Fakultät für
Elektrotechnik,
Informatik und
Mathematik

Market-oriented energy supply for Offshore wind farms and energy storage on methane basis

Von der Fakultät für Elektrotechnik, Informatik und Mathematik
der Universität Paderborn

zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften (Dr.-Ing.)

genehmigte Dissertation

von

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Tag der mündlichen Prüfung: 16.11.2015

Paderborn 2015

Diss. EIM-E/317

UNIVERSITÄT PADERBORN
Die Universität der Informationsgesellschaft

FAKULTÄT FÜR
ELEKTROTECHNIK,
INFORMATIK UND
MATHEMATIK

Summary of the Dissertation:

Market-oriented energy supply
for Offshore wind farms and energy storage
on methane basis

Mr. Yassin Bouyraaman

Operating wind turbines under economic considerations leads to the challenge that forecasted and actual wind power do often differ widely. This makes it difficult to participate in the free energy market and destabilizes the power supply network without appropriate countermeasures.

This thesis investigates whether the combination of wind farm and methane-based energy storage can provide relief. The basic idea is to compensate the differences between forecasted and actual wind power with the help of the methane based storage system. To accomplish this, a concept for energy schedule is developed which is based on forecast wind data, corrected by a factor derived from a temporal analysis of the deviation of forecast to actual wind power with an added impact to control the storage level.

Moreover, the thesis also examines how wind farms in combination with energy storage system meet the criteria for participation in the free energy market and how such participation in return affects the system. Hence, some commercialization scenarios are created in which the virtual power plant participates in the energy exchange and/ or in the control energy market in order to determine the influence of energy storage on whole operating results.

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Zusammenfassung der Dissertation:

Market-oriented energy supply
for Offshore wind farms and energy storage
on methane basis

des Herrn Yassin Bouyraaman

Beim wirtschaftlichen Betrieb von Windkraftanlagen stellt sich die Herausforderung, dass die Windprognosen und die tatsächlich erreichte Leistung oftmals stark voneinander abweichen. Dies erschwert eine Teilnahme am freien Energiemarkt und destabilisiert ohne geeignete Gegenmassnahmen zudem das elektrische Energieversorgungsnetz.

In dieser Arbeit wird untersucht, ob die Kombination eines Windparks mit Energiespeicher auf Methanbasis (Power-to-Gas) hier Abhilfe schaffen kann. Grundlegender Gedanke dabei ist, die Differenzen zwischen Prognose und tatsächlichem Ertrag eines Offshore Windparks mit Hilfe des Energiespeichers auszugleichen. Zur intelligenten Fahrplanbildung wird ein Konzept, das auf aus Prognosen abgeleiteten Soll-Einspeisungen beruht, entwickelt. Diese korrigierte Fahrplanbildung basiert auf der zeitlichen Analyse der Prognose/ Ist-Abweichung und wird durch die Nutzung des Speichers unter Berücksichtigung des Speicherfüllstands ergänzt.

Weiterhin wird untersucht inwiefern ein solches System aus Offshore Windpark und Speicher den Kriterien zur Teilnahme am Regelenergiemarkt genügt und wie eine solche Teilnahme das System beeinflusst. Dazu werden Szenarien erstellt, in denen die Windenergie z.B. am Energiemarkt verkauft wird und/ oder der Windpark Regelleistung bereitstellt. Die dabei erstellten Varianten werden untersucht, um den Einfluss eines Speichers auf das Betriebsergebnis zu ermitteln.

Acknowledgments

First of all I am sincerely grateful to my supervisor Prof. Dr.-Ing. habil. Stefan Krauter for his kindness, his encouragement, his valuable suggestions and discussions throughout this PhD work. Furthermore, I am thankful to Prof. Dr.-Ing. habil. Rolf Hanitsch for his acceptance to become the co-supervisor and the motivation he gave me during the writing phase of this thesis.

I would like to give thanks to Mr. Dipl. -Phys. Joerg Bendfeld for his support and his stimulative discussions with me, so that I could present my PhD work on a national and international conferences. Furthermore, I am really very glad that I worked with all my colleagues in our department.

I am truly thankful to my parents, for their unconditional love and the great opportunity to unfold my talents by ideally supporting my education and my ideas.

Finally I appreciate my wife, my lovely son and daughter for their patience, their encouragement and their constant mental support. I dedicate this work to them.

Yassin Bouyraaman
Paderborn, November 2015

Contents

Acronyms and abbreviations

Formula symbols and units:

$\varnothing E^{-}_{CP,PR}$	MWh/month	Average provided negative control energy per month
$\varnothing E^{+}_{CP,PR}$	MWh/month	Average provided positive control energy per month
$\Delta E_W(t_i)$	MWh	Difference between the actual and predicted energy of the wind farm
$\Delta E_{W,Area}(t_i)$	MWh	Over or undershoot energy amount of the energy difference between actual and predicted energy of wind farm
$\Delta E_{W,S}(t_i)$	MWh	Difference between the actual wind energy and energy schedule
ΔH^0	kJ/mol	standard reaction enthalpy
$\Delta E(t_i)$	MWh	Difference between the actual energy production and the actual energy demand
$\Delta P_P(t_i)$	MW	Deviation between the real power of the producer and the forecast in time t
$\Delta P_C(t_i)$	MW	Deviation between the real power of the consumer and the forecast in time t
$\Delta P_W(t_i)$	MW	Difference between the actual and predicted wind power
$\Delta P_{W,S}(t_i)$	MW	Difference between the actual wind power and schedule
$\Delta P_{W,corr}(t_i)$	MW	Correction value from short-term forecasting correction
$\Delta t^{-}_{CP}(t_i)$	h	Duration of a retrieval of negative control power
$\Delta t^{+}_{CP}(t_i)$	h	Duration of a retrieval of positive control power
$E_E(t_i)$	MWh	Balancing energy on the producer side
$E_{GN}(t_i)$	MWh	Injected or extracted gas amount from Gas Network
$E_{CP}(t_i)$	MWh	Caused demand for Control Power
$E^{saved}_{CP}(t_i)$	MWh	Saved Control Energy
$E^{required}_{CP}(t_i)$	MWh	Required Control Energy
$E^{-}_{CP,RV}(t_i)$	MWh	Negative retrieved Control Energy
$E^{+}_{CP,RV}(t_i)$	MWh	Positive retrieved Control Energy

$E^{-}_{SCR,RV}(t_i)$	MWh	Negative retrieved Secondary Control Reserve
$E^{+}_{SCR,RV}(t_i)$	MWh	Positive retrieved Secondary Control Reserve
$E^{-}_{MR,RV}(t_i)$	MWh	Negative retrieved Minute Reserve
$E^{+}_{MR,RV}(t_i)$	MWh	Positive retrieved Minute Reserve
$E_S(t_i)$	MWh	Current storage filling capacity of the methane tank
$E_{S,max}$	MWh	Maximum storage filling capacity of the methane tank
$E_{W,max}$	MWh	Maximum energy output of the wind farm
$E_C(t_i)$	MWh	Balancing energy at the the consumer side
EV	ct/kWh	Base price Value (according to § 33g section 2 EEG)
MP	ct/kWh	Market Premium
$P^S_P(t_i)$	MW	Producer energy schedule
$P^{real}_P(t_i)$	MW	Real provided power by energy producer
$P^{Day-Ahead}_S(t_i)$	MW	Day-Ahead energy schedule
$P^{Intra-Day}_S(t_i)$	MW	Intra-Day energy schedule
$P_{G,max}$	MW	Maximum power output of the gas power plant
$P^{max}_{G,pot}(t_i)$	MW	Maximum required power output of the gas power plant for capturing extreme forecast deviations
$P^i_{required}(t_i)$	MW	Required power by the power plant pool
$P_{M,max}$	MW	Maximum power input of the methanation facility
$P^{max}_{M,pot}(t_i)$	MW	Maximum required power input of the methanation facility for capturing extreme forecast deviations
MB	ct/kWh	Management Bonus
$P_{CP}(t_i)$	MW	Caused demand for Control Power
$P^{saved}_{CP}(t_i)$	MW	Saved Control Power
$P^{required}_{CP}(t_i)$	MW	Required Control Power
$P^{-}_{CP,max}$	MW	Maximum negative Control Power
$P^{+}_{CP,max}$	MW	Maximum positive Control Power
$P^{-}_{CP,pot}(t_i)$	MW	Maximum available potential for negative Control Power
$P^{+}_{CP,pot}(t_i)$	MW	Maximum available potential for positive Control Power
$P^{-}_{CP,PR}(t_i)$	MW	Provided negative Control Power
$P^{+}_{CP,PR}(t_i)$	MW	Provided positive Control Power
$P_{delivery}(t_i)$	MW	Delivered Control Power

$P_{S,corr}(t_i)$	MW	Correction value from storage filling level optimization
$P^{-,max}_{SCR,PR}$	MW	Maximum provided negative control power for SCR
$P^{+,max}_{SCR,PR}$	MW	Maximum provided positive control power for SCR
$P^{-,max}_{MR,PR}$	MW	Maximum provided negative control power for MR
$P^{+,max}_{MR,PR}$	MW	Maximum provided positive control power for MR
$P^{+}_{MR,RV}(t_i)$	MW	Positive retrieved Minute Reserve Power
$P^{-}_{MR,RV}(t_i)$	MW	Negative retrieved Minute Reserve Power
$P^{+}_{SCR,RV}(t_i)$	MW	Positive retrieved Secondary Control Reserve
$P^{-}_{SCR,RV}(t_i)$	MW	Negative retrieved Secondary Control Reserve
$E^{S}_{C}(t_i)$	MW	Consumer energy schedule
$E^{real}_{C}(t_i)$	MW	Real demand side consumption
$P_{W,corr}(t_i)$	MW	Corrected forecast of wind power
$P_{W,max}$	MW	Maximum power output of the wind farm
$P_{W,prog}(t_i)$	MW	Predicted power of wind farm
$P_{W,real}(t_i)$	MW	Actual power of wind farm
RMV	ct/kWh	Reference Market Value
S	%	Control energy savings factor
$SFL(t_i)$	%	Storage filling level
t	h	Time
t_i	-	Calculation interval
t_{int}	h	Duration of the calculation interval
T_k	h	Period of time to sign changes of $\Delta E_{W,Area}$
t_{PH}	h	Length of the forecast horizon
t_{PVZ}	h	Forecast lead time
T_{ZS}	h	Period of time slice
V	%	Energy loss factor
α	-	Linear factor
a	-	Increment number for positive control power
β	-	polynomial potency
b	-	Increment number for negative control power
γ	-	root degree

δ	-	Weighting of the previous period for exponential smoothing
ζ	-	Correction value for the Day-Ahead schedule
$f_{linear}(t_i)$	MW	Linear function for the correction of the storage filling level
$f_{Polynomial}(t_i)$	MW	Polynomial function for the correction of the storage filling level
$f_{Root}(t_i)$	MW	Root function for the correction of the storage filling level
η_G	%	Efficiency of the gas power plant
η_M	%	Efficiency of the methanation unit
ϑ	-	Correction factor for the Day-Ahead schedule
i	-	calculation step
i_{end}	-	last iteration step
$\mu_{\Delta P_W}$	MW	Expected value of the difference between the actual and the predicted power of the wind farm
$\mu_{\Delta P_{W,corr}}$	MW	Expected value of the difference between the actual and the corrected predicted power of the wind farm
$\mu_{\Delta W_{W,Area}}$	MWh	Expectation value of $\Delta E_{W,Area}$
$\sigma_{\Delta P_W}$	MW	Standard deviation of the difference between actual and predicted power of the wind farm
$\sigma_{\Delta P_{W,corr}}$	MW	Standard deviation of the difference between actual and corrected predicted power of the wind farm
$\sigma_{\Delta W_{W,Area}}$	MWh	Standard deviation of $\Delta E_{W,Area}$

Indices:

$-$	Negative
$+$	Positive
BP	Base price
C	Consumer side
$Control$	Caused demand for control energy or control power
$corr$	Correction

CP	Control Power
CR	Control Reserve
DP	Demand Price
end	End
FP	Schedule
G	Gas power plant
Gas	Natural gas
GN	Gas network
i	Calculation step of the simulation
int	Iteration
k	Calculation step until change of sign of $\Delta\ P_W(t_i)$
M	Methanation facility
max	Maximum
P	Producer side
PH	Prediction Horizon
pot	Potential
PVZ	Prediction lead time
$real$	Real value
$reBAP$	Uniform Control Reserve Price across all control Areas
RV	Retrieved control power
$saved$	Saved control power
PR	Provision
W	Wind park
WO	Wind Offshore
ZS	Time slice

Abbreviations:

(g)	gaseous
(l)	liquid
$^{\circ}C$	Degree Celsius
BG	Balancing group

BGS	Balancing group supervisor
CBG	Consumer balancing group
$CCPP$	Combined-Cycle Power Plant
CHP	Combined Heat and power
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
$cp.$	Compare
$dev.$	Deviation
$DENA$	German Energy Agency
EE	renewable energy
EEG	Renewable Energy Sources Act
EEX	European Energy Exchange
$EPEX$	European Power Exchange
$ENTSO-E$	European Network of Transmission System Operators for Electricity
$EnWG$	Energy Industry Act
$EPEX$	European Power Exchange
$exp.$	Exponential
$e.g.$	for example
GW	Gigawatt
h	Hour
H_2	Hydrogen
$IWES$	Fraunhofer Institute for Wind Energy - Energy System Technology
$i.e.$	id est- that is
KOH	Potassium Hydroxide
kW	Kilowatt
kWh	Kilowatt Hour
m^3	Cubic meters
$MaPrV$	Management premium Regulation
MAV	Monthly Average Value
min	Minute

MB	Management Bonus
MP	Market premium
MR	Minute Reserve
MW	Megawatt
MWh	Megawatt hour
$\mathbb{N}_0$	Speed range of the normal numbers incl. 0
$n.a$	Not available
Na_2CO_3	Sodium Carbonate
$NaOH$	Sodium Hydroxide
Nm^3	Standard cubic meters
O	Oxygen
OTC	Over-The-Counter
PBG	Producer Balancing Group
$P2G$	Power-to-Gas
PCR	Primary Control Reserve
PSP	Pumped Storage power Plant
s	Second
SCR	Secondary Control Reserve
$StromNZV$	Electricity Network Access Regulation
$StrEG$	Electricity Feed-In Act
TWh	Terawatt hour
TSO	Transmission System Operator
$UCTE$	Union for the Coordination of Transmission of Electricity
VPP	Virtual Power Plant
WT	Wind turbine
WF	Wind farm
ZSW	Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

1 Introduction

In recent years, Germany has agreed to an energy transition. For a long time the supply of electrical energy was almost exclusively ensured by coal, oil, natural gas, nuclear power and hydropower. However, the knowledge of the finite nature of fossil fuels and the increased carbon dioxide emissions causing overheating of the global climate have moved Germany to reform its energy market and strategies. Since the 1990s, wind, photovoltaic and biomass have continuously expanded and taking part in electricity production in Germany. After the nuclear power has been discussed for many years of controversy and initiated a shutdown of the power plants depending on the political situation, or yet again a term extension was launched. However the nuclear accident in Fukushima, which ushered in the spring of 2011, the world again saw the nuclear technology as a looming danger. The response was the immediate decision to shut down all nuclear power plants in Germany gradually until 2022.

1.1 Motivation

As in the future, renewable energies should constitute the foundation of the energy supply, the expansion of wind turbines, photovoltaic and biomass is forced (§ 1 Abs. 1 EEG). In 2020, according to the Renewable Energy Sources Act (§ 1 Abs. 2 EEG), renewable energies shall already account for 35% of Germany's electricity production. By 2050 this share should increase to at least 80% [EEG, 2012]. Particular interest and hope is placed in the expansion of offshore wind farms. Today, offshore wind energy contributes only a very small share of less than 0.1% to the german power production, because virtually no commercial plants have been constructed. But in the future they could make a significant part of the energy supply, possibly even for the largest share of the energy production [BMU, 2013].

Here, one of the biggest problems of the energy transition is the uneven geographical distribution of renewable energy power plants in Germany; this requires a large expansion of the power network. For example, the wind power generated mainly in the north can be distributed throughout Germany. But engineers also face a very different problem with major challenges. So far, power stations were operated according to the energy demand, so always fed the same amount of energy to the grid as was taken . Energy storage plays only a minor role. The renewable energies sources (solar energy, wind energy,...) has been collected so far by the conventional power plants. The on-demand-renewable energy sources such as biomass and hydropower are able to respond quickly to the fluctuations of supply-dependent wind and solar power. In the future, however, these technologies are not enough in itself to create a balance between demand and production. To ensure the stability and to continue to guarantee a stable and reliable system, an intelligent load management must be sought and the expansion of storage power plants be promoted.

To know how much power a wind turbine will provide at a determined time, wind forecasts are produced with the help of those whom the income of an investment is calculated. However, these statements are subject to error [Mackensen, 2011]. So far, wind energy may be marketed through a special remuneration according to the Renewable Energy Sources Act (EEG), the problem of fluctuations must be, in accordance with the Power Network Access Ordinance, resolved by the transmission system operator (§ 11 StromNZV). However, this does not solve the above-mentioned economic problems of supply and load management, but initially only promotes the rapid expansion of wind power plants through a guaranteed purchase of wind energy at a fixed price. If a wind farm operators take into account this marketing option, it may not participate in the free energy market. Does he want to do this to be able to get a better price for his energy; he must first solve the problem of forecast of its wind energy yield. One possible solution is the use of energy storage together with the wind farm, a so-called virtual power plant. By using an intelligent optimization system feeding schedule can be determined based on the wind forecast, which can be observed from the virtual power plant. The basic idea states that the energy storage is able to compensate the differences between actual and forecast wind power. Thus, an experienced storage power plant or energy storage will be considered in near future. Looking for new storage technologies, one storage system gets special attention- the so-called Power-to-Gas storage system.

As the name suggests, this energy is converted into gas. More specifically, electrical energy is converted by means of electrolysis into hydrogen and further in synthetic natural gas (methane). If necessary, this gas can be converted via fuel cell or gas power plant back into heat or/and electrical energy. A particular advantage is the possibility to store large amounts of energy in gas form. Furthermore the German natural gas grid can hold, distribute and store huge amounts of energy. Thus Power-to-Gas not only serves as a storage technology for the concept of a virtual power plant, but also as a storage power plant in the energy grid of the future. It has the potential to also compensate seasonal fluctuations in supply dependent renewable energy.

1.2 Main research task

In this work, a virtual power plant from the Offshore wind farm and methane-based energy storage system is considered. The aim is to develop a concept for intelligent schedule that determines the amount of provided energy into the grid and keep them as well as possible. It should not only compensate between predicted and actual wind power, but also consider the maximum of provided power and storage capacity of the storage unit. The system regulation is done in the virtual power plant to allow it to participate in the free energy market as well as in the control energy market. Here the legal regulations and the guidelines of the various energy markets are considered.

For this concept, a simulation program is developed with the help of real data sets from forecast and actual wind power. In addition, different variables of interest are optimized using simulation program of the concept experimentally. The optimization principle was applied not only from economic viewpoint, but also from environmental and stabilizing network approaches. Thus the difference between the indicated and actual supply should be zero so that there is no need for balancing power, i.e. short-term counter-regulation is not required. On the other hand, the losses due to the storage of electric energy are kept as low as possible. Both aspects also lead to economic optimization of the plant. A close look at the economics of the concept is not part of this work however, only a brief consideration of the prices achieved on the market is performed on the basis of simulation.

1.3 Structure of the thesis

The present work can be divided into three main subject areas: fundamentals, design and simulation including evaluation. In Chapters 2 and 3, basic elements of this work, i.e. the energy market and methane storage technology explain what constitutes the basis of the considered subject area and contribute to the understanding of the materials in the following chapters.

Chapter 2 deals with the German energy market, with particular emphasis on the current and future development of offshore wind energy. The players of the energy market are illuminated with a special focus on the legal aspects. Finally, an outlook on the future role of storage technologies is given. Chapter 3 explains methane as a storage medium and the technical aspects related to methanation. It also elaborates how the gas power plants are treated and gives an overview of possible sources of CO_2, that are essential for the process.

Based on the facts from the previous chapter, a concept of a virtual power plant will be developed in Chapter 4. In order to do that, different concepts of virtual power plant is designed and discussed (i.e. regarding its applications, advantages and disadvantages). Furthermore, the energy schedule development of virtual power plant will also be made (i.e. the determination of the expected value of the provided power is developed). And in the next step, the marketing possibilities are investigated in order to determine the control power types, that virtual power plant can provide and how they can be incorporated into the concept.

In the following two chapters (Chapter 5 and Chapter 6) a simulation of virtual power plant (VPP) that was designed in Chapter 4, is developed, which also enables the optimization of used variables and parameters experimentally. And in this simulation, the forecasting and measurement data of a real wind farm will be used. This simulation is first developed in Chapter 5 without provision of control power. Based on an analysis of a given data set, a first dimensioning of the storage unit is collected. With this, the first statements about the maximum storage capacity of methane gas storage (as well as the power input and power output of the storage unit) can be made. Then, various optimization approaches for the operation of the VPP will be developed and incorporated into the simulation, which then will be analyzed and improved based on the evaluation parameters named control energy saving factor S and energy loss factor V. Furthermore, the selected initial sizes of the storage unit (i.e. storage capacity, power input and power output) will be investigated, whether these can be corrected by the optimization steps.

Chapter 6 extends the simulation by the participation in the control energy market. At first, a provision and then a call of control power will be worked into the simulation. These measures will then be assessed again according to the evaluation parameters (control energy saving factor S and energy loss factor V) that was introduced in Chapter 5. In addition to that, it will be also investigated, how far a smaller dimensioning of the storage unit (i.e. storage capacity, power input and power output) effect on the results of the simulation.

To complete the thesis, the simulation of the various market-oriented scenarios will be presented in Chapter 7. The purpose of this chapter is to answer the question of whether the better market performance can be achieved through the application of the storage unit and the usage of the optimization concept that introduced in the previous chapters. This chapter presents two kinds of scenarios: one is based on EEX-Trading without the participation in the control energy market (according to the simulation concept in Chapter 5) and the other is based on EEX-Trading and the participation in the control energy market (according to the simulation concept in Chapter 6). And after that, it will be discussed whether, the participation in the control energy market using the presented concept is worth the effort.

Finally , this thesis will be closed by the conclusion in Chapter 8, in which the results of this work will be critically evaluated.

2 German energy market with focus on wind energy

This chapter presents the principles of the current energy market as well as the relevance of wind energy in Germany. Furthermore, the expansion of offshore wind energy, its remuneration and the difficulties with the grid integration are described. Subsequently, the grid stability and security of the energy supply within the German electricity grid is discussed. With that, grid balancing, control energy market and electricity trading are presented. Finally, a short overview of future electricity power system is given. The purpose of this chapter is to give a legal and technical background for subsequent discussions.

2.1 Wind energy in Germany

First of all, the role of wind energy in Germany is considered. With that, the share of wind energy in the German electricity mix, the expansion of offshore wind energy in the Germany's North and Baltic Sea, the current remuneration of wind energy and the difficulties with the integration into the German electricity grid are discussed.

2.1.1 Share of wind energy in the German electricity mix

The contribution of electricity generation from renewable sources to the total electricity consumption (600 TWh) grew by 1.2% in 2013. The feed-in of 147.2 TWh of electricity generated from renewables corresponds to 24.7% of the total electricity consumption (Figure 1). As such, renewables provided more electricity to the grid than all nuclear power plants together. Brown coal (lignite), which is currently the most important energy source in the German energy mix, made only a slightly higher contribution with 162 TWh. If the contribution of renewables to total power generation continues to grow at a similar rate, the target in the energy concept of the German government to increase the renewable energies in the energy mix to 35% by 2020 will be reached. Wind energy was, as in previous years, the largest contributor in 2013 (34%) to the renewable energy mix (Figure 2). Over the year some 49 TWh of energy was supplied by wind turbines (WTs) to the electricity grid. Energy from biomass showed the largest growth. The electricity generated from biomass installations increased by 4.05 TWh to 42.7 TWh. [Fraunhofer, 2013]

Figure 2 shows the total electricity production from renewable energies and the installed nominal power of renewable energies in 1990 and 2013. Wind energy and PV today represent 83%

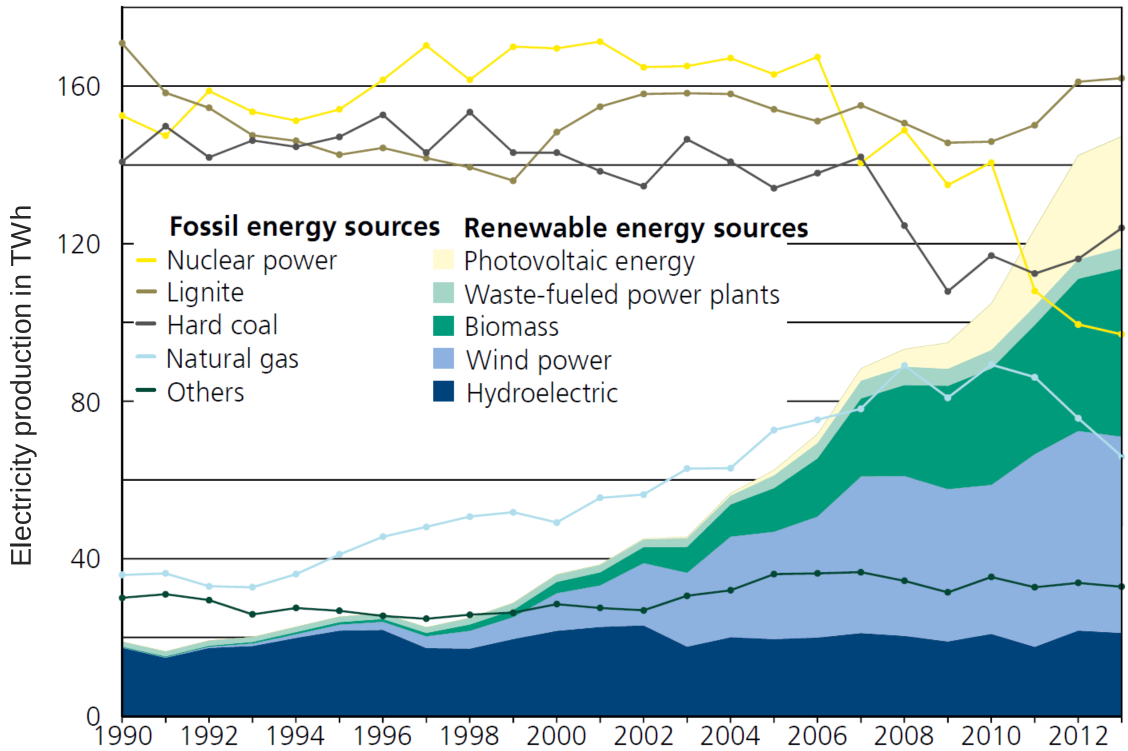

Figure 1: Electricity generation from renewable energy sources since 1990. Data sources: [AGEE, 2013] and [AGEB, 2013]

of the installed nominal power of renewable energies. Whilst the largest percentage of the generated electricity can also be attributed to wind energy (34%), the second largest contributor is biomass (29%), and in third position PV (19%). The hydroelectric power that is generated has remained almost constant since 1990 (on average 19.7 TWh), but only represents 14% of the current renewable energy mix [Fraunhofer, 2013].

The quantity of energy that is produced highlights the characteristic features of the different renewable energy sources. PV installations are highly dependent on incident sunlight. They account for 43% of the installed generating capacity. However, they contribute only about a fifth of the electricity that is produced. In 2013, PV installations supplied electricity for the equivalent of 825 hours at full load. Biomass plants, which do not depend on the weather, achieved much higher utilization rates (6,666 hours at full load). Hydroelectric plants achieved on average 3,790 hours at full load in 2013 [Fraunhofer, 2013].

2.1.2 Offshore wind energy in Germany

Offshore wind farms in the North Sea and Baltic Sea with a total nominal power of 521 MW are now connected to the grid. Offshore wind energy accounts for 1.9% of the total electricity generation from wind. This represents a small share but one which has grown since 2004.

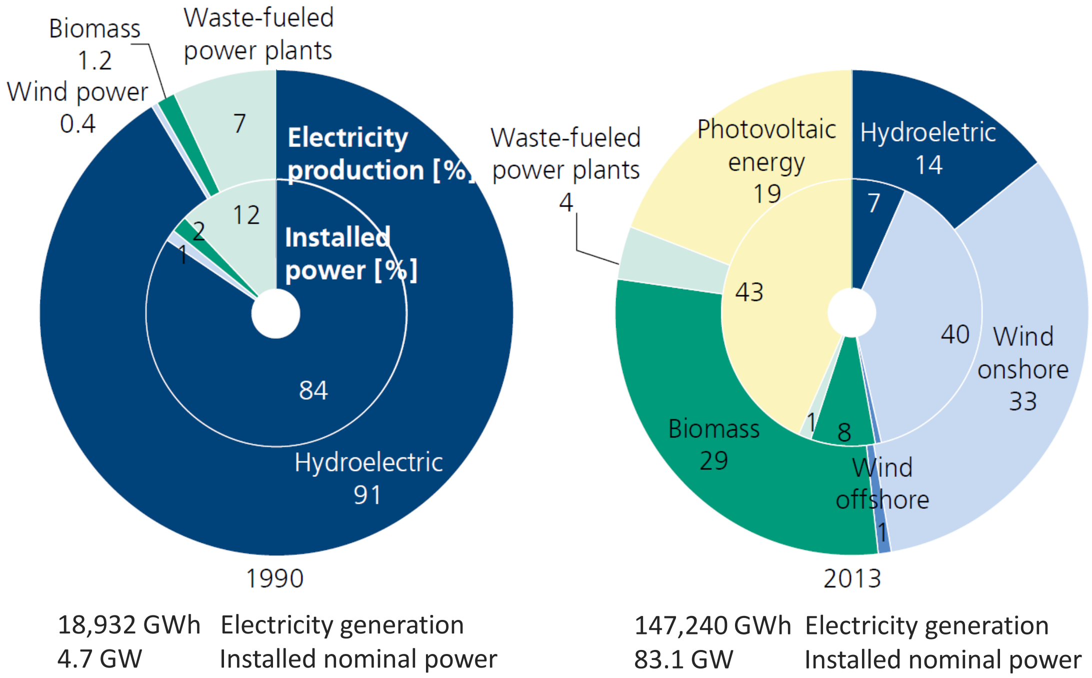

Figure 2: Gross electricity production and installed nominal power of renewable energies in 1990 and 2013. Data sources: [AGEE, 2013]

Figure 3 shows the electricity feed-in from offshore WTs in 2013. In 2013, a new record for electricity feed-in from offshore WTs was achieved by 906 GWh and this value exceeded the 2012 feed-in by 25%. This considerable increase was due to the 48 new WTs in the BARD Offshore 1 wind farm. In March 2013 there was a very high feed-in of about 120 GWh, representing some 13% of the total annual feed-in. This contrasts with the less productive months of July, November, and December which gave a cumulative feed-in of only 128.03 GWh [Fraunhofer, 2013].

A closer consideration of the offshore WTs reveals the reasons for its small share in the German gross electricity mix. In Germany's North and Baltic Sea there are currently 116 WTs having a total nominal power of 521 MW. Germany is focusing its offshore wind projects in deep waters and in farshore locations in order not to adversely affect the marine environment in the Wadden Sea (Wattenmeer) National Park (Figure 4). Hence, the planned locations for offshore wind farms in Germany's North and Baltic Sea differ considerably from the locations of international offshore projects that have already been realized.

In total, 39 offshore wind farms have been approved in Germany up to December 2013, with 34 of it are located in the North sea, while five of it are located in the Baltic Sea. The Nordergründe and Riffgat (North Sea) wind farms and the Baltic I and GEOFReE (Baltic Sea) wind farms lie within the 12 mile zone. The relevant provincial government is responsible for

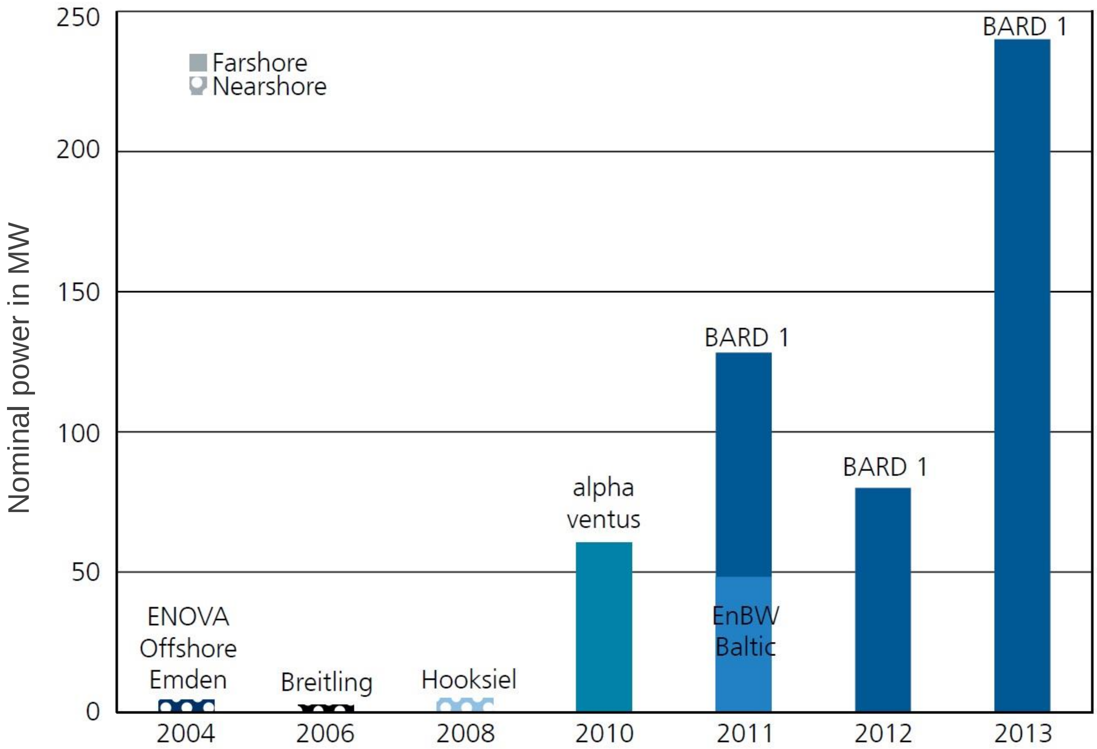

Figure 3: The installed offshore wind power from the North Sea and Baltic Sea. Data sources: [50Hertz-ol, 2013] and [Tennet-olb, 2013]

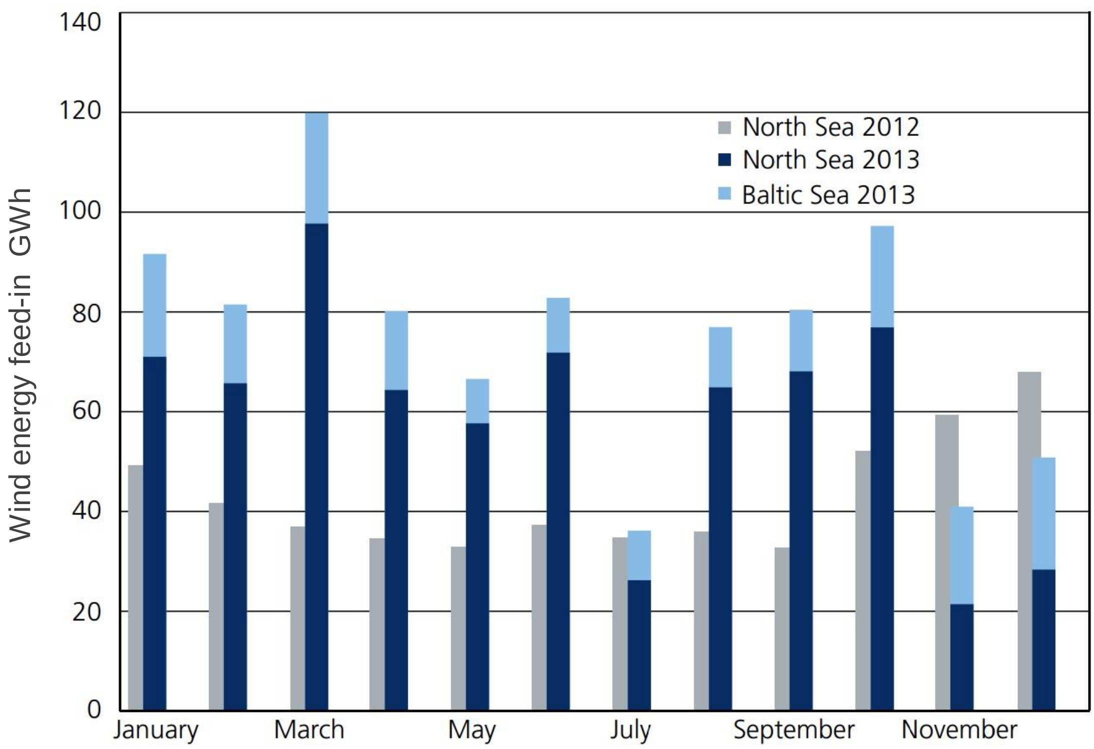

Figure 4: Start-up of new German offshore wind farms. Data source: [Fraunhofer, 2013]

giving approval for wind farms in this zone [Fraunhofer, 2013]. The Federal Maritime and Hydrographic Agency (BSH) is responsible for approval procedures outside the 12 mile zone, in the Exclusive Economic Zone. Further offshore wind farms are in the approval process. Up until now, offshore wind farms have been approved for an area covering almost 1235 km^2 and having a nominal power of 10.8 GW. The wind farms in the North Sea are planned at an average water depth of 29.3 m and at an average of 60.8 km from the shore. In the Baltic Sea the average planned water depth is 22.8 m and the average distance from the shore is 24.5 km [BMU-a, 2013].

An overview of (installed, in operation, under construction and approved) offshore wind farms in the Germany's North and Baltic Sea is presented (Table 23, 24 and 25 in Appendix A). Note that the offshore wind farms are established in several construction stages, during which only activation of a small part of total power can be delivered. This is because only one wind turbine, or even just parts of it, are completed at a time. For instance, in wind farm (Bard Offshore 1) wind turbines went online in several stages, and the whole wind farm with its 80 wind turbines has not yet been completed. Whereas the (Borkum West II) facility is completed in just two construction stages [Fraunhofer, 2012].

If the German government will reach its goal of 10 GW of offshore wind energy in 2020, wind energy would become significantly more important in the German electricity mix. In comparison, it has to be mentioned that, more than 38 GW onshore wind installed power already have been achieved in 2014 [BWE-ol, 2014].

2.1.3 Network stability and grid integration of offshore wind energy

In Germany, there are four transmission system operators which are supervised by the German Federal Network Agency (BNetzA). Their main task is to guarantee a stable and reliable power supply. Germany is divided into four areas on high voltage level, each one is controlled by one of the four transmission system operators (TSO) (Figure 5).

All these areas are interconnected with high voltage power transmission lines and form the German power network. All European national transmission systems together form the European power network (ENTSO-E). As mentioned before the main task of the transmission system operators is to provide a stable and reliable network. It means that, the net frequency is as close to its given value as possible. The given value for the European power network (ENTSO-E) is 50 Hz. The frequency is allowed to deviate $\pm$20 mHz. When the difference between nominal and actual value is too big, a breakdown of the whole power network is possible. To prevent this, TSOs have to keep the net frequency as stable as possible. Thus, control energy is required once the frequency has reached the range of tolerance. In case

Figure 5: The four areas which are controlled by the Transmission System Operators (TSO) can be seen here. [Soptim-ol, 2014]

of an excessively high frequency, the negative control energy is needed, while in case of an exceedingly low frequency, the positive control energy comes to operation. Positive control energy means that, more power supply capacities are needed and For that reason the power plant which are switched on or consumer load has to be decreased. Consequently, the negative control that describes the opposite behavior now will let the power plants to be switched off or consumer load has to be increased.

In case of conventional power plants, it is comparatively easy to handle and realize a stable power network. The transmission system operators instruct the energy companies to switch on and off their power plants, just the way it is needed. But due to an increasing portion of renewable energy, which means a growing portion of volatile energy, it is quite challenging, to keep the net stable. The strength or direction of wind, or the time of sunshine are hardly predictable parameters, which makes it nearly impossible to prearrange a power supply schedule. There might be a greater demand for control energy, as there will be with conventional power sources. Providing a stable power net is one of the main challenge of the future.

Due to the expansion of offshore wind turbines in Germany, new challenges regarding management of electrical load arise therefore its generation and securing grid stability must be addressed. Energy generation is not only related to weather conditions and power demand, but also to the daily variation during summer and winter.

