial level costs of a maturing technology. The author follows the recommendation of Hvelplund (1998:49):

We have no specific methods to use when estimating future prices of newcomer technologies, and their impacts on the technology development process in a country. Nevertheless we think that this point is one of the most important in a socioeconomic feasibility study, and we recommend that it is given a place and discussion in the structure of such studies.

Therefore the cost development is discussed in here, because it is one of the most important factors for the feasibility.

Over the past decades it was seen, especially in the energy sector it that costs of new technology decreased steadily. Wind power development in Denmark is one example, where costs/kWh have gone down with a factor 2-3 between early eighties and late nineties (Hvelplund 1998).

When Sterner (2009) and Trost et al. (2011) speak about today´s investment cost they refer to the demonstration plant existing so far, which could lead to a price overestimation. However, a cost development like described for wind turbines is unlikely, when considering the core of the innovation: It is a combination of two existing technologies, a so-called process innovation. Wind turbines were rather a product innovation. This is an important differentiation to make, when looking at the key drivers of investment cost reductions for maturing technologies.

Hearps and McConnell (2011:6) define the main drivers for technological improvements into two categories:

1. “Technological improvements – changes to the basic design of the technology”, which includes “Learning by doing” –coming from the experience gained from more efficient construction and operating methods and “Technical efficiency”, coming from continued research & development processes and and upgrading to state-of-the-art components what results in incremental efficiency gains (Hearps and McConnell 2011:6)

2. “Economies of scale – increase in the size or volume of units results in lower costs per unit” consisting of “Economies of scale in the physical size of components” – meaning efficiency gains in the manufacturing process by the use of larger components for a larger scale of the plants. The second element of the economies of scale is the cost saving through “large-volume manufacturing”

– mass production allows a highly efficient, industrialised manufacturing process (Hearps and McConnell 2011:6)

As already mentioned in section 4.1 both components of the PtG process are well known and “old” technologies what may lower the effect of the first key driver, incremental technological improvements. But the second point seems to be promising. The investment cost are so far estimated for a demonstration plant. Economies of scale could have a significant effect in the future. Sterner (2009:111) writes about upscaling: “Basically, the only significant modification in methanation are larger diameters of the reactors pipelines and fitting concepts for using surplus heat” and that electrolysers are modularly available in all scales and generally cheaper (€/kW) in a larger scale with the same efficiencies (DEA and energinet.dk 2010). Therefore cost reduction for technological improvements might be low, while significant and immediate cost reductions through upscaling the technology, especially in the physical size of components seem to be realistic. A reduction of investment cost by factor 2, like assumed by the authors named above and like it was seen in the “hot phase” of wind power in Denmark seems to be a bit optimistic, while reductions from upscaling could be realized immediately with a larger plant size. Based on these consideration investment costs for a 10 MW PtG plant are in the following calculations assumed to be 1750 €/$kW_{el\ input}$.

4.4 Summary

The presentation and discussion of the current state of the art technology for a PtG plant unveilled that different there is no fixed state of the art factsheet. Even among leading experts and different articles of same experts, there are different assumptions, especially for investment costs. Another source of differences is the numbers found for conversion efficiencies, coming from different possible operational combinations and synergies between a PtG and biogas plants. The following table shows the external technological assumptions used in following analyses. Some are based on the discussion of the most important literature, presented above; others are set externally by the author.

Lifetime	20	Years
Investment	1.750	Euro/$KW_{el\ input}$ capacity
O&M (3% of Inv. Costs)	525000	Euro/year
Electrical input Capacity	10	MW
Electricity to Gas Conversion Efficiency	62	%
hourly Gas Output	6,2	MWh gas
Water Consumption	200	l/$MWh_{el\ input}$
Useful heat	0,11	MWh_{heat}/$MWh_{el\ input}$

Table 5: Overview of key assumptions for following calculations

5. Regulations, Markets and Prices

This chapter depicts the most important legal framework for the power to gas technology at the moment, basically, the rules concerning electricity tariffs, feed-in of gas into national gas grid, legal definition and status of the gas and rules for further use of the gas. It is important to fully understand the legislation, as it results in different taxation and price level of the gas and the business economic feasibility. Therefore each input and output factor will be analyzed on, its own in order to understand how it has to be integrated into the hourly model. A more deeper analysis is conducted for electricity and gas, because of their special importance in the PtG process. The sections on CO_2, Water, Heat and O_2 are limited to the most important points and their prices used in the calculations of chapters six and seven.

5.1 Input

5.1.1 Electricity

Electricity prices are the most important factor for the price of the produced methane. Prices for electricity mainly depend on how electricity it is bought. The majority of electricity in Germany is still traded "over the counter" in long term contracts. The rest is traded on the spot market. Spot market prices vary from hour to hour. Like every market the price describes a balance between demand and supply. Theoretically, prices are high in times of low production and high demand, and low in times of high production and low demand. In order to guarantee a balancing operation, PtG is meant to operate in times of low prices.

Two studies calculate the cost of renewable methane, both published by the Frauenhofer Institute, which holds the patents for the technology, namely Sterner (2009) and Trost et al. (2011), both assuming that surplus electricity from wind energy production can purchased on very low price level: „Variable costs arise from the purchase of electricity, which is the most volatile parameter in cost calculations. In future power grids, wind power is likely to be very economic and available at 0-2 EUR-cents kWh_{el} in times of high wind penetration." (Sterner 2009:112). It is true, that a future 100% renewable energy system will face a lot of surplus electricity coming from wind power production. However, under the current market situation such price level occurs very rarely. And it can be doubted if such low prices for electricity will be arise very often in the future. An example of an electricity system with a high share of wind energy is the Danish system: Looking at the Danish system, elspot prices of 20 €/MWh and below appeared in 334 hours during 2011, while the average price for electricity was 47,96 €/MWh. The average price for downward regulation was 31,35 €/MWh, Downward regulation prices of 20 €/MWh and below appeared in 468 hours of 2011. Price assumptions of 0-20 MWh in 1000 hours today and 3000 hours in the future (Trost et al 2011) do not reflect today´s reality. Compared to the German market prices it is cheaper.

	DK West (Elspot)	**DK West (Regulating Power)**	**Germany (Epex)**
Average price in €/MWh	47,96	31,35	51,13
total hours with prices of 20 €/MWh and below	334	468	282

Table 6: Average prices and amount of hours with low prices in different Power markets for the year 2010

Apart from the spot market, there are three balancing or reserve markets in the whole ENTSO-E area (ENTSO-E 2012): The primary control reserve, secondary control reserve and tertiary control reserves “minutenreserve”. The following graphic shows how the reserves complement each other:

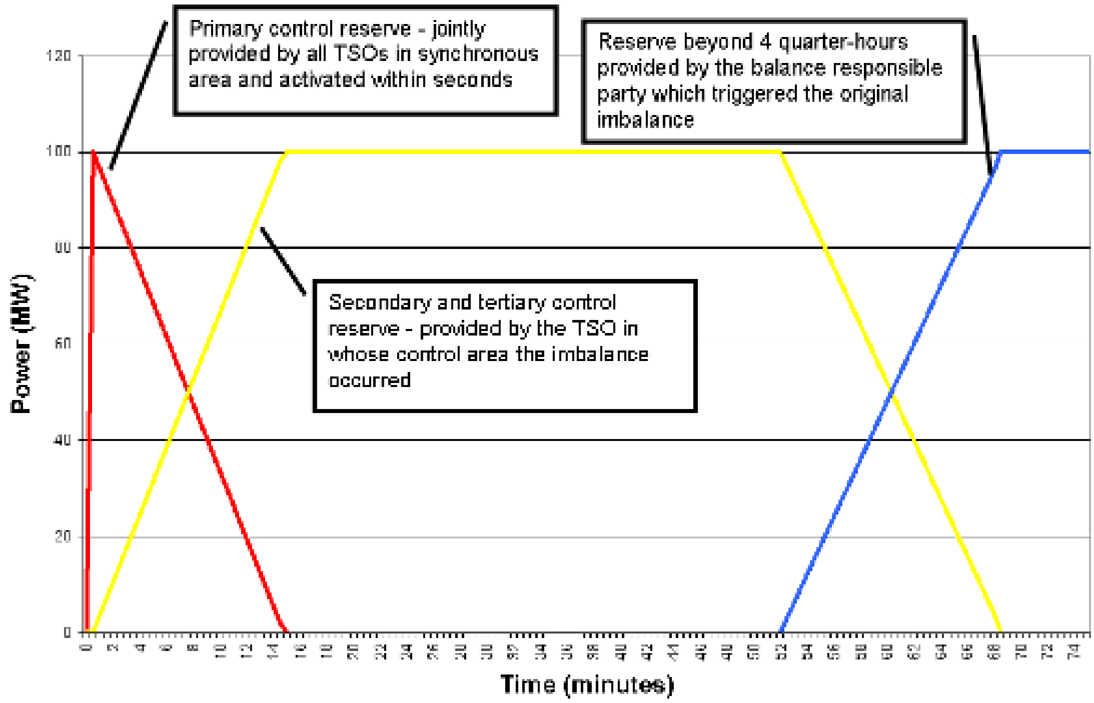

Figure 13: Overview and relationship of the reserve markets (regelleistung.net 2012)

The Primary control reserves can be activated within a maximum of 30 seconds. Eventhough they are highly important to remain the frequency of 50 herz of the grid and therefore guarantee a functioning grid system, there overall work is very restricted, due to the limited amount of time they are running when activates (less than 15 minutes).
Secondary control reserves can need a longer activation time, but are running a longer time period. After 15 minutes the tertiary reserves take over. Tertiary reserves can run up to several hours. (ENTSO-E 2012). The PtG technology fulfils all technical requirements for all three reserve markets and could therefore offer downward regulation (FEA 2010). While the primary and secondary reserves earn their money, mainly with their stand-by service, plants on the tertiary market mainly profit from very low to negative prices for electricity, in case of downward regulation and from very high prices in times of upward regulation.
All three markets become necessary, if planned supply does not meet the demand, or other way around. They can be seen as a support to balance the spot market. Another complement to the spot market is the intra-day market. While the last offers on the spot market have to be submitted 24 hours ahead, offers on the intra-day market can be made until one hour ahead. The average price on the intra-day market was 1,14 €/MWh above the day ahead market (BMU 2011).

The reserve markets are an instrument to balance temporary imbalances in the grid, in order to keep the 50 hertz frequency. 90 % of all production facilities, that theoretically fulfil the requirements are registered for the auctions (Amprion 2012).
In the following calculations the plant is operating on different electricity markets. This brings in one point that needs to be discussed. Buying electricity from electricity markets it cannot be ensured that it is green electricity. It is so-called “black” electricity. This point becomes especially important when it comes to the legal classification of the gas and the prices it can achieve (see chapter 5.2.1 below).
Electricity produced from renewable sources is independent from market prices. According to the EEG it gets fixed feed-in tariffs. If the methane shall be produced exclusively from renewable electricity, the plant operator needs to pay at least the minimum feed-in tariffs. For onshore wind energy feed- in tariff is around 9 ct/kWh for minimum first five years and for maximum of 20 years. After 5 years the feed in tariff is 4,87 ct/kWh. In many cases the higher tariffs are paid for 10-15 years period, in order to enhance the feasibility of lower wind speed sites. Offshore wind tariffs are 15 ct/kWh for offshore for the first 12 years, but are also very likely to be extended according to their distance from the cost. What differences it makes which electricity is consumed for the legal status of the produced gas is described in section 5.2.1 of this chapter.
From this perspective it gets obvious, that surplus electricity from wind energy will not be available for the assumed cost, because it has a fixed feed in tariff and does not follow the market laws in this point. But the electricity is sold on the spot market and causes in times of a high wind penetration cheap market prices for electricity. Therefore it is not the electricity from wind power that is getting cheaper, but the market price is reduced, due to a high supply with electricity with low marginal costs that pushes production units with higher marginal costs out of the market. This effect is known as the merit order effect.
With the further development of wind energy it can be expected, that spot prices for electricity will drop in the future (Morthorst 2007, Sensfuß and Ragwitz 2007). Therefore, sensitivity analysis is conducted in chapter 6 also with lower electricity prices.
It needs to be clarified that, while electricity spot prices are likely to drop, end consumer prices are likely to rise, due to a distribution of feed in tariffs from the TSO to the end consumer. It is clear, that the investment costs of renewable capacity have to be financed. It is quite likely, that this will be shouldered by society, respectively

electricity consumers. However, green technology might bring investment costs, it also brings savings from fuel consumption and external effects. But this will not be further investigated in this study. A comprehensive analysis of costs and benefits of an 100% renewable energy system, compared to a conventional system in Denmark can be found e.g. in Ida´s 2050 climate plan (Mathiesen et.al. 2009).

5.1.2 CO_2

CO_2 is a waste product many different processes. It was already mentioned that waste CO_2 of a biogas upgrading process would be an interesting source for CO_2. The small share of CH_4 (2-6%) which is together with the CO_2 as a part of the waste gas would make the methanation process more efficient. In most biogas upgrading plants CO_2 is simply blown out in the atmosphere. Therefore CO_2 should be available for almost no money, as it has no value for most processes at the moment, accordingly CO_2 costs are not taken into the calculation (Jaggy 2012, Jentsch et al 2011). Of course, this assumption must be doubted when it comes to a widespread implementation of the technology, purchase or production cost for CO_2 has to be taken into consideration. Existing biogas upgrading plants could supply CO_2 for a PtG capacity of 680 $MW_{el\ input}$. Theoretically, CO_2 could also be extracted from the atmosphere through absorption and electrodialysis (Bandi 1995). For detailed description see Sterner (2009:114). The use of atmospheric CO_2 would mean additionally electricity consumption of 2,27 MWh per ton CO_2. Around $100Nm^3$ CO_2 are necessary to produce 1 MWh_{th} of gas. (Sterner 2009, Jentsch et al 2011). This would mean an additional costs and is not further investigated in the following.

5.1.3 Water

Water consumption of PtG is low. For each MWh_{el} input 200 l of water are converted. Large coal power plants need 20000-30000 l/s only for cooling. When methane is burnt water steam is a result. Therefore it can be regarded as a “closed” water circle, without a considerable impact for the environment (Sterner et al. 2011). Currently water prices are around 0,005 €/l, what means that water costs for the conversion of 1 MWh electricity are around 1 € (Gehrenberg Wasserversorgung 2011). Today there are no legal considerations concerning the conversion of water into a fuel.

5.2 Output

5.2.1 Methane

The price an operator of a PtG utility can get for the produced renewable methane heavily affects the profitability. The price for import prices for natural gas in Germany varied between 20 and 30 €/MWh gas (Bafa 2012). According to the renewable energy act electricity produced from biogas and biomethane gets fixed feed in tariffs, what accordingly leads to higher prices for biogas and upgraded biogas between 70 and 80€/MWh (Härdtl 2012, Bundesnetzagentur 2011), also depending on the originally biomass used for the plant (EEG, Härdtl 2012). Therefore the legal status of renewable methane is decisive for its business-economical feasibility.

There are two laws which need to be considered: The EnWG (Energy Industry Act) which is the general framework for the whole energy sector and the EEG (Renewable Energy Act) which outlines specific regulations and advantages for renewable energy.

The EnWG defines renewable methane as biogas, if it is mostly produced from renewable electricity. PtG utilities do not have to pay taxes for electricity, nor fees for electricity grid access, nor for gas feed-in-fees. (EnWG §3,10c; §118,7).

The EEG defines renewable methane as storage gas (§3 abs9a, translated by the author): "every gas that is not renewable energy, but produced exclusively out of renewable electricity for the purpose of storage of electricity."

§ 16 of the EEG states that electricity produced from storage gas gets the same feed in tariffs like the original electricity source would have get, refeering to the amount of electricity produced from the storage gas. This means that e.g. 1 MWh of wind energy is converted into 0,6 MWh of storage gas. The storage gas is used as a fuel in a highly efficient gas turbine that produces 0,36 MWh of electricity out of it.

Assuming that the whole production line is owned by the same owner and that the feed in tariff for wind energy is 89,3 €/MWh he gets 89,3 € selling the electricity directly and 32,15 € in the example. There are no incentives for storing renewable electricity voluntarily.

Only if electricity could not be feed into the grid, because of an overload there is an incentive. But the EEG legally prevents renewable excess electricity (§8abs1): TSOs are obliged […] to buy, transmit and distribute the whole amount of renewable electricity offered . In grid stability emergency cases TSOs can disconnect turbines from the grid, so called "Einspeisemanagement", but have to fully refund the lost electricity. This leads to the result, that wind turbines are rather disconnected from the grid in times of excess electricity, instead of lowering market prices.

Taken this discussion into consideration it seems unlikely for a commercial PtG plant to produce renewable “storage gas” according to the EEG, only if the renewable electricity producer voluntary abdicate his money for the sake of grid stability, an unlikely procedure.

Therefore in a first step under the current situation, market prices for gas needs to be assumed as a realistic price for PtG methane. Therefore, gas prices is set on 25€/MWh gas in the model.

In case of an methane production entirely based on electricity from wind energy prices for the gas, if produced on wind would be maximum between 30€/MWh for onshore and 54 €/MWh for offshore wind, calculated in accordance with §16 EEG.

It is quite likely, that the price for natural gas will further increase in the near future. Figure 14 shows the development of average natural gas import prices over the last decade:

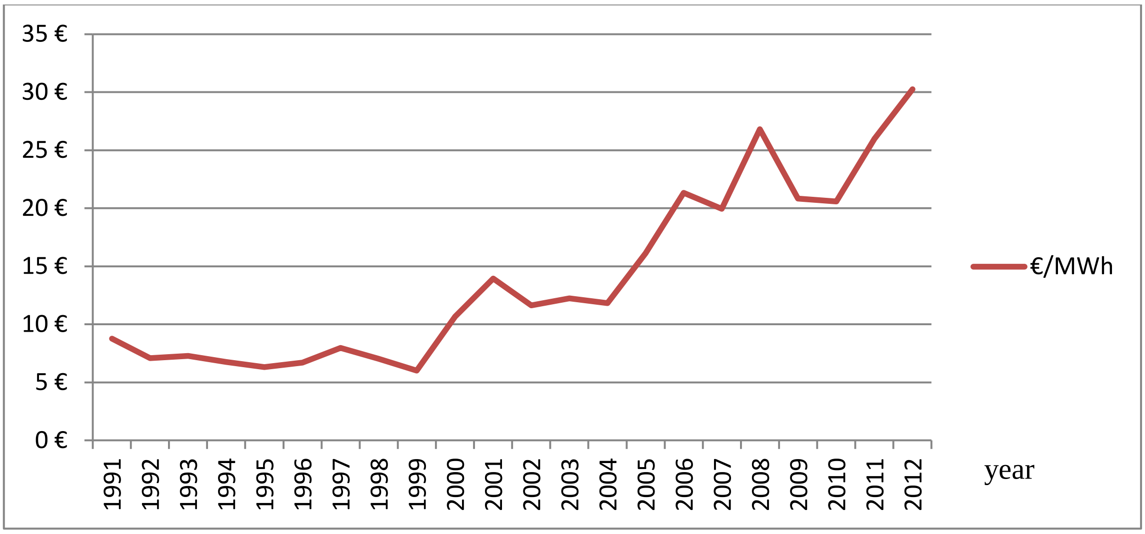

Figure 14: Development of natural gas prices (Bafa 2012)

It can be seen that the prices for natural gas rose constantly rose during the last decade. Prices in the first two months of 2012 have been almost three times higher than in 1991.

Looking at the latest World Energy Outlook (IEA 2012) it seems to be likely that the price development will continue. The IEA speaks about a “golden age of gas” the world is about to enter. Global demand and gas trade will rise further. European import prices are expected to nearly doubly until 2035 (IEA 2012). Eventhough it is only one possible scenario, it shows that gas has a huge potential to become the most important fossil energy carrier in the near future. In a long term perspective the prices are very likely to raise, due to limited conventional gas resources: While conventional resources are estimated to cover the current demand for the next 120 years, a growing demand could reduce this number dramatically. European resources only are expected to last 75 years. After that Europe will heavily really on mainly Russian gas imports (IEA 2010). All this considerations lead to the result, that the gas market will show a development towards higher prices in the near, and especially in the long-term future.

In January 2012 the three most important gas supplying countries of Germany are: Russia (33,3TWh), Norway (31,3 TWh) and the Netherlands 29,3 TWh). The imported natural gas had a value of 3,1 billion Euro (Bafa 2012).