Figure 6 shows these variations for 2013 from the extrapolated data for the Baltic Sea. The winter month average power output in 2013 of 27 MW is close to 12 MW (80%) greater than the summer month average [Fraunhofer, 2013]. The reason for this is that much more favorable wind conditions in the winter months. This is very typical for wind turbines. Despite this tendency, there are also days with very high variations (Figure 7), burdening additionally the energy management. Usually, the effects of local daily variation are reduced by the spatial distribution of wind turbines all over Germany.

Despite all compensatory effects and the priority rule from the Renewable Energy Act- EEG, a reduction of wind turbine power is necessary in some occasional instances. This reduction was 0.2% in 2009 and already 0.34% in the following year. The ongoing expansion of wind energy will intensify this effect, because of this its economical and ecological features will be exposed [Fraunhofer, 2012].

2.2 Marketing possibilities of offshore wind energy

In order to provide the wind farm operator with stable sources of income achieving his profit targets, alternative marketing options are developed.

2.2.1 Current remuneration models

In Germany the remuneration for electricity feed-in was initially regulated by the Electricity Feed-In From Renewables Act (StrEG) which came into force in the start of 1991. The level of remuneration at that time was at least 90% of the average revenue per kilowatt hour (kWh) from electricity supply by electricity supply companies to all end-consumers. In April 2000 the Electricity Feed-In From Renewables Act was replaced by the Renewable Energy Act [Quaschning-ol, 2014]. This has been altered several times since then. The act defines offshore WTs in § 3 section 9 EEG as:

> *Offshore wind turbine is a wind energy turbine, which has been established at a distance of at least three nautical miles from the coastline of seaward.[...]*

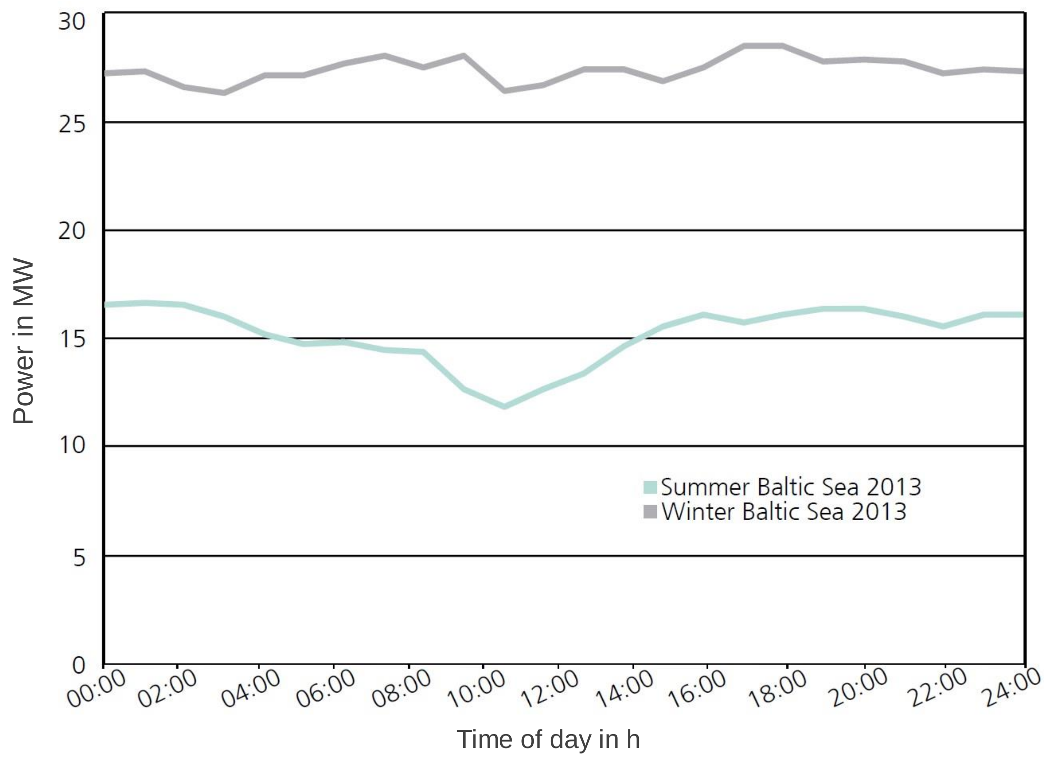

Figure 6: Average daily variation of the offshore wind power generated in the Baltic Sea during a summer and winter day of 2013. Data source: [Fraunhofer, 2013]

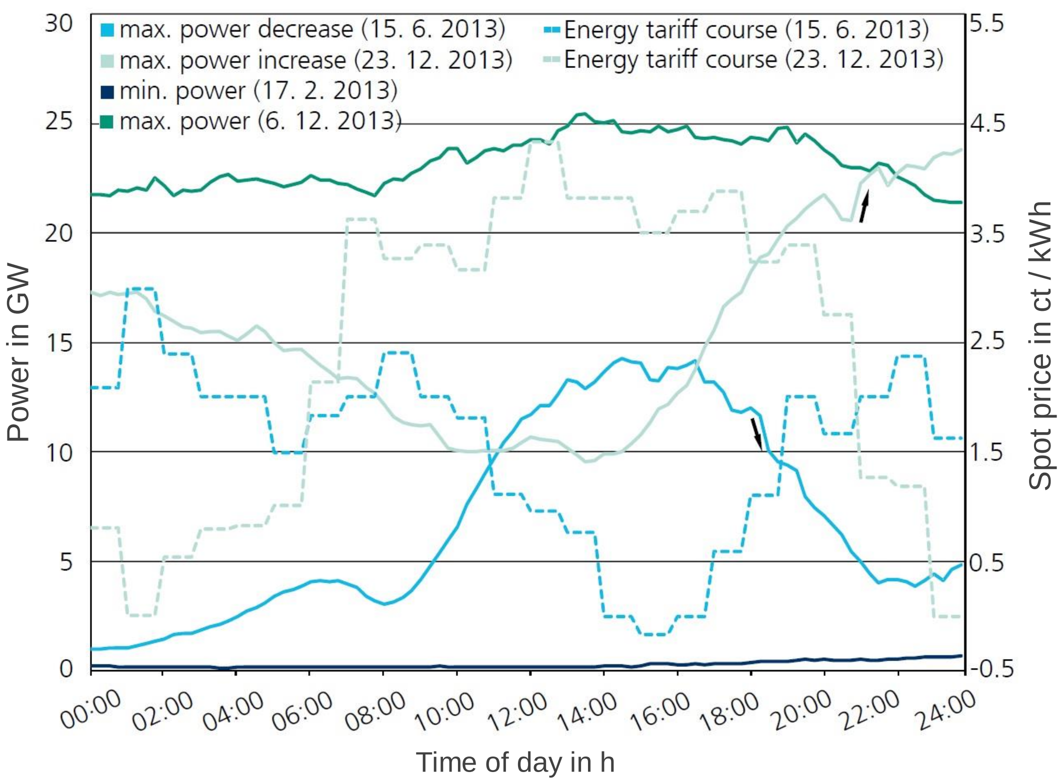

Figure 7: Extreme daily variations in the feed-in of wind energy to the German electricity grid in 2013, based on fifteen minute extrapolations of the wind power, and the electricity price movement on these extreme days in the EPEX spot auction market. Data source: [Fraunhofer, 2013]

Operators of EEG sponsored facilities can chose between Feed-in remuneration for electricity provided to the grid or Direct marketing including additional premiums. Both models will be outlined subsequently.

2.2.1.1 Base remuneration and initial remuneration

The Renewable Energy Act provides down a minimum remuneration based on electricity output. In addition, a so-called (reference output) is defined. The reference output is the amount of electricity which the relevant type of WT would generate at a fictitious reference location under set conditions over five operating years. For WTs it formulates an initial remuneration for a period of at least five years. Depending on the quality of the location, the feed-in remuneration may subsequently be reduced to a base remuneration [Fraunhofer, 2013].

The base remuneration for offshore wind energy is 3.5 ct/kWh (§ 31 section 1 (EEG)). During the first 12 years the initial remuneration rate is 15 Cent per kWh (§ 31 section 2, sentence 1 (EEG)). The rate during period of initial remuneration depends on the distance to the coast and the water depth (§ 31 section 2, sentence 2 (EEG)).

> *The period in accordance with the first sentence above in which the initial tariff is paid shall be extended by 0.5 months for each full nautical mile beyond 12 nautical miles that the installation is distanced from [...] , and by 1.7 months for each full meter of water depth beyond a water depth of 20 meters*

On the other hand, according to the first sentence of § 31 section 3 of the EEG, an initial remuneration rate of 19 cent/kWh for the first 8 years can be chosen for offshore wind turbines activated before 01.08.2018. After that period, again 15 ct/kWh will be paid according to the second sentence of § 31 section 2 of the EEG.

Furthermore, § 31 section 4 EEG explains how the initial period is extended in case of power line disruption.

> *If feed-in from an offshore installation is not possible for a period of more than seven consecutive days because the cable pursuant [...] disruption, the tariff pursuant to subsections (2) and (3) above shall be extended for the duration of the disruption, commencing on the eighth day of the disruption*

According to (§ 20 (EEG)), for all off-shore wind farms which were brought on the line after the 31.12.2012, the remuneration decreases by 7% per year, starting at the 01.01.2018.

2.2.1.2 Direct Marketing

Besides provision of fixed remuneration for wind energy feed-in, the Renewable Energy Act also allows an option of using Direct marketing. The sale of electricity directly to third parties in this way can be undertaken to claim the market premium, to reduce the so-called (EEG cost allocation) of the energy provider. At the end of 2013 over 85% of the generating capacity from installed WTs was sold by direct marketing [Fraunhofer, 2013].

There are several possible direct marketing schemes, which are all mutually exclusive (§ 33b EEG and § 56 section 1 (EEG)). The use of direct marketing with the sole purpose of claiming additional premiums is explained. These additional premiums (§§ 33g-33h (EEG)) have to be paid by the grid operator and are received by the facility operator. It is calculated as following:

$$MP = EV - RMV \tag{2.1}$$

$$RMV = MAV - MB \tag{2.2}$$

Where

- MP the amount of the market premium in cents per kilowatt hour in (ct/kWh),
- EV the base price value (according to § 33g section 2 (EEG)) in (ct/kWh),
- RMV the reference market value in (ct/kWh),
- MAV the actual monthly price average value on the spot market (EPEX) in (ct/kWh), and
- MB the management bonus in (ct/kWh)

The reference market value (RMV) is composed of actual monthly price average value on the spot market (EPEX) (MAV) which is less than the management bonus (MB), where MB contains costs for exchange admission, exchange connection, transactions regarding gathering reference value and accounting, IT infrastructure, staff and service, creating forecasts and deviations regarding effective electricity fed into the grid. Table 1 gives an overview of the management bonus based on management bonus act (§ 2, section 1 (MaPrV)) from 02.11.2012:

The feed-in remuneration based on EEG reflects on an economical meaningful and reliable way of operating a wind farm. However the main goal is to incorporate all kinds of renewable energy in the given energy structure. Thus energy has to be fed into the grid purely on demand. The market premium as well as the management bonus gives a financial incentive for direct marketing. Figure 8 visualizes the correlation between feed-in remuneration, manage-

Management Bonus (§2, section 1 (MaPrV))	
Produced Power 2013	0.65 ct/kWh
Produced Power 2014	0.45 ct/kWh
Produced Power 2015	0.30 ct/kWh
Management Bonus for remote controlled facilities(§2, section 2 (MaPrV))	
Produced Power 2013	0.75 ct/kWh
Produced Power 2014	0.60 ct/kWh
Produced Power 2015	0.50 ct/kWh

Table 1: Management Bonus

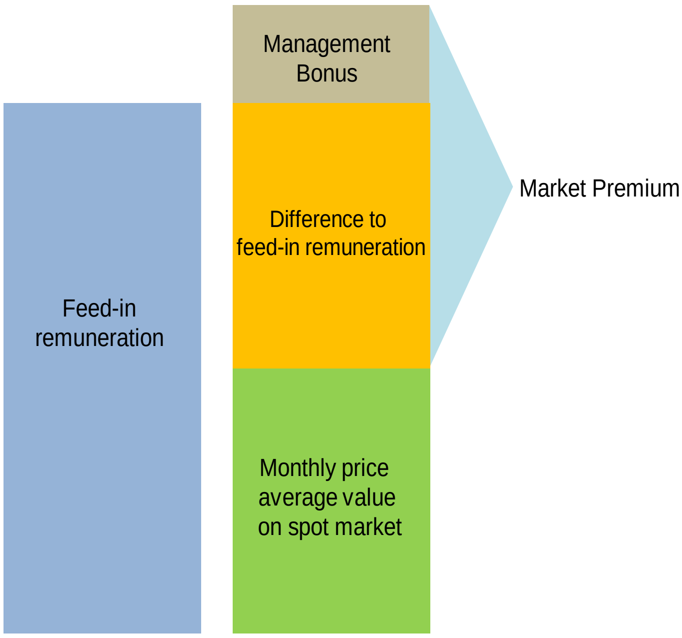

Figure 8: Structure of Market Premium. [BMWi, 2012]

ment bonus (MB) and market premium (MP). In addition further marketing success can be generated, if monthly average achieved sale price exceeds the real monthly average price.

2.2.2 Alternative marketing possibilities

In the following section alternative options for energy selling e.g. control energy market and electricity market will be explained and the interaction of market participants will be outlined.

2.2.2.1 Control Energy Market

As mentioned in former sections the main task of TSOs is to control the power grid in a way, that a stable and reliable power supply can be achieved. That means, keeping the balance of input and output of energy. A disturbance of this balance can lead to deviation of the net frequency. Therefore control energy is applied to keep the net frequency at its given value [Mackensen, 2011]. A distinction is made between positive and negative control energy:

- **Positive control energy** is required, if there is a lack of energy. That means the demand of energy is greater than the production. This causes a decrease of the net frequency. To avoid this frequency decrease, more power plants can be switched on or already running power plants can raise their performance. Furthermore energy consumers can be turned off.
- **Negative control energy** is used in the opposite case. There is too much energy as compared related to the whole consumption, thus power plants have to reduce their performance or more energy consumers have to be activated.

A good example of how control energy can be used, represent by pumped storage power plants (PSP). The PSPs actually are not power plants in the classic sense, since they have only a storage function. By energy excess the water will be pumped in a higher elevation reservoir which is used again in a classical hydro plant to generate electricity when needed. With a need for negative control energy, which means actually energy excess in power network, PSPs take out this excess to pump up the water in a higher reservoir level. With a need for positive control energy, which means here energy deficit in power network, PSP turbines will be operated by the pumped water to feed energy into the grid. Other storage technologies can also work in this way.

Figure 9 shows three different kinds of control reserve, which differ in working periods, handling time and time for announcements. Primary control reserve (PCR), secondary control reserve (SCR) and minute reserve (MR).

Primary control reserve

This kind of control energy is used for fast corrections of a not optimal frequency. The energy has to be provided by all transmission system operators in Europe in equal shares. In case of frequency disturbance all power plants, no matter to which balancing zone they belong, have to provide enough control energy to correct these disturbances. The activation of the control energy is fully automatic and it has to be provided within 30 seconds for a period up to 15 minutes. Technically, this fast response is achieved by speed controllers at the power plants turbines and a small portion of the power plants capacity is detained for primary control reserve.

Secondary control reserve

The secondary control reserve is only called up within a balancing zone in contrast to the primary control reserve, which is called up in the whole European power network. It is automatically activated after the primary one. It has to be established within five minutes and has to be available for up to 15 minutes. Thus, it is necessary to capture enough energy to replace the primary control reserve.

Minute reserve

In case of a greater disturbance, the minute reserve is activated. In contrast to the two kinds of control energy mentioned before, the minute buffer is called up manually e.g. by a phone call of the transmission system operator. It has to be established within 15 minutes for four quarters of an hour and in extreme situations even for a couple of hours.

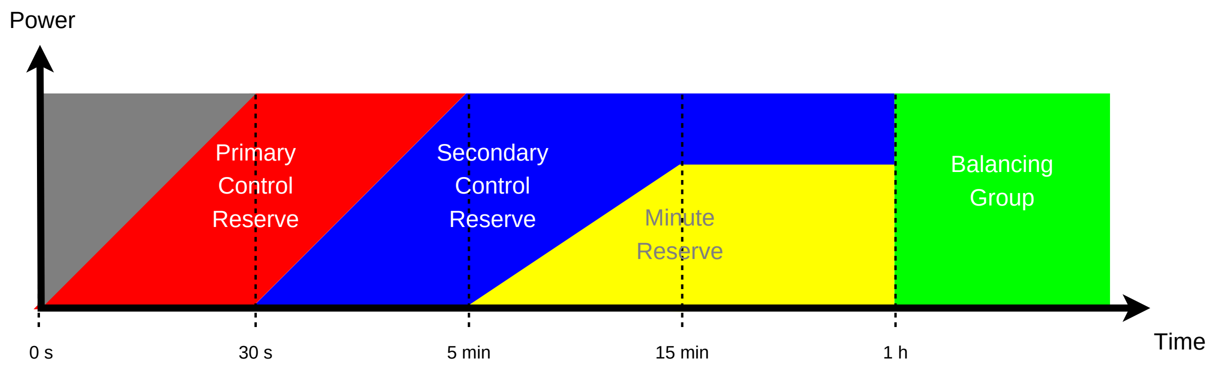

Figure 9: Control reserve types. [Bouyraaman, 2011]

An overview over the different kinds of control reserve is given by table 2. The providers of control energy who are paid according to the so called base price respectively demand payment. The base price is related to the provided energy and is paid in either case.

The called energy is compensated according to the demand price. The PCR is paid only in base price. In case of negative control energy related to SCR and MR also negative demand prices often occur, which results in payments of the control energy providers to the transmission system operator. The participation in the control energy market is difficult for wind farm operators and usually makes little sense. For economical or ecological considerations offering positive control energy is not always meaningful, because the wind turbines sometimes have to run throttled most of the times in order to adapt the required power in the system. Offering negative control energy makes only sense if the storage capacities are available. The reliable

<table>
<tr><th colspan="4">Control Reserve</th></tr>
<tr><th></th><th>Primary Control Reserve</th><th>Secondary Control Reserve</th><th>Minute Reserve</th></tr>
<tr><th colspan="4">General</th></tr>
<tr><td>Max. Power reached in</td><td>30 s</td><td>5 min</td><td>15 min</td></tr>
<tr><td>Max. covered time period</td><td>15 min</td><td>15 min</td><td>couple of hours</td></tr>
<tr><td>Responsibility</td><td>all TSO in ENTSO-E Zone* (solidary)</td><td>concerned TSO</td><td>concerned TSO</td></tr>
<tr><th colspan="4">Control Reserve Market</th></tr>
<tr><td>Submittal of Quotation</td><td>weekly, following week until Tuesday 3 pm</td><td>weekly, following week until Wednesday 3 pm</td><td>daily, preceding day until 11 am (working days)</td></tr>
<tr><td>Seperate Advertisment for Positive and Negative CR</td><td>no</td><td>yes</td><td>yes</td></tr>
<tr><td>Time Slice</td><td>no</td><td>Main Time: (Mo-Fr: 8 am - 12 pm) | Hidden Time: (Mo-Fr: 0 am - 8 am | Sa, Su 0 am - 12 pm)</td><td>0 am - 3.59 am | 4 am - 7.59 am | 8 am - 11.59 am | 12 am - 3.59 pm | 4 pm - 7.59 pm | 8 pm - 11.59 pm</td></tr>
<tr><td>Provision Time</td><td>all week, starting Monday 0 am</td><td>all week, starting Monday 0 am in their respective time slice</td><td>Time period of the respective day</td></tr>
<tr><td>Minimal Offer</td><td>± 1 MW</td><td>+ / - 5 MW</td><td>+ / - 5 MW</td></tr>
<tr><td>Offer Increment</td><td>1 MW</td><td>1 MW</td><td>1 MW</td></tr>
<tr><td>Compensation</td><td>Base Price</td><td>Base Price + Demand Price</td><td>Base Price + Demand Price</td></tr>
<tr><td colspan="4">* ENTSO-E Zone: European Network of Transmission System Operators for Electricity</td></tr>
</table>

Table 2: Summary of all different kinds of control reserve

use of positive and negative control reserve requires reliable wind forecasts, which are available only for short periods [Mackensen, 2011]. Therefore only MR can be offered in a suitable way, because it can be offered a day ahead (Table 2).

For a better integration of wind energy in the control energy market, the pooling of wind farms with other regenerative power plants might be a solution. Such a combination of two or more power plants is called virtual power plant (VPP) and this can take part in the control energy market under certain conditions. To make sure the contribution of VPP in the free energy market and EEX, a VPP should contain energy storage system. The section (2.3.3) gives more details about energy storage systems.

2.2.2.2 Balancing Groups

Transmission system operators sub-divide their control areas in so called balancing groups (BG), in order to enhance the balancing of inputs and outputs of energy to the grid. According to the transmission code 2007, the balance groups and sub balance groups are defined as follows [VDN, 2007]:

> *A balancing group is a composition of arbitrarily many input- and output spots within a control area. These in- and output spots have to be reported to the responsible transmission system operator. The main target is to achieve a balance between all in- and outputs. An input can be an input within the control area, or supplies from other balancing groups. Corresponding to that, an output can be an output within the control area or supplies to other balancing groups. A sub balance group is nearly the same as a balance group, but in contrast to a balance group, it is not responsible for adjustments of the transmission system*

The balancing groups are managed by a balance group manager (BGM) or supervisor (BGS). That could be energy trader, sales departments or larger companies. The main task of the BGM is to create the balance between energy production and import on the one hand, and energy consumption and export on the other hand. If the balance can not be achieved, the transmission system operator has to correct this drawback by the use of control energy (Section 2.2.2.1). The use of control energy has to be paid by BGM to the TSO. The amount depends on the overall uniform control energy price (reBAP). [NK-ol, 2013]

Because of the adjustments among balance groups, payments can go other way round. That is the case if:

- The control area is oversupplied, whilst the corresponding BG is undersupplied.
- The control area is undersupplied, whilst the BG group is oversupplied.

Due to negative control energy, there are also negative prices. Thus the reBAP can take negative values which results in an inverted payment flow. In accordance with §§ 10-11 StromNZV (Electricity Network Regulation Act) the transmission system operators are assigned to perform two different kinds of balancing groups:

- Balancing groups for balancing of energy losses (§ 10, sentence 2 (StromNZV))
- Balancing groups for EEG-facilities (§ 11 (StromNZV))

§ 11 (StromNZV) in more detail:

> *The operators of transmission systems are nominated to lead a balance group which only refunds energy according to the EEG act, and not according to § 33a (EEG) (Direct Marketing). Exempted from this practice are transmission system operators, when there are less than 100,000 customers connected to their grid*

The wind farm operators, who sell their energy on the basis of EEG-Remuneration are not responsible for balancing their forecast errors and thus they need not to bother for the control energy. In contrast to that, operators who preferred a direct marketing for their wind farms are attached to a balancing group and therefore they are responsible for inappropriate forecasts.

2.2.2.3 Energy Trading

Since not every power plant operator, especially renewable energy power plant operator has direct consumers for its energy, most of the energy produced is traded in other ways. A distinction here is primarily between the off-exchange energy trading, so-called over-the-counter market (OTC) and the exchange energy trading (Figure 10).

The Exchange energy trading is divided into two main components. First there is future market which means long-term trading, whereas the second energy market describes the short-term trading (spot market).

The spot market itself is divided into EEX (European Energy Exchange) spot market which is for the Day-Ahead market and EPEX (European Power Exchange) spot market which is for the Intra-Day market. The EPEX is focused on the hour trading and the EEX-spot market is on the Day-Ahead trading.

While the future contracts are traded with different offer periods (weeks, months, up to 6 years) on the future market, the Day-Ahead auctions refer always to the next day and Intra-Day products can be traded even up to 45 minutes before the energy delivery. The majority of the products traded in the electricity market have a provision period of one hour [EEX-ol, 2013].

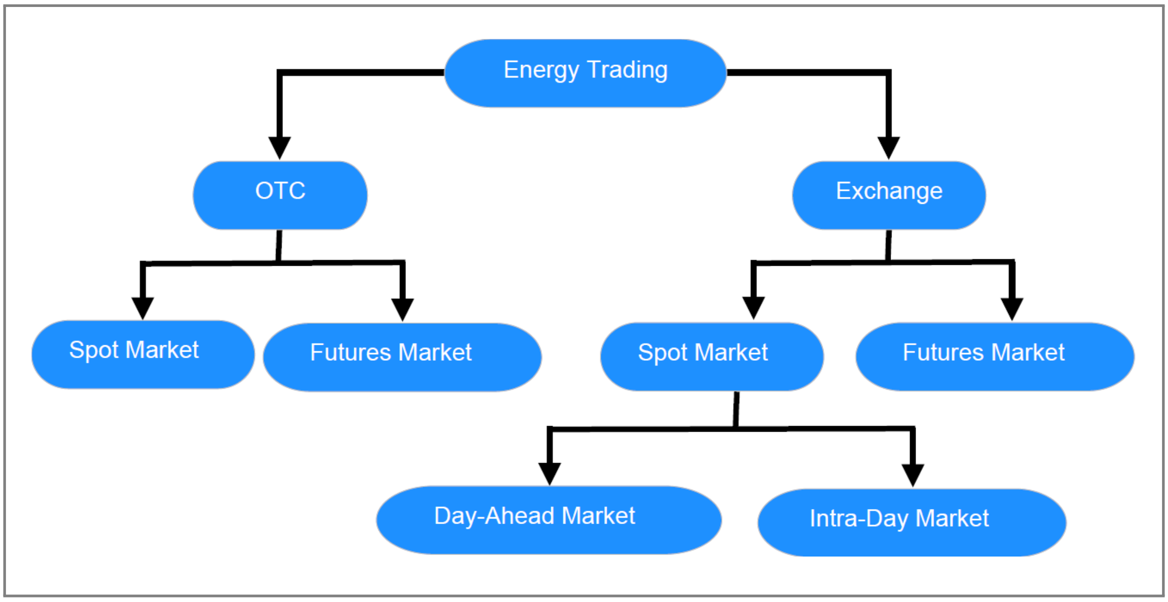

Figure 10: Energy trading in Germany

2.2.3 Co-action of all market players

Figure 11 gives an overview about the co-action of all market players in the energy market. This schematic distinguishes between consumer balancing groups (CBG) that do not produce the energy themselves but only import it and producer balancing groups (PBG) who have no own consumption of energy but export it completely.

The load forecast of the energy consumption is estimated on quarter hourly basis. Based on this estimation a schedule P_C^S on the consumer side is made usually, on hourly basis. This schedule is used for the trading at the energy market and in addition it has to be sent to the TSO. The deviation ΔP_C of the real consumed power P_C^{real} and the P_C^S is registered by the TSO on quarter hourly basis and is called balancing power P_C which is charged to the CBG supervisor.

Similar procedure is followed for the energy production. The produced energy is sold at the energy market which leads to the producer energy schedule P_P^S that also must be reported to the TSO. The deviation ΔP_P between the real produced power P_P^{real} and P_P^S is registered by TSO on quarter hourly basis, too. Usually one-hour-packages are traded at the energy exchanges, hence the energy producers provide new energy schedules only every hour.

The difference ΔP between the real produced power P_P^{real} and the P_C^{real} has to be compensated by the TSO with the activation of so called control reserve (Figure 11).

In practice there are lot of balancing groups which have an absolute energy schedule based on power plant use (Figure 12). Only an energy demand is covered, which results from orders of the energy market or other channels of distribution.

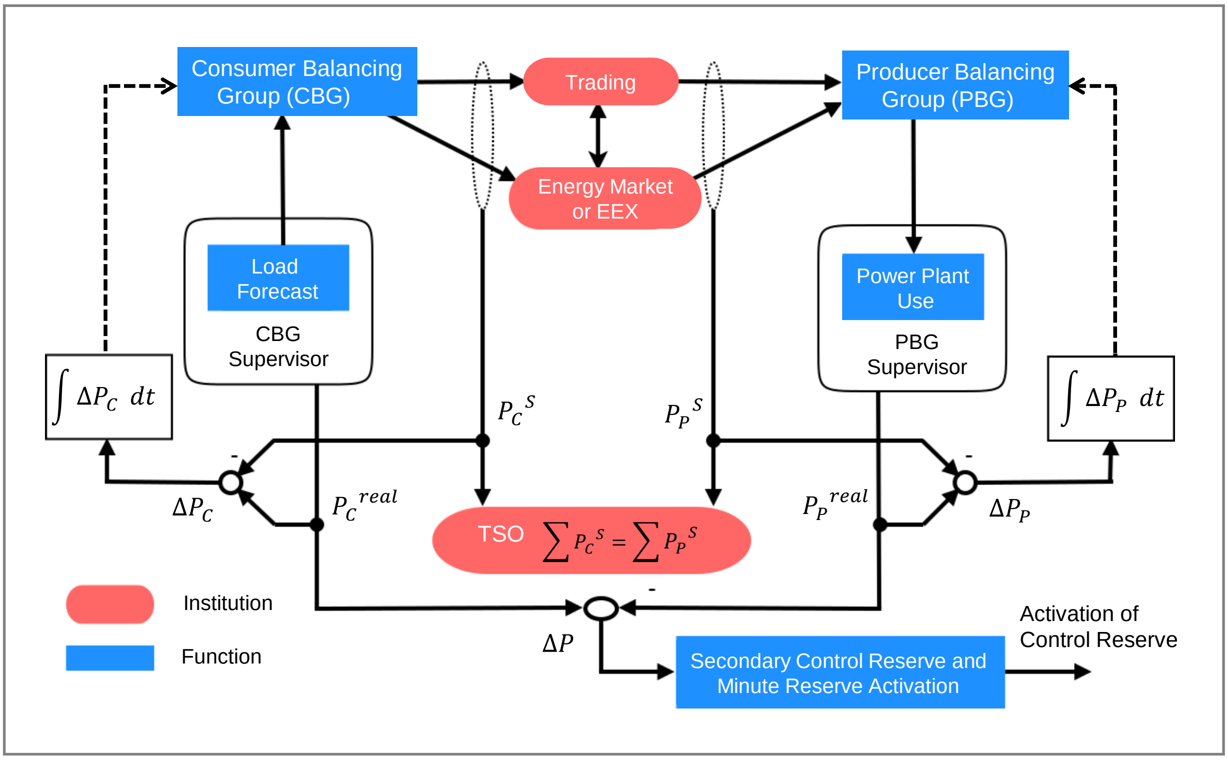

Figure 11: Interaction of all market players. Adapted to [Weißbach, 2009]

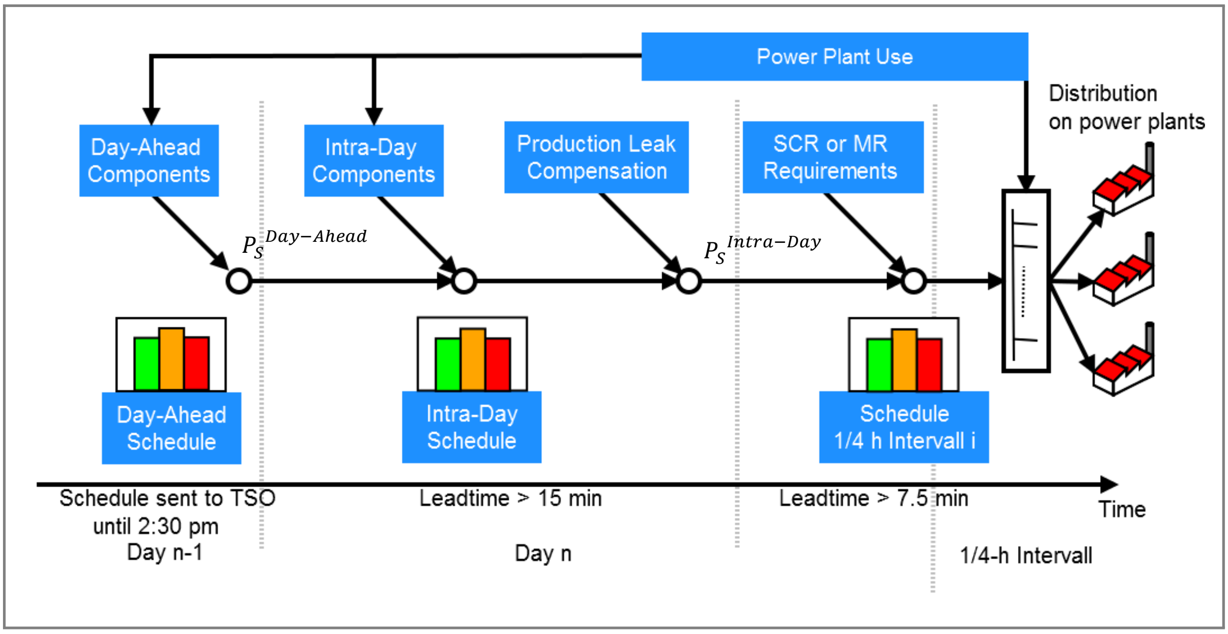

Figure 12: Scheme of a schedule-based power-plant use. Adapted to [Weißbach, 2009]

The next day energy schedule has to be submitted to the TSO until 2:30 pm by all balancing groups (§ 5 section 1, sentence 2 (StromNZV)), so that the TSO can perform a network security calculation. The components of this energy schedule $P_S^{Day-Ahead}$ are named Day-Ahead parts. Within the current day, the BGSs can adapt their schedule until 45 minutes before the next energy provision hour (exception here are the unpredictable power plant outages, adaptations until 15 min). These schedule adaptations are called Intra-Day adjustments and the resulting schedule is called Intra-Day energy schedule $P_S^{Intra-Day}$.

In the determination of the producer balancing group Day-Ahead schedule $P_S^{Day-Ahead}$, contracts from the Day-Ahead trading, long-term supply contracts, and loss of energy are very important to determine the demand side load forecasts within the current balancing group, whereas the power plant availability and forecasts of weather conditions for the following day are the main components on the production side. The Intra-Day changes of the energy schedule come out due to the activation of control reserve, adjustment of energy production deficits, or deviations of the consumption respectively production estimation. Finally, the required energy schedule $P^i_{required}$ corresponds to the Intra-Day schedule with short-term adjustments of MR or SCR requirements.

2.3 Long term energy storage in the future power network

This section discusses the need for and the integration of long term energy storage systems into the German power network. Several possible technologies for conversion and storage of electrical energy are discussed and analyzed in terms of long term potential. Acceptable technologies are chosen among the various discussed and their practical potential is considered. The current state of the art technology for the chosen method is described briefly and upcoming projects and research is also reviewed.

2.3.1 Importance of long term energy storage for security of the network operation

In order to satisfy the need for electrical energy of the future and to maintain the sustainability of the electrical system, the emphasis of this section lies on harnessing the potential of renewable energy. Keeping in view the limited supply of fossil fuels and the objective to reduce toxic waste and by-products of conventional power generation systems, renewable energy has been integrated on an enormous scale. In Germany alone, the renewable based electricity supply figures rose from 71.6 TWh in 2006 to 152.5 TWh in 2013. Consequently the share of renewably generated energy in total electricity consumption also rose from 11.6% to 25.4% during this period.

With the renewable sources contributing such huge amounts of electrical energy to the grid, it is often the case that the combined power generation of renewable and conventional exceeds the instantaneous local consumption. This results in surplus electrical energy. Such case occurred in 2010 of about 127 GWh, in which 98.6% was wind power [Trost et al., 2012]. The current trend and future projections show the widespread use of renewable energy generation. In such systems, the integration of long-term electrical storage is absolutely essential.

The addition of storage systems to the energy grid not only compensates for the overflow of generated power but also adds to the security of the energy grid of the future. Integration of storage system with renewable energy upgrades the stability of the energy grid as well. For example, with the assistance of the integrated storage technologies, fluctuations and deviations from the predicted consumption and supply data can be avoided by compensation with the stored energy. Thus the storage systems aid in the smoothing of fluctuations in the energy grid, making it more stable and reliable.

Storage systems are not relatively new and therefore volumes of research has been done over the past decades. However, the proposed technologies and storage systems like compressed air storage and pumped water storage now appear only as a small fragment of the energy network of the future. The widespread use of hybrid and electric vehicles in the upcoming years will also serve as a significant portion of the energy storage systems of the projected future.

2.3.2 Contemporary long term storage technologies

The increasing accessibility of renewable energy plants, particularly wind energy into the power grid causes a lot of energy surplus in the network. For this reason and to operate the plant at an efficient and economical rate, TSOs must also establish storage devices and systems for times when energy generation exceeds energy consumption. As also stated before, such overflow of energy can also cause unstable and fluctuating grid values and therefore the integration of storage technologies is inevitable. Furthermore, assistance can be provided in grid expansion and integration of new technologies. The feasible storage systems must be capable of storing high amounts of energy efficiently for long periods of time, even months. Therefore, a suitable technology would be characterized by high storage capacity and low self-discharge rate.

Energy Storage Technologies			
Electrical	**Mechanical**	**Electrochemical**	**Thermal**
1. Double Layer Capacitors 2. Superconducting Coils	1. Compressed Air Storage 2. Pumped Storage 3. Flywheel	1. Accumulators 2. Batteries 3. Power-To-Gas	1. Heat Storage

Table 3: Contemporary Storage Technologies

Table 3 shows the current energy storage technologies. Heat storage is listed merely as to cover all of the major storage technologies and therefore is not part of discussion in this report any further. Also electrical storage technologies are omitted since their properties do not meet our previously defined requirements of low self-discharge and high capacity. Modern cells and batteries are not yet equipped to store such large power and therefore are not discussed any further.

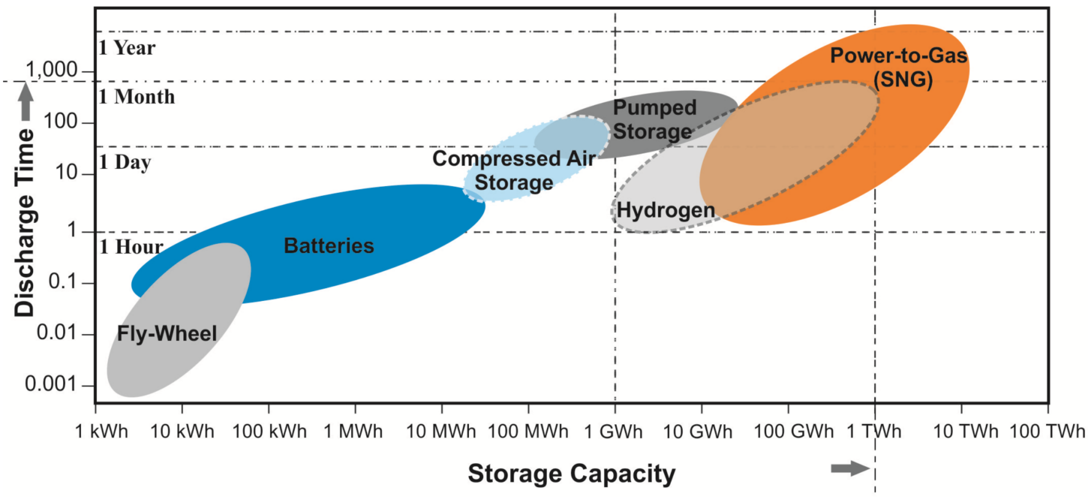

Figure 13: Discharge Time and Storage Capacity of Different Storage Technologies. Based on [Sterner-ol, 2011]

Figure 13 shows the electrochemical and mechanical storage technologies according to their capacity and discharge time. It can be seen that the most promising technologies are pumped storage as well as hydrogen and methane. Pumped storage is particularly popular and a well-established storage technology. The most common storage in the form of potential energy of pumped water because of the low cost and high efficiency. Comparatively, methane and hydrogen offers more storage capacity and longer storage periods. Pumped water storage systems are efficient and easy but their construction times are long, and the project opportunities are limited in Germany. Hence it is also eliminated from further analysis as a potential storage technology.

The acceptable technology must be able to store huge energy for up to several months. It is observed from Figure 13 that methane meets these requirements adequately. Compared to hydrogen it also offers lower risks. In addition, methane can be viewed as synthetic natural gas and large capacity is available. In Germany, this gas can be used as a substitute in the German natural gas grid. Therefore the use of methane gas as a storage capacity offers a practically limitless storage potential of 200 TWh. If just the hydrogen potential is considered it marks up to only 10% of this potential.

Table 4 compares the characteristics of hydrogen and methane as potential storage technologies. It can be seen from the comparison that, while methane storage technology holds low

Hydrogen and Methane in comparison		
	Hydrogen (H_2)	**Methane (CH_4)**
Efficiency Total • Production • Reconversion	Approximately 42% • 54 - 77% • 54 - 77%	Approximately 36% • 49 - 65% • 49 - 65%
Infrastructure • Gas Network • Heat • Traffic	Additional Gas • Limited • Limited • Limited/Incompatible	Exchange Gas • Compatible • Compatible • Compatible
Energy Density	10 MJ/Nm^3	33 MJ/Nm^3

Table 4: Hydrogen and Methane in comparison. Data sources: [Sterner-ol, 2011]

efficiency but still offers more attractive features. The efficiency is low due to the additional methanation. Overall, the benefits of methane outweigh the features of hydrogen and is therefore chosen for further analysis and study in this work.