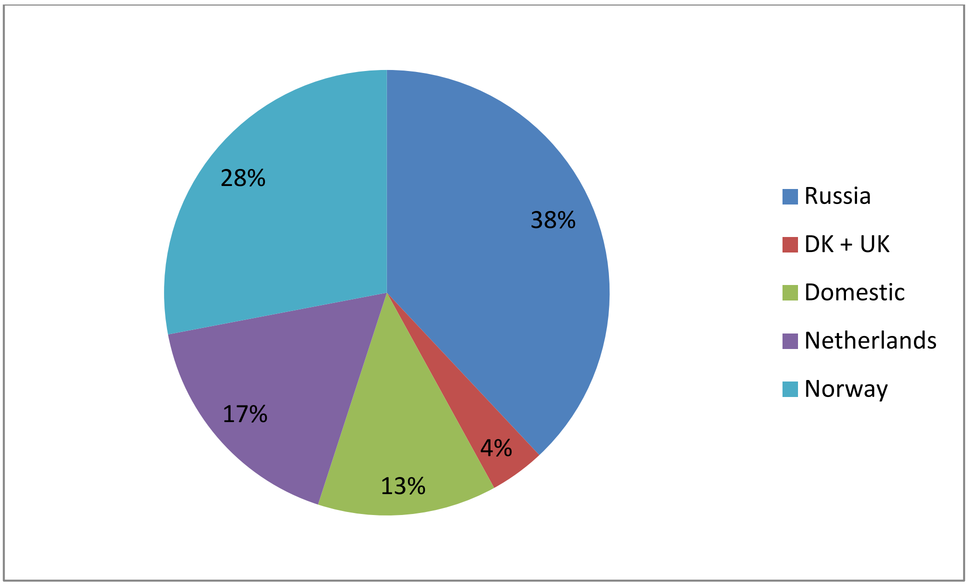

Figure 15: Germany´s gas supply according to gas origin in 2008 (BmWi 2009)

Southern Germany is almost fully supplied with Russian gas. In February 2012, imports from Russia had been unexpectedly reduced by 30% below traded amount, due to a very cold period in Russia that caused a higher demand and Russian domestic politics (Bundesnetzagentur 2012). In the same time central Europe suffered from a very cold period as well. In order to guarantee gas supply for private households some industrial southern German consumers could not be supplied any more, among them system-relevant gas power plants. The consequence was a highly problematic situation for the electricity system (Bundesnetzagentur 2012). In 2009 russian gas delivery was reduced by almost 90%, but could be covered by full gas storages (Bundesnetzagentur 2012).

5.2.2 Heat

Because electrolysis and methanation are both exothermic reaction waste heat can be further used. Around 11% of the energy input to the process can be considered as useful heat with a temperature above 200°C. In the model it is assumed, that the plant is connected to a district heating grid and can sell all the produced heat for 30 €/MWh heat.

This is an assumption, based on the fact, that a district heating gas boiler has a marginal production cost of around 55 €/MWh and is one of the most expensive district heating technologies (Anderson 2010). It can be assumed, that the heat is cheaper, as it is a waste product. Differences in heat demand over the year are not considered, what makes a heat storage unnecessary, as well.

The use of heat to produce electricity in an Organic Ranking Cycle as proposed by Sterner (2009) is not further investigated in this study, as it would heavily oppose the intention to convert and store surplus electricity. It would be contra productive to produce more electricity in times of surplus electricity. Also from a business-economical point of view it can be doubted. In times of surplus electricity market prices for electricity are low. The income from sold electricity would be low as well.

5.2.3 O_2

Electrolysis of water results in H_2 and O2. While all H2 is further used in the process, O_2 can be easily bottled and sold. Prices for O_2 are around 70 €/t, equivalent to 13 €/MWh input electricity (Sterner 2009). This price is quite high, what makes it an important factor for the economical feasibility of the plant. The income coming from selling O_2 has not been considered in any study so far, but will be part of the calculations in the following chapter.

5.3 Summary

This chapter described the most important external regulations, market and price conditions for each in and output factor of the PtG process, with a special emphasis on the electricity and gas market structure and characteristics, including directions for future prices and developments.

The most important regulations concerning PtG is the legal status the produced methane obtains. If it is produced from conventional electricity it does not get a particular support, only if it is produced solely on renewable electricity, it is objective of an EEG support. Purchase costs of wind energy are assumed to be equal to the EEG tariff, which is 9 ct/kWh for onshore and 15 ct/kWh for offshore. If market electricity is used, purchase cost for electricity depends on the hourly market value. The following markets are used in the following: EPEX, ELSPOT and the Danish Regulating Power market (tertiary reserve). All other external cost and input factor are set as follows:

Costs CO_2	0	€/t
Costs Water	0,005	€/l
Price Methane	25	€/MWh_{th}
Price heat	30	€/MWh_{heat}
Price O_2	70	€/t

Table 7: Overview of Costs and Prices of in- and output factors for following calculations

6. Economics of PtG

This chapter analyses the economic performance of the plant. Firstly, an introduction presents the main economical characteristics. Among them the relationship between price of electricity and methane production cost, the influence of the amount of full load hours on the price, and the detailed cost structure, including the sensitivity of the cost towards changes in investment costs, interest rates or electricity prices.

After these general economic characteristics, the profitability of a investment of the plant is analysed in two specific cases. In the first case the plant operates under current market conditions in the German spot market (EPEX), the Danish spot market (Elspot) and the Danish regulating power market. The analysis is made in this case from the perspective of any regular market participant. For an analysis of the short term perspective, this approach is sufficient. In order to make statements about the long-term perspective, on the backdrop of the FEA scenario and ways towards a renewable energy system presented in chapter 3, environmental input factors need to be adjusted. This is done through a sensitivity analysis with changed average electricity and gas prices.

In the second case the analysis of the profitability is conducted from a different perspective. Here the analysis focuses on the question if PtG could be a profitable investment from a TSO´s point of views, keeping in mind the high refunds for renewable excess electricity and problems in the high voltage grid development, described in chapter 3.3. In order to gain a better understanding of the economics of PtG, it is compared in both cases to simple Electrolysers, an alternative to PtG.

6.1 Economic Performance

The following graphic shows what it costs to produce 1 MWh of methane. It depicts only the marginal production cost with the plant characteristics depicted in table 5 on page 33, without investment and O&M costs, and market costs and prices of table 7 on page 43 above.

Figure 16: Marginal Production Costs of PtG Methane under different Electricity Prices

Figure 16 shows, that the purchase costs of electricity are clearly an important driver of marginal production costs. Considering that prices for electricity, especially downward regulating can even be negative, this finding seems to be very promising for a balancing operation of the technology.

Closer to the "real" costs of renewable methane is the following figure which depicts the specific cost in €/MWh methane, calculated for different amounts of full load hours and different electricity prices. For all the calculations investment costs of 1750 €/kW, yearly O&M costs of 3% of investment cost, and an interest of 3% and a lifetime of 20 years are used. This results in fixed annuity rates of 170.500 €/MW el. input capacity.

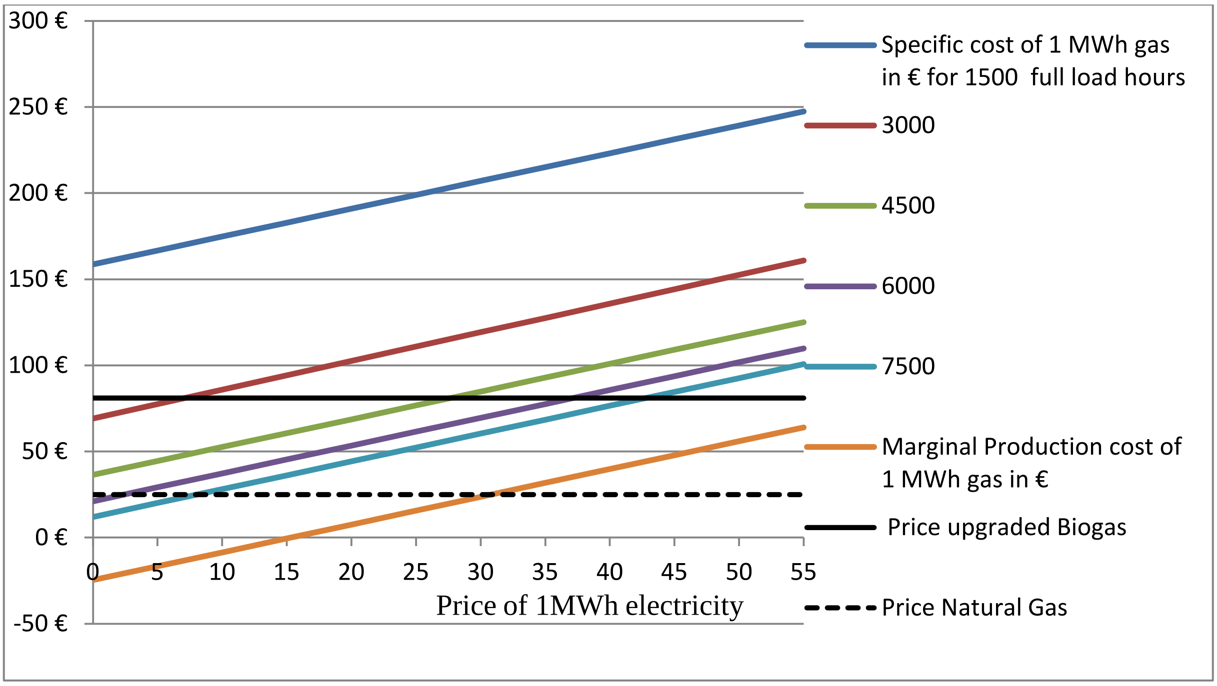

Figure 17: Specific Costs of PtG Methane under different Electricity Prices and Full Load Hours

It can be seen that the amount of full load hours is the decisive driver for the specific costs, even more important than the electricity price.
The top end prices for upgraded biogas in 2010 was around 81 €/MWh (Bundesnetzagentur 2011), symbolized in the graphic by the fat black line, the price for natural gas is marked by the black dotted line. Assuming the price level of biogas maximum price that can be achieved for the gas, a PtG plant could only operate economically between with 4500 or more full load hours per year and electricity prices below 30 €/MWh electricity. If the plants can only operate in 3000 hours or less, electricity prices may not exceed ca.10 €/MWh electricity. If methane has to be sold for the natural gas market prices (dotted black line in the graphic), only scenarios with more than 7500 full load hours and very low electricity prices (5-10€/MWh electricity) seem to be an option where an investment could be profitable.

The calculations above already indicated, that there are two main drivers for the profitability of the plant: Electricity prices and full load hours. The following graphic shows a more detailed picture of each cost factor for the production of 1 MWh methane. In all the scenarios the plants operates 4500 full load hours over 20 years lifetime and an electricity to methane efficiency of 62% (75% for electricity to hydrogen).