2.3.3 Methane as an energy storage technology

As previously discussed, this thesis is primarily focused on the potential of methane used as an energy storage due to its attractive features including long term storage with low losses and a large storage capacity. Furthermore, methane is the primary component of natural gas and therefore can also be substituted and further used there. The surplus generated energy is stored using the Power-To-Gas technology using methane as the gas.

The key idea behind this approach is to store the excessively produced electric power when consumption is low and to be able to convert the energy stored back to electric power when demand is high. In Germany, the integration of such a system would consequently mean that the wind power generation system can be used at its maximum potential without breaks and without compromising the stability and security of the energy grid.

Additionally, stored energy and back conversion can help stabilize and balance the energy consumption and market and set more efficient schedules. Availability of stored energy means that differences in predicted and actual power generation from wind power generation systems can be compensated for easily. The result is a more stable and reliable grid network since fluctuations are smoothed out. For these reasons, the integration of a feasible storage system such as the Power-to-Gas methane technology is essential for Germany to secure a reliable grid network in the future. The method and various processes of Power-to-Gas are discussed next.

2.4 Current state of Power-to-Gas technology

As stated earlier, the (Power-to-Gas) process is still early in its research and development phase and therefore stills holds massive room for improvement in efficiency. Several teams and researches are dedicated with the common goal to make this technology ready for integration into our modern energy systems. The investment costs are to be lowered to promote future integration and commercial usage of this technology [dena-ol-b, 2013].

The (Power-to-Gas) Strategy Platform of the German Energy Agency (DENA) stands as a progressive step. It promotes the contribution of different personnel and industries for the research process in exchange for the interdisciplinary experience. With academics and researchers from several disciplines, there is massive exchange of ideas for improvement of the process. [dena-ol-b, 2013]

Figure 14 shows the various plants and partner research projects as of March 2012. Some of the projects and plants have already been established while others were in the planning phase. Initial plants help in the optimization of the methanation process and production of methane while few plants focus on the production of hydrogen.

The company ETOGAS (formerly SolarFuel) in collaboration with Centre for Solar Energy Hydrogen Research (STW) and the Fraunhofer Institute for Wind Energy and Energy System Technology (IWES) laid the foundation stone with the investment project SolarFuel-Alpha project in 2011. This project focused on the production of renewable methane and became the motivation for further projects like the Audi E-gas plant in Werlte. In the fall of 2012, the 250 kW Power-to-Gas pilot plant was commissioned in Stuttgart.

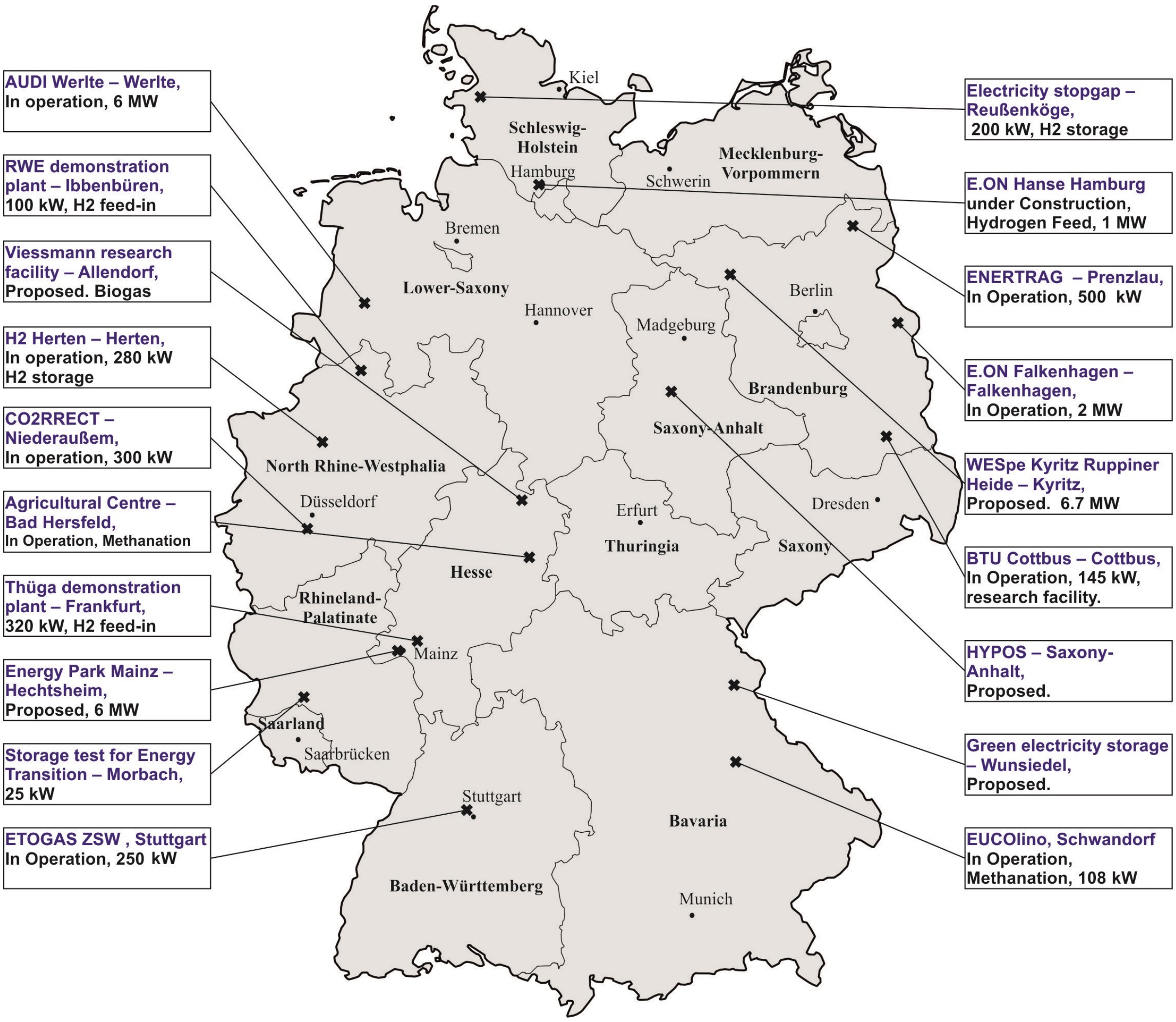

Figure 14: Current and Planned Projects for Power-to-Gas in Germany. Data sources: [BMVi, 2014]

3 Power-to-Gas as energy storage technology

In this chapter the technical aspects of storing energy in form of methane are presented. The process of the conversion of electrical energy into the gas is commonly referred to as (Power-to-Gas) (P2G). The Federal Network Agency [BNA, 2011] defines (Power-to-Gas) as follows:

> *Power-to-Gas is a concept in which excess energy is used by water electrolysis to produce hydrogen and the hydrogen is converted into synthetic methane using (CO_2) in the second step of the process. As storage for this methane could be used the existing natural gas infrastructure, the gas network connected with the underground storage facilities*

Power-to-Gas technology must provide high performance and capacities (Section 2.3.2) over the long time and also has to be economically reasonable. The P2G technology allows to transform electrical energy to hydrogen (H_2) or methane (CH_4). This gas is also named renewable gas or EE-gas, and is deemed to (CO_2) neutral. Hydrogen or methane can be converted back to energy, but they can also be used as fuel for cars or respectively as heating sources. Now methane is discussed in more detail whereas hydrogen is not the subject of this work [Bouyraaman et al., 2014-a].

The main advantage of methane as gas storage is the already existing natural gas network and gas storages in Germany which can handle the storage as well as the transportation of huge amounts of gas. Furthermore there are hundreds of thousands natural gas consumer devices and there are lots of different natural gas technologies available in the market [Bouyraaman et al., 2013]. Methane can be transported via the gas network and can be used as fuel for cars, energy source for power plants or for process heat technologies. A further advantage of an energy storage like this is an improved handling of short term fluctuations for a better balancing between energy consumption and production. An energy storage should be realized at a strategic reasonable location, that means near to the power grid. Thus the needed development of the energy grid can be relieved. The energy transportation is transferred to the natural gas network, which has greater input and output capacities. These capacities are about 20 times larger compared to current grids. [Sterner et al., 2011]

Nowadays, methane is the only possibility for nationwide long term energy storage and transport. A model on an energy supply structure with 100% renewable energy by using the Power-to-Gas process is shown in Figure 15. It shows schematically the contexts of gas systems, heat supply, electricity network with producers and consumers. The Power-to-Gas process is also accurately represented.

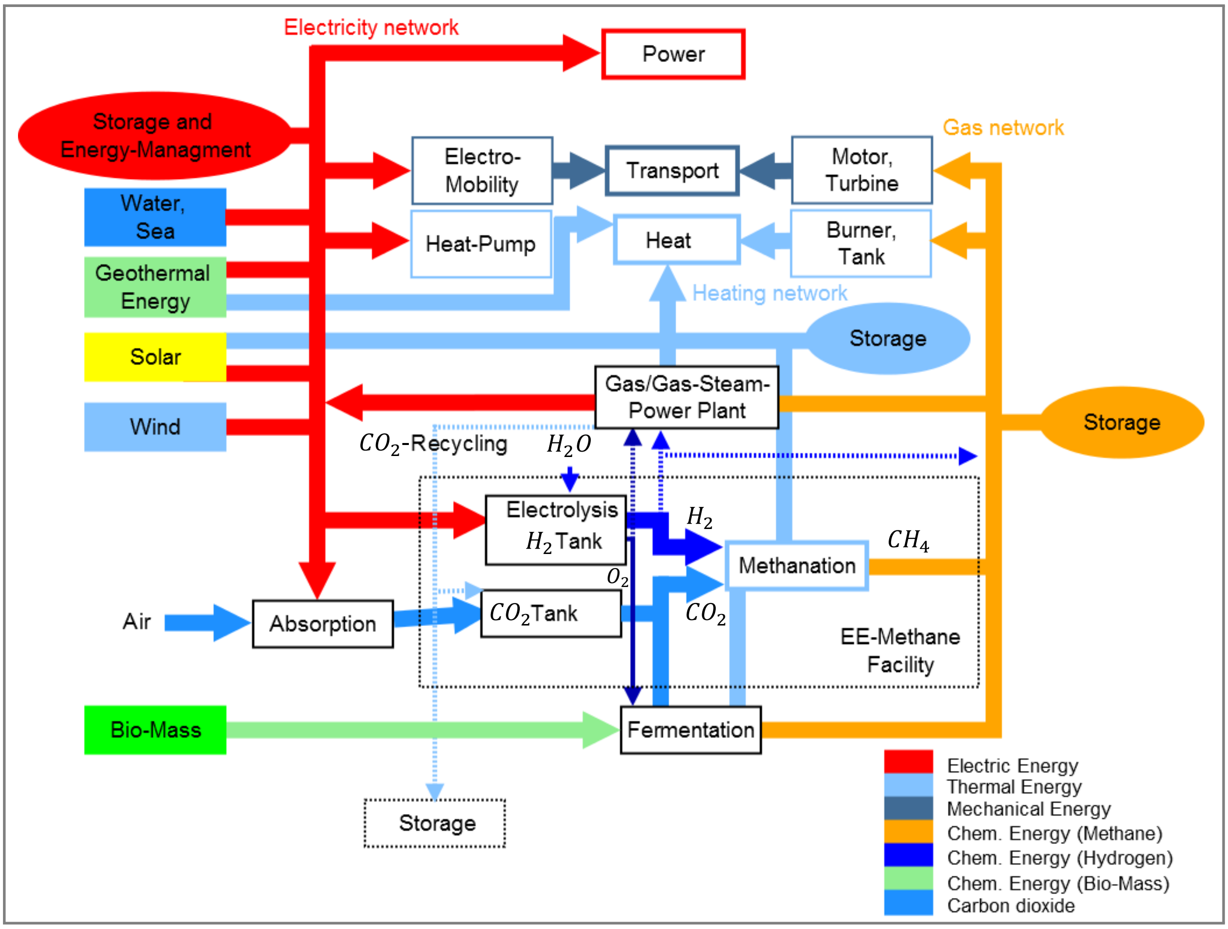

Figure 15: Schematic of a 100% regenerative Energy Supply Structure for power, Heat and Traffic. Based on [Sterner et al., 2011]

3.1 Power-to-Gas Concept

Methane is produced by methanation of hydrogen (H_2) and carbon dioxide (CO_2). First, based on the principle of water electrolysis, water is decomposed into hydrogen (H_2) and oxygen (O_2). For hydrogen electrolysis there are three different methods:

- Alkaline Electrolysis
- Proton Exchange Membrane Electrolysis (PEM)
- High-Temperature Electrolysis

The overall reaction scheme of this endothermic reaction at 25°C and atmospheric pressure is:

$$2H_2O \longrightarrow 2H_2 + O_2 \qquad \Delta H^0 = 571.8\ kJ/mol \tag{3.1}$$

For the production of 1 m^3 (H_2) and 0.5 m^3 (O_2) at (20°C, atmospheric pressure), 5 kWh of energy are required [Gerthsen, 2006].

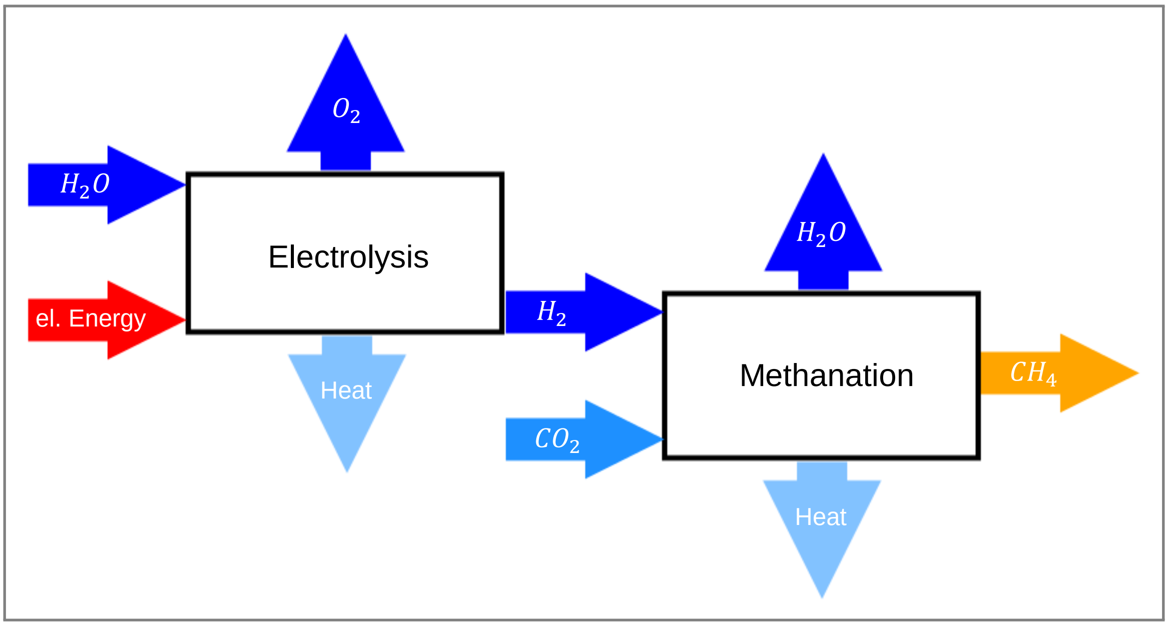

Figure 16: Power to Gas Schematic

The generated hydrogen can be used to produce methane (CH_4). Therefore carbon dioxide (CO_2) is needed. This extreme exothermic reaction at 25°C and atmospheric pressure known as Sabatier-reaction, looks as follows [Halmann, 1993]:

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \qquad \Delta H^0 = -164.9\ kJ/mol \tag{3.2}$$

The reaction is divided into two sub reactions:

$$H_2 + CO_2 \longrightarrow CO + H_2O \qquad \Delta H^0 = 41.5\ kJ/mol \tag{3.3}$$

$$3H_2 + CO \longrightarrow CH_4 + H_2O \qquad \Delta H^0 = -206.4\ kJ/mol \tag{3.4}$$

As mentioned before, there are three different methods of hydrogen electrolysis. In this work all further explanation are made on the basis of the alkaline electrolysis. Both other alternatives actually are not relevant, because of technological and economic issues. Alkaline electrolysis need temperatures of approximately 40°C to 80°C and are realized with a performance range of 1 - 760 Nm^3/h per module, related to a power input of 5 kW up to 3.4 MW per module. Energy consumption of electrolyzers is about 4.1 - 4.5 $kWh/(Nm^3H_2)$, which results in a system efficiency of 85% (based on the calorific value of hydrogen). Due to compression of the hydrogen up to 30 bar, another 0.2 $kWh/(Nm^3H_2)$ is required, which leads to a decreased system efficiency of about 78% [Smolinka et al., 2010].

The methanation based on the Sabatier-reaction is still under development. There are some research demonstration facilities and the methanation achieves a system efficiency of approximately 80% at temperatures of about 250°C to 500°C [Trost et al., 2012]. Nowadays the largest P2G facilities reach all in all efficiency of about 40% and power outputs of 25 kW [ZWS, 2012]. In the near future, facilities with of multiple MW and system efficiency of 60% and more are planned [SolarFuel-ol, 2013]. With the further use of wasted heat and the usage of other CO_2 sources, the system efficiency of a methanation facility can be improved. The start up time and the corresponding time line of the reaction is highly dependent upon the temperature and pressure conditions. In a study, it was found that the start up time for the Sabatier-reaction increased with decreasing temperature. For the starting temperature of 187.3^0C, the start up time was about 6 minutes. This increased to about 8 minutes and further to 10 minutes when the temperature was decreased to 179.5^0C and 168^0C respectively [Huang et al., 2009]. In the next section CO_2 sources are discussed.

3.2 Carbon dioxide (CO_2) sources

Due to the fact that carbon dioxide CO_2 is required, the question is where to get this gas. There are several possibilities for the acquisition of CO_2 [Sterner, 2009]:

- Biogenic CO_2 generated with biomass fermentation
- CO_2 extraction from the atmosphere
- CO_2 as a waste product from industrial processes
- CO_2 as a waste product from the combustion of fossil fuels
- CO_2 from recycling processes of power plants

3.2.1 Biogenic CO_2

CO_2 from fermentation processes is referred to as biogenic CO_2. Before the biogas is fed into the gas network, it has to be prepared because it contains about 40 to 45% CO_2. A combination of a biogas plant with a methanation plant seems to be suitable because biogas plants have already a connection to the gas network which the methanation plant can use as well. This concept leads to two different options: Firstly, separation of the CO_2 from the raw gas, or secondly a direct usage of the raw gas. The methane in the raw gas does not disturb the process, but it has to be desulphurized first. Thus the preparation of the raw gas from the biogas plant can be avoided [Sterner et al., 2011].

3.2.2 CO_2 extraction from the atmosphere

The exploitation of carbon dioxide from the ambient air can be done in many ways, in which the absorption is the most promising method. A pilot installation in Stuttgart (Section 3.1) uses a Natriumhydroxid (NaOH)-acid to bond CO_2 in the form of Natriumcarbonat (Na_2CO_3)-solution. This solution is acidulated with acid sulphur (S) to separate the CO_2. Finally, solutions are separated by doing an electro-dialysis to lead them back to the process.
Figure 17 illustrates this approach.

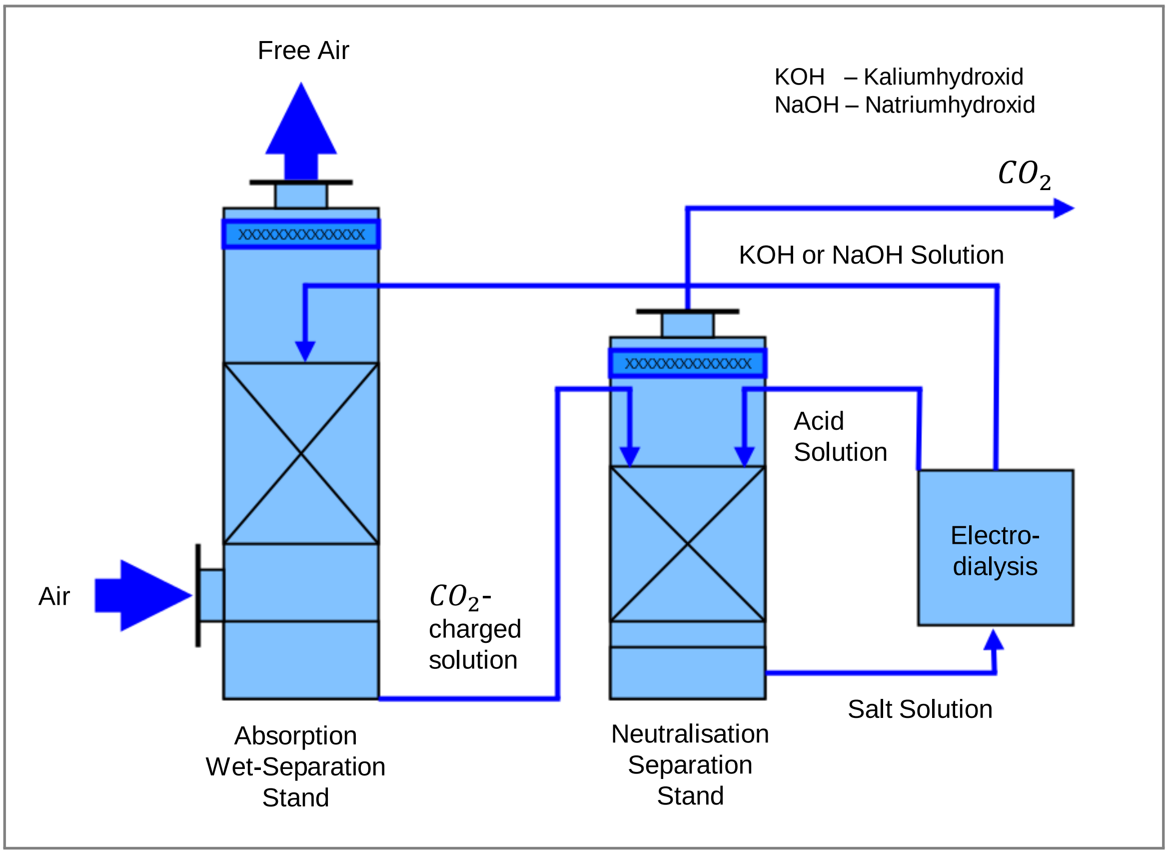

Figure 17: Scheme for CO_2 absorption of the pilot plant in Stuttgart. Based on [Sterner et al., 2011]

To produce one ton of CO_2, about 2.26 MWh of electrical energy are required. The so produced CO_2 is deemed to be CO_2-neutral. Thus the methane can be denoted as EE-gas. However the absorption of CO_2 from the atmosphere requires further energy, hence this method is only suitable, when there are no other CO_2 sources in the area [Sterner, 2009].

3.2.3 CO_2 as a waste product from industrial processes

A cheap way of getting CO_2 is the use ofvindustrial processes emissions. There are lots of industries where clean CO_2 is generated which can be used for methanation. Steel-, cement-, chemical- or beerindustry are some examples. However the so generated methane might loose the status of CO_2 neutral gas, which will reduce the market value and it can not be sold as EE-gas [Sterner et al., 2011].

3.2.4 CO_2 as a waste product from the combustion of fossil fuels

Another possibility is to separate CO_2 from the emissions of coal- or gas power plants. However the generated methane can not be deemed as CO_2 neutral. In the long run there will be no power plants which need fossil resources in Germany, hence this kind of methane generation is not sustainable [Sterner, 2009].

3.2.5 CO_2 from recycling processes of power plants

A suitable way to generate methane is to separate CO_2 from the emissions of the re-electrified EE-methane in gas power plants. Therefore a CO_2-cycle is established. With help of the Oxyfuel-method the whole process can be clearly improved. Oxygen which is separated during methanation is used for combustion instead of normal air. Thus the CO_2 separation of the emissions is more simplified. Furthermore an oxygen-circle is established [Sterner et al., 2011].

3.3 Gas power plants

Gas power plants are able to vary their power production relatively quickly, making them suitable fast reserve balancing provider to counterbalance the fluctuating renewable energy resources plants. There are different kinds of gas power plants. All of them are using thermal energy which is generated by the combustion of gas. Gas power plants can be further distinguished into two types: Open cycle gas turbine power plants (OCPP) and combined-cycle power plants (CCPP).

3.3.1 Open-cycle power plants

The open-cycle power plants (OCPP) are more flexible, faster, compact and requires less investment then combined-cycle power plants. The operation of a gas turbine power plant is illustrated in Figure 18 in a schematic way. First fresh air is aspirated by the compressor which compresses up to 20 bar, then it is combusted together with the natural gas in the combustor. This combustion gas reaches temperatures up to 1500°C and drives the gas turbine, which itself drives the generator [Heuck et al., 2010].

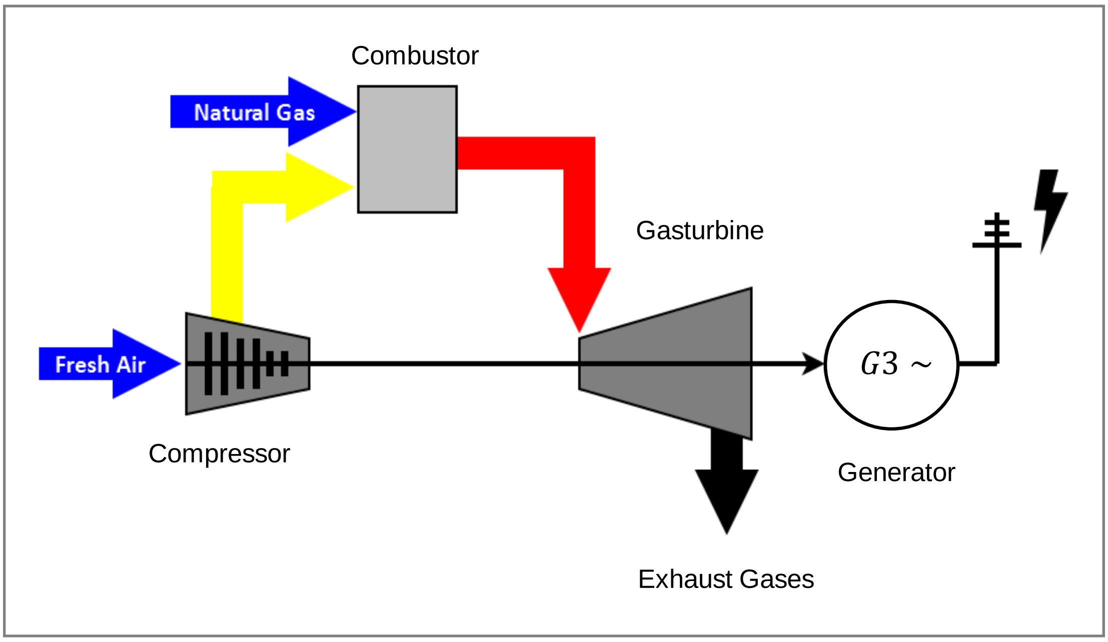

Figure 18: Schematic of a gas power plant

The start-up time of OCPP is 3 minutes, reaching nominal power in 6 minutes. An OCPP has an electrical efficiency of approx. 40% and a performance of up to 375 MW [Heuck et al., 2010]. They are typically used as peal load plants due to their low construction cost but also lower efficiency and thus higher operating costs. The low efficiency results in large CO_2, NO and other emissions per produced MWh compared to CCPP [MIT-ol, 2015], [EC-Europa-ol, 2015].

3.3.2 Combined-cycle power plants

Combined-cycle-power-plant is a combination of gas and steam turbines. The first steps are same as the gas power plant, but in addition to that the heat emissions are used to drive a steam turbine. Figure 19 gives a short overview. The emissions of a gas turbine power plant have high temperatures up to 625°C and are applied to a heat recovery boiler which generates steam under high pressure of up to 170 bar and temperatures of 600°C. This steam then runs a steam turbine which runs a generator. Modern power plants can reach an efficiency of up to 60% and due to their short response time they are qualified for the minute reserve market [Heuck et al., 2010].

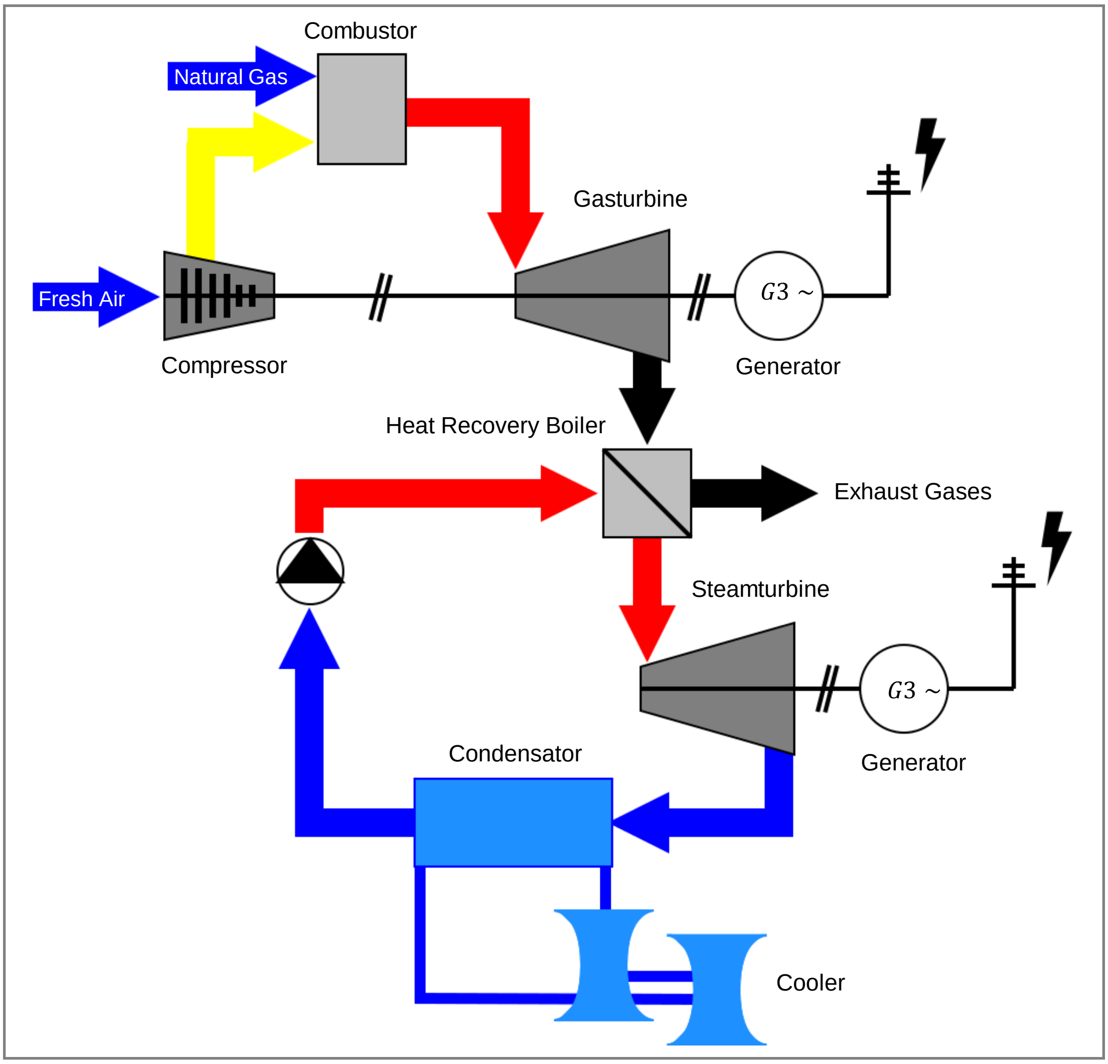

Figure 19: Schematic of a combined-cycle power plant

The start-up time of a state of the art CCPP can be as low as approx. 8 minutes, reaching nominal power. A CCPP has an electrical efficiency of up to 60%. It is possible to reach an overall efficiency of up to 95% by using the heat plant condensers in community heating systems [MIT-ol, 2015].

3.4 Contribution of Power-to-Gas in the control energy market

Applicability of different technologies may to some extend are location specific, when talking about Power-to-Gas (P2G), it contributes in the energy market for the services of frequency reserve, time shifting, transmission and distribution upgrade deferral.

Water electrolyzers producing hydrogen can quickly adopt to different load conditions. They can provide positive and negative balancing power under different electrolyzer operating conditions. Combination of gas power plant or fuel cell and electrolyzers with hydrogen storage can also provide time shift. Large potential storage capacity reserves also makes hydrogen storage applicable for longer duration. Moreover, hydrogen can be useful for mobility, in the gas grid and in the industry sector.

3.4.1 Balancing power

The main drivers behind the short term balancing are generation outages, forecast errors in load and production, sudden load variations, grid unavailability and congestions. This variable and less predictable output levels of renewable energy is thus expected to have a notable impact on the need for system balancing requirements.

Different algorithms developed and research carried out by professionals working in P2G area to make the optimal operation of the system, such that it could play a significant role in the secondary energy balancing market. Following are the modern key aspects and focused areas for the betterment of P2G in control energy market.

3.4.1.1 ITM Electrolysis

Electrolyzing process is one of the focused areas. Testing and experimental studies have been carried out by research professionals of Thuega AG, ITM Power on electrolyzers by keeping it for hours under variety of operating conditions to see its behavior on different load conditions. According to [Thuega, 2015], analysis shows that the time response in meeting the required output was significant enough that it allows the ITM electrolysis process in contributing towards the balancing of the secondary market.

3.4.1.2 SILYZER process

The Siemens SILYZER is an innovative electrolysis system based on PEM (Proton Exchange Membrane) technology for converting electric current into hydrogen. The SILYZER is a strong performer for all P2G solutions and networks, providing flexibility in the energy network, optimal utilization of fluctuating renewable energy, and has an excellent CO_2 balance. The basic system of SILYZER technology consists of at least one 1.25 MW skid, with the overall effieciency of 65-70 %. Multiple basic systems can be combined into a PEM electrolysis network that delivers up to 20 MW and beyond. SILYZER facility also effortlessly handels hydrogen production when oprated under high pressure of up to 35 bar - a direct benefit for the customer [Siemens, 2015-a], [Siemens, 2015-b] .

Taking into account different types of balancing power; the primary balancing power, the secondary balancing power and the minute reserve which take cares of the system during different frequency fluctuations and disturbances. The use of the SILYZER also pays off in this scenario. As a dynamic load component in the balancing power market, it compensates for supply fluctuations in the power grid. The SILYZER can therefore be an important strategic component for energy suppliers and transmission network operators. It contributes in following ways [Siemens, 2015];

- dynamic power availability within milliseconds.
- reliable and proven component for balancing power and P2G concepts.
- superior attributes such as robustness, low maintenance requirements, and safety
- produces hydrogen as a dependable energy carrier and recyclable material

3.4.2 Balancing in the gas sector from P2G perspective

Natural gas has numerous application usage such as power production, heating, domestic usage as cooking, feed stock and to some extend at transport level. Out of these, three latter applications remains stable in the short term and causes a limited diurnal swing only, however the usage of gas devoted to power generation and heating are largely influenced by large diurnal swings, sudden load changes and planning/ forecast errors during the day.

The following factors in particular influence gas demand instability from daily balancing viewpoint:

- Temperature variance is dependent on specific weather conditions. Variation of temperature impacts both residential and power sector (thermal plants) efficiency. In both sectors, it influences the diurnal swing as well as potential forecast errors.
- Volatile or unexpected off take by power plants, highly impact the balancing in the electricity market or more generally the unpredictability of electrical prices in the Intraday market. Consequently, gas consumption of gas fired power plants are subjected to considerable fluctuations and unforeseen load variation changes during the day.

Nevertheless, the flexibility of the gas system is secured in practice through the deployment of various sources that can be utilized in parallel by keeping within the limits of the local/regional network. Most common in particular are:

- Line pack system; that typically maintains the pressure level required for safe operation of the system. It covers very short time needs as it is available without any delay, but has limited volumes.
- Gas Storage; appropriate in geographical sites such as salt caverns. Available volume much longer than those available with line pack system.
- Modulation of gas production capacities; option available for the countries who are gas producers and which remains within the limits of the flexibility offered by different gas fields.
- Quality conversion of mixing gas of different nature; gases having different calorific values. Operation of gas networks with two different gas qualities, technical means of converting high calorific gas to low calorific gas. But the option is exceptional and restricted to countries, e.g. Netherlands.

3.5 Statistical information about the participation of P2G in the control energy market

Table 5 lists projects (some functional, some proposed), which exhibit an exceptional promise of P2G plants participation in the control energy market. While there are numerous other demonstration projects undergoing both in Germany and elsewhere in the world, these projects stand out as they contribute directly to the electrical grid.

Many other plants which feature methane feed-in into the natural grid can also be considered as contributing indirectly to the control energy market by providing gas reserves to gas power plants elsewhere. Hence, such P2G plants convert the excess of electrical power to natural gas which is fed into the nationwide (or local) natural gas grid and some gas power plants may use gas from the grid to contribute to power system when the need to stabilize the grid may arise.

Nr.	Project	Site, Year	Details
1	ENERTRAG - Hybrid power plant Prenzlau	Prenzlau, Germany. In operation since 2011	500 kW pilot plant. The project aims to evaluate the potential storage system P2G to the Energy Transition on a small scale
2	EUCOlino	Schwandorf, Germany. In operation since 2012	108 kW, methanation. The synthetic methane is used for electricity production along with biogas
3	Energy Park Mainz	Hechtsheim, Germany. Proposed for 2014	6 MW electrolyzer, hydrogen storage, reconversion, feed-in into the natural gas network
4	Sotavento grid stabilisation	Galicia, Spain. In operation since 2014	The wind park consists of 24 wind turbines equipped with different technologies. The system further contains a Hydrogenics HySTAT 60 Outdoor electrolyser producing 60 Nm^3/h hydrogen, a compressor, a storage depot, and a combustion engine for reconversion
5	Wind-hydrogen plant Utsira	Utsira, Norway. In operation since 2004	Independent energy supply via wind-hydrogen for 10 households. Hydrogen is produced and stored with a 50 kW electrolyser. The hydrogen is reconverted via fuel cell and hydrogen-fuelled combustion engine based on demand
6	Glamorgan Smart Grid project	Port Talbot, United Kingdom. In operation since 2008	Small P2G plant with hydrogen refueling station. Hydrogen is in part reconverted via fuel cell and in part utilized as fuel for a minibus operated by the university
7	Ontario grid frequency control	Canada. In operation since 2013	Investigation of the responsiveness of a Hydrogenics HySTAT hydrogen generator. A HySTAT S 4000 Indoor plant producing 100 Nm^3/h hydrogen is used for frequency control of the electricity network
8	Emerald H_2 wind to hydrogen facility	Minnesota, USA	10 MW wind park for peak load electricity. Feed-in of wind energy and reconversion is only intended during peak load periods
9	Wind to hydrogen project Boulder	Colorado, USA. In operation since 2009	The hydrogen is in part reconverted via a fuel cell during peak load periods. A small hydrogen refueling station is also available
10	Smart City Portal	Kitakyushu Japan. In operation since 2010	PV systems with a combined output of 100 kWp are installed in combination with a small wind turbine. Excess energy in the form of hydrogen is stored and reconverted on demand via a community energy management system

Table 5: P2G projects with promise for significant contribution and participation to control energy market. Data sources from: [BMVi, 2014], [INGRID, 2015], [ENERTRAG-ol, 2015]

4 Concept of a virtual power plant

In this chapter a concept is presented, which allows offshore wind farm to participate in the direct marketing in accordance to § 33a EEG (Section 2.2.1) and contribute to the control energy market. For that purpose the offshore wind farm should be combined with a storage unit based on methane to build a virtual power plant. This should provide a clear schedule of the power feed-in to the transmission system operator. This means that the provision of energy should be maintained as good as possible over the time. Furthermore the virtual power plant should have sufficient reserves of available energy to position itself on the control energy market. First of all different concepts are explained in order to enable the participation of virtual power plant in the free energy market. Subsequently an expanded concept to participate in the control energy market is described.

4.1 Concepts for the participation in the free energy market

The main problem regarding the direct feeding of wind energy for the wind farm operators or rather the balancing group supervisor is the uncertainty of wind forecasts. These usually come from institutions or TSOs and are normally published at 8:00 AM for the entire day and are in 15 minutes interval starting at the hour [Tennet-ol, 2013]. This means that the forecasts are nearly two days old at the end of the day. With an almost one hundred percent accurate forecast, a one hundred percent of energy supply of wind farm would be economically ideal, however such forecasts are not as accurate as expected. By direct marketing of wind energy in the power system the TSOs try to correct the forecast error using control energy (Figure 20), in this case the wind farm operator or BGS has to pay the used control power. If the operator obtains the feed-in tariff then the TSO is obliged to pay by himself. This is because he must perform the balancing group to which the wind farm is attributed (Section 2.2.1 and Section 2.2.2).

As an approach to solve the problem of forecast uncertainties, a combination of wind farm with storage system based on methane (P2G) should be considered. This storage system consists of a methanation unit, a methane gas tank, and a gas power plant as (combined-cycle power plant (CCPP)) (Section 3.3.2). The basic idea of this combination is:

- at forecast uncertainties that lead to a surplus of energy, this will be converted to methane and stored in gas tank,or

- at forecast uncertainties that cause a deficit of energy, the stored methane can be converted back to electrical energy to balance this deficit

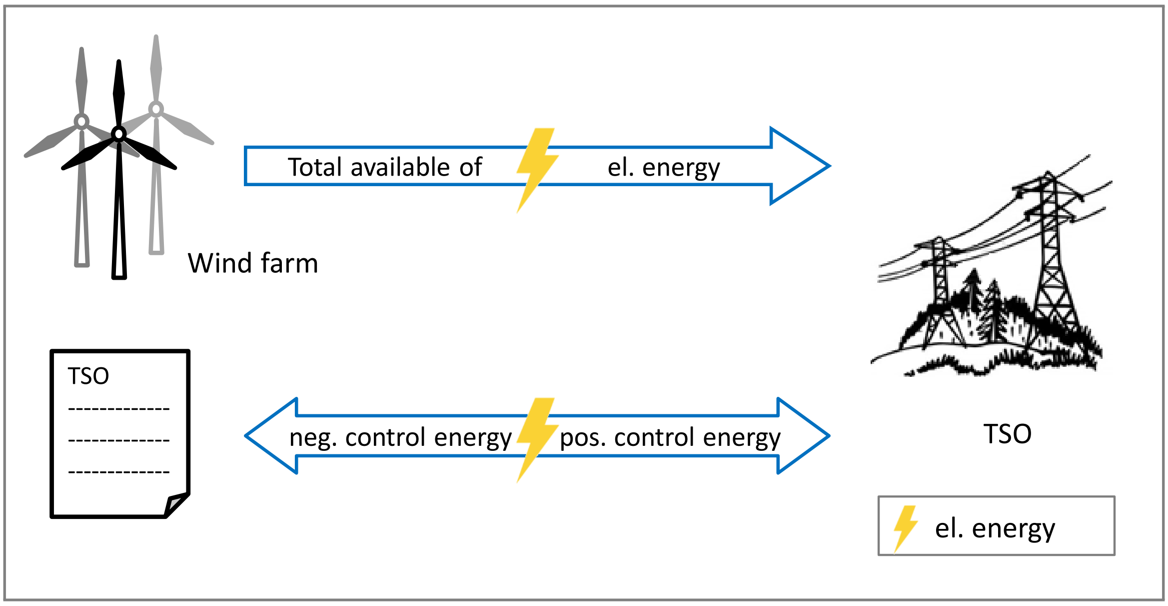

Figure 20: Direct marketing of wind energy: Balance of forecast errors by control energy or balancing energy

The pool of the wind farm and the storage unit is shown in Figure 21. The illustrated methanation plant receives its CO_2 not only from the ambient air, but also from other sources (Section 3.2). To guarantee a stable mode of operation of such virtual power plant, a possible use of the methanation plant and the CCPP is important at every time. That should not be restricted by the fill level limits of the methane tank. As a result this storage should never be filled completely otherwise the further excess of power cannot be achieved by the storage unit. Analog to this the methane storage unit should never be completely empty alternatively the deficit of power could not be balanced by the CCPP. The dimensioning of maximum power input $P_{M,max}$ of the methanation plant and the maximum power output $P_{G,max}$ of the CCPP plays an important role in the whole system. These should be determined by the difference between the forecast and the actual wind power of the wind farm. An over-sizing has to be prevented.

A power plant operating plan for this concept is shown in Figure 22. The Day-Ahead schedule with the required target Power $P_S^{Day-Ahead}$ for the Day n is based on the 8:00 AM forecasts of the day before (Day $n-1$) in which these forecasts have to be reduced a little bit in order to relieve the whole virtual power plant (VPP) and balancing the energy loss of conversion processes in the storage unit. The scheduled provided power by the VPP will be sold in One-hours-package on the Day-Ahead market.

The Intra-Day optimization allows the balancing group supervisor or wind farm operator to adjust the energy schedule up to 45 minutes before the next trading hour to reach the required

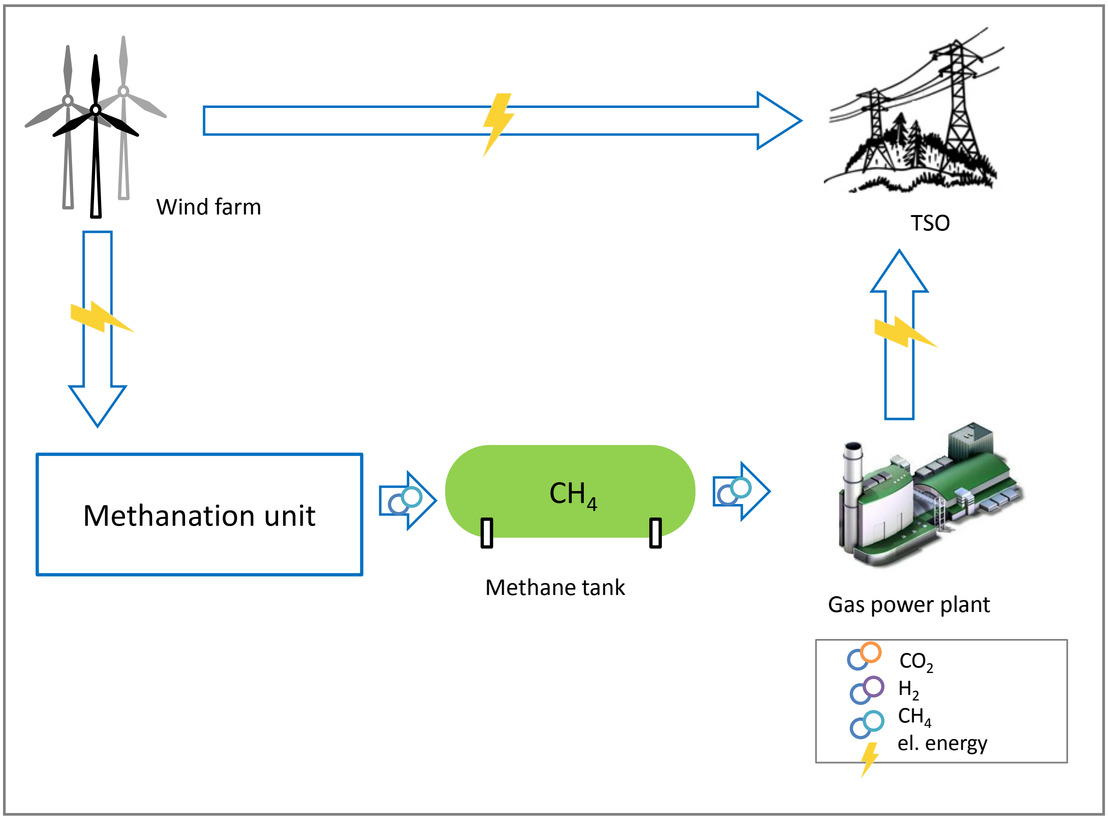

Figure 21: Pool of the wind farm and methane storage unit create a virtual power plant

balance between generated and consumed power of the balancing group (Section 2.2.3). This adjusted energy schedule with the required target power $P_S^{Intra-Day}$ is named Intra-Day schedule. In this concept $P_S^{Intra-Day}$ will be used to improve the wind forecasts, to optimize the filling level of the methane storage, and to balance a possible shut down of some or all wind turbines (or the emergency shutdown in case of a sudden heavy storm) [Bouyraaman et al., 2014] . The improved wind forecasts can be provided by the institutions themselves or taking from short-term previous values of the wind farm operation. The Intra-Day adjustments find their counterpart in the Intra-Day market (EPEX SPOT).

The target power value $P^i_{required}$ that is necessary for the virtual power plant operation, which is based to $P_S^{Day-Ahead}$ must be continuously passed on to the wind farm and the storage unit, whereas the storage unit has to react on the basis of power values of the wind farm. If the storage unit comes up to its maximum operation limit and therefore endanger the promised energy schedule, the balancing group must expect penalties for the use of balancing power by the TSO. The aim of this concept is to develop a stable operation for the virtual power plant which suspends such penalties and works as economically and ecologically as possible.

Theoretically it is not required that the wind farm and the storage unit belong to the same balancing group (but they must belong to the same control area). The delivered energy by the storage unit could also be seen as energy provision between the balancing groups. The short-

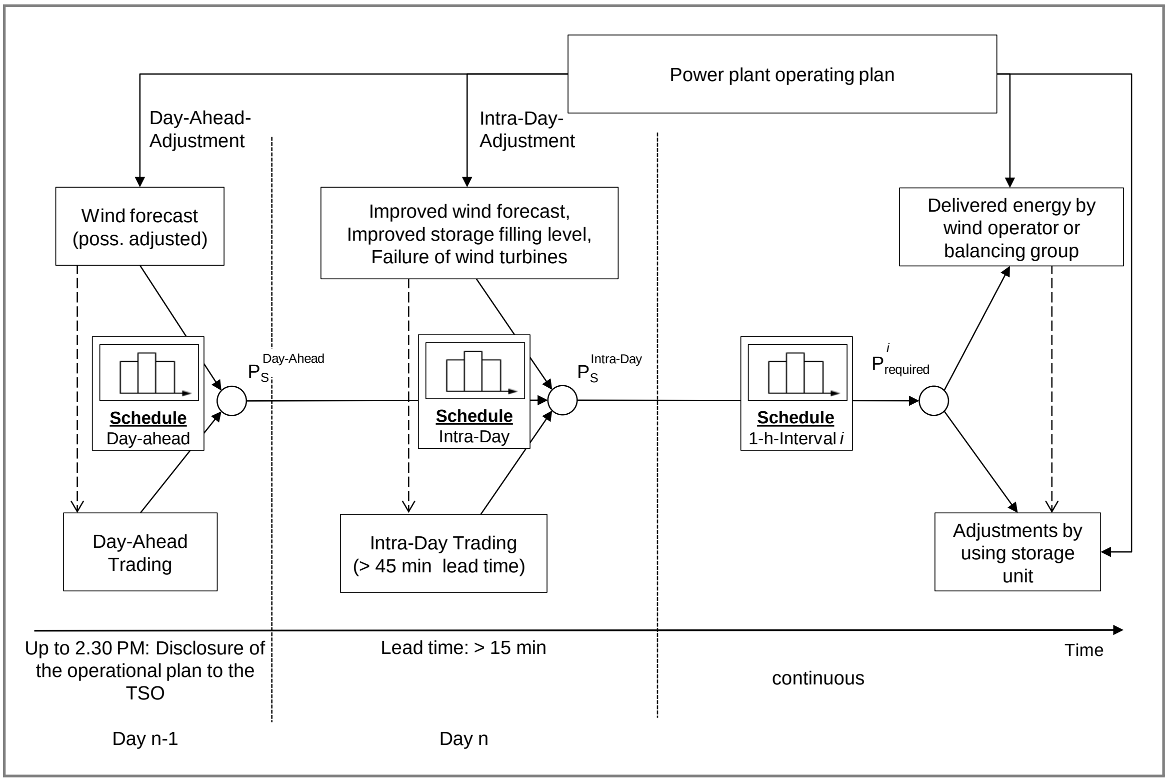

Figure 22: Schedule-based power plant operational plan of the virtual power plant concept for direct marketing of electrical energy. Adapted to [Weißbach, 2009]

term adjustments (refer to the 15 minutes adjustment period) are considered as (subsequent schedule changes of internal control area until 4:00 PM for the following working day). In the same way it would be conceivable that the methanation plant and the combined-cycle power plant must not be in the same balancing group, if the methane transport is fed into the gas network.

The following subsections explain three different construction concepts in reference to methane storage. Advantages and disadvantages of each construction concept should be clarified, as well as its influences on the power plant operation plan.

4.1.1 Stand-alone concept

The presented stand-alone concept claims to produce and use an equal amount of methane in the long run, and thus it can work only in combination with methane (CH_4) gas storage (Figure 23). In this concept, the different parts of the storage system, so the methanation unit, the methane gas tank, and the combined cycle power plant should be placed very near to each other.

The stand-alone concept must be used in case where there is no access to the public gas network, or it is very complicated to realize it.

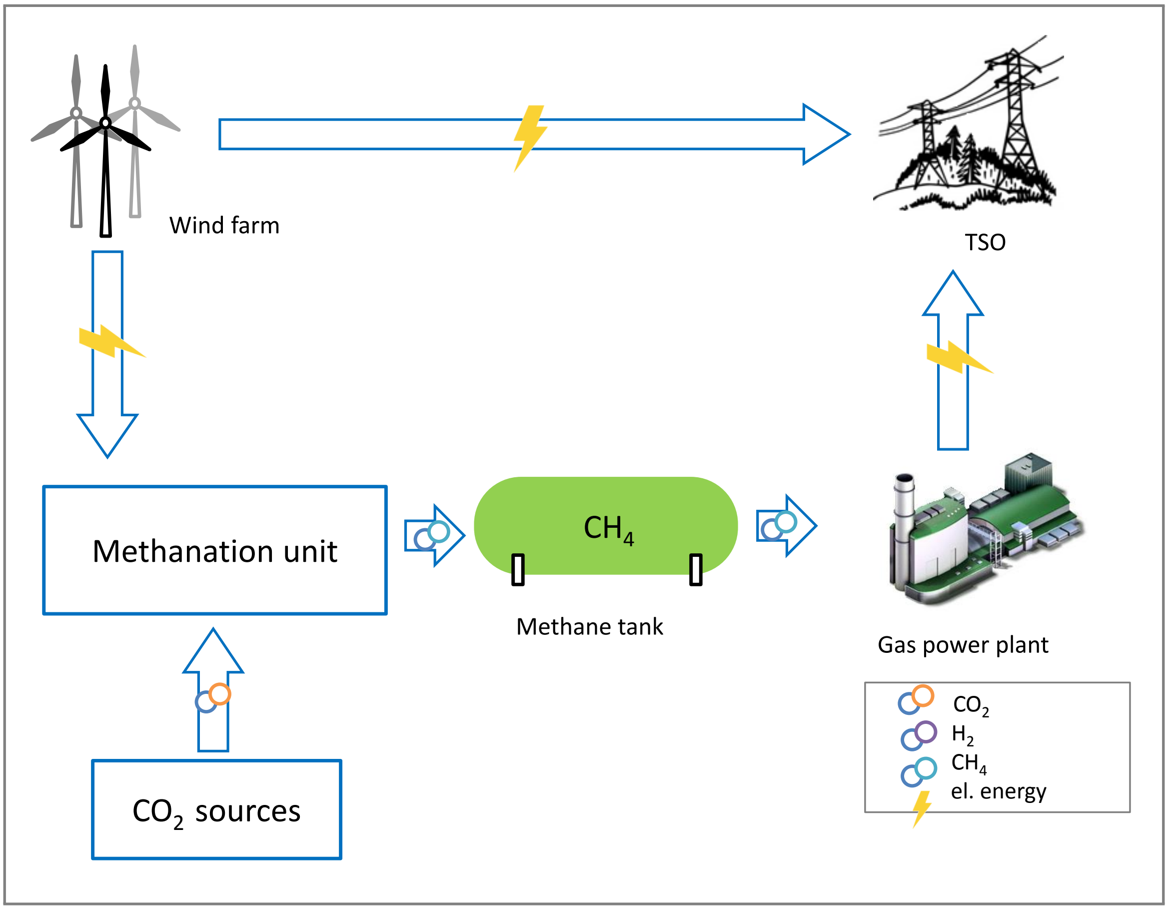

Figure 23: Stand-alone concept of the virtual power plant

Also in extreme situations, as for example, small isolated systems or general distribution of power to small districts; it should be considered if the system can be utilized to stabilize the network. The plant is used according to the forecast of the load. This is not relevant in Germany therefore it will not be discussed further. The dimensions of the storage unit and permanent observation of the level of methane in the storage tank are of supreme importance to the stand-alone concept.

4.1.2 Stand-alone concept with access to the gas network

The following is an extension to the basic stand-alone system. In this concept the stand-alone system also has access to the public gas network (Figure 24). The methane storage tank should always be used as the primary choice, but in exceptional cases the public network can be used. The physical proximity to the power generation facility must also be taken into account with this concept as the public gas network should not be seen as a transportation system, but instead as an unlimited methane tank in cases of an empty or full methane storage unit. In these cases, additional methane has to be bought or sold to keep the methane storage tank in the optimum level.

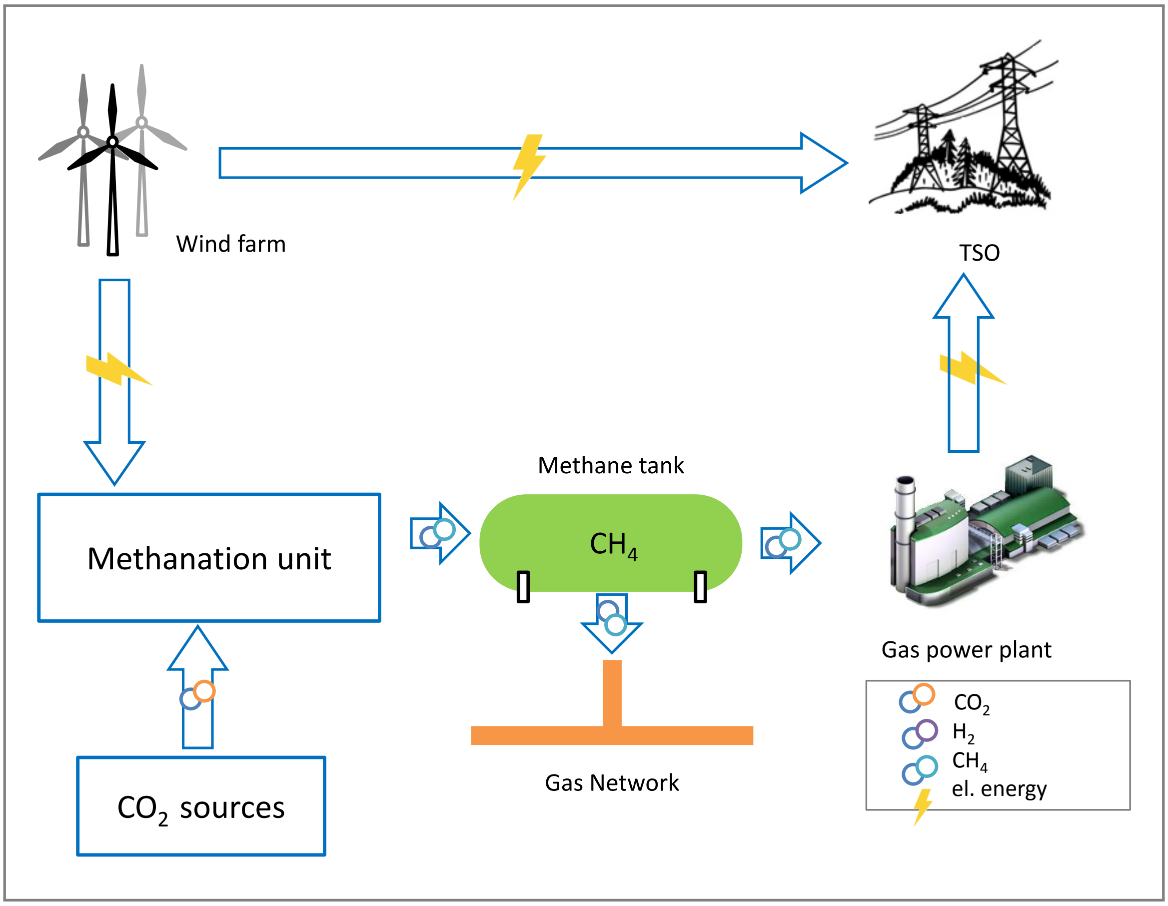

Figure 24: Stand-alone concept of VPP with access to the gas network

However there is one main problem with this concept that the access to the public gas network is required. A combination of the storage system with a biogas plant would solve the first problem, as biogas plants already have a connection to the public gas network. It should be made clear that the recovered power from the gas network should still be referred to as (renewable) power, otherwise the market value of this power would decrease. Advantage of this concept is the almost complete prevention of penalties by non-adherence to the energy schedule. Bottlenecks caused by the limitation of the size of the storage tank are also avoided with this concept, although bottlenecks caused by the limitation of the power input or output of the storage unit are still possible.

4.1.3 Concept for storage of methane directly in the gas network

The public gas network is well developed in Germany and as such it is conceivable to store the methane directly in the gas network (Figure 25). An advantage of this concept is the geographical proximity between the gas power plant and the methanation unit, so that we can profit from the existing gas power plant for the power reconversion. Furthermore, it is easier to achieve the stability of the whole system. An adjustment of the Intra-Day schedule regarding the filling level of the methane storage is not necessary, however the Intra-Day optimization for forecasting correction should be considered.

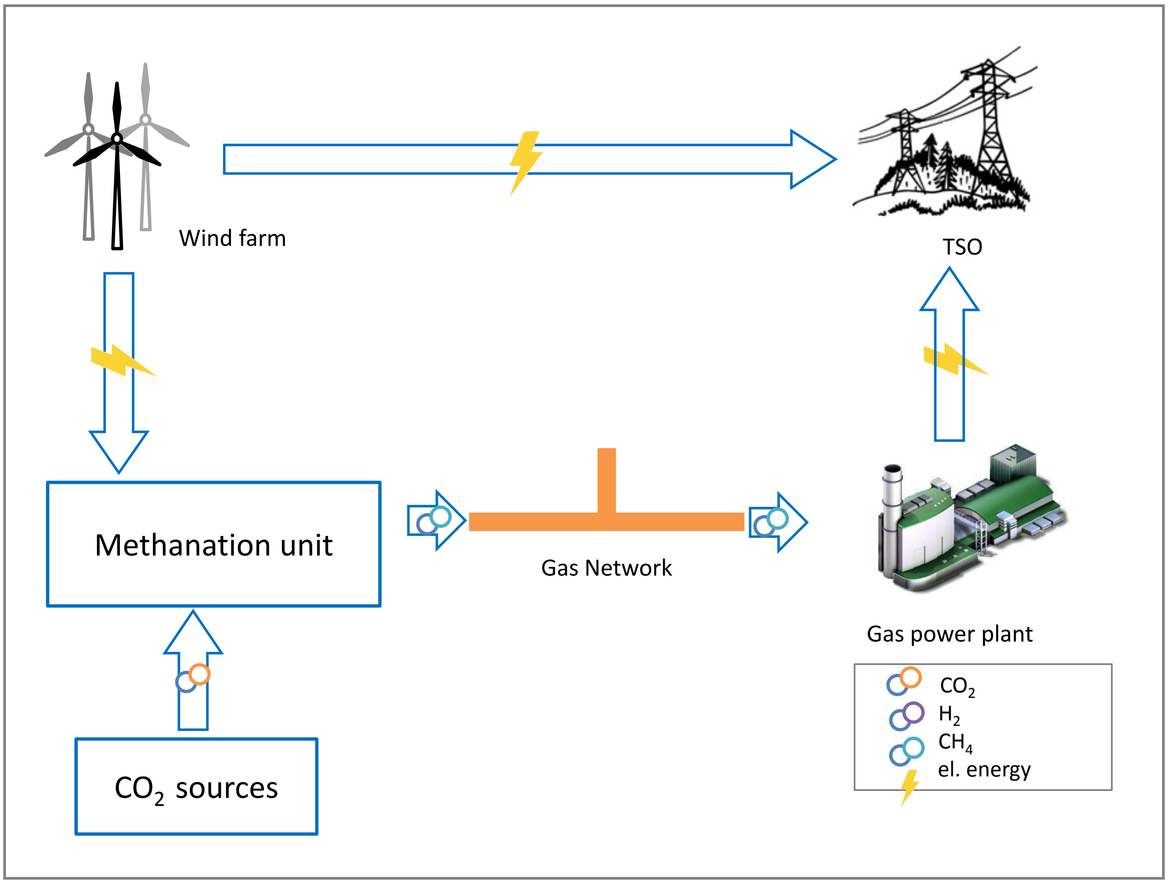

Figure 25: Concept for storage of methane directly in the gas network

There are two options for using the public gas network as a storage unit. On one hand, the input and output of methane from the gas network must be balanced. On the other hand, the whole virtual power plant can participate in the gas market in the same way it would participate in the energy market. In this case the storage unit would not be simply a storage unit, but would also use the variability of power and gas prices as an indicator to convert methane to power or power to methane depending on the current situation of the market.

4.2 Concepts for the participation in the control energy market

In order to participate with our virtual power plant in the control energy market, the stand-alone concept with access to the gas network will be suitable for this purpose (Section 4.1.2). The aim here is to find a possibility to participate in the control energy market, which requires no throttling or shutdown of wind turbines.

The power plant operating plan in Figure 22 is extended for the participation in the control energy market, as shown in Figure 26 . If the control power is required, the target value of the required power $P^i_{required}$ of VPP will change and will not match the Intra-Day energy schedule $P_S^{Intra-Day}$.

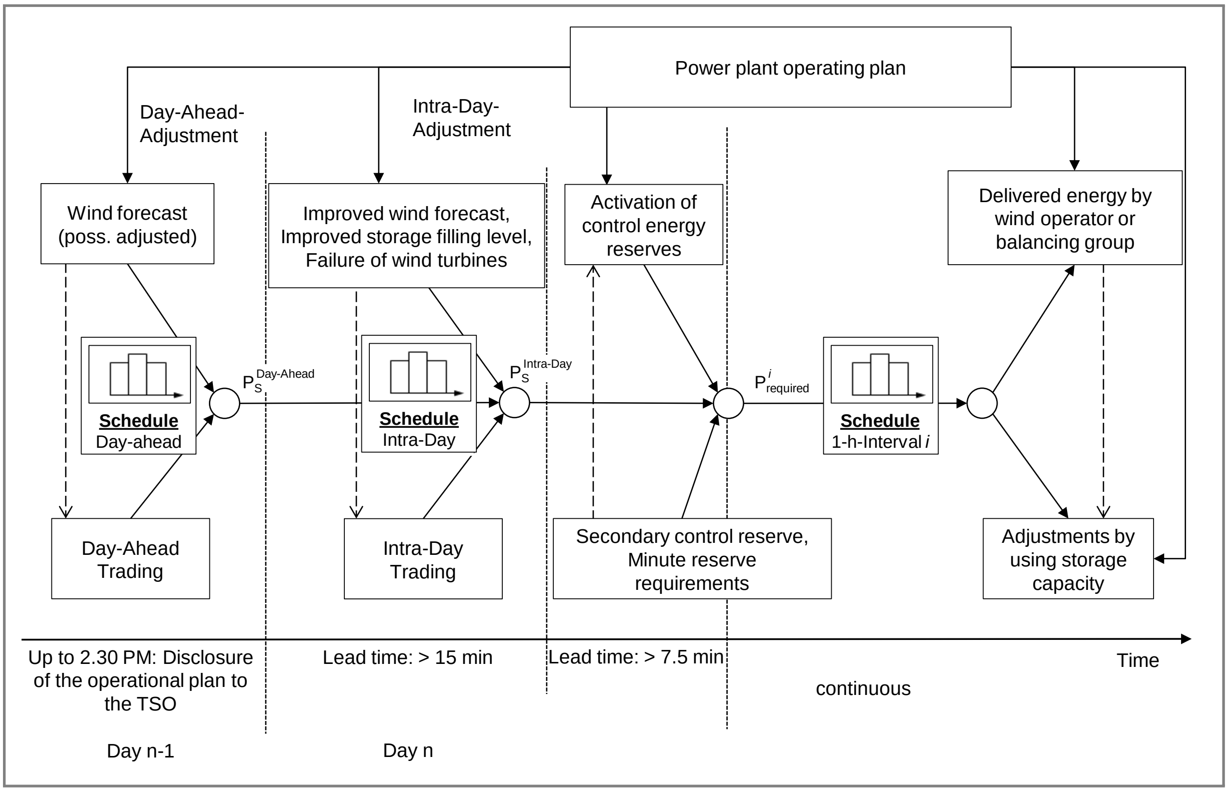

Figure 26: Schedule-based power plant operational plan of the virtual power plant concept for direct marketing and control energy market. Adapted to [Weißbach, 2009]

There are many different aspects to consider when choosing the type of control reserve. For instance, the provision time until the full power and the submission of the tender are very important (Section 2.2.2.1). Due to the long ramp-up time required by the methanation unit and gas power plant, the primary control reserve has to be excluded. In order to enable participation in the energy market, reserves have to be determined or kept free. This relates to the methane tank, and the maximum power input $P_{M,max}$ and the maximum power output $P_{G,max}$ storage unit.

In the previous concept, it was necessary to compensate the difference between the forecast and the actual wind power, so to check whether additional volume is required in the storage unit to allow for participation in the control energy market. However, the connection between the storage unit and the public gas network solves this problem. The variations in the level of the methane tank caused by over production or over consumption of methane will be balanced by the Intra-Day adjustment (Section 4.1).

To create reserves for the control energy market, two options are available. On one hand, larger power input of the methanation unit and power output of the gas power plant could be chosen, than necessary for the forecast error adjustment. However, this would require a large investment. On the other hand, an intelligent use of the already existing reserves. The basic idea is, according to Day-Ahead schedules, capacities of the storage unit that are not required to compensate the forecast error for certain time periods can be determined. These capacities can be offered in the control energy market. This concept will be described later.

Since the wind forecasts are released one day ahead at 8 AM, a submission of the control energy can be made later than this. This is just for the case of the minute reserve which can be submitted by 11 AM of the day before. The relatively short time periods for the minute reserves, a period of only 4 hours, help to simplify the participation of the virtual power plant in the control energy market. Since changes in the wind forecasts are not very dramatic over just 4 hours and so, it is easy to determine the free capacities for the control energy market. The minimum bid for SCR and MR is + 5 MW or - 5 MW and the submission increment is 1 MW (Section 2.2.2.1).

Figure 27 shows how much positive or negative energy the storage unit can provide at any time when the operating point of the storage unit is known. This is based on a continuous power spectrum for the storage unit. The purpose of the storage unit is primary to compensate not predictable forecast errors in a short period of time. This means that the operating point cannot be known before the actual moment of operation and thus cannot be used to determine the provided control power.

It is possible to catch extreme positive differences between the forecast and the actual wind power by calculating the maximum power that can be absorbed by the methanation unit $P_{M,pot}^{max}(t)$ at the time t. This can be determined on the basis of required power $P_{required}^{i}(t)$ of the VPP at the time t according to the Day-Ahead schedule $P_S^{Day-Ahead}(t)$. Analogous, the maximum power output $P_{G,pot}^{max}(t)$ of CCPP at the time t is determined, this is necessary to dump extreme negative differences between forecast and actual wind power. From these values a possible working range of the storage unit at the time t can be determined (Figure 28).

$P_{G,pot}^{max}(t)$ sees itself as a power reserve of the storage unit for the extreme case, when no power is produced by the wind farm, due to a windless period or a technical defect. In this case the required power (when no power is produced by wind farm) should be produced by the gas power plant. The following applies to:

$$P_{G,pot}^{max}(t) = P_S^{Day-Ahead}(t) \tag{4.1}$$

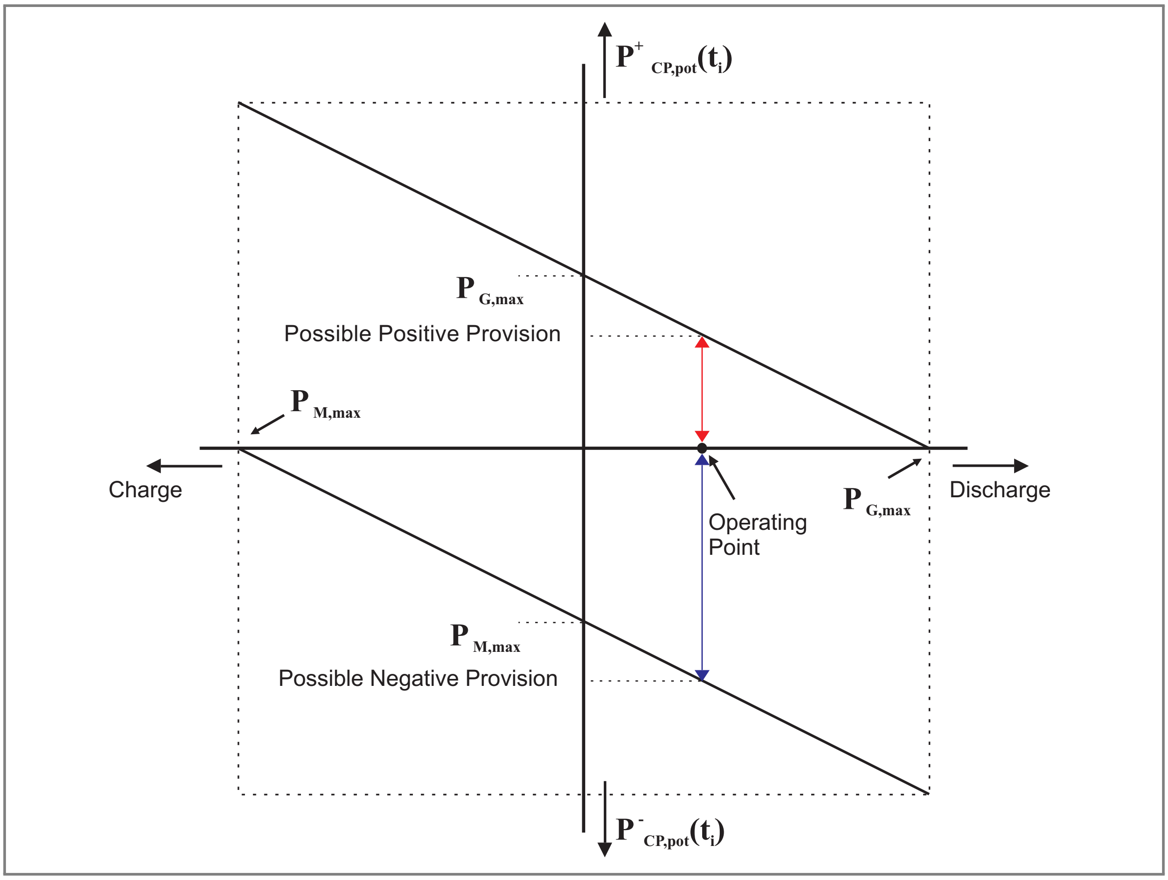

Figure 27: Possible control power provision of the storage unit with defined working point. Based on [Wulff, 2006]

If the wind farm unexpectedly reaches maximum power $P_{W,max}$, then $P^{max}_{M,pot}(t)$ is the necessary capacity in the storage unit to absorb the surplus completely. The methanation unit transforms the excess power into methane. $P^{max}_{M,pot}$ is the absorbed power of the storage unit, therefore it is always defined to be negative ($P^{max}_{M,pot} \leq 0$). The following applies to:

$$P^{max}_{M,pot}(t) = P^{Day-Ahead}_{S}(t) - P_{W,max} \tag{4.2}$$

$P_{G,max}$ and $P_{M,max}$ are not selected to replace completely the wind farm, they are only selected in order to compensate forecast uncertainties and as such they are chosen to be small. Extreme deviations of the forecast cannot be compensated fully with the storage unit, due to the lack of power capacity ($P_{G,max} < P^{max}_{G,pot}(t)$ or $|P_{M,max}| < |P^{max}_{M,pot}(t)|$) caused by deviations. However, extreme cases can normally be predicted in advance, so the Intra-Day optimization can be used to compensate. As a result, the possible working range of the storage unit from figure 28 would shift to the right or left edge of the figure and consequently only capacities of control power in the positive or negative directions exist.

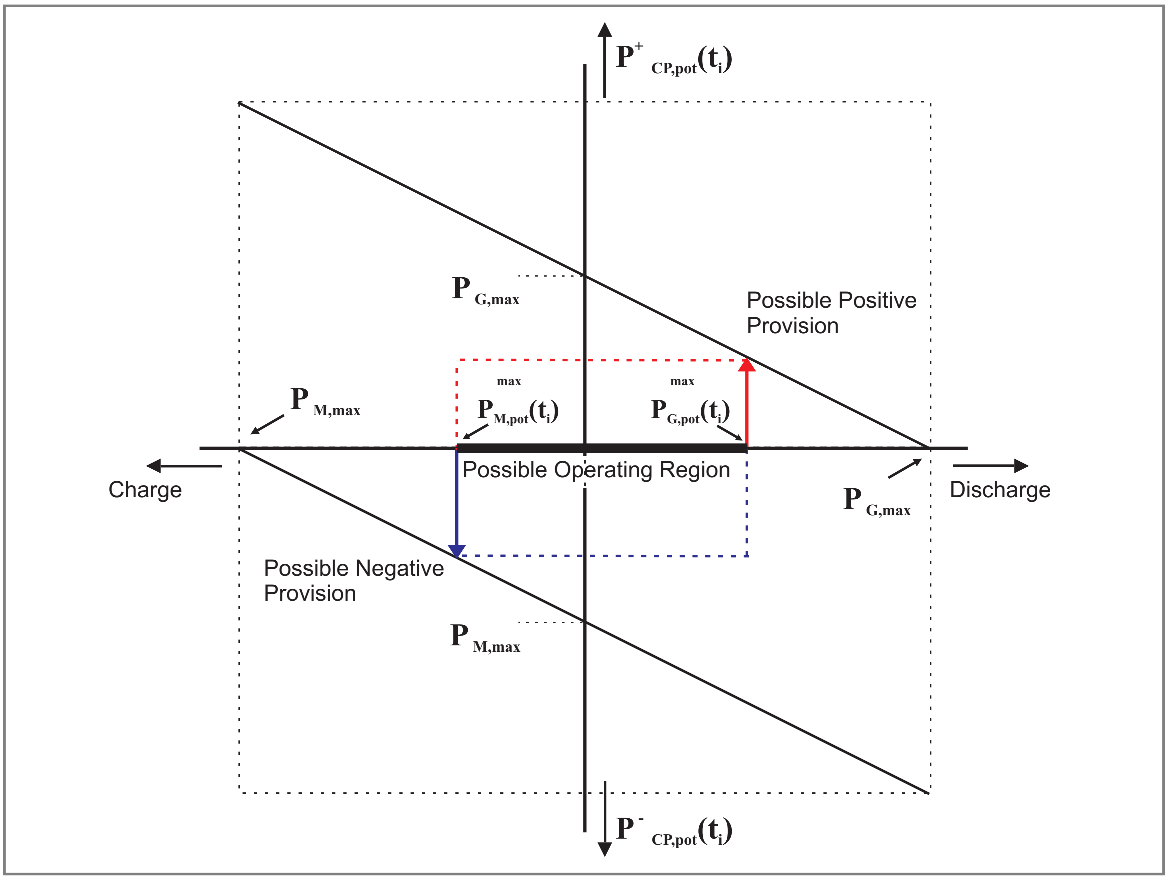

Figure 28: Possible control power provision of the storage unit with undefined working point

The maximum available power capacities for positive control power $P^+_{CP,pot}(t)$ and negative control power $P^-_{CP,pot}(t)$ shall be calculated as follows. $P_{M,max}$ and $P^-_{CP,pot}(t)$ are defined negative again ($P_{M,max} \leq 0$ and $P^-_{CP,pot}(t) \leq 0$) :

$$P^+_{CP,pot}(t) = P_{G,max} - P^{max}_{G,pot}(t) \tag{4.3}$$

$$P^-_{CP,pot}(t) = P_{M,max} - P^{max}_{M,pot}(t) \tag{4.4}$$

Figure 29 shows an example for the case of low forecasted wind and thus low power values in $P_S^{Day-Ahead}(t)$ and $P_{W,max} = P_{G,max} = -P_{M,max}$. This implies a large potential for positive control power and a small potential for negative control power. Figure 30 shows analogous to the case of a high forecasted wind and thus large power values in the $P_S^{Day-Ahead}(t)$ and also for $P_{W,max} = P_{G,max} = -P_{M,max}$. A large potential for negative control power and a small one for positive control power can be identified.

Figure 31 and Figure 32 show simulations for $P_{G,max} < P_{W,max}$ and $|P_{M,max}| < P_{W,max}$, which are the cases of more and less forecasted wind and how they affect the potential for the control power. The control power is reduced remarkably and in the shown cases only either positive or negative control power is possible.