Investment costs, interest rates and electricity prices vary between scenarios, according to table 8 (assumptions for electrolysers in parenthesis):

	Investment Costs in €/kw$_{el\ input}$	**Interest Rate in %/year**	**Electricity Price in €/MWh$_{el\ input}$**
Scenario 1	1250 (750)	6	20
Scenario 2	1750 (1000)	6	20
Scenario 3	1750 (1000)	3	20
Scenario 4	1750 (1000)	3	35
Scenario 5	1750 (1000)	3	150

Table 8: Overview of assumptions for following figure 18

The objective for the following figure is it to understand how sensitive the economics of the plant reacts to changes in investment costs, interest rates and electricity prices:

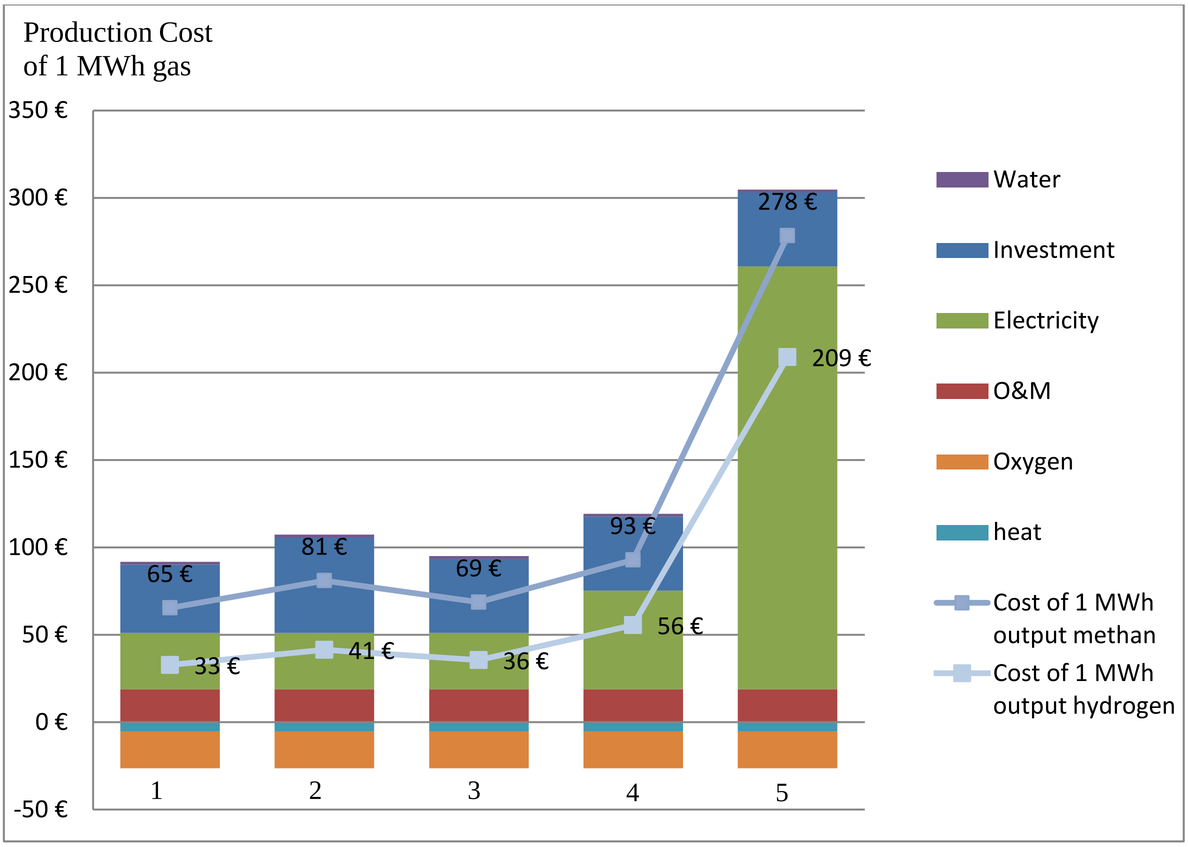

Figure 18: Cost structure of 1MWh methane in different scenarios

It shows that the two big cost blocks are the investment cost and electricity costs, while water costs are close to zero. The income of selling oxygen and heat decreases the costs per MWh methane of 26 €. Scenario 1 and 2 only vary in their investment costs, what already causes a considerable difference. Scenario 3 has a reduced interest rate, making it cheaper again. Methane can be produced for the lowest cost in the low investment cost scenario 1. In scenario 4 and 5 only costs for electricity are raised, by 50% compared to scenarios 1-3 resulting in the second highest costs for methane. Scenario 5 deals with price levels for electricity, equal to the EEG fed-in tariff for offshore wind energy, what led the production costs explode. The bright blue line shows the corresponding costs of hydrogen. The cost structure of hydrogen can be found in the annex. In scenarios 1 and 2 pure hydrogen production is almost half the cost for methane. It is significantly cheaper in all scenarios, due to lower investment costs and higher efficiencies. These cost estimations are rather optimistic, as especially in the case of hydrogen high infrastructural, compression and storage costs need to be added and in the case of methane CO_2 costs are assumed to be zero.

Figures 17 and 18 showed that PtG has a very high sensitivity towards full load hours, Investment costs and electricity prices, what makes it very difficult to determine production costs for methane using PtG.

Therefore the real performance of the PtG technology can only be assessed in a “real world” hour-by-hour model where prices for electricitiy are given by the real market prices of electricity and not assumed by “wishful thinking” . A yearly profit is calculated for the PtG plant participating in different markets in an hourly intermittent operation. The markets are the German spot market for electricity (EPEX), the Danish spot market for electricity (Elspot), referring to the price area of Western Denmark and the Danish auctioning market for downward regulation. A fourth scenario is an optimized operation on the price basis of Elspot and the regulating power market.

6.2 Case 1: Normal market participant

After analysing the general economics of PtG on in the section before, this section analyses the economics and profitability of the plant of an investor´s point of view. The FEA scenario, presented above in chapter three foresees 44 GW capacity of PtG, in order to balance the energy system. An investor and market participant is basically interested in a profitable operation of the plant and a profitable investment. This can contradict the idea of a balancing operation.

The FEA scenario is done for the year 2050 and thus is a long-term perspective, also for the implementation of PtG. In order to deal with changed market conditions in the future sensitivity analysis is conducted.

Firstly, the most promising market for an operation of the plant is determined, which is the market where the plant can make the highest yearly profit and achieves the best NPV. For this market the distribution of operation hours and income is depicted over one year. Then dynamic payback times are calculated, for the different market scenarios, followed by a sensitivity analysis under changed market conditions. After that the operation hours of the sensitivity scenarios are pointed out. Electrolysers are used as an alternative investment and a "point of orientation" for the performance of PtG.

The following figure shows the yearly profit (blue bar) and working hours (red bar) on different markets:

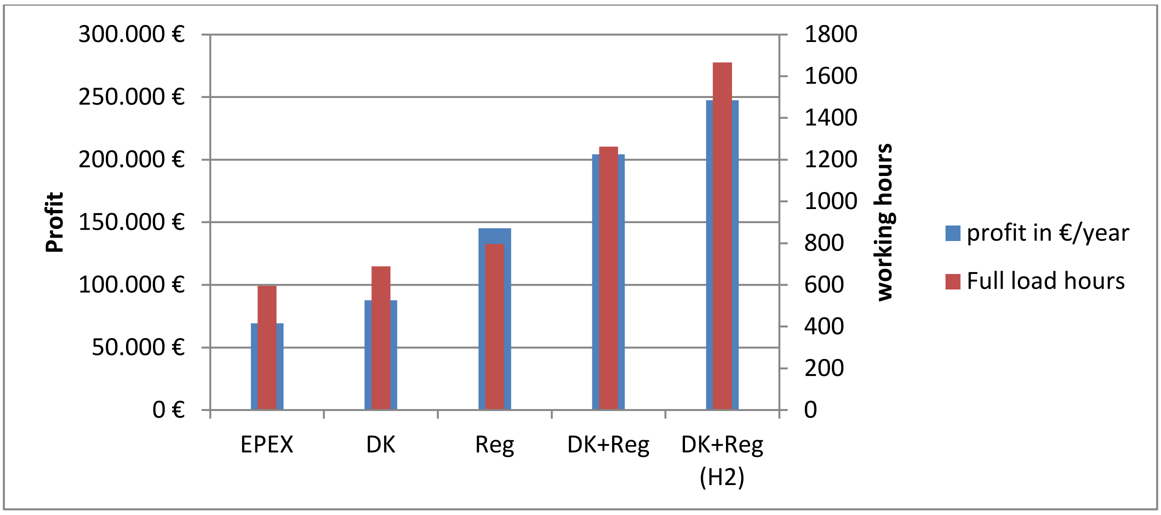

Figure 19: Yearly profit and full load hours in different markets

Figure 19 clearly indicates that the highest profit can be achieved in Scenario DK+Reg (combination between Danish downward regulation market and Danish spot market). It also shows that the differences in profit between buying electricity on the German spot market and on the Danish spot market is enormous, due to lower average prices and more hours with extremely cheap electricity (below 20 €/MWh). This effect is even bigger in the Danish regulating power market. Electrolysers could achieve a higher profit. Under current market conditions the amount of working hours still seems to suit a balancing operation. Looking at the distribution of profit and working hours, it seems that the plant operates, especially in autumn, generally, months of high wind energy production and medium temperatures (no high heating or cooling demand):

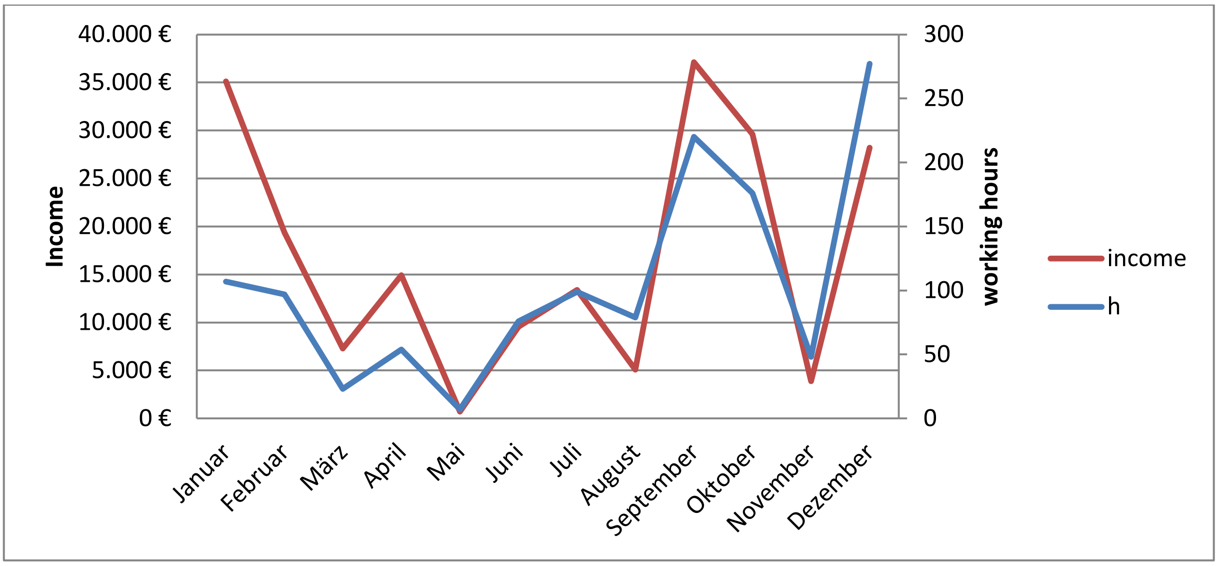

Figure 20: Distribution of working hours and profit over the year

Interesting is also the peak of full load hours in December and the profit peak in January. In January 2010 hours with very low, even negative electricity prices occurred. December production peak could be explained by a lot of wind energy and a high electricity demand, leading to medium prices for electricity.