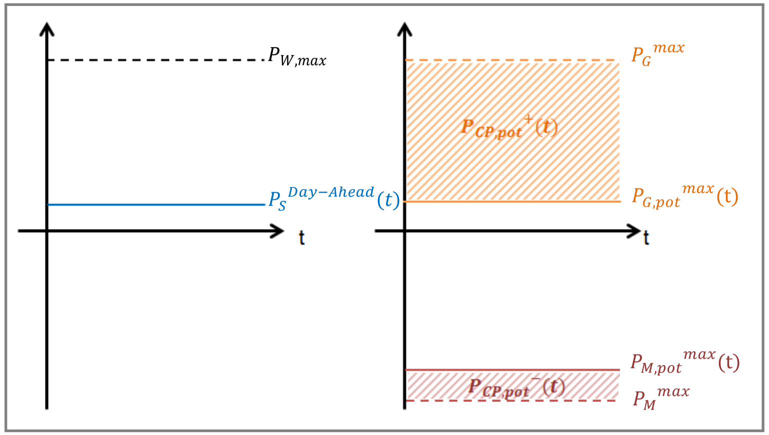

Figure 29: Power reserves at low forecasted wind energy and $P_{W,max} = P_{G,max} = -P_{M,max}$

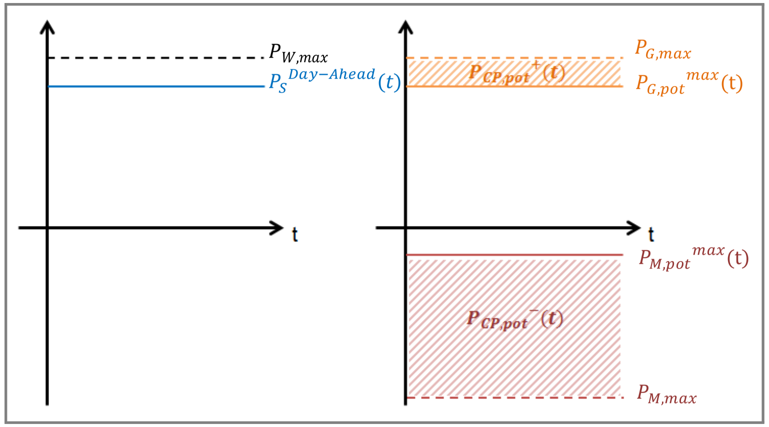

Figure 30: Power reserves at high forecasted wind energy and $P_{W,max} = P_{G,max} = -P_{M,max}$

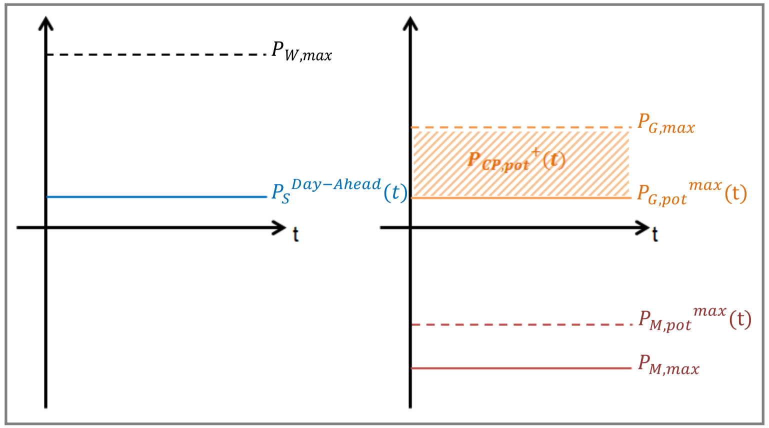

Figure 31: Power reserves at low forecasted wind energy and $P_{W,max} > P_{G,max}$, $P_{W,max} >= -P_{M,max}$

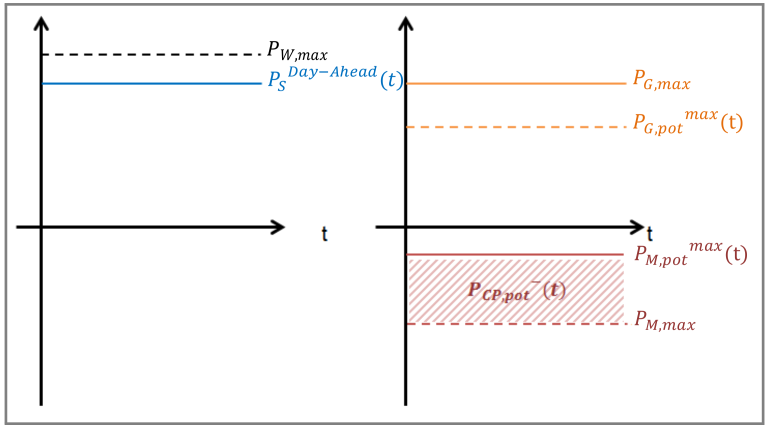

Figure 32: Power reserves at high forecasted wind energy and $P_{W,max} > P_{G,max}$, $P_{W,max} >= -P_{M,max}$

Control power provision should be kept in a time window of four hours with constant power value. As a consequence, the actual positive $P^+_{CP,PR}(t)$ or negative $P^-_{CP,PR}(t)$ control power that is kept in reserve has to stay constant within the four hours. $P^-_{CP,PR}(t)$ is defined to be negative ($P^-_{CP,PR}(t) \leq 0$).

For the positive control power the maximum value is the smallest amount of $P^+_{CP,PR}(t)$ within the time window. For the negative control power the maximum value is the smallest amount of $P^-_{CP,PR}(t)$ within the time window. The following applies under the condition that is the time span of the time window in which t appears $T_{ZS}(t)$:

$$P^+_{CP,PR}(t) = 5\ MW + a \cdot 1\ MW\ or\ P^+_{CP,PR}(t) = 0 \qquad with\ a \in \mathbb{N}_0 \tag{4.5}$$

$$P^-_{CP,PR}(t) = -5\ MW - b \cdot 1\ MW\ or\ P^-_{CP,PR}(t) = 0 \qquad with\ b \in \mathbb{N}_0 \tag{4.6}$$

$$5MW \leq P^+_{CP,PR}(t) \leq min\{P^+_{CP,pot}(T_{ZS}(t))\}\ or\ P^+_{CP,PR}(t) = 0 \tag{4.7}$$

$$-5MW \geq P^-_{CP,PR}(t) \geq max\{P^-_{CP,pot}(T_{ZS}(t))\}\ or\ P^-_{CP,PR}(t) = 0 \tag{4.8}$$

Where a is an increment for positive control power and b is an increment for negative control power.

Figure 33 shows examples of $P^+_{CP,PR}(t)$ and $P^-_{CP,PR}(t)$ as functions of $P^+_{CP,pot}(t)$ and $P^-_{CP,pot}(t)$.

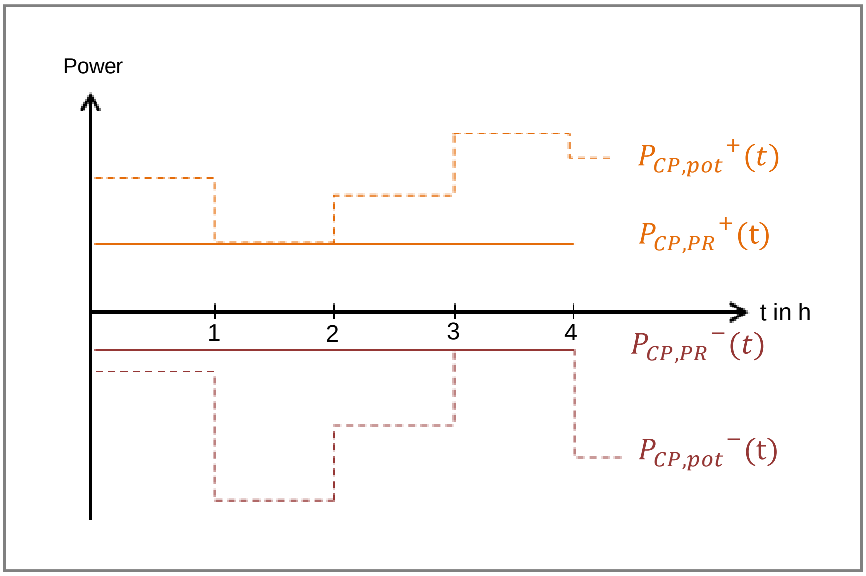

Figure 33: Exemplary presentation to select the positive provided control power $P^+_{CP,PR}(t)$ and negative provided control power $P^-_{CP,PR}(t)$ as a function of the maximum available power capacity for positive provided control power $P^+_{CP,pot}(t)$ and negative provided control power $P^-_{CP,pot}(t)$

It is appropriate that the limitation of the provided control power should be based on the control energy market. A closer check of submitting tender at the control energy market for minute reserves for example shows that the majority of the offers remain under 20 MW, however some sporadic offers are up to 60 MW and above [RL-ol, 2013]. Therefore, the following applies to $P^{+}_{CP,PR}(t)$ and $P^{-}_{CP,PR}(t)$ as well as the maximum positive control power $P^{+}_{CP,max}$ and the maximum negative control power $P^{-}_{CP,max}$:

$$P^{+}_{CP,PR}(t) \leq P^{+}_{CP,max} \tag{4.9}$$

$$P^{-}_{CP,PR}(t) \geq P^{-}_{CP,max} \tag{4.10}$$

In order to select the correct volume of storage for the reserve control power, it should be selected in such a way that the minute reserve can be provided until the end of the time window. In cases where the storage volume is insufficient for the control power, there is the possibility to fall back to the public gas network. The called control reserve of SCR occurs very often, however the called control reserve of minute reserve does not occur often and does not last very long. Therefore the participation in the control energy market with provision of SCR (positive and negative control power) will be more worthwhile than MR.

4.3 Summary of the concept

The target of the virtual power plant, consisting of an offshore wind farm and a methane based storage unit, is to participate in the free energy market and the control energy market in Germany. The storage unit consist of a methanation unit, a methane gas tank and a combined cycle power plant. The required CO_2 can be extracted from the ambient air. The assumed efficiency factors of the methanation unit and the CCPP are both 60% (cp. Section 3.1 and Section 3.3).

The stand-alone concept is used with access to the public gas network (Figure 24). The gas network should only be used when the methane storage tank is reaching its limits. The virtual power plant is seen as an independent balancing group, in which the operator of the VPP should be the same legal person who is responsible for the balancing group.

The power plant operation depends on a Day-Ahead and Intra-Day schedule as well as the provision of the positive and negative control power as SCR and MR. The Day-Ahead schedule is determined by the 8 AM wind forecast of the previous day. Based on the free power capacities of the storage unit and according to the Day-Ahead schedule the participation in the control energy market is determined. The output produced in compliance with the Day-Ahead schedule will be sold at the EEX-Day-Ahead market. The adjustment of the Intra-Day schedule offers the possibility to correct the forecast error and optimize the filling level of the storage unit without endangering the storage reserve for the control power. For this purpose energy can be sold or bought at the EPEX-Intra-Day market.

In order to optimize the size of the power plant, the empirical values of forecasts and actual power of the wind farm should be used. The volume of the methane storage unit on one hand should serve to compensate forecast errors and on the other hand to provide adequate reserves for the provision of control power.

To participate in the control energy market, no additional power capacity of the storage unit should be kept free for participating in free energy market. Only free capacities in the storage unit resulting from the Day-Ahead schedule can be used.

5 Simulation of the virtual power plant to participate in the free energy market

In this chapter, a simulation of the temporal sequences of the energy flows in the virtual power plant concept from the Section 4.3 is developed without consideration of participation in the control energy market. The simulation basis is a record over several months from forecast $P_{W,prog}(t_i)$ and actual wind power output $P_{W,real}(t_i)$ of the offshore wind farm. The data set is presented only in relation to the attainable maximum power of the wind farm $P_{W,max}$. The data are available as averaged values collected at one-hour interval. In the first step the given data were analyzed. The analysis was carried out to determine the optimum parameters for the storage unit. Then various optimization steps were integrated and evaluated according to the considerations in the Section 4.1. The optimization phase serves to minimize the necessary control power and energy losses caused by the conversion processes within the storage unit.

5.1 Determination of storage unit parameters for the simulation

In this section, the storage unit parameters which are the power input, power output, and the storage capacity will be determined. In addition two important factors will be introduced for evaluating the simulation.

5.1.1 Analysis of the Data set

The record used in this thesis consists of the forecasted power $P_{W,prog}(t_i)$ and the actual power $P_{W,real}(t_i)$ of the wind farm at one-hour intervals. An exact analysis of the forecast errors is required to determine the optimum dimensioning of the storage unit. For this reason, the difference $\Delta P_W(t)$ between the forecasted power $P_{W,prog}(t_i)$ and the actual power $P_{W,real}(t_i)$ will initially be determined for every time interval t_i. After that the resulting energy difference $\Delta E_W(t_i)$ will be computed within the time interval t_i.

$$\Delta P_W(t_i) = P_{W,real}(t_i) - P_{W,prog}(t_i) \tag{5.1}$$

$$\Delta E_W(t_i) = \Delta P_W(t_i) \cdot t_{int} \tag{5.2}$$

$$t_i = i \cdot t_{int} \tag{5.3}$$

$P_{W,real}(t_i)$	Real power of the wind farm in MW in t_i
$P_{W,prog}(t_i)$	Forecasted power of the wind farm in MW in t_i
$\Delta P_W(t_i)$	Difference between the forecasted and real power of the wind farm in MW in t_i
$\Delta E_W(t_i)$	Difference between the forecasted and real energy of the wind farm in MWh in t_i
t_i	Calculation interval
t_{int}	Duration of the calculation interval (here: 1h)
i	Calculation step

Two cases are distinguished here:

- The wind farm attains an output exceeding the forecast:
  $P_{W,real}(t_i) > P_{W,prog}(t_i)$ bzw. $\Delta P_W(t_i) > 0$.
  In this case any excessive energy $\Delta E_W(t_i)$ will be fed into the methane gas storage, and losses due to methanation should be taken into account.
- The output attained by the wind farm is below the forecast:
  $P_{W,real}(t_i) < P_{W,prog}(t_i)$ bzw. $\Delta P_W(t_i) < 0$.
  In this case the energy required $\Delta E_W(t_i)(< 0)$ can be re-converted from the methane storage to attain the required power level. Here, too, the losses due to re-conversion should be taken into account.

Figure 34 shows a typical extract from a data set for a representative week.

An analysis of the frequency distribution of $\Delta P_W(t_i)$ gives indications of the quality of the forecasted values. Figure 35 clearly shows that underestimation of the wind power dominate in the available data set. The expected value $\mu_{\Delta P_W} = 0.03 \cdot P_{W,max}$ is positive whereas, the the standard deviation $\sigma_{\Delta P_W}$ equals (0.16 $\cdot$ $P_{W,max}$). The most extreme deviations between the forecast and the actual wind power are (0.83 $\cdot$ $P_{W,max}$) for positive deviations and (0.98 $\cdot$ $P_{W,max}$) for negative deviations.

The difference of the energy quantity $\Delta E_W(t_i)$ of several simulation periods is analyzed in which, an overestimation or an underestimation of the wind power is presented. The $\Delta E_{W,Area}(t_k)$ is calculated for a period $T_k(t_i)$ until a change of sign takes place at $\Delta P_W(t_i)$ (Figure 36):

$$\Delta E_{W,area}(T_k(t_i)) = \sum_{t_i \in T_k(t_i)} |\Delta P_W(t_i)| \cdot t_{int} \tag{5.4}$$

The values used in this thesis result in expected values for the differential output $\mu_{\Delta E_{W,Area}} = 0.84 \cdot P_{W,max} \cdot 1h$ and the standard deviation $\sigma_{\Delta E_{W,Area}} = 1.79 \cdot P_{W,max} \cdot 1h$.

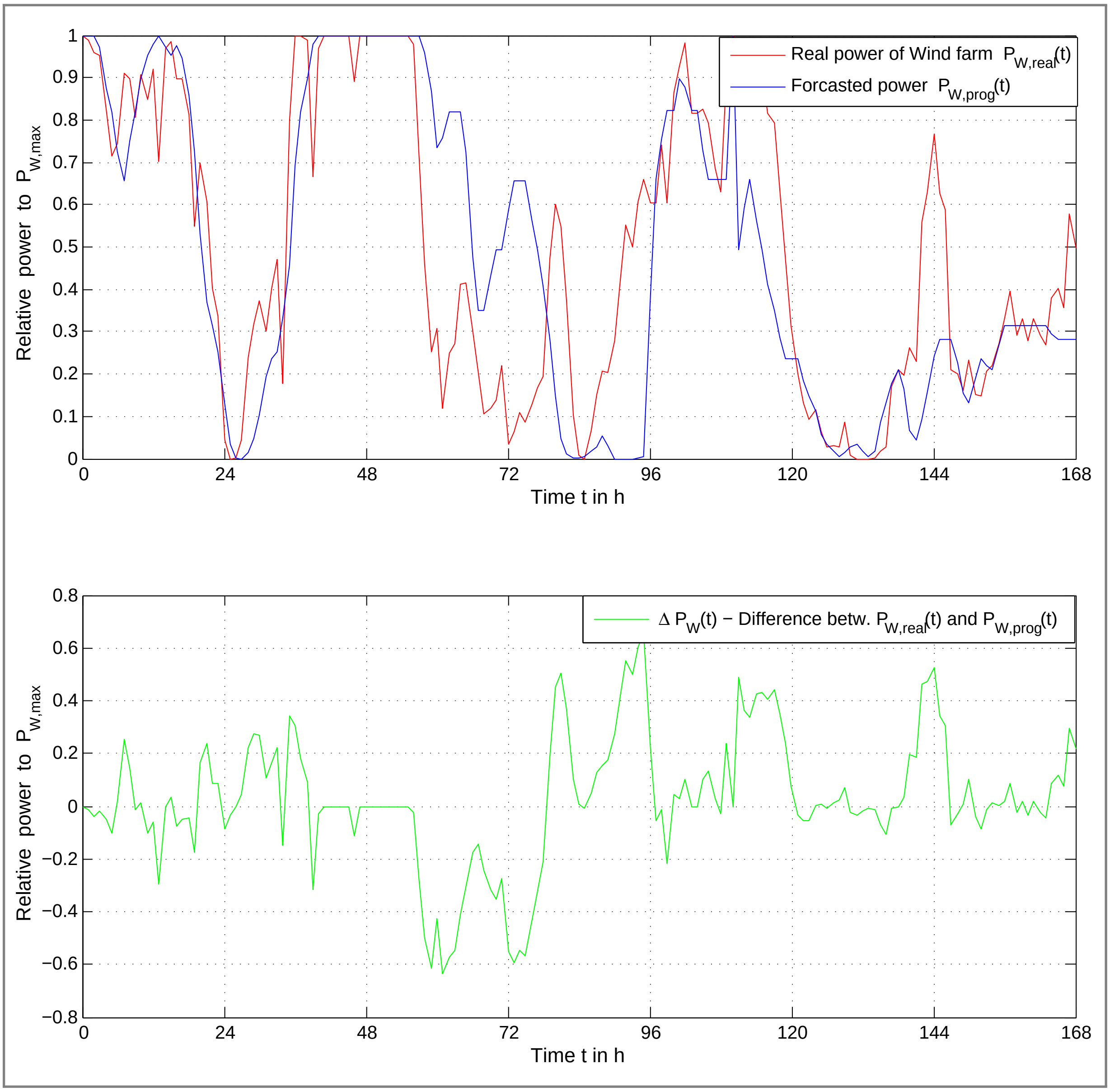

Figure 34: Extract from the data set for a representative week of the forecasted and the real power of wind farm as well as the $\Delta P_W(t_i)$

Finally we will shortly discuss the lengths and the corresponding frequency distribution of the periods T_k. Figure 37 clearly indicating that the periods of over-estimation or under-estimation of the power values are very short in most cases.

5.1.2 Dimensioning of the storage unit

This section introduces a statistical method for determining the optimum power input and power output of the storage unit based on the analysis results of the data set. Such power values will be exclusively selected for compensating the forecast errors caused by the storage unit.

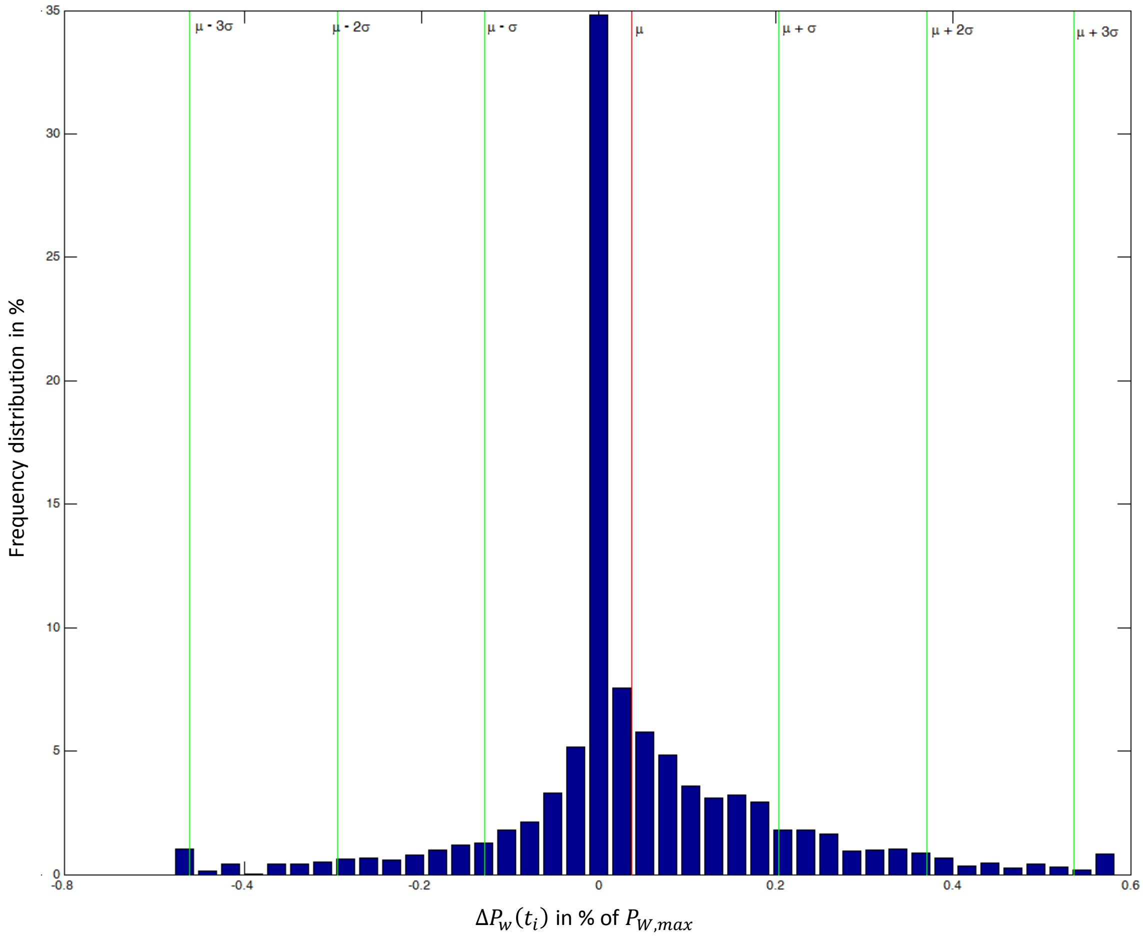

Figure 35: Frequency distribution of $\Delta P_W(t_i)$

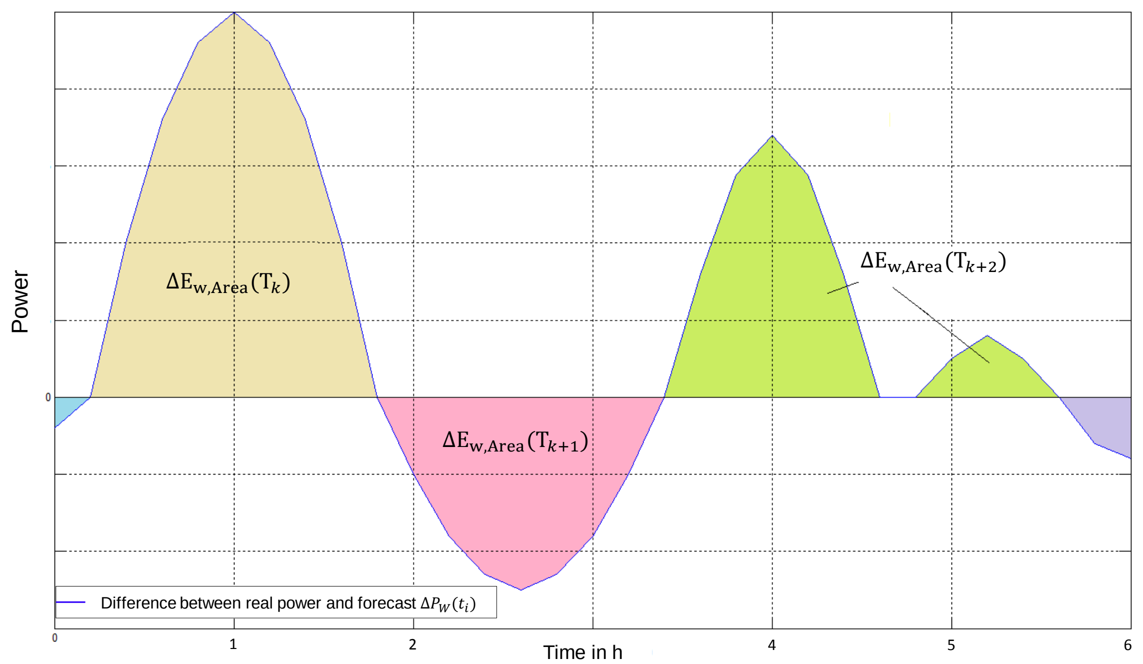

Figure 36: Exemplary representation for the determination of $\Delta E_{W,Area}(T_k)$

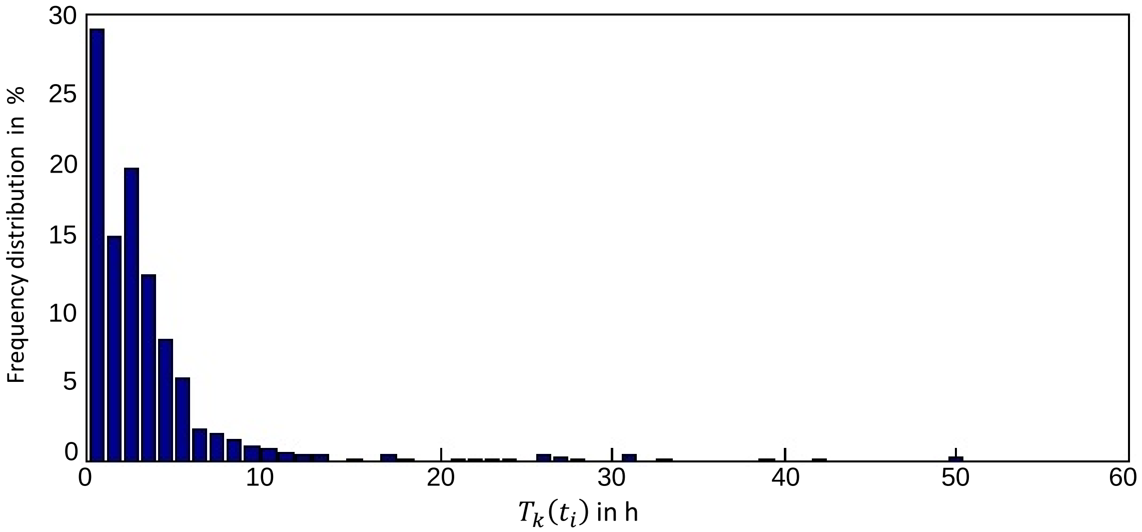

Figure 37: Frequency distribution of the lengths of $T_k(t_i)$

5.1.2.1 Power input and power output of the storage unit

The maximum power input of the storage unit corresponds to the maximum power input of the methanation unit $P_{M,max}$ and the maximum power output of the storage unit equals the maximum power output of the gas power plant $P_{G,max}$. These values should be selected so that a large proportion of the forecast errors can be adjusted without over-dimensioning of the storage unit. With the following formulas:

$$P_{M,max} = -max\{|\mu_{\Delta P_W} + 3\sigma_{\Delta P_W}|, |\mu_{\Delta P_W} - 3\sigma_{\Delta P_W}|\} \tag{5.5}$$

$$P_{G,max} = min\{|\mu_{\Delta P_W} + 3\sigma_{\Delta P_W}|, |\mu_{\Delta P_W} - 3\sigma_{\Delta P_W}|\} \tag{5.6}$$

99.73% of the cases can be used to offset the differences between the forecast and the actual wind power with a normal distribution of the values. With the application of the formulas 5.5 and 5.6 to the data set used, the optimum power input of $P_{M,max} = -0.53 \cdot P_{W,max}$ and optimum power output of $P_{G,max} = 0.46 \cdot P_{W,max}$ of the storage unit are determined.

5.1.2.2 Energy storage capacity of the storage unit

Calculation of the ideal maximum energy consumption $E_{S,max}$ of the storage unit is similar to the calculation of the ideal power input and power output described in Section 5.1.2.1 however, in this case only the energy difference $\Delta E_W(t_i)$ is used. The formula

$$E_{S,max} = max\{|\mu_{\Delta E_{W,Area}} + 3\sigma_{\Delta E_{W,Area}}|, |\mu_{\Delta E_{W,Area}} - 3\sigma_{\Delta E_{W,Area}}|\} \tag{5.7}$$

results in an optimal value of the energy storage capacity $E_{S,max} = 6.20 \cdot P_{W,max} \cdot 1h$ of the storage unit.

5.1.3 Evaluation of the control energy saving factor and the energy loss factor

To assess the quality of the virtual power plant optimization used, the so called control energy saving factor S and energy loss factor V are introduced which are related to the reduction of the economic damage in the concept.

5.1.3.1 Evaluation of the control energy saving factor

We suggest an evaluation of the control energy saving effect of the storage unit to assess the actual saving potential of the methane storage. A control energy saving factor S is calculated during a simulation of the virtual power plant over the time needed to charge and discharge the methane storage. In this case the energy saving factor S is based on the following formula:

$$S = \frac{Need\ to\ control\ energy\ (without\ Storage - with\ Storage)}{Need\ to\ Control\ energy\ (without\ Storage)}$$

$$S = \frac{\sum |\Delta E_W(t_i)| - \sum |E_{CP}^{required}(t_i)|}{\sum |\Delta E_W(t_i)|} \tag{5.8}$$

$$S = 1 - \frac{\sum |E_{CP}^{required}(t_i)|}{\sum |\Delta P_W(t_i) \cdot t_{int}|},$$

where $E_{CP}^{required}$ represents the required control energy despite the use of the storage unit. The control energy saving factor S here is between 0 and 1 (or between 0% and 100%). If no storage is used for the wind farm, $E_{CP}^{required}(t_i) = \Delta E_W(t_i)$ applies to all t_i that means the control energy saving factor $S = 0\%$. The aim is to achieve the maximum values possible for the control energy saving factor S, i.e. to get as close to 100% as possible.

5.1.3.2 Evaluation of the energy loss factor

The losses caused by the conversion of electrical energy into methane and vice versa result a lower energy provision to the power grid than to the direct energy feed-in due to the use of the storage unit. When assessing an optimization concept, loss factor V should also be taken into account. For this purpose the energy loss factor V indicating the deviation of the actual energy amount feed-in to the grid from the actual energy amount generated by the wind farm. This factor is calculated as follows:

$$V = 1 - \frac{Total\ energy\ feed-in\ of\ virtual\ power\ plant}{Total\ energy\ generated\ by\ wind\ farm}$$
$$V = 1 - \frac{\sum(P_S^{Intra-Day}(t_i) \cdot t_{int} - E_{CP}^{required}(t_i))}{\sum P_{W,real}(t_i) \cdot t_{int}} \tag{5.9}$$

If the storage unit is not used, the factor $V = 0\%$. The aim is to achieve the lowest possible percentage of V.

5.2 Simulation without Intra-Day adjustment

Firstly, a simplified simulation of the concept described in section 4.3 is carried out without Intra-Day adjustment and without access to the public gas distribution network. The Day-Ahead schedule in this case corresponds to the forecast of the wind farm:

$$P_S^{Day-Ahead}(t_i) = P_{W,prog}(t_i) \tag{5.10}$$

Figure 38 shows a schematic representation of the simulation sequence. With every simulation step, the difference $\Delta P_{W,S}(t_i)$ between forecasted and actual wind power is calculated for the current time interval t_i which possible to be stored or produced completely by the storage unit.

$$\Delta P_{W,S}(t_i) = P_{W,real}(t_i) - P_S^{Day-Ahead}(t_i) \tag{5.11}$$

Taking into account the power values ($P_{M,max}$, $P_{G,max}$) of the storage unit and the maximum storage capacity $E_{S,max}$ for the current filling level $E_S(t_i)$ and the efficiencies of the conversion processes (η_M, η_G), the additionally required control power $P_{CP}^{required}(t_i)$ and/or the resulting control energy $E_{CP}^{required}(t_i)$ for compensating the forecast errors is determined.
The following formula applies here:

$$E_{CP}^{required}(t_i) = P_{CP}^{required}(t_i) \cdot t_{int} \tag{5.12}$$

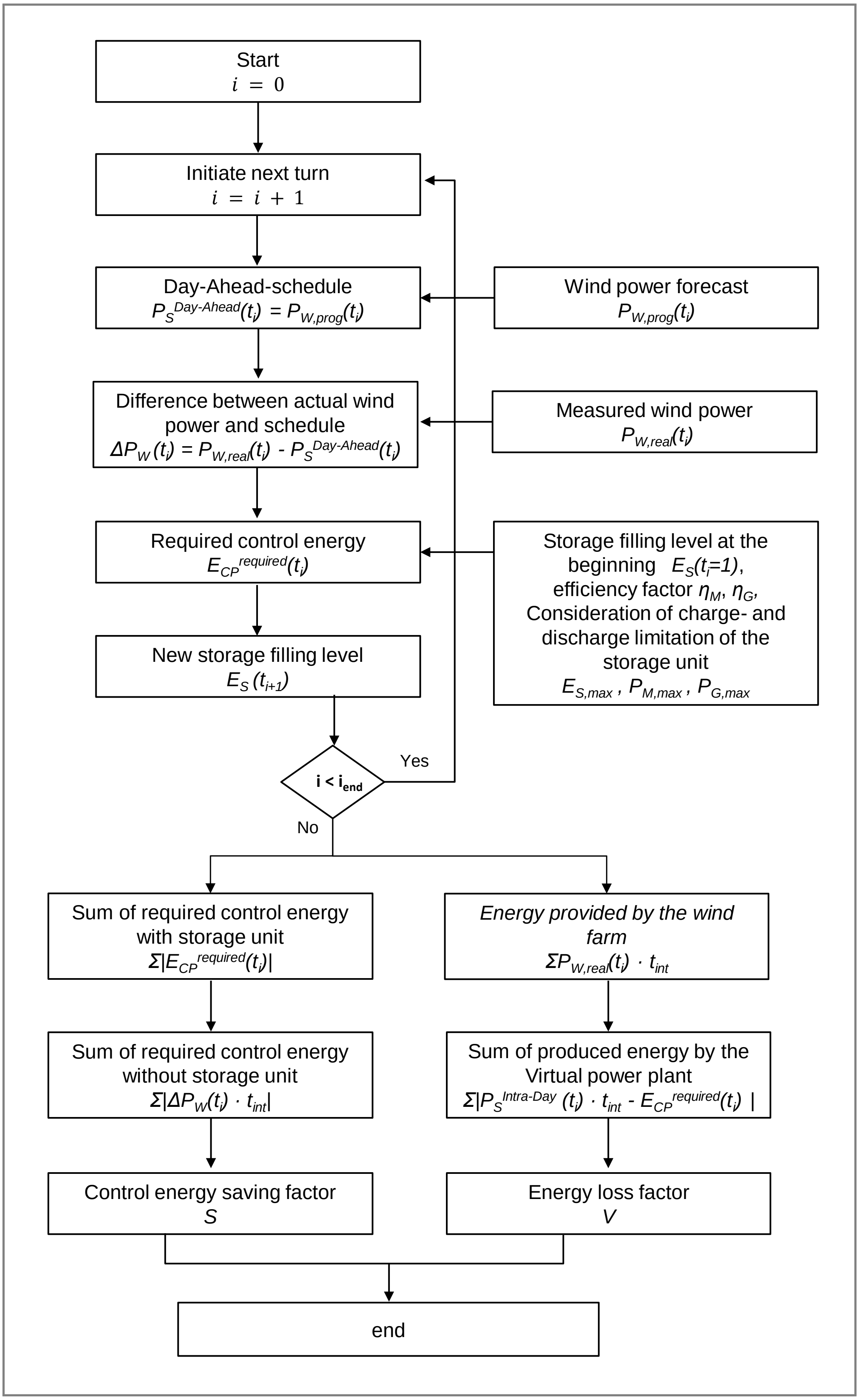

Figure 38: Simulation sequence without Intra-Day optimization and calculation process of control energy saving factor S and the energy loss factor V by using the methane storage to compensate the forecast errors

$E_{CP}^{required}(t_i)$ thus represents the non-compensatable portion of the energy difference between the energy schedule and the real wind energy $\Delta E_{W,S}(t_i)$ on the one hand and the control energy saved by the storage $E_{CP}^{saved}(t_i)$. The following applies here:

$$\Delta E_{W,S}(t_i) = P_{W,S}(t_i) \cdot t_{int} \tag{5.13}$$

$$E_{CP}^{saved}(t_i) = P_{CP}^{saved}(t_i) \cdot t_{int} \tag{5.14}$$

The new storage filling level achieved at the end of the time interval and at the start of the next time interval $E_S(t_{i+1})$ is then calculated.

Eight different cases may arise during the simulation, for which the control energy $E_{CP}^{required}(t_i)$ and the new energy filling level $E_S(t_{i+1})$ of the storage unit can be calculated. Table 26 in Appendix B provides a detailed representation of these cases. The control energy saving factor S and the lost energy factor V are determined at the end of the simulation.

For power values (i.e. power input and power output) and the storage capacity of the storage unit from the Section 5.1.2 a control energy saving factor S of 68.89% is achieved. This makes it clear that the 99.73% in the Section 5.1.2.1 was not reached. The energy loss factor V achieved is 6.25%. The main reason is the limitation of the storage filling capacity. The excerpt of the data used in the simulation shown in Figure 39 illustrates that as long as the storage is not filled or discharged completely, the saved control power $P_{CP}^{saved}(t_i)$ is equal to the negative power difference $\Delta P_{W,S}(t)$. Exceptions are possible if the power difference $\Delta P_{W,S}(t)$ exceeds the maximum power output of the combined-cycle power plant ($P_{G,max}$) or falls below the minimum power input of the methanation facility ($P_{M,max}$).

In case of the methane storage capacity limitations, the saved control power $P_{CP}^{saved}(t_i)$ is zero and the required control power $P_{CP}^{required}(t_i)$ deviates from zero contra directional to $\Delta P_{W,S}(t_i)$. The actual delivered power $P_{delivery}(t_i)$ is also given as following:

$$P_{delivery}(t_i) = P_S^{Day-Ahead}(t_i) - P_{CP}^{required}(t_i) \tag{5.15}$$

A simulation of the control energy saving factor S for different $P_{M,max}$, $P_{G,max}$ and $E_{S,max}$ shows, whether these selected values of the storage unit are meaningful.

Figure 40 shows the control energy saving factor S for different values of $P_{M,max}$. From $P_{M,max} = -0.72 \cdot P_{W,max}$ onwards, the control energy saving factor S decreases slowly from 69.13%. At $P_{M,max} = -0.53 \cdot P_{W,max}$ a smaller value of S of 68.89% is observed.

Similarly, it is possible to represent the control energy saving factor for different $P_{G,max}$ as shown in Figure 41.