The decisive question is now, if this low amount of working hours can achieve enough profit to pay back the investment costs and profit expectations within the lifetime of the plant.

The following graphic shows the Net Present Values with the technical characteristics of table 5 on page 33 and market costs and prices of table 7 on page 43 above. Investment costs for electrolysers are set at 1000 €/kW$_{el\ input}$ and efficiency of 75%. Discount rate is set at 6%.

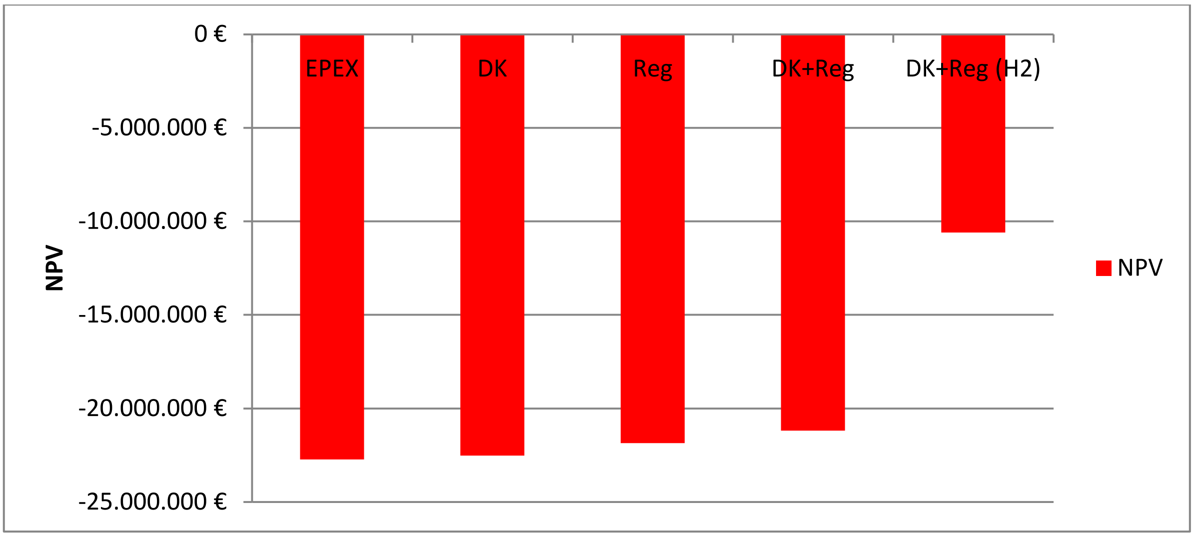

Figure 21: NPV for PtG and Electrolysers in different Electricity Markets

The result is disillusioning. In none of the four markets the PtG plant can operate economically successful. The OM costs exceed the yearly income in all markets. Results for all different markets are clearly negative. The differences between the markets are rather small. More promising, but still negative seems to be the result for electrolysers. Under slightly changed conditions this technology could become profitable. Dynamic Payback time accordingly shows the same picture:

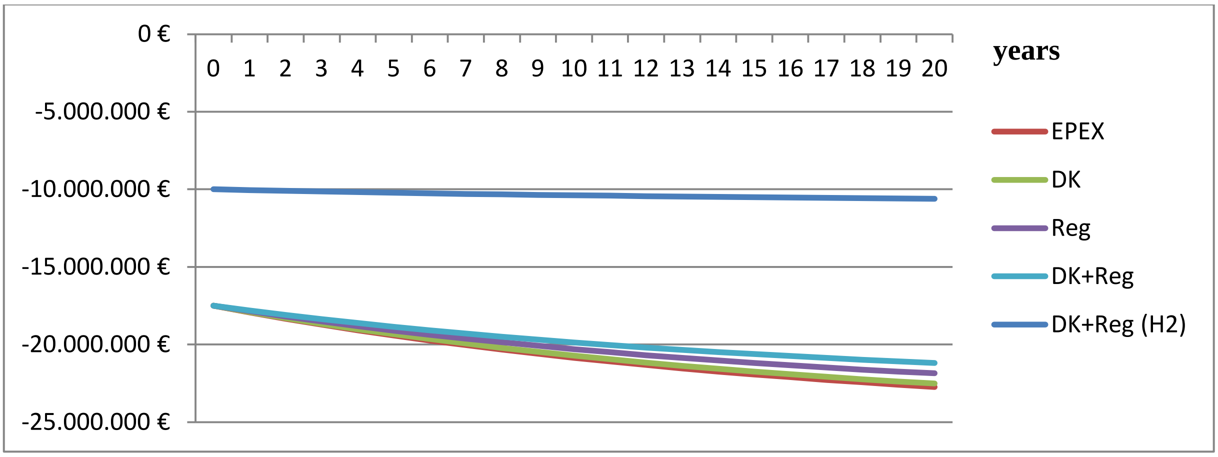

Figure 22: Dynamic Payback Times for PtG and Electrolysers in different Electricity Markets

From a business point of view an investment in a PtG plant is unfeasible under current market and regulative conditions for normal market participants. The same is true, but less drastically for electrolysers.

It was already mentioned that PtG plants are operating on two volatile markets, the electricity and the gas market. The direction of the development curve of market prices for electricity can be expected to go down with a further employment of wind energy in the future, due to the merit-order effect (Munksgaard and Morthorst 2008), while the price for methane and natural gas are expected to rise further in the future (IEA 2012). Therefore sensitivity analyzes is conducted for different electricity and natural gas price scenarios and changed discount rates. The reference for the sensitivity analysis to the most promising scenario for PtG: a combined operation on the Danish spot and balancing market.

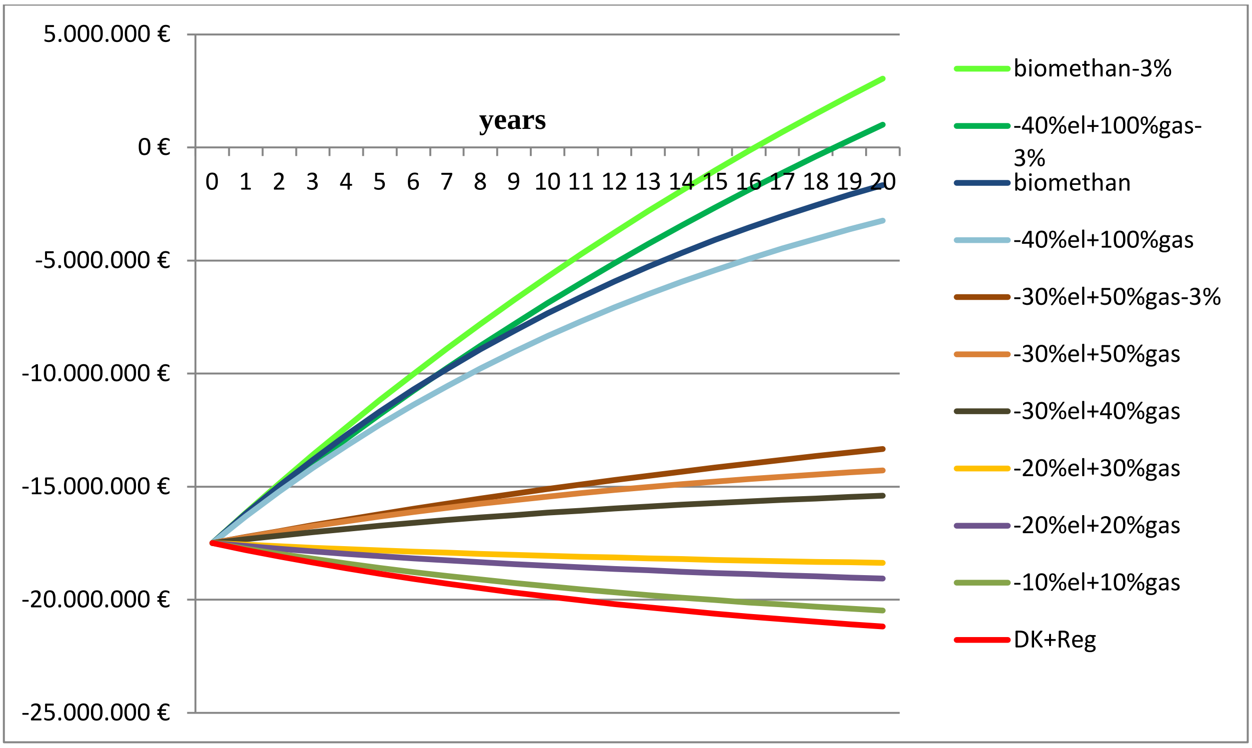

Figure 23: Sensitivity Analyses of PtG operating in changed Market Conditions

Figure 23 shows sensitivities for electricity price, gas prices and discount rates, at the dynamic payback times. Nomenclature refers to the changes made from the previous assumptions "-10" el means that the hourly market price for electricity price is reduced by 10%, "+10% gas " indicates a gas price raised by 10% (from a 25 €/MWh base level) and "-3%" indicates a discount rate of 3% (instead of 6%). Biomethan means that the produced methane has the same status like biomethan, what means that prices of 81€/MWh are achieved. The red line is the most promising scenario from figure 22: a combined operation on the Danish spot and balancing market for electricity, which is the base scenario for all sensitivities.

Also in case of a beneficial market development of electricity and gas prices, the NPV stays negative development. The investment does not pay out within technological lifetime of the plant. Price reductions of 30% in the electricity markets and 50% higher gas prices do not significantly change the result. Neither does a reduction of the discount rates from 6% to 3%.

Two scenarios result in a positive NPV the “biomethan-3%”, shown in light green and the „-40%el+100%gas-3%” scenario, shown in dark green. In the biomethan scenario it is assumed, that the produced methane achieve a price level of biomethan (81 €/MWh). The “-40%el+100%gas-3%”-scenario assumes reduced hourly electricity market prices by 40% and a gas price of 50 €/MWh. Both scenarios are calculated with a 3% disount rate and do not break even with a 6% discount rate, as the dark and light blue lines, named “biomethan” and “-40%el+100%gas” show.

What needs to be considered in this performance is the amount of full load hours the plant is running:

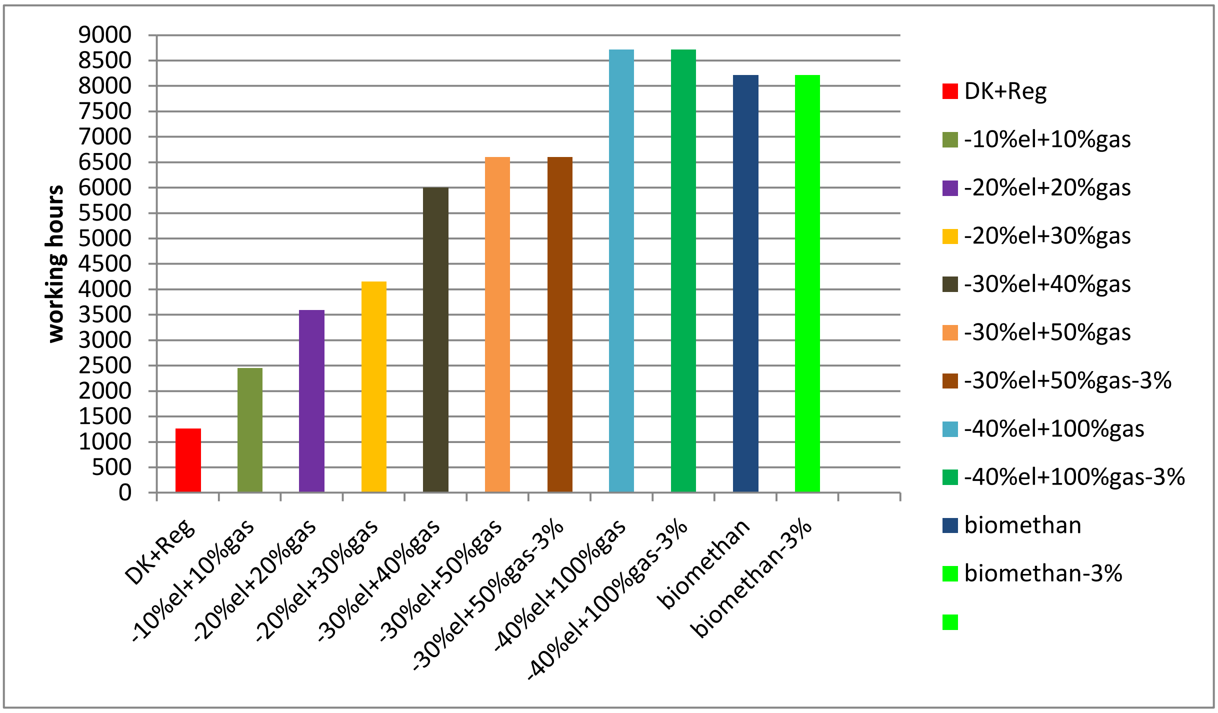

Figure 24: Full Load Hours of PtG in changed Market Conditions

Figure 24 clearly shows that the profitability of the plant is highly connected to the hours it is operating. In a scenario with low electricity and high gas prices the plant is operating almost every hour of the year and cannot be considered as a balancing element in the energy system anymore, instead it turns into an additional demand side element, an energy consumer.

6.3 Case 2: PtG operating for TSO

While the section before observed the economics and profitability of the plant of an investor´s point of view, with a long-term focus of a long-term 100% scenario and perspective for private investment in PtG capacity, this section analyses the economics and profitability of the plant from a TSO´s point of view. This is rather a short-term perspective and a transitory solution until planned high voltage transmission lines are realized.

Under the given provisions the stakeholders who have a direct interest in finding a solution how to deal with excess electricity are the TSOs of the wind intensive areas. As it was already described in chapters 3 and 5 they are directly financially involved, because they have to refund the excess electricity to the renewable energy producers, which are 150 €/MWh for offshore wind energy. According to the EEG the electricity produces from this 100% renewable gas gets the same feed-in like the original electricity source. Gas prices of 54 €/MWh could be achieved with an 0,36 electricity to gas to electricity efficiency. This fact may enhance the feasibility of the PtG technology in two ways:

Firstly, opportunity costs coming from non-investment can be considered and secondly, feed-in management exclusively refers to disconnected renewable energy sources. If this electricity is used to produce gas, the gas has the status of "storage gas" according to the EEG definition and therefore can achieve higher prices, as described in section 5.2.1. In section 3.1 it was already described that a renewable energy system would most of PtG capacity between 1000 and 2000 full load hours. The following graphic shows the Net Present Values for three scenarios: In scenario NPV PtG the TSO invests in a 10 MW PtG plant and operates it in 1000 hours on offshore wind electricity. In scenario No Investment the TSO makes no investment and fully refunds the lost electricity, in scenario NPV H_2 the TSO invests in an Electrolyser (1000 €/$kW_{el\ input}$ and efficiency of 75%). Discount Rates are 6% :

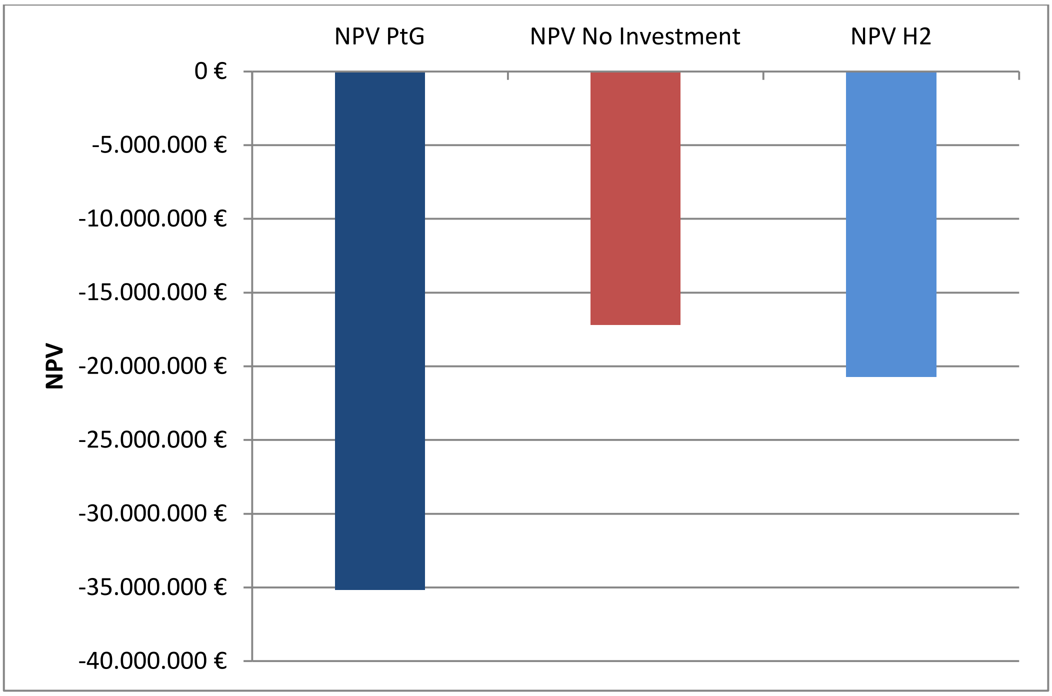

Figure 25: NPV of three alternative Investments for a TSO

Figure 25 shows that it is cheaper for TSOs in case of 1000 hours of offshore wind energy to refund the money, neven if it is over a time frame of 20 years, it is much cheaper, than an investment in a PtG plant. NPV of Electrolysers is getting close to the NPV of no investment.

In a future 100% renewable energy system more hours of excess electricity are likely, especially in the North Sea regions, where electricity from large offshore wind parks have to be integrated into the grid. If a PtG plant will be place on this "hot spots" full load hours will be propably higher. The following graphic shows how many full load hours it takes to make an investment in a PtG plant a preferable choice for a TSO, instead of not investing and refunding the unused electricity:

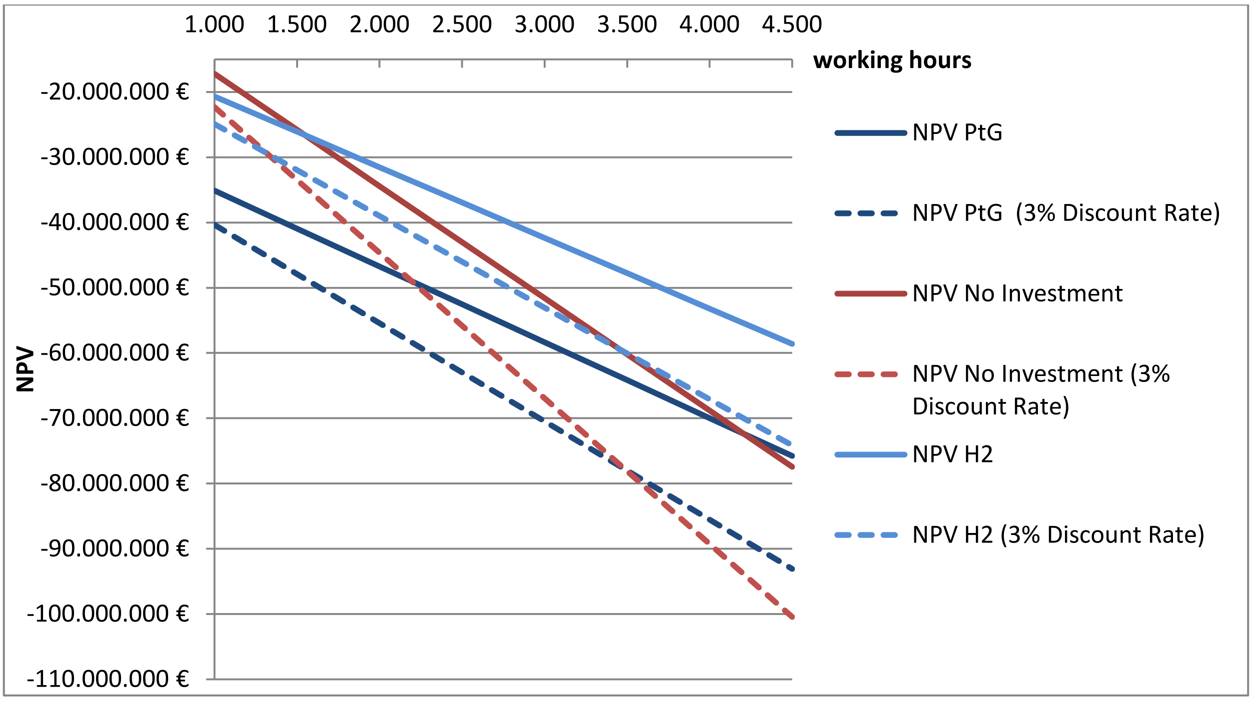

Figure 26: NPVs with different Full Load Hours and Discount Rates

It can be seen that that over a 20 year period and with a 6% discount rate the investment is a preferable choice in times 4500 hours of excess electricity per year. Electrolysers are already preferable with more than 1500 hours excess electricity. Even the 100% scenario of the FEA did not show more than 3500 hours of excess electricity (FEA 2010). Therefore, it has to be said that under the given legal framework there are serious financial burdens for an investment in a PtG plant. Even from the perspective of a TSO in an excess electricity "hot spot", one of the stakeholders with the highest opportunity costs of a non-investment, an only becomes likely under very extreme assumptions. The dotted lines indicate the sensitivity analysis with a 3% discount rate. In this case the investment in a PtG plant is already getting a better choice in cases of more than 3500 hours of excess electricity. But it can be doubted if any TSO would make such an investment. Electrolysers are already a prefirable investment in case of more than 1500 hours of excess electricity. However, electrolysers can only be a transitory solution, if the high voltage grid development is further delayed for external reasons.