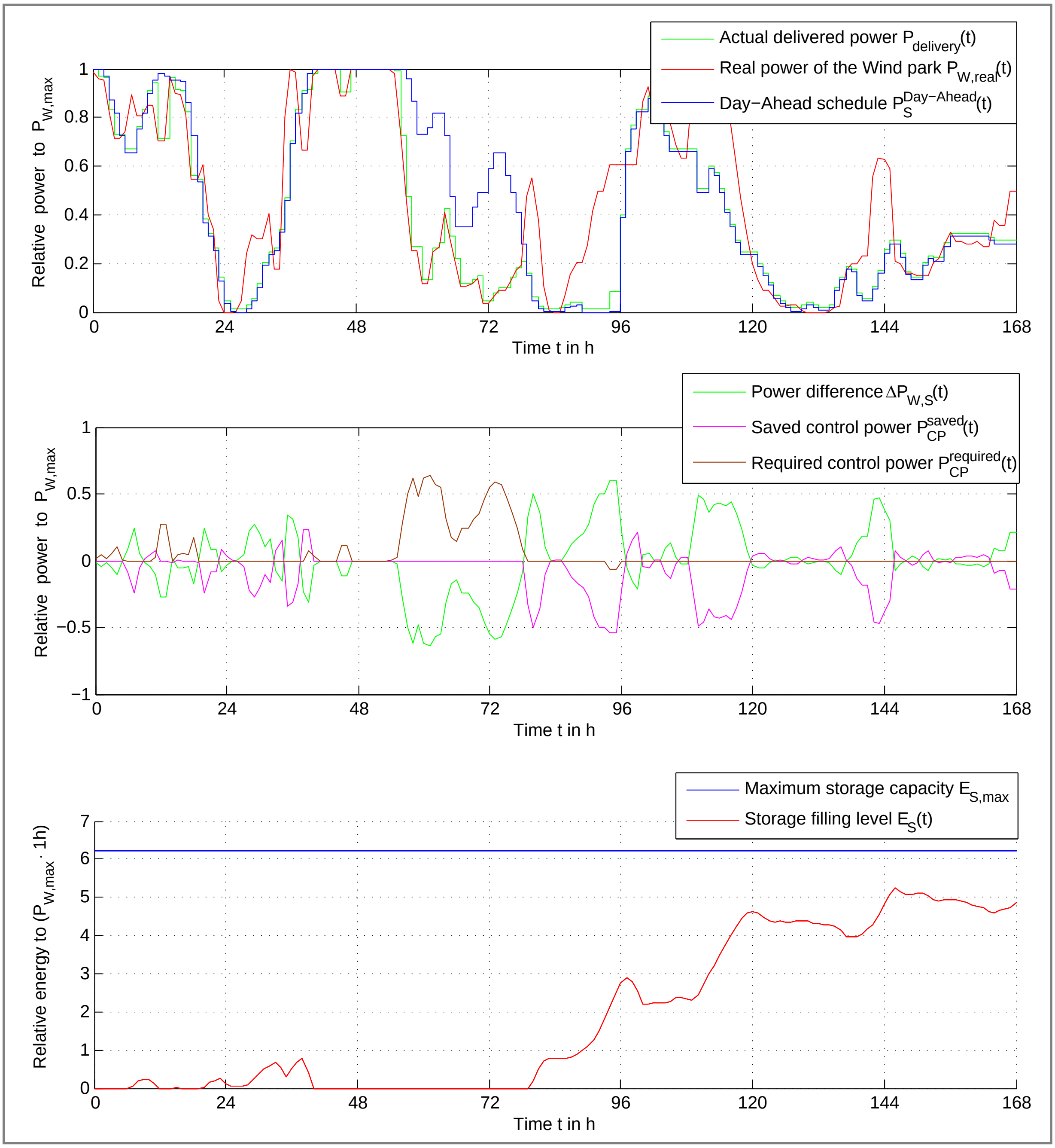

Figure 39: Representation of the various power values of the simulation without optimization approaches for a representative week

An increase in the control energy saving factor does not occur at larger values than $P_{G,max} = 0.33 \cdot P_{W,max}$. Consequently, a smaller value of $P_{G,max}$ could be selected.

Finally, the control energy saving factor is considered for different storage sizes $E_{S,max}$. Figure 42 shows the factor for $P_{G,max} = 0.33 \cdot P_{W,max}$ and $P_{M,max} = -0.53 \cdot P_{W,max}$.
A considerable increase in the control energy saving factor does not occur with volumes exceeding $E_{S,max} = 18.70 \cdot P_{W,max} \cdot 1h$ with S = 85.01%. A control energy saving factor of 68.89% is attained with $E_{S,max} = 6.20 \cdot P_{W,max} \cdot 1h$. This means that these values are almost

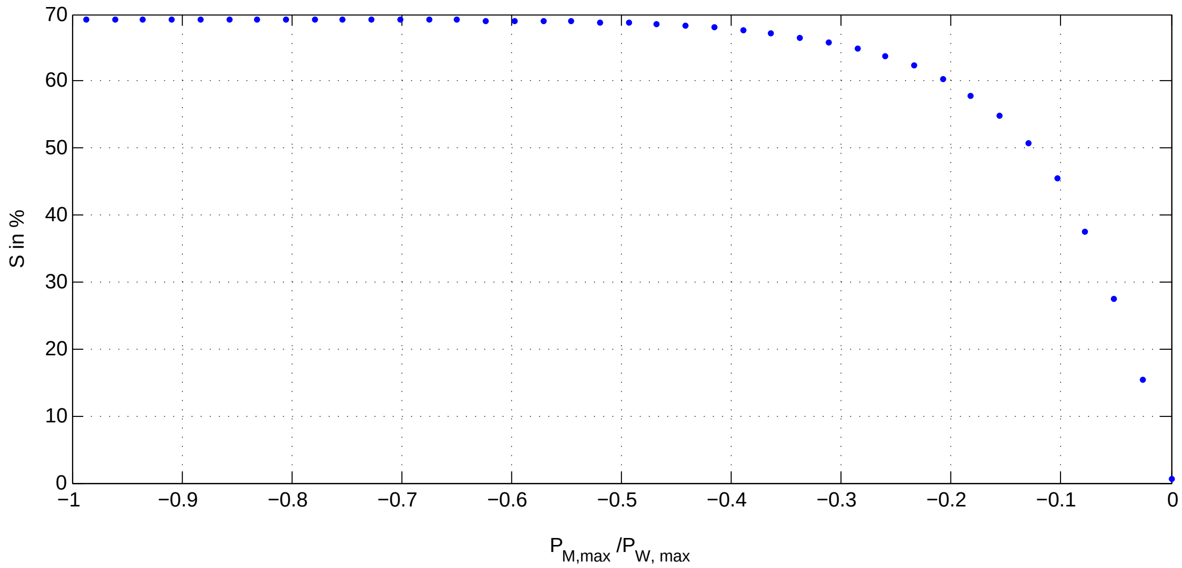

Figure 40: The control energy saving factor S for various $P_{M,max}$ with $E_{S,max} = 6.20 \cdot P_{W,max}$ and $P_{G,max} = 0.46 \cdot P_{W,max}$

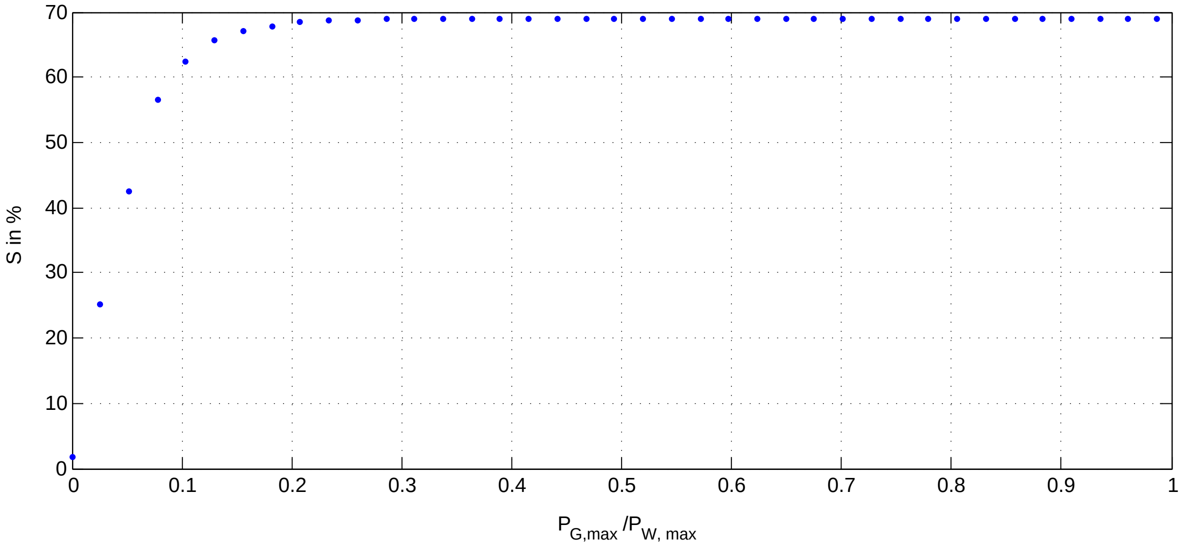

Figure 41: The control energy saving factor S for various $P_{G,max}$ with $E_{S,max} = 6.20 \cdot P_{W,max}$ and $P_{M,max} = -0.53 \cdot P_{W,max}$

within the Pareto optimum with an effort of approximately 33% of the best value for $E_{S,max}$ and approx. 80% of the corresponding value for S.

5.3 Simulation with Intra-Day adjustment

As discussed in the preceding subsections, the use of the methane storage system actually leads to a significant reduction of the control power of the wind turbines. Nevertheless, with

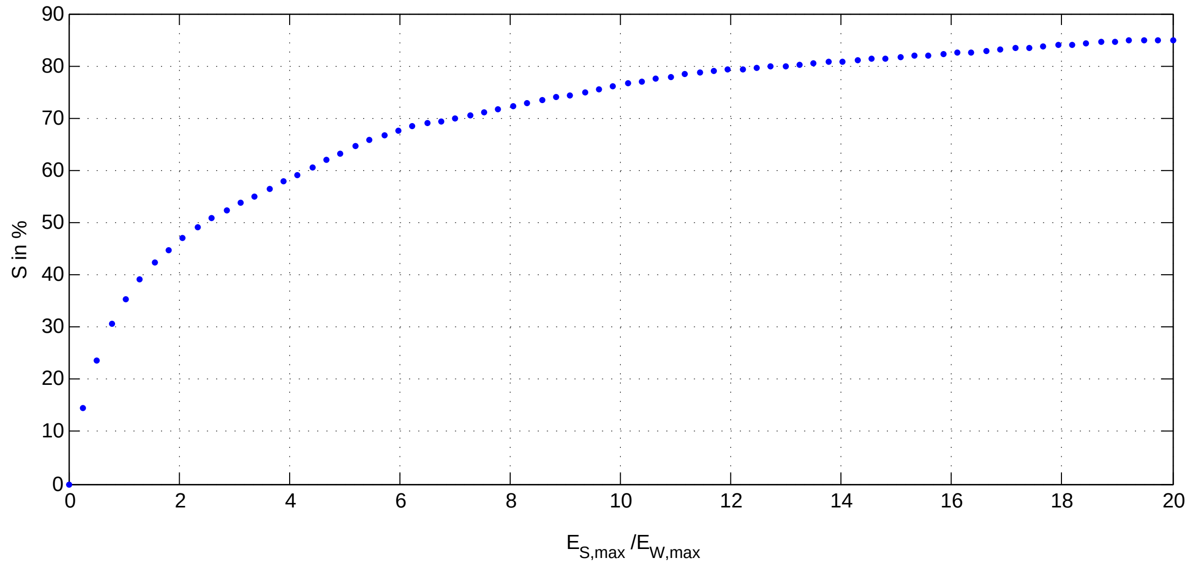

Figure 42: The control energy saving factor S for various $E_{S,max}$ with $P_{M,max} = -0.53 \cdot P_{W,max}$ and $P_{G,max} = 0.46 \cdot P_{W,max}$

control energy saving factor $S =$ 68.89%, potential for optimization is still high.
In section 5.2, it is explained that although an increase in the control energy saving factor to 86.23% is possible by increasing the maximum storage capacity $E_{S,max}$, but it is not economically feasible.

The simulation will now be extended to the Intra-Day optimization as introduced in section 4.1. This includes optimization of the storage filling level and short-term forecast corrections. The corrections are added to the Day-Ahead schedule forming the Intra-Day schedule. The following applies here:

$$P_S^{Intra-Day}(t_i) = P_S^{Day-Ahead}(t_i) + P_{W,corr}(t_i) + P_{S,corr}(t_i) \tag{5.16}$$

the Intra-Day schedule should never be larger than the maximum attainable output $P_{W,max}$ of the wind farm, and should never attain negative values:

$$0 \leq P_S^{Intra-Day}(t_i) \leq P_{W,max} \tag{5.17}$$

Figure 43 shows the adjusted simulation sequence which will be discussed in detail in the following two subsections. For this purpose, the determination of the power difference $\Delta P_{W,S}(t_i)$ must be adjusted which refers to the Intra-Day schedule:

$$\Delta P_{W,S}(t_i) = P_{W,real}(t_i) - P_S^{Intra-Day}(t_i) \tag{5.18}$$

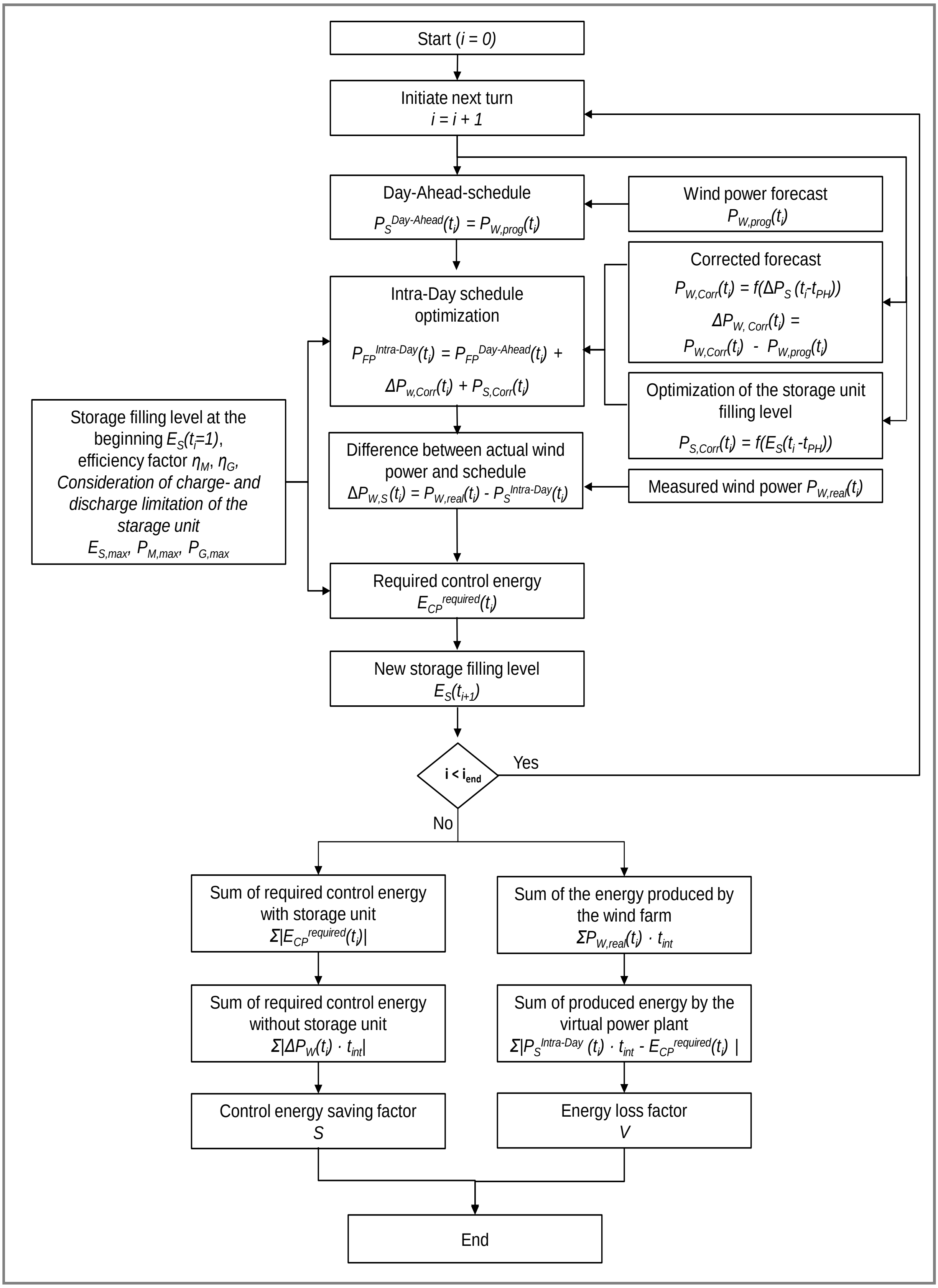

Figure 43: Simulation sequence with Intra-Day optimization and calculation process of the control energy saving factor S and the energy loss factor V by use of methane storage for the compensation of forecast errors

5.3.1 Forecast side correction

The forecast data for the wind power are the critical factor for creating the Day-Ahead schedule, as the forecast values are often more than 24 hours old. In Section 5.1.1 the variations between measured and forecasted wind power are analyzed in detail. The analysis showed that variations in one direction are often maintained over several hours. This is why a forecast correction should be applied to the Intra-Day schedule. Two methods for a short-term forecast correction will be introduced in the following sections.

Using an average correction method:

$$P_{W,corr}(t_{PH}+1) = P_{W,prog}(t_{PH}+1) + \frac{\sum_{t_i \in PH} \Delta P_W(t_i)}{t_{PH}/t_{int}} \tag{5.19}$$

whereby it must always apply:

$$0 \leq P_{w,corr}(t_{PH}+1) \leq P_{W,max} \tag{5.20}$$

$P_{W,corr}(t_i)$	Corrected forecasted wind power in MW in t_i
$P_{W,prog}(t_i)$	Forecasted power of the wind farm in MW in t_i
$P_{W,max}(t_i)$	Maximal power output of the wind farm in MW in t_i
$\Delta P_W(t_i)$	Difference between the forecast and real power of the wind farm in MW in t_i
t_{PH}	Length of the forecast horizon in h
t_i	Calculation interval

This approach is suitable in the case where the prediction error does not change over a longer period of time. It is necessary to check this case for the given values. This reference is made to the data already used in Section 5.1.1, while also considering the temporal change in the difference values $\Delta P_{W,S}(t_i)$ more accurately. Figure 37 shows that the periods of overestimation or underestimation of the power values are usually very short. In this case the method of average correction method is not favorable, even if an improvement of the mean values and the standard deviation can be observed. Table 27 in Appendix B gives an overview of the achieved prediction improvements of the two adjustment methods with different values of δ and t_{PH}.

Another way to correct the predicted values is the exponential smoothing. This is a recursive method, the weighting of prior periods for the calculation of the current period decreases significantly, the longer of the periods are lagging behind. In the present case, a modified shape of the exponential smoothing is proposed as follows:

$$\begin{aligned} P_{W,corr}(t_i) &= P_{W,prog}(t_i) + \delta \cdot \Delta P_W(t_i - t_{PVZ}) \\ &= P_{W,prog}(t_i) + \delta \cdot (P_{W,real}(t_i - t_{PVZ}) - P_{W,corr}(t_i - t_{PVZ})) \\ with \quad & 0 < \delta < 1. \end{aligned} \tag{5.21}$$

Typical values for the weighting δ lie between 0.7 and 0.8. t_{PVZ} are the number of time intervals of the prognosis lead time. Since, the Intra-Day adjustment must be made at least 45 minutes before the start of next period (spot market for Intra-Day transactions) for t_{PVZ} applies:

$$t_{PVZ} \geq 45min/t_{int} \tag{5.22}$$

where t_{PVZ} must always be rounded up to an integer value. In the case of $t_{int} = 1h$ results $t_{PVZ} = 1h$.

It is apparent that the method of exponential smoothing provides better values than the mean value correction method. However, a combination of the two methods shows only a slight improvement, which does not justify the additional effort. For the values used, an exponential smoothing with $\delta = 0.8$ is proposed. The optimized value of $\Delta P_{W,corr}(t_i))$ is defined as:

$$\Delta P_{W,corr}(t_i) = P_{W,corr}(t_i) - P_{W,prog}(t_i) \tag{5.23}$$

Figure 44 shows the corrected prediction compared to the original one and the actual performance of the wind farm.

5.3.2 Storage side correction

The purpose of the optimization approach is to avoid bottlenecks for the amount of energy stored in methane gas storage. A full storage unit cannot absorb more methane and thus cannot intercept more required negative control energy. On the other hand, an empty storage cannot counteract any positive control energy consumption. Therefore, both of these situations should be avoided. The optimum storage level is therefore 50% of the maximum storage filling level and should always be achieved.

The compensation power for the correction of the storage level $P_{S,corr}(t_i)$ shall be determined by a function depending on the storage filling level $SFL(t_i)$ and the maximum power output

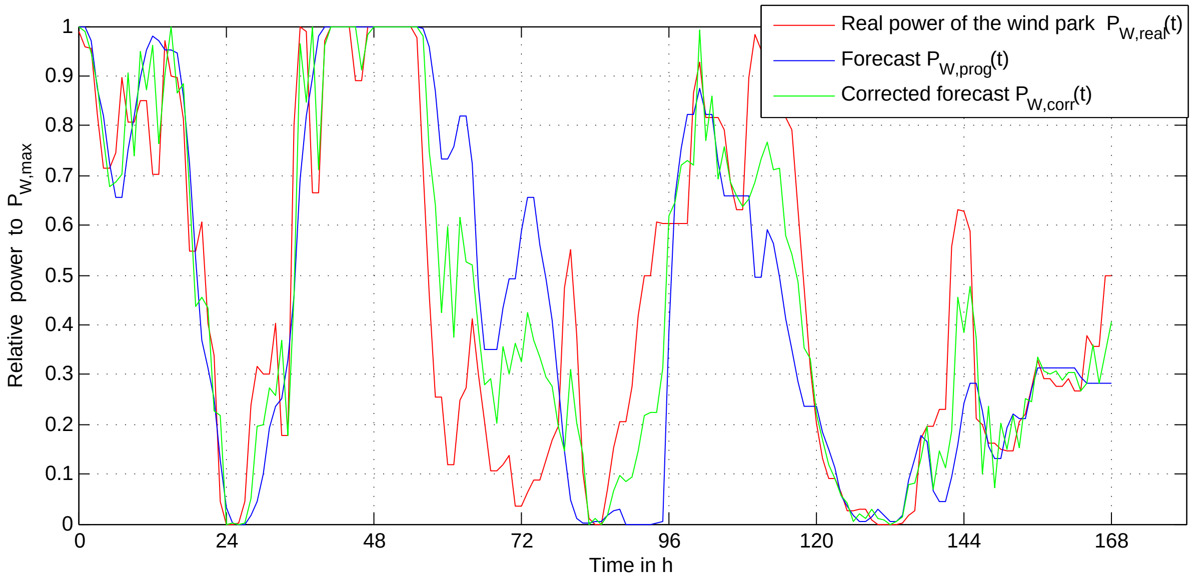

Figure 44: Representation of the corrected forecast compared to the original forecast and the actual power of the wind farm for a representative week

$P_{G,max}$ or power input $P_{M,max}$ of the storage unit. Furthermore, the lead time of the Intra-Day adjustment must be at least 45 minutes. In order to determine the compensation power $P_{S,corr}(t_i)$, following forecast lead time t_{PVZ} is required:

$$t_{PVZ} = 45min/t_{int}, \tag{5.24}$$

Where t_{PVZ} should be rounded up to the nearest whole number. Thus, $t_{PVZ} = 1h$ applies to the data used within this work. For determination of $P_{S,corr}(t_i)$ following equations should be applied:

$$P_{S,corr}(t_i) = f(SFL(t_i - t_{PVZ})) \tag{5.25}$$

$$SFL(t_i) = \frac{E_S(t_i)}{E_{S,max}} \tag{5.26}$$

$$max\{f(SFL(t_i))\} \leq -P_{G,max} \tag{5.27}$$

$$min\{f(SFL(t_i))\} > -P_{M,max} \tag{5.28}$$

$$f(SFL(t_i) = 0.5) = 0 \tag{5.29}$$

In the following, various functions $f(SFL)$ would be investigated in order to determine $P_{S,corr}(t_i)$. The simplest variant represents a linear function, which is:

$$f_{linear}(SFL(t_i)) = \begin{cases} (2 \cdot \alpha \cdot SFL(t_i) - \alpha) \cdot |P_{G,max}| & \text{for} SFL(t_i) > 0.5 \\ (2 \cdot \alpha \cdot SFL(t_i) - \alpha) \cdot |P_{M,max}| & \text{for} SFL(t_i) \leq 0.5 \end{cases} \tag{5.30}$$

with $0 < \alpha \leq 1$.

In Figure 45 the linear form is shown for different linear factors α:

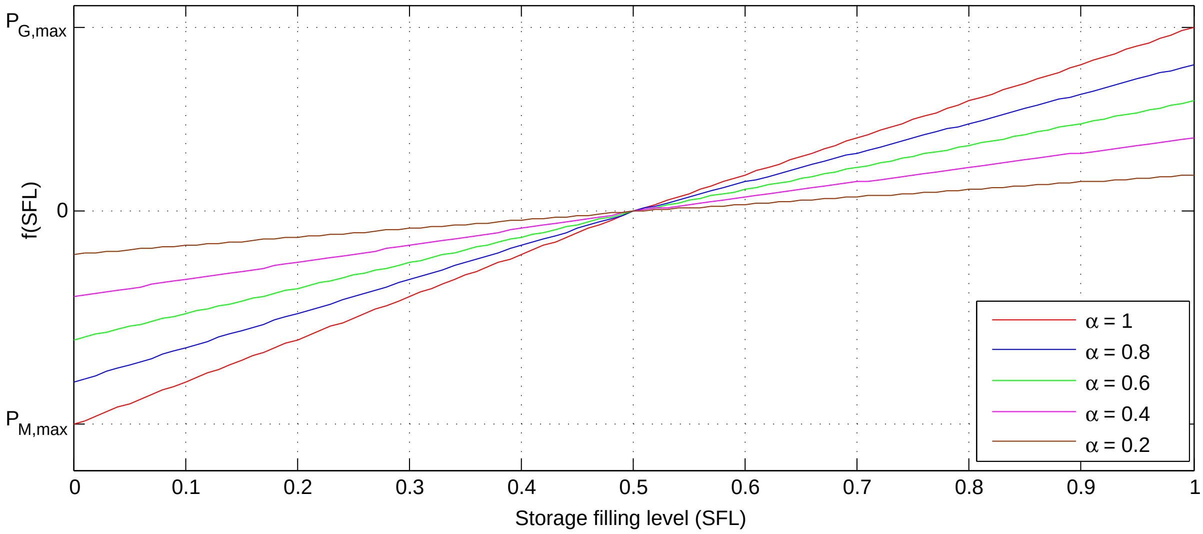

Figure 45: Course of the linear function for different α

Furthermore, the polynomial function and root function are investigated. For the polynomial function, it applies:

$$f_{Polynomial}(SFL(t_i)) = \begin{cases} \alpha \cdot (2^{\beta} \cdot (SFL(t_i) - 0.5)^{\beta} \cdot |P_{G,max}| & \text{for } SFL(t_i) > 0.5 \\ -\alpha \cdot |2^{\beta} \cdot (SFL(t_i) - 0.5)^{\beta}| \cdot |P_{M,max}| & \text{for } SFL(t_i) \leq 0.5 \end{cases} \tag{5.31}$$

With $\beta > 1$ and $0 < \alpha \leq 1$

and for the root function, it applies:

$$f_{Root}(SFL(t_i)) = \begin{cases} \alpha \cdot \sqrt[\gamma]{2 \cdot (SFL(t_i) - 0.5)} \cdot |P_{G,max}| & \text{for } SFL(t_i) > 0.5 \\ -\alpha \cdot \sqrt[\gamma]{2 \cdot (0.5 - SFL(t_i))} \cdot |P_{M,max}| & \text{for } SFL(t_i) \leq 0.5 \end{cases} \tag{5.32}$$

With $\gamma > 1$ and $0 < \alpha \leq 1$.

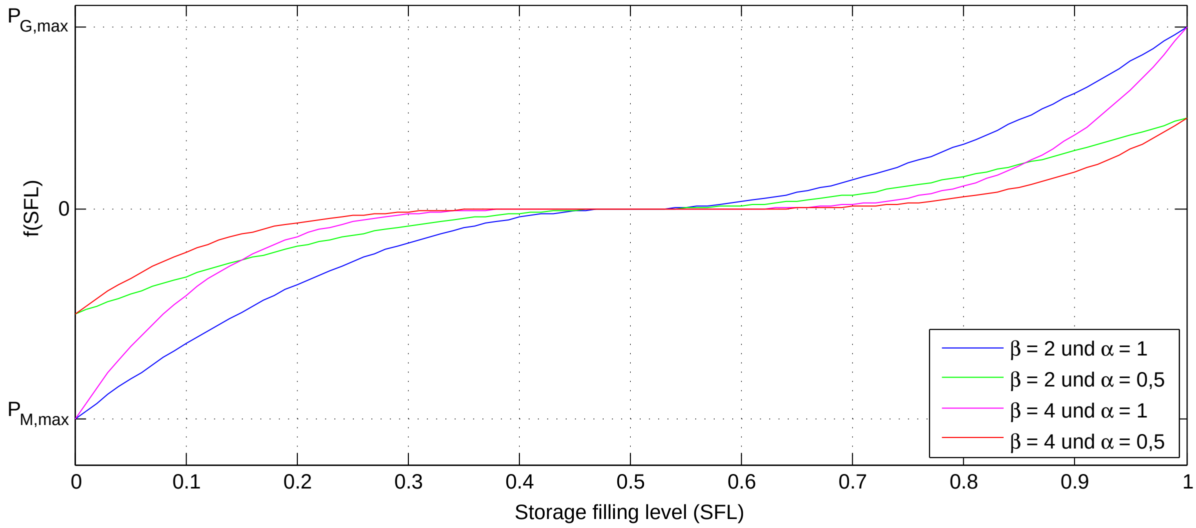

Figure 46: Course of the polynomial function for various degrees β and various α

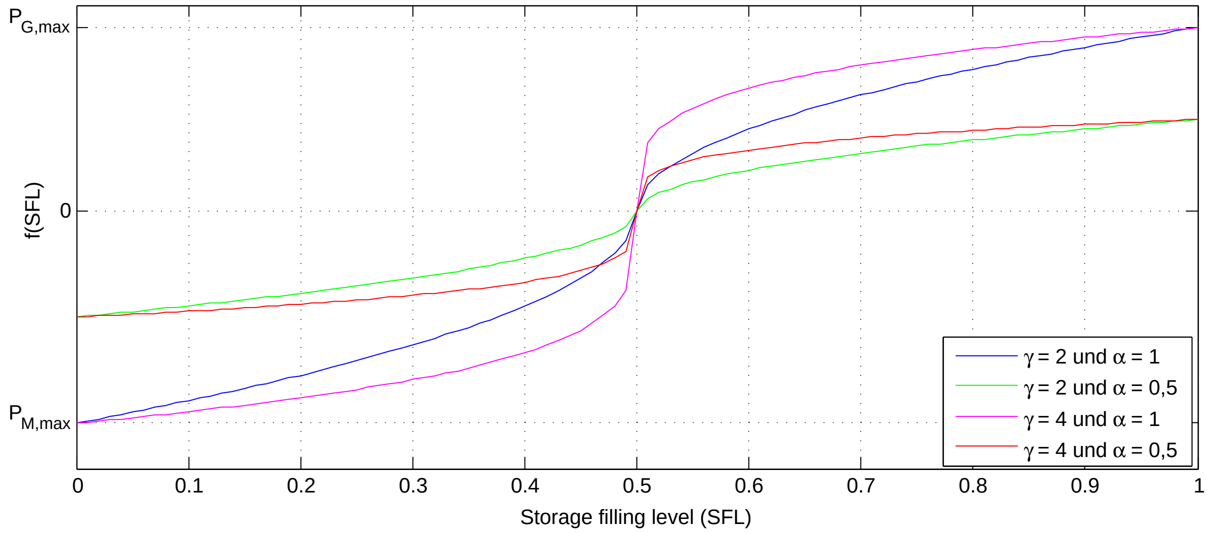

Figure 47: Course of the root function for various γ and α

Figure 46 and Figure 47 show the different courses of the polynomial function and root function for different polynomial degrees β and root degrees γ in combination with various linear factors α. The polynomial functions, have in the area $SFL \approx 0.5$ a fairly flat course, while the root functions at this point have their largest slope. Using a polynomial function means that the correction of the storage filling level SFL occurs only by a larger deviations of SFL from the optimum storage level. In contrast, while using a root function, there are massive interventions to the smallest deviations from the ideal storage level.

To assess the functions, a simulation is performed (without prognosis adjustments) for the various functions and various parameters, as shown in Figure 43. The results are shown in Table 28 in Appendix B.

In the polynomial functions, there is an apparent liaison between the energy loss factor V and the control energy saving factor S. A relatively good control energy saving factor brings a relatively bad energy loss factor with it. This relation is not clear by the root functions. Low values of γ and high values for α lead to better results of the S. For V, low values for γ also lead to better results of V, but high values of α cause a deterioration of V. Consequently, when using a root function, low values of γ and moderate values for α should be chosen.

Furthermore, it is important to note that the root functions overall have significantly worse values in the energy loss factor V than the polynomial function, but have slightly better values in the control energy saving factor S (Table 28 in Appendix B).

By selection of the appropriate function, the effect of the function to the Intra-Day schedule is to be viewed. Figure 48 and Figure 49 show a section of the curve of the Day-Ahead and Intra-Day schedule with storage-side optimization by a polynomial and a root function.

With the polynomial function, the Intra-Day schedule course is still oriented to the Day-Ahead schedule, whereas the Intra-Day schedule strongly differs from the Day-Ahead schedule with the root function. In addition, the Intra-Day schedule is subjected to large jumps and thus shows a fluctuating movement to the Day-Ahead schedule. The large fluctuations can be attributed to the large adjustments of the Intra-Day schedule with only small deviations of the ideal storage filling level, which means that the adjustments are too big and exceed or falls below the 50% of the SFL. This leads to more movement in the storage than necessary and thus to larger energy losses in the overall balance. This is reflected in the values for the energy loss factor V in Table 28 in Appendix B. Therefore the root function will not be considered in this thesis.

A possible solution is to combine linear and polynomial functions. However, an improvement in the evaluation factors compared to the pure polynomial functions could not be achieved experimentally for the data set used. Therefore, a polynomial function is proposed.

In the following, the polynomial function with $\alpha = 0.8$ and $\beta = 2$ is used with which a control energy saving factor S 90.67% and an energy loss factor V 6.67% can be achieved (Table 29 in Appendix B), without the forecast adjustments from Section 5.3.1.

5.4 Reflection of the simulation results

This section deals with the critical examination of the results from the previous simulations. At first, the results of the simulation will be scrutinized. Figure 50 shows an exemplary sequence of the Day-Ahead schedule, the Intra-Day schedule, the forecasts of the wind power, the

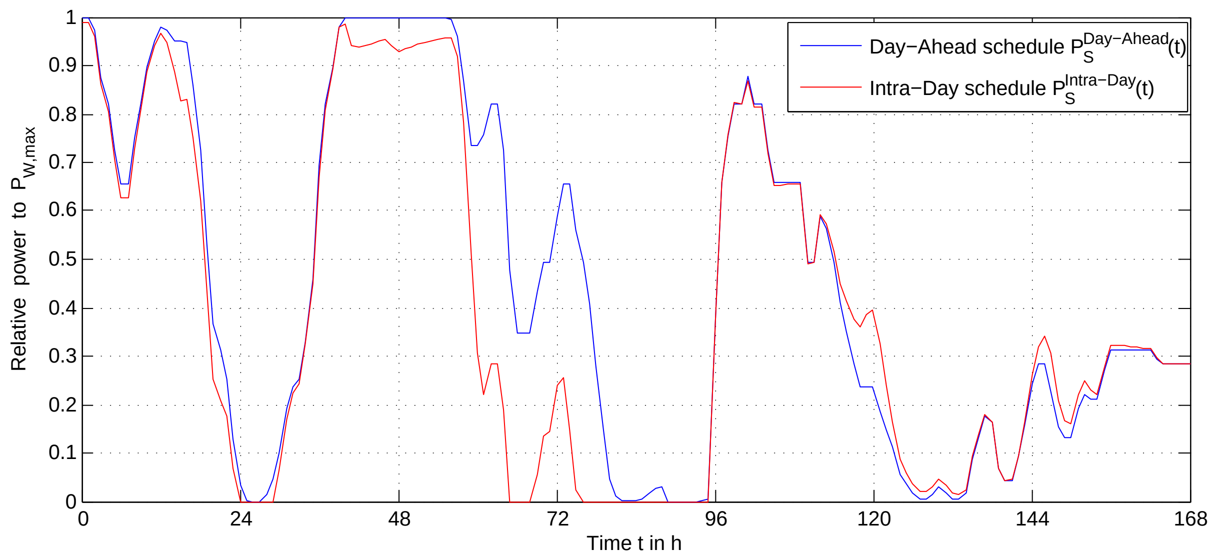

Figure 48: Excerpt of the course of the Day-Ahead and Intra-Day schedule with Storage-side correction by a polynomial function with $\beta = 2$ and $\alpha = 1$

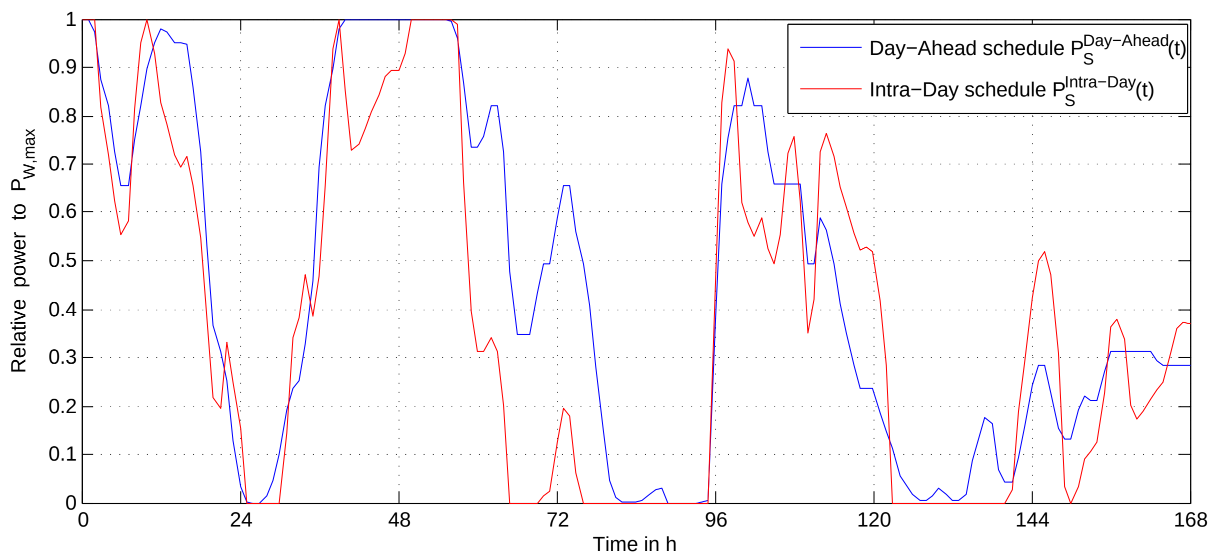

Figure 49: Excerpt of the course of the Day-Ahead and Intra-Day schedule with Storage-side correction by a root function with $\gamma = 2$ and $\alpha = 1$

corrected wind forecast by the exponential smoothing and the actually measured wind power for a representative week. Furthermore, the power difference between Intra-Day schedule and actually measured wind power is determined and the demand of control power is presented. In addition, the storage filling level as well as the gas purchase and sales are shown. First, it can be seen that the corrected forecast values are much closer to the actual wind power than the original forecast values. The corrected forecast mostly lies between the actually measured wind power and the original forecast. In the observation period, demand of control power is not recorded. The control energy saving factor S has a value of 99.78%, so the demand

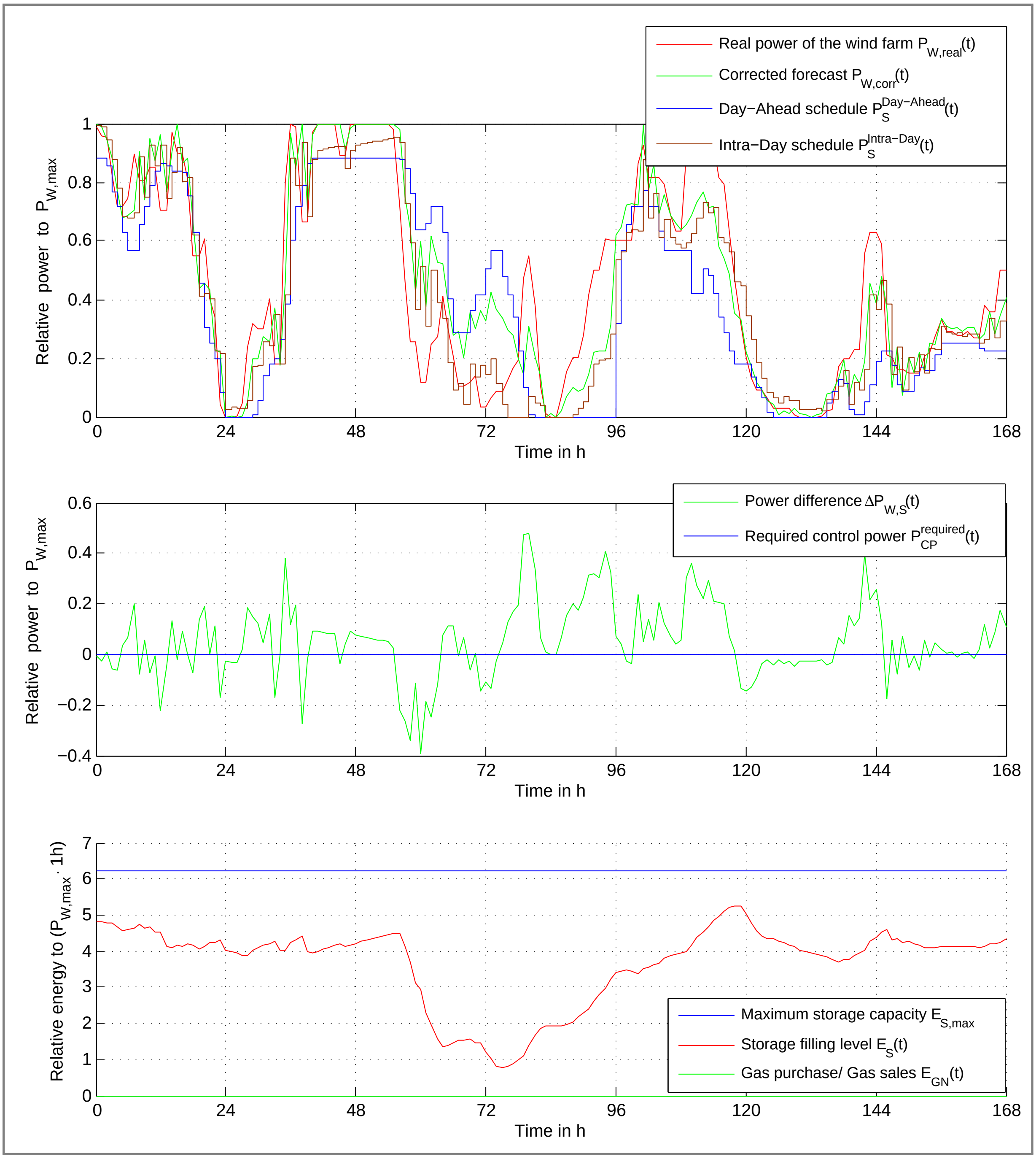

Figure 50: Representation of the various wind power courses of the simulation with all optimization approaches from the chapter 5 for a representative week

of control power must have been caused in another period. The factor S surpasses even the values estimated in Section 5.1.2.1. Furthermore, the storage does not reach its capacity limits and there is no need for an injection or extraction of gas from the gas network. Therefore, it is quite conceivable to reduce the size of the storage in order to minimize investment costs.