6.4 Summary

Firstly this chapter presented the general economics of PtG plants. It turned out that the cost of PtG methane production are driven by investment cost, electricity prices and amount of working hours. Electrolysers have a significant cost advantage over PtG, coming from lower investment costs and higher conversion efficiency.

After that the profitability of an investment was analysed in two different cases. In the first case the investment was assessed from the perspective of a market participant and in the second case for a TSO. In none of the cases analysed an investment into a PtG plant is profitable under current market conditions. In all of the cases Electrolysers would be a less costly balancing technology than PtG. Under two conditions an investment seems to be considerable: Firstly, in a market with low electricity prices and/or high methane prices as it was presented in the sensitivity analysis (figure 23). However, in this case the plant would operate in almost every hour of the year and would not be a balancing technology any more (figure 24). Secondly, in case two, from the perspective of a TSO if opportunity costs of high refunds for excess electricity are taken into account (figure 26) for more than 3500 hours of excess electricity, or 1500 for electrolysers.

7. Public Regulation Strategies

The scenario of the FEA described in chapter 3 came to the conclusion that PtG plants with an overall capacity of 44 GW are necessary to stabilize the system. The analyzis of the previous chapter unveiled, that it seems to be very unlikely under the current legal framework and market conditions to realize this capacity. High investment costs and low gas prices lead to an unsatisfactory economic performance of the plant. Apart from that it turned out, that under changed market condition, the technology would become an additional quasi-permanent consumer.

The following chapter focuses on the different possibilities of a regulative framework, in order to give incentives for an investment and a guarantee of a balancing operation.

The difficulties are to implement political measures, able to combine three different poles: a thriftiness spending of taxpayers´ money, an operation of the plant balancing the energy system and a financial incentive for potential investors. Figure 27 shows the three poles that an optimal political measure should combine:

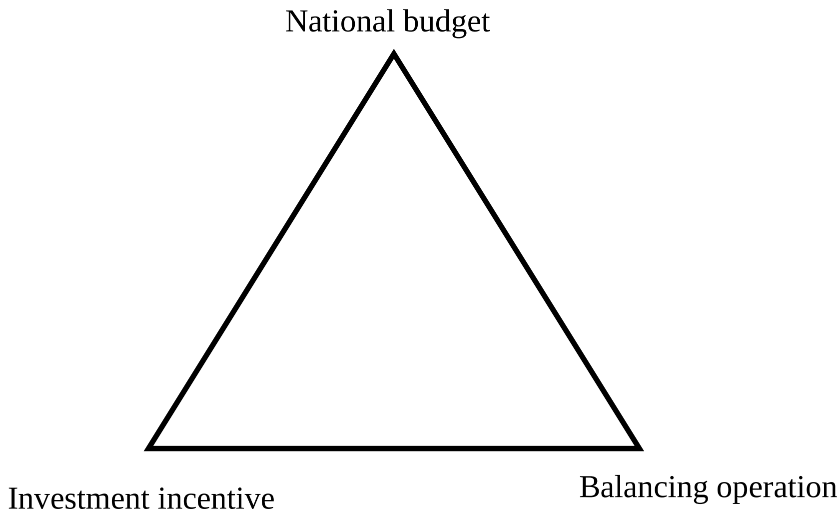

Figure 27: Policy Triangle

Several positive and negative incentives are thinkable. Positive incentive means that concerned stakeholder profits from building a PtG plant, negative incentive means that the financial burden of not investing in a plant would be higher than the burden of an investment. The saved opportunity costs can be regarded as a negative financial incentive.

The sensitivity analysis, done in chapter 6 already indicated that positive incentives have to be placed carefully, in order to prevent a permanent operation of the plant, but to foster an operation of the plant in times when downward regulation is necessary. Conventional feed in tariffs could place wrong incentives opposing the intentional goal of having a balancing technology by making permanent production the most cost effective mode of operation.

7.1 Political measures to support a wide implementation of PtG plants

As chapter 6 showed, there are significant differences in the feasibility between TSOs of heavy wind areas and other market participants. Therefore, the question from whose perspective the profitability is calculated is crucial.

For a TSO the high investment costs are probably the decisive argument to avert an investment. Other potential investors are probably put off by the investment costs and the bad economic performance of the plant. This could be change by several new public regulations:

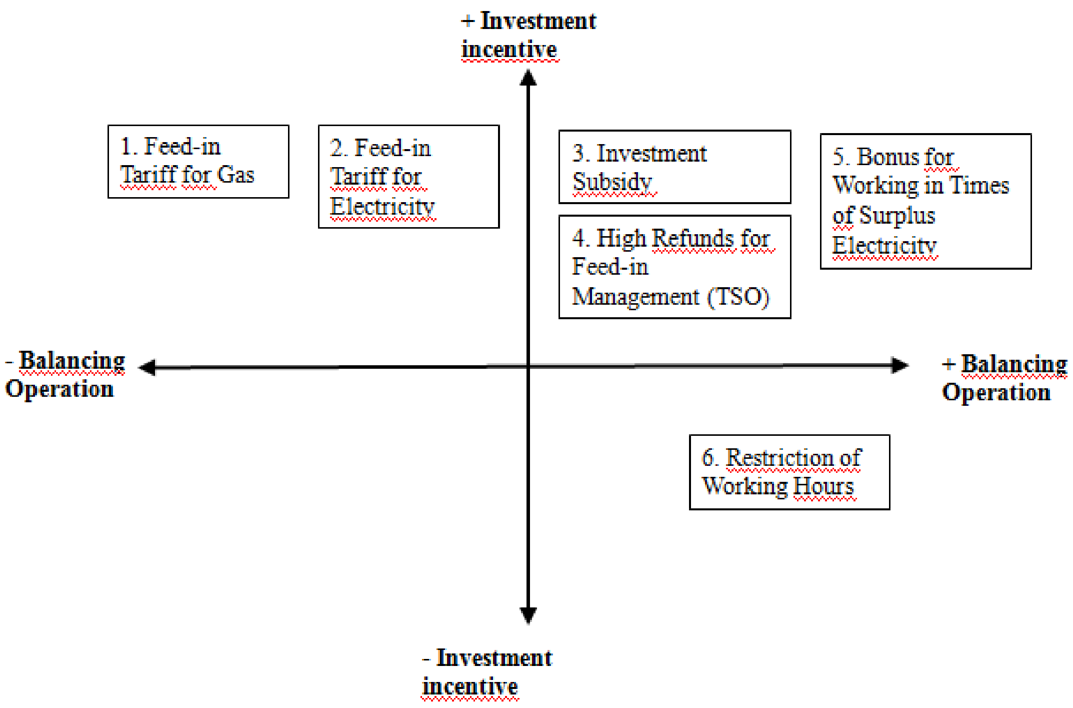

Figure 28: Mapping of political measures fostering Investments and Balancing Operation

Figure 28 maps some of the possible regulative incentive strategies and categorizes them according to their effects on investment incentive and balancing operation. The policies in the top right category (number three, four and five) are of a special interest, because the offer an investment incentive and foster a balancing operation for the plant. The other listed policies needs to be combined, but are not suitable as an solitary policy. Combining for example a feed-in tariff for the produced gas with a restriction of yearly working hours or respectively a maximum production could offer an investment incentive and fostering a balancing operation.

7.2 Investment subsidy

Case 1: For a normal market participant the subsidy in form of a single payment would need to be around the same height of the NPV (see figure 21), around 21.000.000 € or 2100 €/kWh under the current market conditions. This is more than the total investment costs of the plant.

Case2: In case of a TSO investing in a PtG plant and if opportunity costs of not investing are taken into consideration with the assumptions of case 2 and a 3% discount rate, a investment subsidy would be a possible incentive. For 3000 full load hours a single subsidy of 3.500.000 €, respectively 350 €/kW capacity would make an investment for the TSO less costly than no investment.

In both cases investment incentives would be very high, bringing very high costs for society. In case 1 the incentive would foster a balancing operation, under the market conditions because the operator is still dependent on the market prices for electricity. The correlation between working hours and hours with downward regulation is 0,35. However this effect could change with higher gas and/or lower electricity prices in the future. The same is true for case 2. Here the TSO would try run its plant only when he has to, as long as no other regulations are changed.

7.3 Bonus for Working in Times of Surplus Electricity

A bonus for running the plant in times of surplus electricity could combine an investment incentive with a balanced operation of the plant. If market prices for downward regulation are reduced by 90 €/MWh the NPV turns positive. The plant is then operating in every hour when downward regulation is needed and additionally in times of low spot market prices, 2724 hours in total of which 2258 hours are downward regulation hours. The correlation between working hours and hours with downward regulation is accordingly high (0,88). Costs for society of this policy would be around 2.000.000 € per year for a 10 MW plant.

7.4 Higher Refunds for excess electricity

This policy is only employable on the case 2, a plant operated by a TSO only in times of excess electricity from renewables, in this case offshore wind turbines. Contrarily to a bonus it is a negative incentive. If the refund payment for unused excess electricity is raised by 10 €/MWh on the basis of the original tariff (for excess electricity from an offshore wind turbine the TSO then has to refund 160 €/MWh instead of 150 €/MWh) and assuming 3000 excess electricity hours per year, it pays out for the TSO to invest in a PtG plant. This model is highly interesting for two reasons: Firstly, it fosters a local integration of PtG plant in areas with many wind turbines and secondly, it does not cause any direct additional costs for society. In a long term perspective the costs will probably be handed over to the end user.

Apart from that, this policy seems to be very unlikely in the current political climate. Mr. Rösler, the German minister of economic, just announced that the accountability of the TSO for excess electricity should be capped (Spiegel 2012).

7.5 Feed in Tariff for synthetical methane and electricity produced from it

Feed in Tariffs alone do not enhance a balancing operation. A maximum number of yearly operation hours needs to be set, otherwise over 8000 full load hours will be the consequence of a feed in level of upgraded biogas. If feed in prices for gas are set at 108 €/MWh the NPV is positive, even with a working restriction of 4000 hours. The correlation between working hours and hours with downward regulation is still quite low (0,37).

108 €/MWh of gas correspond to an electricity feed in of around 180 €/MWh for electricity produced from synthetical methane. The feed- in tariff for small photovoltaic is 287,4 €/MWh. A fixed tariff for input electricity is not calculated, because it would fundamentally oppose a market integration

7.6 Summary

This chapter showed that it takes tremendous efforts in a changed public regulation to make the plants a profitable investment. It also needs to be understood, that not every policy to foster PtG automatically helps an integration of renewable energy into the system.

Policy	**Investment Incentive**	**Fostering Balancing Operation**	**Costs for society**
Investment subsidy	High	No	High
Bonus for Working in Times of Surplus Electricity	High	Yes	High
High Refunds for excess electricity	high	Yes	Low
Feed in Tariff for synthetical methane and electricity produced from it	High	No	High

Table 9: Summary of effects of analysed measures

It can be summarized, that all political attempts to foster PtG would result in very high costs for society. Only High refunds for excess electricity would leave the costs for the TSO. Following, the current political discussions on the issue it can be doubted that TSOs will have to take more responsibilities for the grid integration.

8. Discussion of Results

The analysis unveiled that PtG has too high investment cost to be profitable under current market conditions and public regulation would be very expensive, if it makes attempts to promote the technology. In all calculations the solely use of electrolysers, without methanation would be less costly, if it can be sold for the same price per MWh like methane, but would be still unprofitable under the current market conditions. Only in one case an investment could become likely under current framework conditions. In the second case, from a perspective of a TSO who has to deal with high costs due to high refunds for disconnected wind production, PtG gets closer to be profitable. However, even then it is outcompeted by electrolysers. In all calculations electrolysers are ahead of PtG. Until the possible 5% share of hydrogen in the natural gas grid is not yet utilized, there is no point in a promotion or investment into PtG.

In a long term perspective PtG technology can undoubtedly play an important role in the German energy system. However, this role might not be the role suggested in the scenarios. While the scenario described in section 3.1 foresees less than 4000 full load hours of PtG plants, offering downward regulation and an electricity storage potential through the combination of electricity and natural gas infrastructure, the economics of the plant make a different interpretation of the future role necessary.

The sensitivity analysis showed that in a market with very low electricity or high gas prices PtG technology become profitable, working over 8000 full load hours. The technology will then be an additional consumer.

In a long-term perspective without changed regulation and considering the market developments described in chapter 5, mainly for electricity and natural gas, the situation will change. The sensitivity analysis in chapter 6 unveiled, that decline of electricity spot prices and rise of natural gas prices are likely and will make the investment profitable, due to a lucrative operation in more than 8000 hours. Under such conditions the plant cannot be considered a balancing technology any more. It would simply be an industrial electricity consumer that might offer upward operation through an abstinence from producing. Based on these considerations the thesis proposed some public regulations measures. It turned out that a suitable legislation could place considerable investment incentives under current market conditions. However, these incentives would create tremendous financial burden for society.

9. Conclusion

The study analysed the economics and perspectives of the PtG technology in order to answer the question if PtG is suited to be the main solution for the problem of balancing and storing of excess electricity.

A starting point was the theoretical framework for implementation of new technologies. It was shown that a business-economic profitability is among the crucial criterias for an implementation, but it was not proofen by any study so far, that PtG can be profitable. Two different perspectives were given for the role of PtG. In the presented 100% scenario done on behalf of the FEA, PtG played the role of the most important balancing and storage technology. In order to achieve this, somebody would have to invest in PtG. This long-term perspective for PtG is complemented by a short-term perspective, dealing with local integration problem of wind energy, German TSOs are facing already today and how PtG could help to solve this problem. Accordingly, the economics of PtG was analysed in two cases. In case 1 it was analysed from the point of view of a private investor and in case 2 from a TSO´s perspective.

Before that the state of the art of PtG technology was explained, its investment and O&M costs, the technical process and performance data. Further, the legal and market framework was described and expected prices discussed.

Then the analysis of the economics of PtG was conducted for the two business cases: In case 1, investment was made by a normal market participant. This case evaluates PtG under current and future market conditions. This a perspective built up on the framework of the 100%scenario. A second case assessed the investment from a TSO´s perspective. This case gives an idea about a short-term perspective for PtG, as an temporary solution to the problems with excess electricity. After that several political measures to enhance the feasibility of investment were discussed.

The analysis showed that an investment in a PtG plant cannot be profitable under current market and regulative framework conditions. There is no financial reason for any private investor to invest in a plant. It is ca. 20 Million Euro away from being profitable and current public regulation does not enhance the profitability.

In a short-term PtG could be worth an investment from the perspective of a TSO. On the basis of the delayances in grid developments and possible future grid overloads coming from the fast growing amount of offshore wind energy, PtG could be a short-term emergency solution to avoid high refunds for unused offshore wind electricity, but only if electrolysers and alternatives are already exploited.

It can also be concluded that the economics of the PtG technology contradicts the idea of a balancing technology for the electricity system, due to its dependency on a very high amount of working hours in order to be profitable. The hours with low electricity prices under current market conditions are not sufficient to operate profitable and pay back investment costs. It turned out that a suitable legislation could place considerable investment incentives under current market conditions but that would cause tremendous costs for society.

On the basis of these results it must be concluded, that the economics of PtG is not suited to be the main solution for the problem of balancing and storing excess electricity. In a long-term perspective under market conditions characterized by low electricity and high gas prices it seems to be a promising technology from a business point of view, but not as a balancing technology. Without changed public regulation it would become an industrial consumer: The technology would not serve the energy system any more, the energy system would serve the technology.

10. Perspective

The study unveiled that the economics of PtG contradict the idea of a balancing technology. There is no reason to believe, that these problems are restricted to PtG. It is quite likely, that the problems of PtG are problems of most balancing technologies. Very low prices for electricity in case of downward regulation and high prices for upward regulation cannot compensate for high investment costs and low capacity utilization. Apart from the question if PtG is a smart way to balance an energy system or not, it needs to be understood that the existing markets do not provide a fruitful soil for investments into regulating plants. Existing political measures like tax-free electricity for storage technologies or exclusion form fees for gas grid connection and utilisation in the case of PtG do not create enough incentives. It is very questionable if changed market conditions in the future can create these incentives. Even if the markets theoretically will arrive at a point with extremely cheap or high electricity prices, so that plants could operate profitably in a balancing operation, such market radicalism cannot be a responsible position against the background of security of electricity supply.

It needs to be understood, that markets cannot plan energy systems. The market conditions needs to be politically adjusted or supplemented by a more strategic energy planning.

For PtG the thesis presented some market based political incentives all of them creating tremendous costs for society. Another possible solution would be an “outsourcing” of responsibility, e.g. on TSOs, like in the case of offshore grid connections. Even if they would have to take the responsibility costs and risks will probably be forwarded to the end-user. A stakeholder or interest analysis of TSO would also be highly interesting. TenneT, for example is completely owned by the Netherlands will have to make investments on a billion Euro scale, for Germany´s transmission lines.

Another idea, that was neglected in this thesis is the idea long-term capacity auction markets, a regulating power market, but with a long-term perspective, where the bidder who can offer regulating capacity at the lowest cost gets the necessary money. Then again, costs would be shouldered by society.

If the end-user, mostly identical to society has to pay the bill anyway, either through the high costs of financial incentives or through forwarded costs of TSOs, the question becomes legitimate, why a state should not invest directly into necessary capacity and own it.

If this model is considered a more strategic energy planning approach would become necessary, supplementing the existing market based approach. A technology which would turn out to be socio-economic feasible in a scientific, deliberative and democratic process could be easily implemented.

Due to the limitations of this thesis it cannot be concluded that PtG should or should not be one of these technologies, or which technologies would be less costly. What can be said is that from its economic characteristic it seems to contradict a balancing technology in a market based system, a point that was neglected in the current discussion on PtG so far. However, the long-term perspective for the technology seems to be promising from a business point of view under future market conditions, but then rather as an industrial methane producing technology, than a downward regulating element. It cannot be answered here, if this is good or not for society. That would be a task for further research.

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ANNEX

Cost structure of hydrogen:

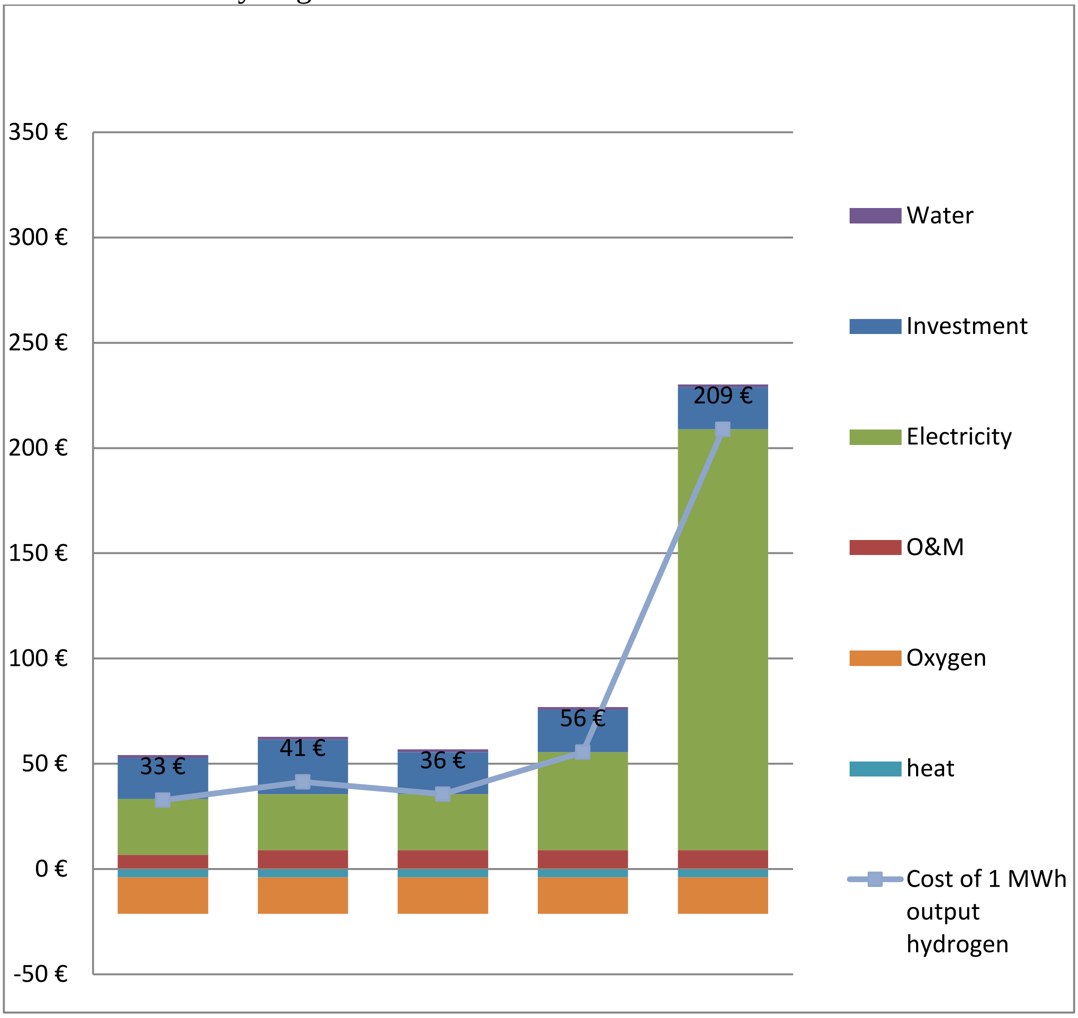

Figure 29: Cost structure of hydrogen