However, the curve of the power difference between Intra-Day schedule and actually measured wind power exhibits strong jumps and often oscillates around zero. This requires methanation facility to be turned on and off repeatedly. The simulation assumes a continuous adjustable control and therefore cannot be put into practice.

The evaluation factors S and V, which were used for the optimization approaches, are suitable for this model because they reflect the economical damages in it. The control energy saving factor S represents the caused demand of control power, which has to be paid from balancing group supervisor to Transmission System Operator. However, the energy loss factor V always represents an economical damage, namely the amount of energy losses and thus lost income. The assessment of the evaluation factors against each other is difficult because this would require specific values of penalty heights for the demand of control power.

Putting this concept into practice, necessitates an assessment of the factors against each other on the basis of market data. Since these changes are constant, the optimization should be executed frequently to adapt them to the actual market factors. Additionally, improvements in the wind forecasts by the responsible institutions are to be expected. Their data should be regularly analyzed and compared to the actual wind power. The results have to be implemented into the concept.

5.4.1 Selection of smaller power values of the storage unit

Today methanation facilities exist only as experimental plants with low power input. Therefore, building a storage unit would lead to high investment costs. This suggests evaluating the size and power values of the storage unit according to the previous optimization. Figure 51 shows a simulation of smaller $P_{M,max}$. A minimization of $P_{M,max}$ to $(-0.3 \cdot P_{W,max})$ shows hardly a deterioration of S and V barely changes. If $P_{M,max}$ is smaller, then the results of S are still good whereas, the values of V are improved because of an increase in gas purchase. it should be taken into account that reducing $P_{M,max} = -0.5 \cdot P_{W,max}$ to $(-0.3 \cdot P_{W,max})$ does not affect S and thus it leads to a large economical potential savings.

The analogous simulation of the maximum power output $P_{G,max}$ of the storage unit arrives at similar results, shown in Figure 52. This illustrates that the high $P_{G,max} = 0.3 \cdot P_{W,max}$ does not have any impact on the results of S. A reduction of $P_{G,max} = 0.2 \cdot P_{W,max}$ also does not affect the results much but leads to a significant reduction of investment costs.

5.4.2 Selection of a smaller storage capacity for the storage unit

Furthermore, it is important to investigate whether a reduction in the maximum energy capacity of the storage $E_{S,max}$ makes sense. For this, Figure 53 will be analyzed in analogy to the Section 5.4.1. The significant reduction of $E_{S,max}$ leads barely to the diminution of S however, the

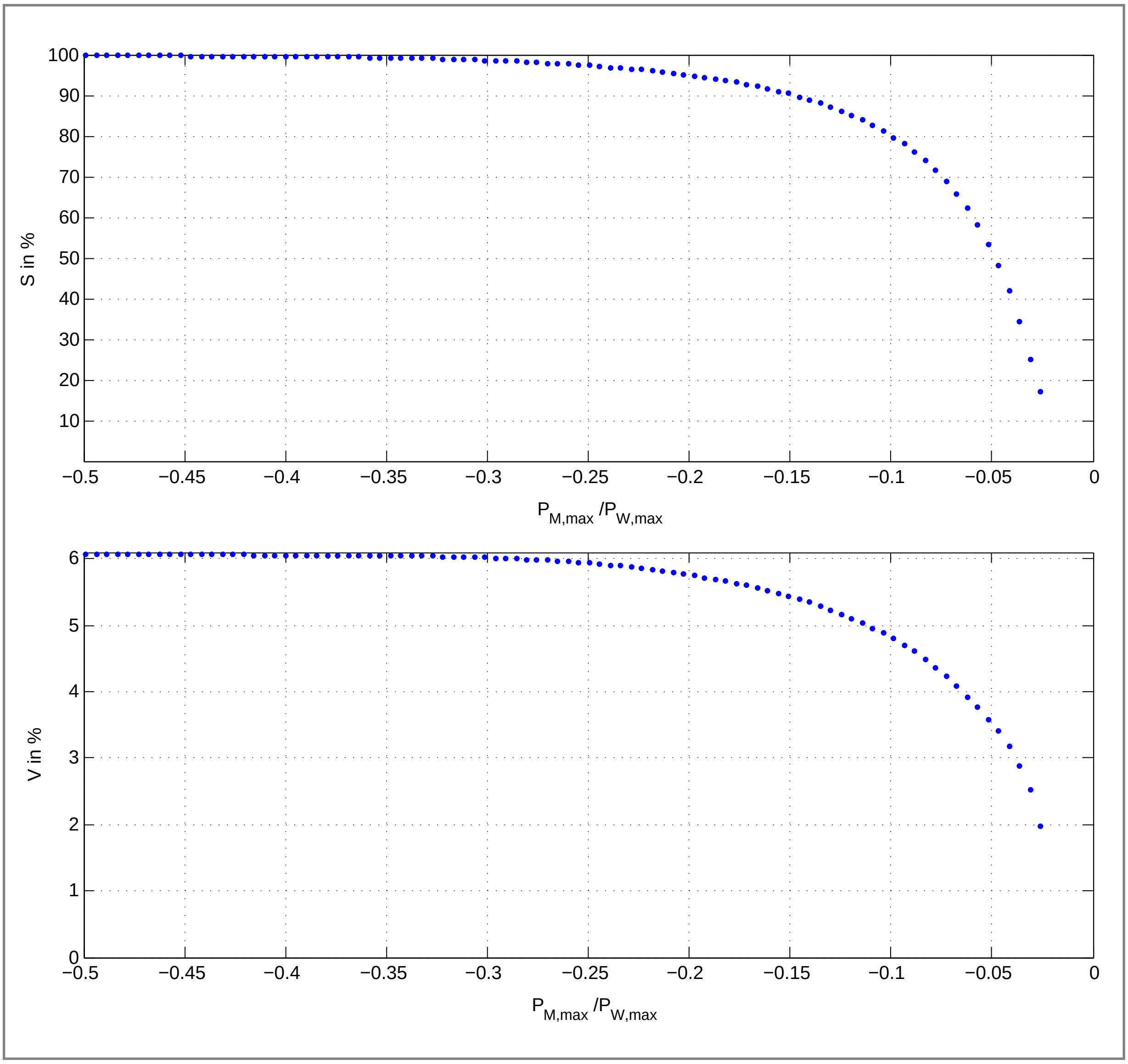

Figure 51: Control energy saving factor S and energy loss factor V for different maximum power input values $P_{M,max}/P_{W,max}$

factor V is even improved. A reduction of $E_{S,max}$ to $(1.5 \cdot E_{W,max})$ is possible. At this point the factor S is not a good factor to evaluate whether the size of the storage unit is adequate, because the gas network can counterbalance the storage deficit. Therefore, it is more significant to consider the total amount of gas transferred between the gas network and the storage unit.

Simulations also show for values smaller than $E_{S,max} = 1.5 \cdot E_{W,max}$ significant differences in gas exchange can be observed. Hence the methane gas storage can be built smaller than originally assumed.

Using $E_{S,max} = 1.5 \cdot P_{W,max} \cdot 1h$, and the reduced values of the power input and output of the storage unit $P_{M,max} = -0.3 \cdot P_{W,max}$ and $P_{G,max} = 0.2 \cdot P_{W,max}$ from Section 5.4.1 yields

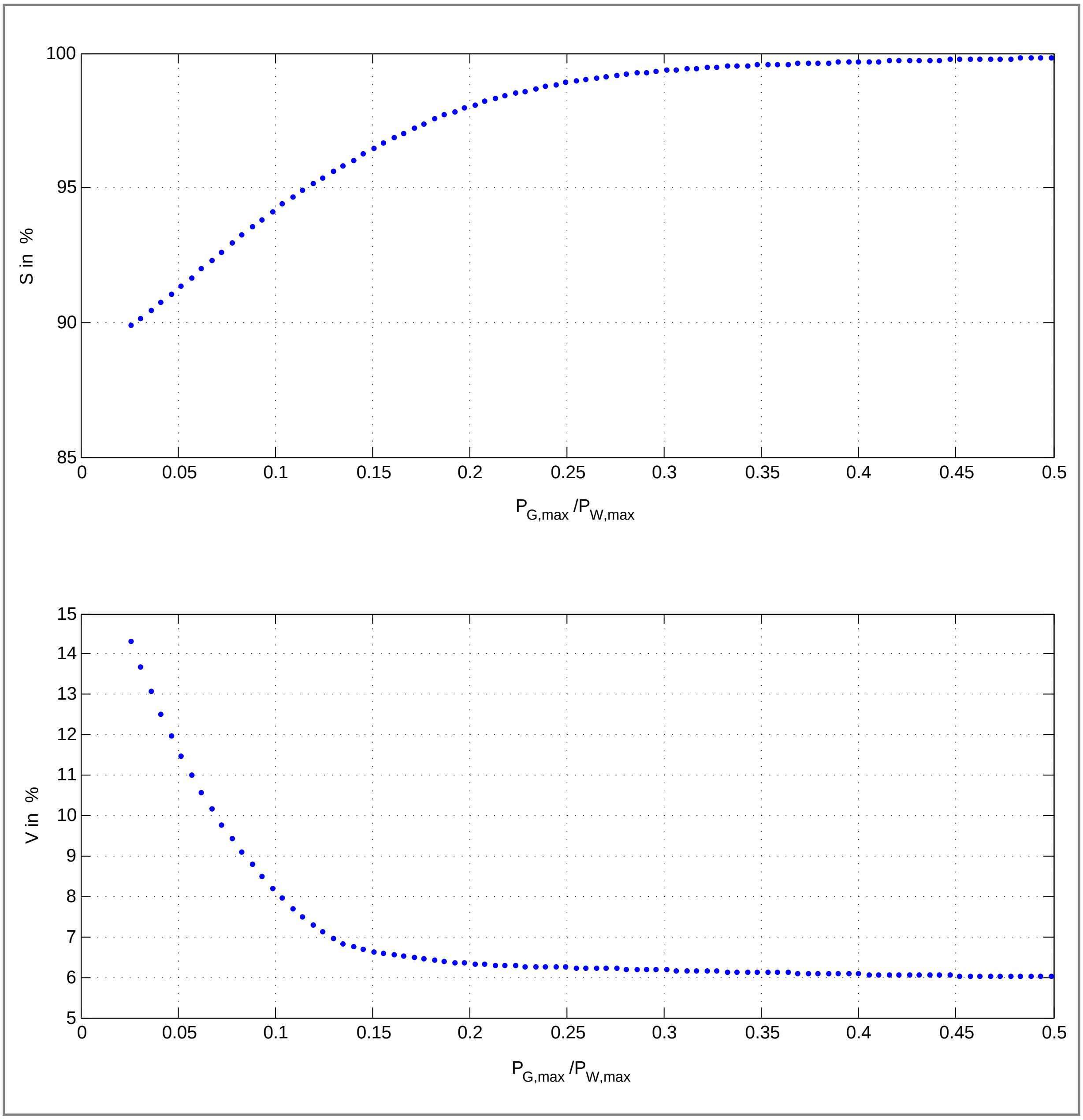

Figure 52: Control energy saving factor S and energy loss factor V for different maximum power output values $P_{G,max}/P_{W,max}$

$S = 97.62\%$ and $V = 5.96\%$ can be achieved. Even though the input values are significantly reduced, the results for S are still very good. Figure 54 shows the results for one exemplary week. Surprisingly, there is demand of control power that did not appear before (Figure 50) in this week. Furthermore, it can be seen that the storage reaches limiting capacity more often and so the exchanges to the gas network increase in frequency. This is legitimate when using a connection to the gas network, which would be superfluous otherwise.

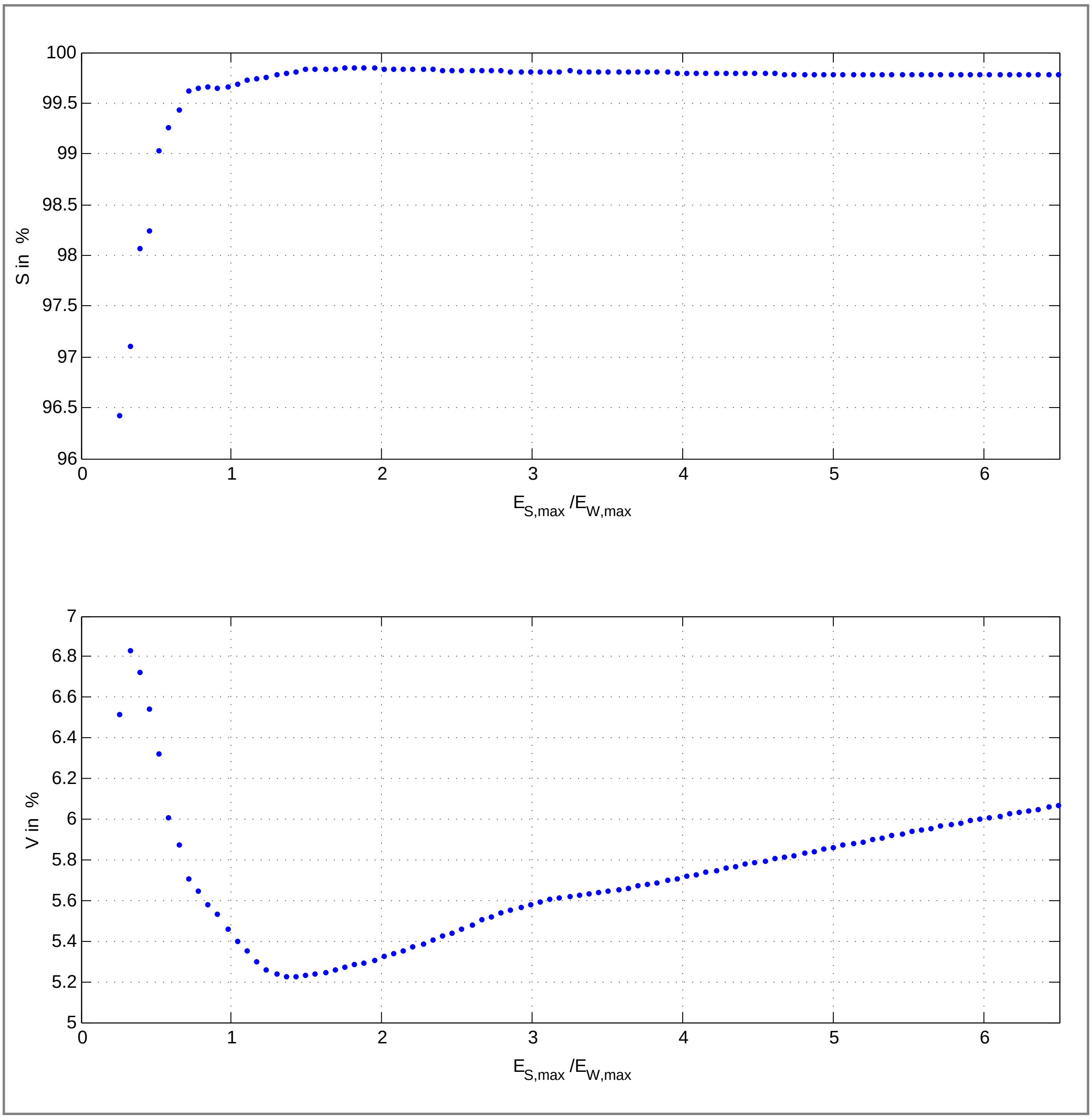

Figure 53: Control energy saving factor S and energy loss factor V for different maximum storage capacity $E_{S,max}$

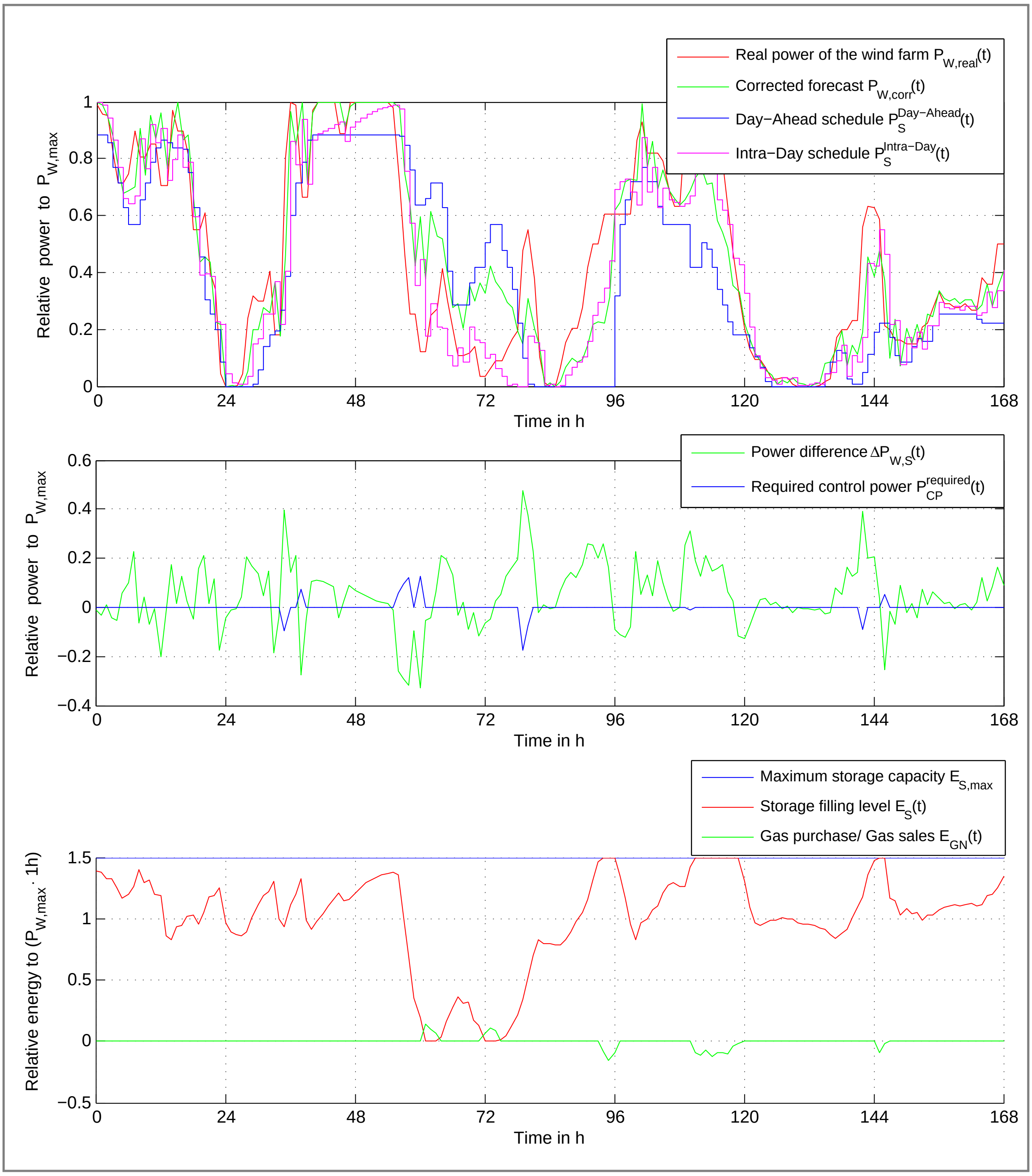

Figure 54: Representation of the various wind power courses of the simulation with all optimization approaches from the chapter 5 for a representative week with $E_{S,max} = 1.5 \cdot E_{W,max}$, $P_{M,max} = -0.3 \cdot P_{W,max}$ and $P_{G,max} = 0.2 \cdot P_{W,max}$

6 Simulation of the virtual power plant to participate in the control energy market

In this chapter, the simulation of temporal sequence of energy flows in the virtual power plant concept from chapter 5 will be supplemented by those of the Section 4.2. First of all the provision of control power is analyzed in order to evaluate his influence on the quality of the optimization. And then the retrieval of control power will be considered.

6.1 Provision of control power

The simulation from Chapter 5 will be complemented by the provision of positive and negative control power referred to the section 4.2. For this the potentials of positive control power $P^{+}_{CP,pot}(t_i)$ and negative control power $P^{-}_{CP,pot}(t_i)$ are determined according to the equations (4.1) to (4.4). These are dependent on the maximum power input of the methanation facility $P_{M,max}$ respectively the maximal power output of the gas power plant $P_{G,max}$. Therefore the maximal values for the potentials of the positive control power provision $max\{P^{+}_{CP,pot}(t_i)\}$ and negative control power provision $max\{P^{-}_{CP,pot}(t_i)\}$ can be expressed in terms of their dependence:

$$max\{P^{+}_{CP,pot}(t_i)\} = P_{G,max} \tag{6.1}$$

$$max\{P^{-}_{CP,pot}(t_i)\} = P_{M,max} - \zeta \cdot \vartheta + (1 - \vartheta) \cdot P_{W,max} \tag{6.2}$$

ζ	Correction value for the Day-Ahead schedule
ϑ	Correction factor for the Day-Ahead schedule

The determination of the actual provided positive control power $P^{+}_{CP,PR}(t_i)$ and negative control power $P^{-}_{CP,PR}(t_i)$ is done in consideration of the Equations (4.5) to (4.10). The next step is to determine the maximal positive control power $P^{-}_{CP,max}$, respectively negative control power $P^{-}_{CP,max}$, which is to be offered. Because the fixed free power capacity for control power have to be considered, the calculation of the caused demand of the control energy $E_{CP}(t_i)$, the storage filling level $E_S(t_i)$, the fed and extracted gas amount from the gas network $E_{GN}(t_i)$

is adjusted, according to the Tables 30 and 31 in the Appendix C. In addition the decreased power capacity of the storage at storage-sided Intra-Day optimization must be considered:

$$max\{f(SFL(t_i))\} \leq -P_{G,max} + P^-_{CP,pot}(t_i) \tag{6.3}$$

$$min\{f(SFL(t_i))\} \geq -P_{M,max} + P^+_{CP,pot}(t_i) \tag{6.4}$$

With the changes of $E_{S,max} = 1.5 \cdot P_{W,max} \cdot 1h$, $P_{M,max} = -0.3 \cdot P_{W,max}$, $P_{G,max} = 0.2 \cdot P_{W,max}$, $P^-_{CP,max} = 0.1 \cdot P_{W,max}$ and $P^-_{CP,max} = -0.1 \cdot P_{W,max}$ the results are $S = 97.39\%$ and $V = 5.94\%$. This shows a barely perceptible deterioration of S and V with respect to a non-offering of control power (Section 5.4.2 with $S = 97.62\%$ and $V = 5.96\%$). Figure 55 shows the temporal sequence of the offered control power as well as the potentials of control power for a representative week.

An improvement of the values S and V could be achieved with a lower maximal positive control power $P^-_{CP,max}$ and negative control power $P^-_{CP,max}$. Other possibilities are the larger maximal power values of the storage unit $|P_{M,max}|$ and $P_{G,max}$ as well as the maximal energy capacity $E_{S,max}$. This is analyzed in more detail later on. Therefore various simulations are made for different $P_{M,max}$, $P_{G,max}$ and $E_{S,max}$ on the one hand and on the other hand for different $P^-_{CP,max}$ and $P^-_{CP,max}$. Afterwards the resulting values for S and V are analyzed along with the monthly average of the provided positive control Energy $\varnothing E^+_{CP,PR}$ and negative control Energy $\varnothing E^-_{CP,PR}$. Table 32 in Appendix C shows the simulation results.

An increase of the maximal offered control power hardly reduces the control energy savings factor S. The technical variables of the storage in the considered time interval show the same behaviors. This shows again, that the effort of a larger sizing of the storage unit does not brings any economical benefit. However the energy loss factor V got its minimum for the technical use variables $E_{S,max} = 2.7 \cdot P_{W,max} \cdot 1h$, $P_{M,max} = -0.35 \cdot P_{W,max}$, $P_{G,max} = 0.26 \cdot P_{W,max}$, independent of the offered control power. Therefore the values which are larger than the previous technical used variables are not considered anymore, because the energy loss factor V is more important for the economical view than the control energy savings factor S.

Conspicuous is the control energy savings factor S at $E_{S,max} = 1.5 \cdot P_{W,max} \cdot 1h$, $P_{M,max} = -0.3 \cdot P_{W,max}$, $P_{G,max} = 0.2 \cdot P_{W,max}$, $P^-_{CP,max} = 0.2 \cdot P_{W,max}$ and $P^-_{CP,max} = -0.2 \cdot P_{W,max}$, because $S = 90,69\%$ varies clearly from the other values. This is due to the fact that the maximal offered positive control power locks the whole power capacity of the gas power plant, consequently no more storage level corrections are allowed.

The monthly averaged provided positive control energy $\varnothing E^+_{CP,PR}$ and negative control energy $\varnothing E^-_{CP,PR}$ increase with larger values for the maximal offered control power and larger technical

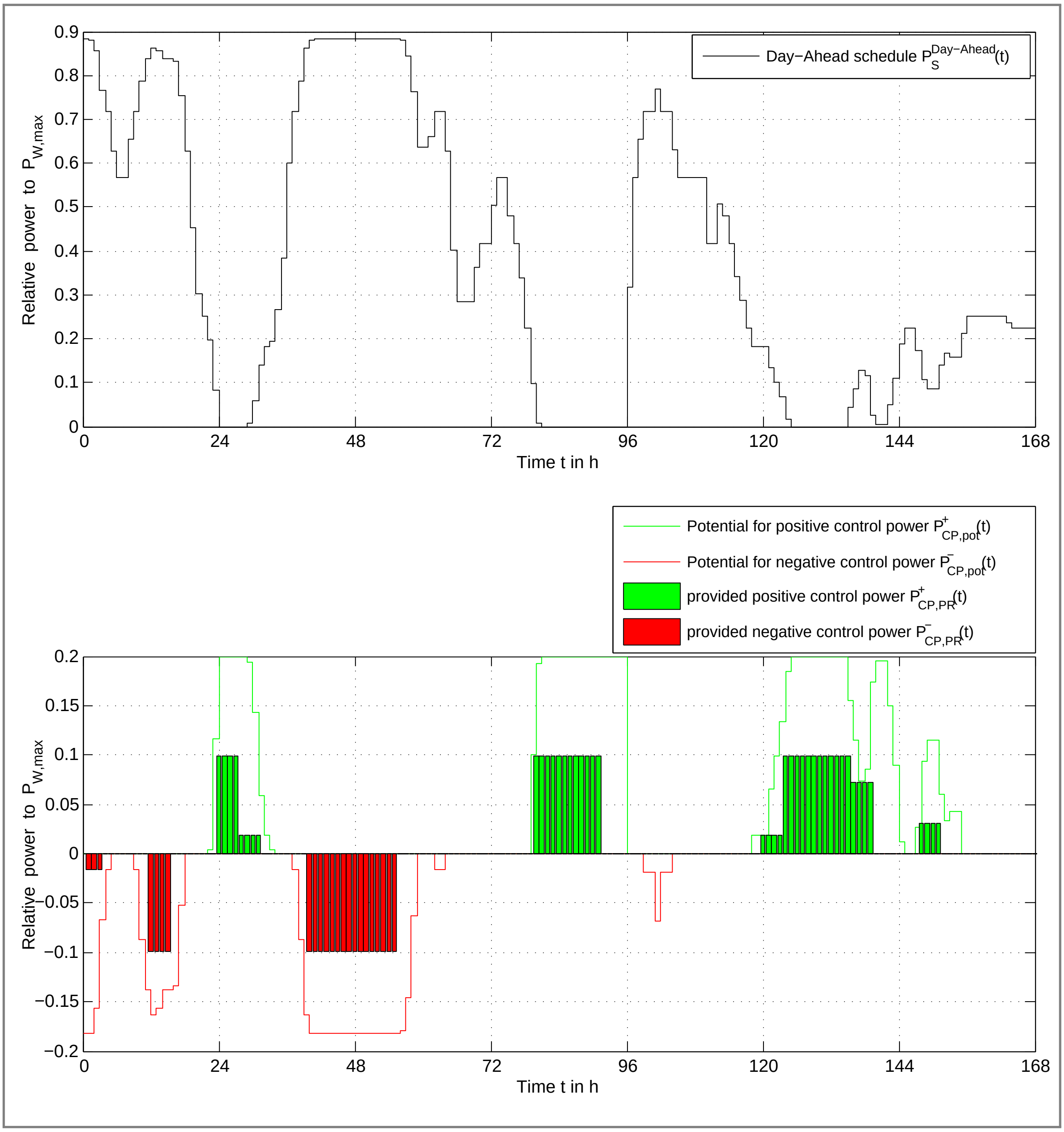

Figure 55: Representation of the provided control power and the Day-Ahead schedule of a representative week from the simulation with $E_{S,max} = 1.5 \cdot P_{W,max} \cdot 1h$, $P_{M,max} = -0.3 \cdot P_{W,max}$, $P_{G,max} = 0.2 \cdot P_{W,max}$, $P^-_{CP,max} = 0.1 \cdot P_{W,max}$ and $P^-_{CP,max} = -0.1 \cdot P_{W,max}$

values for the storage unit. However, this increase is non-linear in both cases so this gain increase will reduce with larger use variables. But since the energy loss factor V and the control energy savings factor S are hardly decreased, the values $P^+_{CP,max} = 0.2 \cdot P_{W,max}$ and $P^-_{CP,max} = -0.2 \cdot P_{W,max}$ are selected in the following manner. So the known values from the table 32 arises: $S = 98.01\%$, $V = 5.75\%$, $\varnothing E^+_{CP,PR} = 41.86 \cdot P_{W,max}(\frac{h}{Month})$ and $\varnothing E^-_{CP,PR} = 36.87 \cdot P_{W,max}(\frac{h}{Month})$.

6.2 Supply of control power

Now the retrieval of control power will be added to the simulation. The used data about the retrieved SCR or MR for this simulation are provided by the internet platform for allocation of control power [RL-ol, 2013]. They are provided in intervals of 15 minutes and include the total retrieved positive and negative control reserve (SCR or MR) of different control areas or the whole system control network. To allow a simulation based on this data, the following assumptions were made:

- The offers of the virtual power plant always get the acceptance of the tender.
- The provided control power can only be retrieved completely.
- The provided control power by VPP will be retrieved completely, if control power is needed in the power system.
- Since the simulation works in 1 hour intervals, the data which are present in 15 minute intervals have to be averaged for each hour.
- As a result there are values for the retrieval of positive and negative control power for each hour, lying between zero and one in the distance of 0,25.
- These values are declared as duration of retrieval of positive control power $\Delta t^{+}_{CP}(t_i)$, respectively negative control power $\Delta t^{-}_{CP}(t_i)$.

The retrieved positive control energy $E^{+}_{CP,RV}(t_i)$ and negative control energy $E^{-}_{CP,RV}(t_i)$ are calculated in the following way:

$$E^{+}_{CP,RV}(t_i) = P^{+}_{CP,PR}(t_i) \cdot \Delta t^{+}_{CP}(t_i) \tag{6.5}$$

$$E^{-}_{CP,RV}(t_i) = |P^{-}_{CP,PR}(t_i)| \cdot \Delta t^{-}_{CP}(t_i) \tag{6.6}$$

As part of the consideration of the altered storage filling level by energy delivery, the calculation of the caused demand of the control energy $E_{CP}(t_i)$, the storage filling level $E_S(t_i)$ and injected respectively extracted gas amount from the gas network $E_{GN}(t_i)$ is adjusted according to the Tables 33 and 34 in the Appendix C.

The Figure 56 shows the temporal progress for a representative week of provided power and retrieved control energy. The temporal resolution of the graph is one hour , thus the retrieval of control energy duration is represented as the height of the retrieved control energy. That must be considered in relationship to the provided control power.

The control energy savings factor S falls slightly to 97,87% and the energy loss factor V increases to 6,42%. These deteriorations are explained by the frequent access to the gas storage.

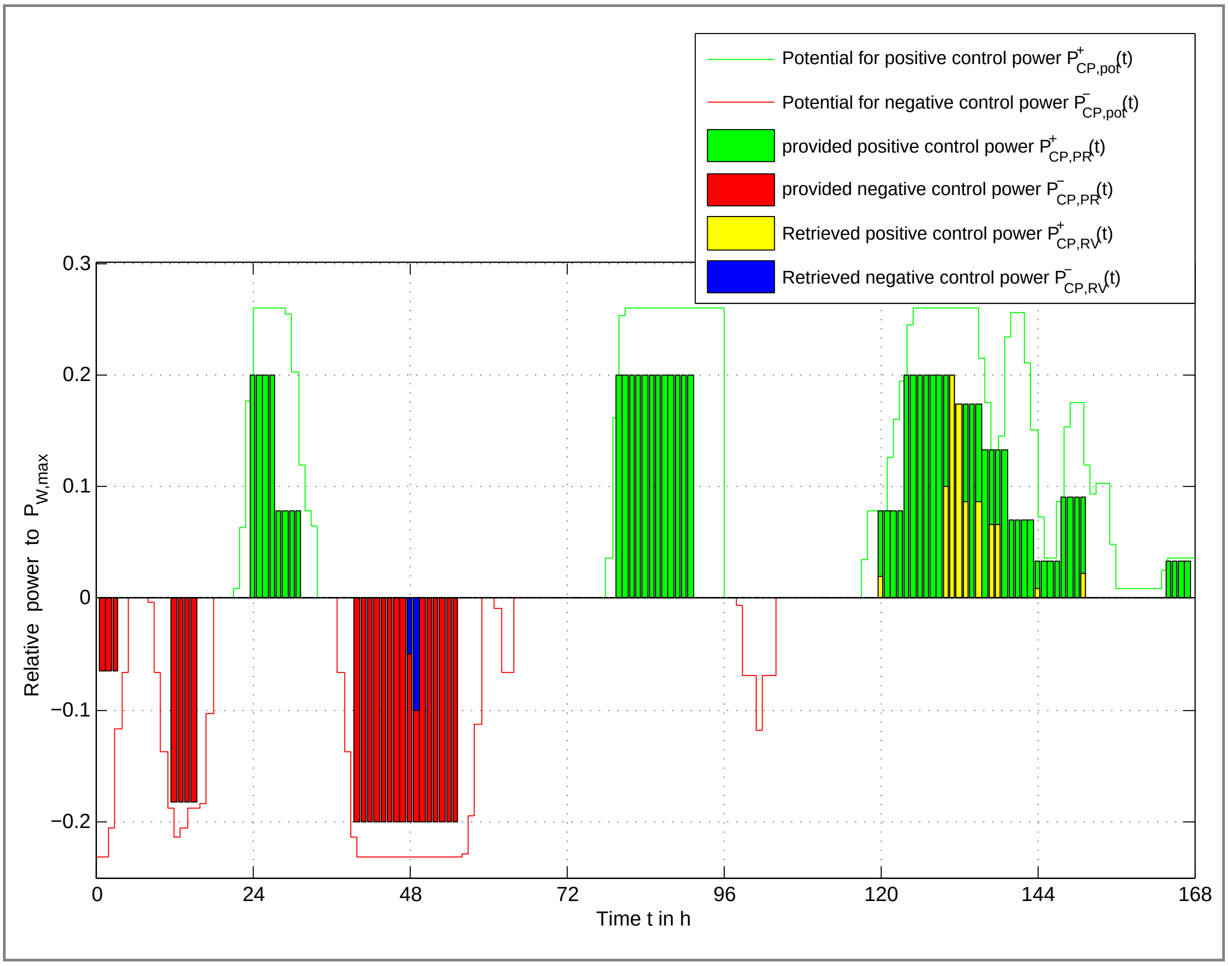

Figure 56: Representation of the provided and retrieved control energy of a representative week from the simulation with $E_{S,max} = 2.7 \cdot P_{W,max} \cdot 1h$, $P_{M,max} = -0.35 \cdot P_{W,max}$, $P_{G,max} = 0.26 \cdot P_{W,max}$, $P^{-}_{CP,max} = 0.2 \cdot P_{W,max}$ and $P^{-}_{CP,max} = -0.2 \cdot P_{W,max}$. Own illustration

The ordinary retrieved positive control energy per month $\varnothing E^{+}_{CP,RV} = 2.43 \cdot P_{W,max}(\frac{h}{Month})$ is well below the ordinary provided positive control energy per month $\varnothing E^{+}_{CP,PR} = 41.86 \cdot P_{W,max}(\frac{h}{Month})$. However, the difference between the ordinary retrieved negative control energy per month $\varnothing E^{-}_{CP,RV} = 6.90 \cdot P_{W,max}(\frac{h}{Month})$ and the ordinary provided negative control energy per month $\varnothing E^{+}_{CP,PR} = 36.87 \cdot P_{W,max}(\frac{h}{Month})$ is clearly less. Although more positive than negative control power was provided, the retrieval of negative control energy was more than positive. It means that 5.8% of the provided positive control power and 18.7% of the negative control power were retrieved. An increased retrieval of negative control energy is economically an advantage, because the storage can be filled at low cost or gratis and in some situations even money is paid for that by TSO (in case of energy excess in power system). Thus this energy is made available for later use in the form of gas, which can then be sold in a different form.

7 Analysis of market-oriented scenarios

In this chapter simulations of the market-oriented scenarios will be introduced. First there will be an overview of how these simulations are designed and what sort of outputs are generated by these simulations. These simulations are made on the basis of an offshore wind farm with an actual power output of 385 MW. There are predicted and real power data for a time period of one year available. The focus is set to some certain technical parameters, like ($P_{G,max}$, $P_{M,max}$ and $E_{S,max}$). On the basis of these parameters the results of all simulations will be evaluated. Due to the fact that there are lots of parameters and data and furthermore there are many scenario variations, a graphical user interface (GUI) has been implemented. This GUI helps the user to run and configure all simulations in a quite comfortable way. In addition to this, all data and results can be visualized in many different ways and all further plots are made with this GUI.

7.1 Base scenario

In this section, the first scenario is discussed. This scenario acts as the base scenario, to which all other scenarios will be compared. One of the main aspect is to prove the need of a Power-to-gGs storage system. Such a system causes great costs like asset costs or working costs. The first scenario describes a wind farm which produced energy is compensated by the EEG-remuneration (Section 2.2.1.1). In this scenario a Power-to-Gas storage system is not needed because no commitment towards an energy exchange or a transmission system operator (TSO) is listed, thus no sophisticated commercial strategies or other investments are required. The base remuneration for one Megawatt-hour is set to 35 €. Figure 57 shows a representation of the sold wind energy by EEG-remuneration. In the next sections new scenarios are introduced, all of them are based on EEX trading with and without provision of control reserve.

7.2 Market-oriented scenarios based on EEX Trading and control energy market

In the following section four different scenarios are described. EEX trading is the base of all these scenarios and EEX trading is combined with provision of Secondary Control Reserve (SCR), provision of Minute Reserve (MR) or both. It is obvious that an energy storage is required due to delivery commitments towards the EEX or the TSO respectively. As mentioned

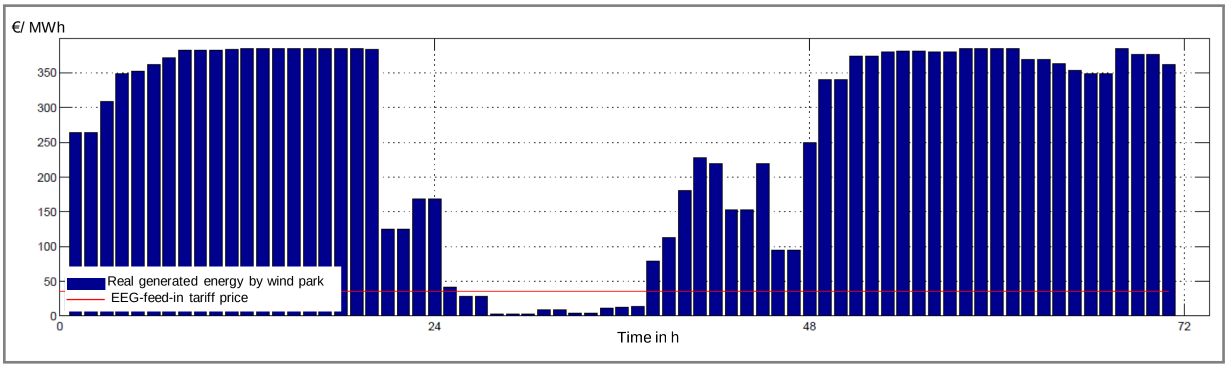

Figure 57: Representation of the sold wind energy through EEG-remuneration for 3 days. Red line indicates the EEG-Remuneration. Blue bars represent the real generated wind energy

before, a maximum amount for positive SCR as well as positive MR is offered to the transmission system operator. This also applies to the negative SCR or negative MR respectively. From the point where such an offer is made, the virtual power plant operator is committed to deliver this amount of energy. As a maximum amount is offered, the real delivered amount of energy might be smaller. This delivery commitment also strains the energy storage, but due to the fact that there is also negative SCR- as well as negative MR retrievals, these amounts of energy can be used to fill up the energy storage. The delivery commitment towards the EEX is based on the Intra-Day schedule (Section 5.3). The wind farm should be able to produce enough energy to satisfy the EEX as well as the transmission system operator. If an energy overrun is achieved, it can be used to fill up the energy storage, in case of an energy deficit it has to be compensated by the energy storage. An overrun is described by:

$$\Delta P_W(t_i) = P_{W,real}(t_i) - (P_S^{Intra-Day}(t_i) + P^+_{SCR,RV}(t_i) + P^+_{MR,RV}(t_i)) > 0 \tag{7.1}$$

otherwise a deficit is described by:

$$\Delta P_W(t_i) = P_{W,real}(t_i) - (P_S^{Intra-Day}(t_i) + P^+_{SCR,RV}(t_i) + P^+_{MR,RV}(t_i)) < 0 \tag{7.2}$$

Where $P^+_{SCR,RV}(t_i)$ or respectively $P^+_{MR,RV}(t_i)$ denotes the positive retrieved SCR or respectively the positive retrieved MR. In case of a deficit, this has to be compensated by the energy storage:

$$\Delta P_W(t_i) < 0 \qquad and \qquad |\Delta P_W(t_i)| < P_{G,max} \tag{7.3}$$

$$\Delta P_W(t_i) < 0 \qquad and \qquad |\Delta P_W(t_i)| > P_{G,max} \tag{7.4}$$

If the deficit is less than the maximum power output of the storage unit $P_{G,max}$ (Formula 7.3), then this can be filled up by the energy storage. If the deficit is greater than $P_{G,max}$ (Formula 7.4), then a further control reserve is required.

This has to be bought from the TSO. Due to the high prices of the control reserve this should be avoided. In case of an energy excess which means that the wind farm produces more energy than required for EEX trading, positive Secondary Control Reserve and positive Minute Reserve, this overrun can be used to fill up the energy storage. Nevertheless filling of the storage is limited by the maximum power input of the storage unit $P_{M,max}$ in time t_i.

$$\Delta P_W(t_i) > 0 \qquad and \qquad |\Delta P_W(t_i)| > P_{M,max} \tag{7.5}$$

In case of a completely filled storage, the energy excess is sold in the form of gas. The sale of gas is also limited by the maximum power input of the methanation facility in time t_i.

Figure 58 and 59 illustrates the described behavior and should help to interpret all following Figures. The first illustrates a called control reserve (1) and the components it is composed of. These components are the portion of the wind farm (2), and the portion of the gas storage (3) and also used control reserve by TSO (4). As mentioned before this control reserve is required in case of deficit, which can not be compensated by the gas storage. Decreasing the need of this correctional control reserve is one of the main advantages of an energy storage. As can be seen, called control reserve (1) is composed of all three components (5), nevertheless a composition of wind farm and energy storage (or only one of them) without correctional control reserve is aspired.

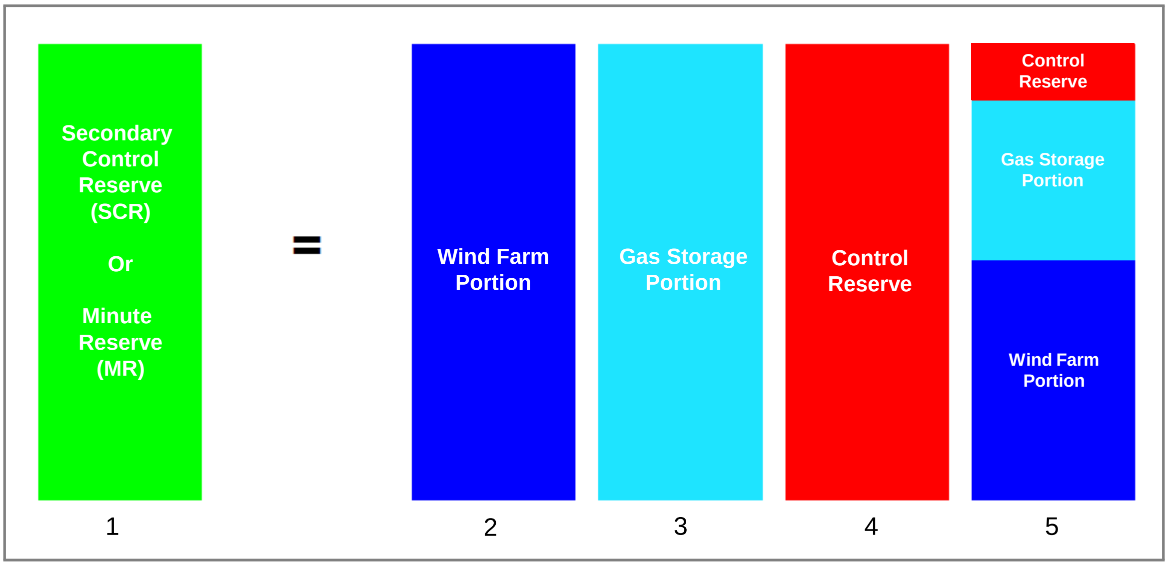

Figure 58: Components of called control reserve

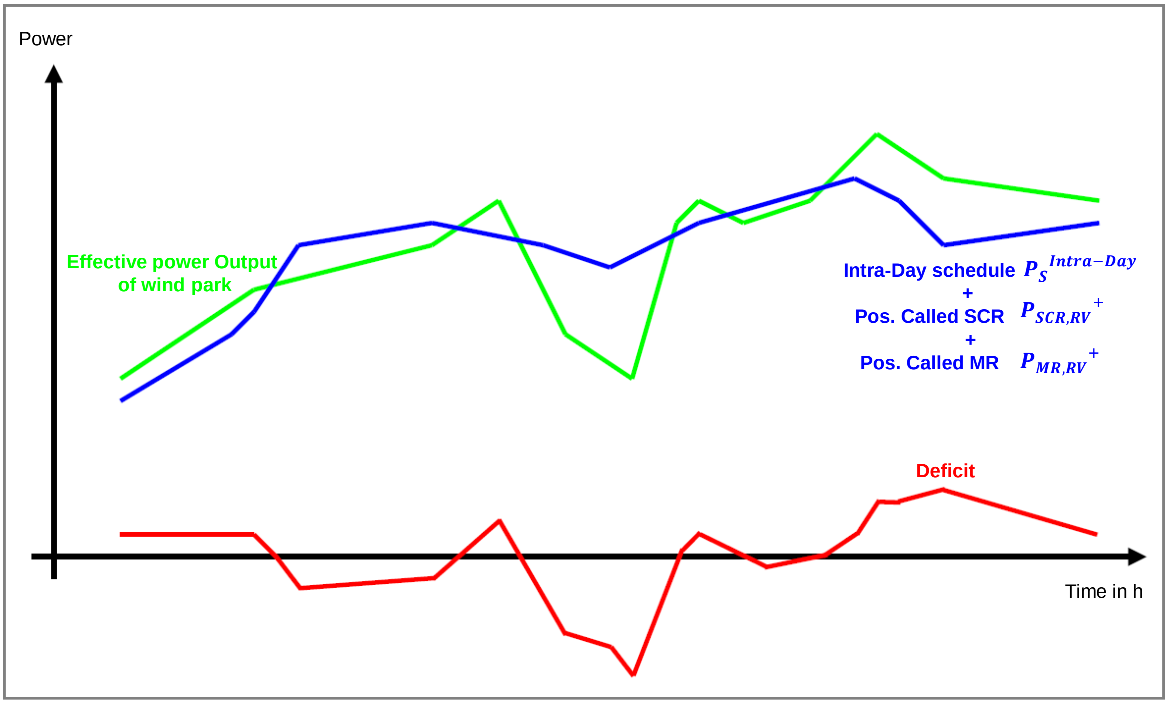

Figure 59: Schematic to show the correlation between the effective power output of the wind farm and the resulting deficit or respectively overrun

Figure 59 illustrates Formula 7.1 and 7.2. The green line represents the power output of the wind farm. The blue line represents the sum of the Intra-Day schedule, positive Secondary Control Reserve and positive Minute Reserve whereas the red line indicates the overrun or respectively the deficit which means the difference between the green and the blue line. In the following graphics, some data sets are printed as lines, stairs or bars. For a better understanding of all following graphics, consider that all bars are printed one after another, except the three components of Figure 58. The portion of the wind farm, the portion of the gas storage and lastly the correctional control reserve are printed in a stacked manner, thus stacking these components result in a bar of the same height as corresponding positive control reserve (Figure 58 (1) and (5)).

At the beginning of all scenario descriptions the basic parameter setting is defined and the technical aspects plus results are discussed (consider that the percentage values in the tables refer to the total wind farm power output). After that a visualization of the graphics is presented. This visualization usually describes a 72 hours time period which is not representing the whole simulation, but it shows some critical aspects, as there are deficit or excess situations, windless periods etc. Thus different time periods might be shown to provide a meaningful cutout of the whole simulation. In the following scenarios we focus on these technical parameters:

- Overall EEX sales $\sum_{t=1}^{end} E_S^{Intra-Day}(t)$
- Overall positive retrieved Secondary Control Reserve (MWh) $\sum_{t=1}^{end} E_{SCR,RV}^{+}(t)$

- Overall negative retrieved Secondary Control Reserve (MWh) $\sum_{t=1}^{end} E_{SCR,RV}^{-}(t)$
- Overall positive retrieved Minute Reserve (MWh) $\sum_{t=1}^{end} E_{MR,RV}^{+}(t)$
- Overall negative retrieved Minute Reserve (MWh) $\sum_{t=1}^{end} E_{MR,RV}^{-}(t)$
- Overall energy deficit (MWh) $\sum_{t=1}^{end} E_{deficit}(t)$
- Overall gas sales (MWh) $\sum_{t=1}^{end} E_{sale}^{Gas}(t)$
- Overall energy overrun (MWh) $\sum_{t=1}^{end} E_{excess}(t)$

As denoted in the list above, $E_{deficit}$ and E_{excess} describes the energy deficit or the energy excess respectively. In case of an overrun the energy is absorbed by the gas storage. In case of a deficit there are some different cases that must be respected. First there is a deficit concerning the EEX trading. Second there is a deficit regarding Secondary Control Reserve and last a deficit regarding Minute Reserve. The amount of energy produced by the wind farm is first used for Secondary Control Reserve, then it is used for Minute Reserve and last it is used for EEX trading. The same applies the gas storage energy output. In other words, the control reserve calls are preferred over EEX trading. That is, because deficits or overruns regarding control reserve has to be compensated by the so called correctional control reserve. The correctional control reserve may cause great cost to the wind farm operator, but also making profit with correctional control reserve is possible. The correctional control reserve is calculated in a 15 minute clock pulse and the calculated prices are unpredictable for the wind farm operator. Thus the amount of energy overruns and energy deficits should be as small as possible. Deficits in case of EEX trading have to be compensated by EEX trading itself. The next list gives an overview over the parameter set which is used for simulations:

- Maximum provided positive control power for SCR (MW) $P_{SCR,PR}^{+,max}$
- Maximum provided negative control power for SCR (MW) $P_{SCR,PR}^{-,max}$
- Maximum provided positive control power for MR (MW) $P_{MR,PR}^{+,max}$
- Maximum provided negative control power for MR (MW) $P_{MR,PR}^{-,max}$
- Maximum power output (Gas Turbine) (MW) $P_{G,max}$
- Maximum power input (Methanation Facility) (MW) $P_{M,max}$
- Maximum Gas Storage Capacity (MWh) $E_{S,max}$

Consider that the economical performance not only depends on the amount of sold energy. The achieved prices in EEX trading may differ hugely from prices for Secondary Control Reserve or Minute Reserve. Furthermore among the demand price there is a base price for provision

Secondary Control Reserve or respectively Minute Reserve which means that money can be earned without delivering of real energy. In addition to that correctional control reserve is expensive and should be avoided. So a smart operating strategy might be the better way as compared to only maximize the energy output.

7.2.1 Scenario 1: EEX Trading

This section describes the simulation of EEX trading without control reserve. Figure 60 illustrates the results for a 72 hours time period. The green line indicates the deficit/overrun of the output power of the wind farm whereas the gray line indicates the filling level of the gas storage. If the gas storage is completely filled up and an energy overrun occurs, the excessive energy is converted into gas and is sold. When the energy overrun exceeds the maximum power input $P_{M,max}$ of the methanation facility, the excessive energy has to be compensated by the correctional control reserve.

Scenario 1: EEX Trading			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	128	$P^{+,max}_{SCR,PR}$	0
$P_{M,max}$	-203	$P^{-,max}_{SCR,PR}$	0
$E_{S,max}$	577.5 (MWh)	$P^{+,max}_{MR,PR}$	0
		$P^{-,max}_{MR,PR}$	0

Table 6: Parameter set for simulation of Scenario 1: EEX trading

This is indicated by a negative correctional control reserve (time step 697 (red bar)). There are four time steps in this time period where correctional control reserve (positive red bar) is needed, which simply means that the produced energy of the wind farm can not satisfy the Intra-Day schedule. It can be observed the gas storage filling level decreases at the next time steps but the storage unit can not cover the deficit, thus further control reserve is required. As mentioned before this further control reserve should be avoided as far as possible. Hence this is a key parameter and it is a measure of the utilization ratio. If there are large amounts of correctional control reserve, this means the wind farm and gas storage are overstressed. On the other hand there is the amount of energy excess E_{excess} which can not be used in a meaningful way.

The value of this parameter should also be small because large values indicate an ineffective operation of the wind farm and the gas storage. The main target is to achieve a high workload,

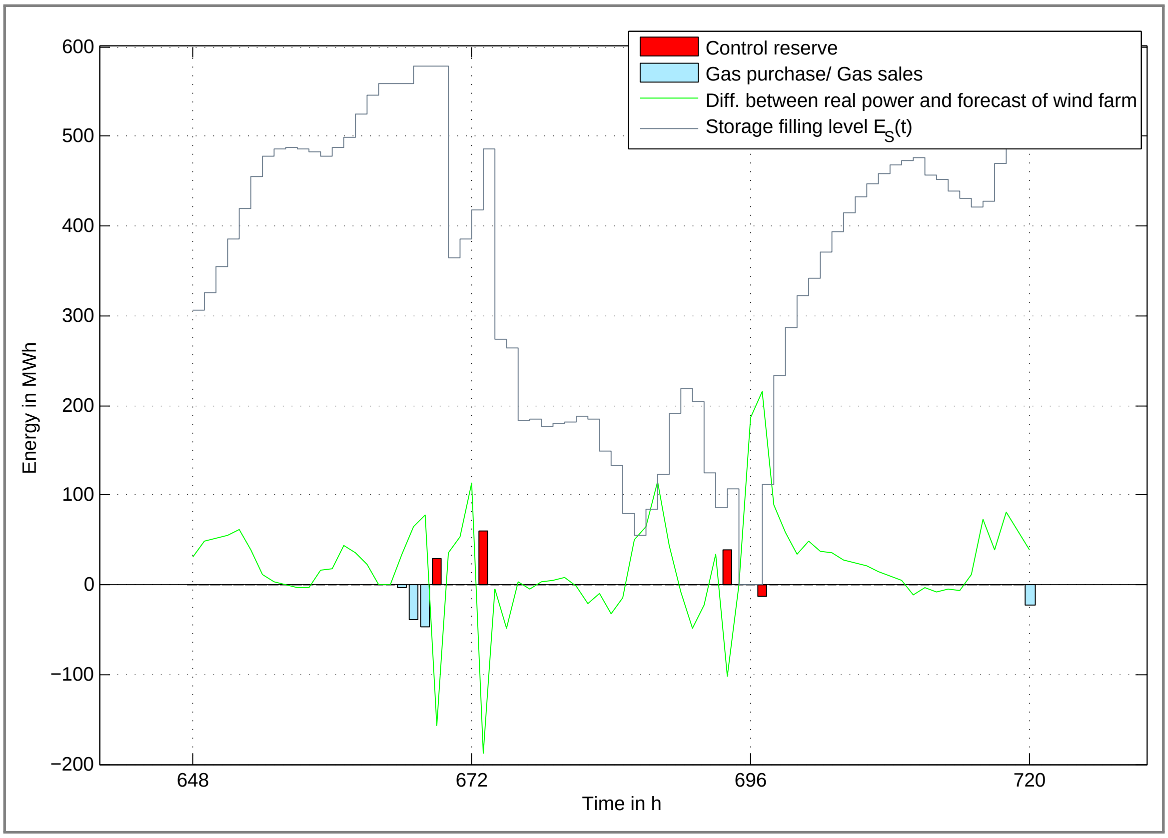

Figure 60: Visualization of Scenario 1: EEX Trading

but neither over-stressing (high $E_{deficit}$) the wind farm or gas storage nor ineffective operation E_{excess}. The amount of sold gas E_{sale}^{Gas} is also an interesting technical value. High gas sales indicate either a too small gas storage capacity or too small methanation capacity. Thus we will also keep an eye on this value. Table 7 lists the results of the simulation of Scenario 1. At this point it is difficult to rate these values due to the fact that there are no comparative values at this point.

Scenario 1: EEX Trading			
Parameter	**Value (MWh)**	**Parameter**	**Value (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	$\sum_{t=1}^{end} E_{SCR,RV}^{+}$	0
$\sum_{t=1}^{end} E_{deficit}$	658.2	$\sum_{t=1}^{end} E_{SCR,RV}^{-}$	0
$\sum_{t=1}^{end} E_{excess}$	114.1	$\sum_{t=1}^{end} E_{MR,RV}^{+}$	0
$\sum_{t=1}^{end} E_{sale}^{Gas}$	1,987.9	$\sum_{t=1}^{end} E_{MR,RV}^{-}$	0

Table 7: Technical results for simulation of Scenario 1: EEX trading

7.2.2 Scenario 2: EEX Trading and Secondary Control Reserve

Now in addition to the EEX trading this simulation involves also the participation in the control energy market with provision of SCR. Now the gas storage is also strained by the retrieved positive Secondary Control Reserve $E^{+}_{SCR,RV}$, else the storage can be filled up by the called negative Secondary Control Reserve $E^{-}_{SCR,RV}$.

Scenario 2: EEX Trading and provision of SCR			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	128	$P^{+,max}_{SCR,PR}$	77
$P_{M,max}$	-203	$P^{-,max}_{SCR,PR}$	77
$E_{S,max}$	577.5 (MWh)	$P^{+,max}_{MR,PR}$	0
		$P^{-,max}_{MR,PR}$	0

Table 8: Parameter set for simulation of Scenario 2: EEX trading and provision of Secondary Control Reserve

Figure 61 illustrates the same 72 hours time period as in the previous simulation. Compared to the first simulation the required control reserve occurs at the same time-stamp period but it has increased due to the call of positive control reserve. Furthermore at time steps (677 - 679) and (695 - 696) extra correctional control reserve occurred. In this time period gas storage filling also have increased due to the call of negative Secondary Control Reserve. Now the results can be analyzed in Table 9 and compared to the previous simulation. Here all three key parameters have increased. E^{Gas}_{sale} (+60.8%), $E_{deficit}$ (+13%) and E_{excess} (+78%). The amount of sold energy on the basis of the Intra-Day schedule remained constant whereas now also called positive as well as negative Secondary Control Reserve have to be considered.

Scenario 2: EEX Trading and provision of SCR			
Parameter	**Value (MWh)**	**Parameter**	**Value (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	$\sum_{t=1}^{end} E^{+}_{SCR,RV}$	46,758.2
$\sum_{t=1}^{end} E_{deficit}$	7,681.8	$\sum_{t=1}^{end} E^{-}_{SCR,RV}$	29,471.7
$\sum_{t=1}^{end} E_{excess}$	203.3	$\sum_{t=1}^{end} E^{+}_{MR,RV}$	0
$\sum_{t=1}^{end} E^{Gas}_{sale}$	3,197.1	$\sum_{t=1}^{end} E^{-}_{MR,RV}$	0

Table 9: Technical results for simulation of Scenario 2: EEX Trading and provision of Secondary Control Reserve

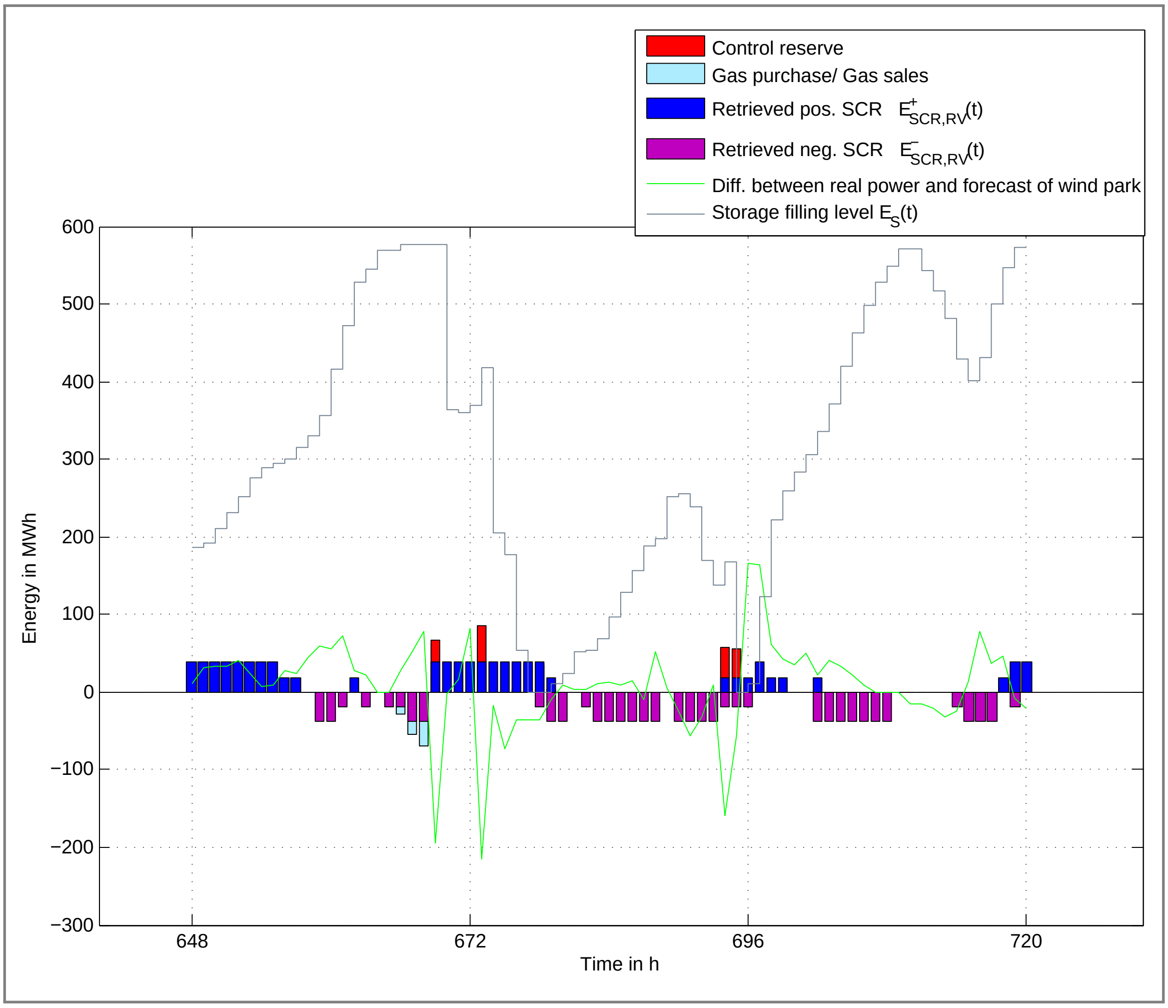

Figure 61: Visualization of scenario 2: EEX Trading and SCR

7.2.3 Scenario 3: EEX Trading and Minute Reserve

This simulation is quiet similar to the previous one. The main difference here is the rare occurrences of MR retrievals compared to SCR ones. Thus Figure 62 gives another 72 hours time period, because in the previous period no Minute Reserve was retrieved. In this time period correctional control reserve is required at time steps 1383, 1385 and 1390.

But as can be seen in the Figure 62 the correctional control reserve has decreased as compared to the previous scenario. This can be explained by a look at the amount of retrieved positive and negative MR ($E^{+}_{MR,RV}$ and $E^{-}_{MR,RV}$). These are much smaller than the amounts of retrieved Secondary Control Reserve (Table 9 and Table 11) which results in a smaller demand of the gas storage. But the main idea is, that in case of Minute Reserve the calls of negative control reserve are about three times greater than the positive ones. In case of SCR the negative retrievals were only two thirds of the positive ones. Due to the objective that in this case the negative calls are much greater than the positive ones, the gas storage is filled up

Scenario 3: EEX Trading and provision of MR			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	128	$P^{+,max}_{SCR,PR}$	0
$P_{M,max}$	-203	$P^{-,max}_{SCR,PR}$	0
$E_{S,max}$	577.5 (MWh)	$P^{+,max}_{MR,PR}$	77
		$P^{-,max}_{MR,PR}$	77

Table 10: Parameter set for simulation of Scenario 3: EEX trading and provision of Minute Reserve

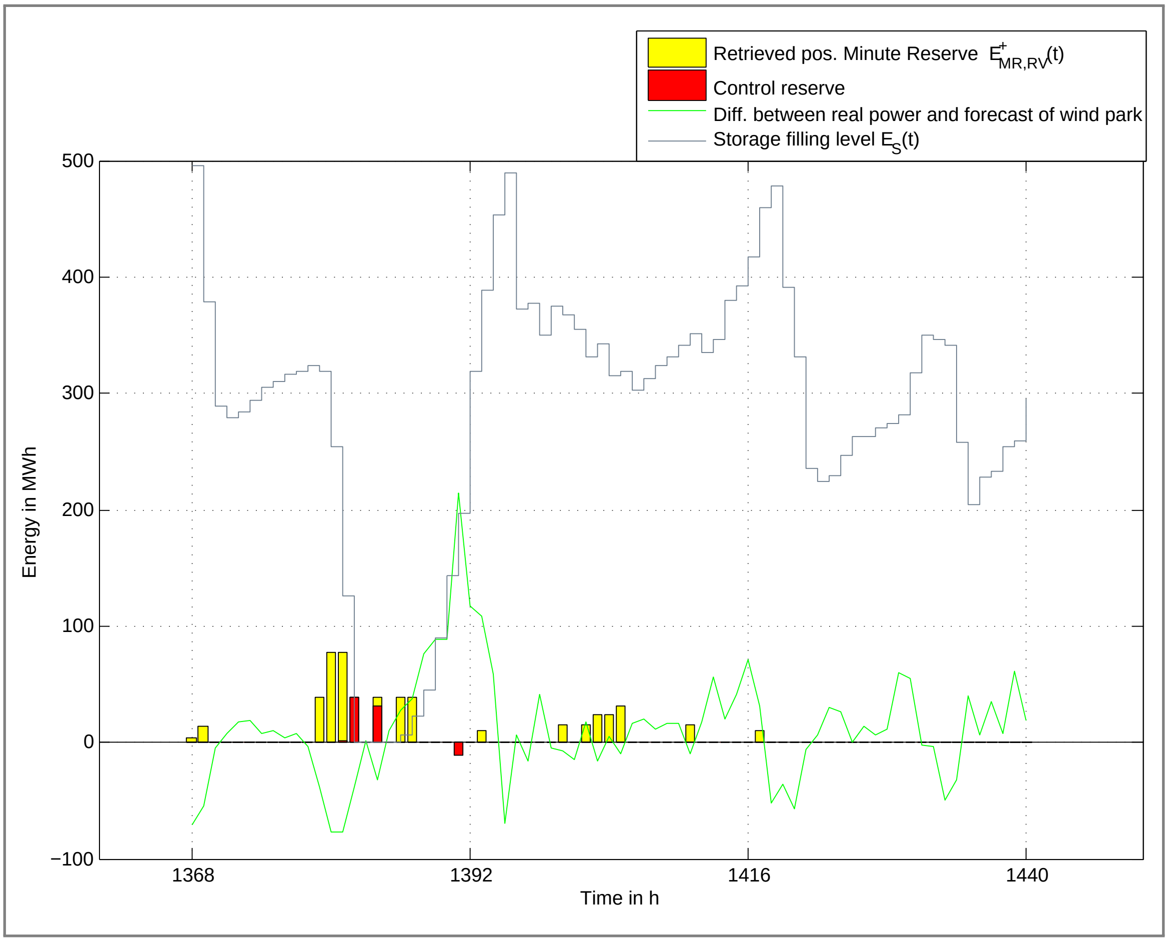

Figure 62: Visualization of scenario 3: EEX Trading and MR

by negative MR and that leads to the much smaller values of E^{Gas}_{sale}, $E_{deficit}$ and correctional control reserve (red bar).

Scenario 3: EEX Trading and provision of MR			
Parameter	**Value (MWh)**	**Parameter**	**Value (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	$\sum_{t=1}^{end} E_{SCR,RV}^{+}$	0
$\sum_{t=1}^{end} E_{deficit}$	1,417.7	$\sum_{t=1}^{end} E_{SCR,RV}^{-}$	0
$\sum_{t=1}^{end} E_{excess}$	127.2	$\sum_{t=1}^{end} E_{MR,RV}^{+}$	4,873
$\sum_{t=1}^{end} E_{sale}^{Gas}$	2,690.4	$\sum_{t=1}^{end} E_{MR,RV}^{-}$	14,066.7

Table 11: Technical results for simulation of Scenario 3: EEX trading and provision of Minute Reserve

7.2.4 Scenario 4: EEX Trading combined with provision of Secondary Control Reserve and Minute Reserve

This scenario describes the composition of all three ways of direct marketing, EEX, Secondary Control Reserve and Minute Reserve. The maximum amount of provided control reserve is 20% of the total wind farm power output, but now it is divided into 12% for SCR (positive and negative) and 8% for MR (positive and negative).

Scenario 4: EEX Trading combined with provision of SCR and MR			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	128	$P_{SCR,PR}^{+,max}$	46.2
$P_{M,max}$	-203	$P_{SCR,PR}^{-,max}$	46.2
$E_{S,max}$	577.5 (MWh)	$P_{MR,PR}^{+,max}$	30.8
		$P_{MR,PR}^{-,max}$	30.8

Table 12: Parameter set for simulation of Scenario 4: EEX trading combined with provision of SCR and MR

When looking at Figure 63, it can be seen that in the illustrated time period nearly all the time a power deficit occurs. The gas storage capacity is used up in the first few hours but almost all the time positive Secondary Control Reserve is called as well as positive Minute Reserve. Furthermore only five calls of negative control reserve were registered. Thus the gas storage is extremely overcharged and the promised amount of control reserve can not be delivered which results in extreme high requirements of correctional control reserve retrievals (Figure 64 and 65). In this Figure you can see the control reserve calls in more detail. Obviously the portion of the gas storage doesn't match the required amount of energy. Only in a few time slots, the storage delivers some energy to satisfy the demand for SCR, for MR there is even no capacity left.

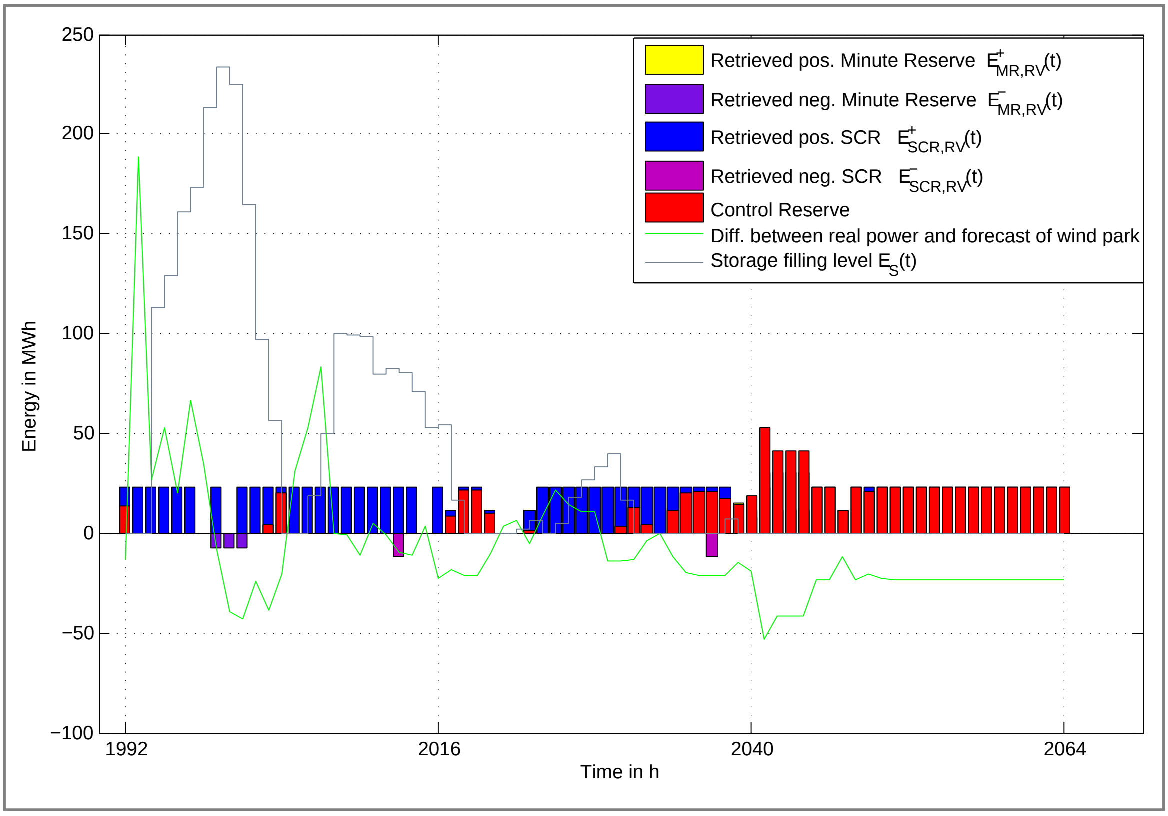

Figure 63: Visualization of Scenario 4: EEX Trading combined with provision of SCR and MR (all bars are NOT stacked!)

In all this problematic may occur, but participation in Secondary Control Reserve is more prone than the EEX trading or participation in Minute Reserve. That is why Secondary Control Reserve has to be provided for one week in advance whereas Minute Reserve can be provided only for a single day in advance. Thus providing Minute Reserve allows you to react in a more suitable way to weather forecasts. Long deficit periods as seen in Figure 63 usually appear due to windless weather conditions. That is another reason for the great amounts of correctional control reserve when providing SCR compared to providing MR.

Scenario 4: EEX Trading combined with provision of SCR and MR			
Parameter	**Value (MWh)**	**Parameter**	**Value (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	$\sum_{t=1}^{end} E^+_{SCR,RV}$	28,054.9
$\sum_{t=1}^{end} E_{deficit}$	3,832.2	$\sum_{t=1}^{end} E^-_{SCR,RV}$	17,683
$\sum_{t=1}^{end} E_{excess}$	163.6	$\sum_{t=1}^{end} E^+_{MR,RV}$	2,197.2
$\sum_{t=1}^{end} E_{sale}^{Gas}$	1,750.8	$\sum_{t=1}^{end} E^-_{MR,RV}$	5,700.5

Table 13: Technical results for simulation of Scenario 4: EEX Trading combined with provision of SCR and MR

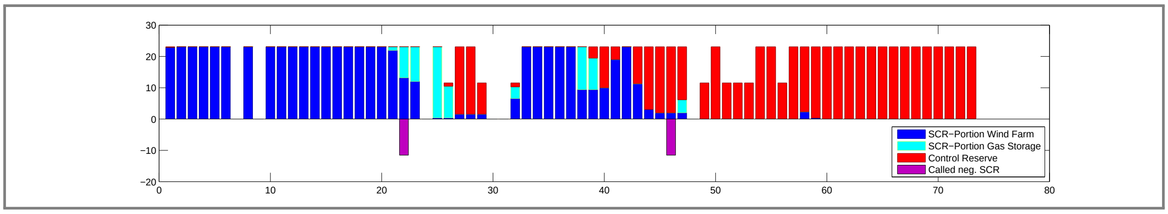

Figure 64: Secondary Control Reserve calls are visualized in the Figure. Huge amounts of correctional control reserve can be seen. (Bars are stacked!)

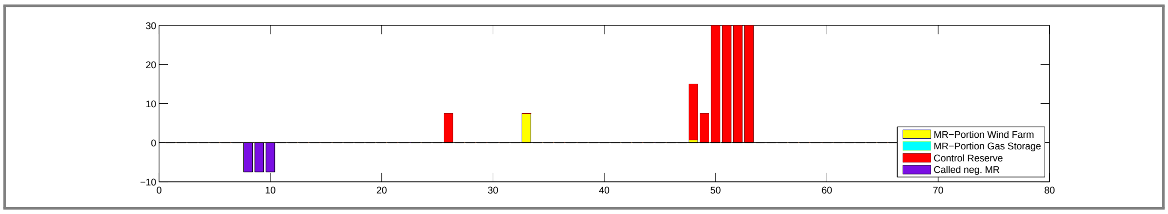

Figure 65: Minute Reserve retrievals are visualized. Compared to Figure 64 significantly fewer correctional control reserve is required. (Bars are stacked!)

7.2.5 Summary of all EEX based scenarios

In this section the results of all four simulations are recapitulated. As has already been said, there are some parameters which are more or less independent of the kind of simulation. But there are also parameters like the retrievals of the correctional control reserve or the amount of gas sales which may depend significantly depending on the kind of simulation. Table 14 gives an overview of the achieved results. Marked with red or respectively green color are the $E_{deficit}$ values of the EEX and SCR- or respectively EEX and MR simulation. This value is about five times greater when offering SCR compared to the offer of Minute Reserve.

Figures 66, 67, 68 and 69 give an overview over the different gas storage modes. The mode is numbered from 1 to 8. The single numbers have the following meanings:

The main difference can be noticed at mode 3 and 7. It can be noticed from tables 15 and 16, mode 3 describes an overrun situation and the gas storage is capable to collect the power, but is not capable to store the whole energy.

As one might have been expected the EEX and Minute Reserve simulation achieves the greatest value- not surprisingly, as the retrieved negative Minute Reserve fills up the gas storage which leads to more overrun situations. Mode 7 describes a deficit situation. The gas storage can handle the required power, but can not deliver the required amount of missing energy. The EEX-SCR simulation achieves the greatest values for mode 7, due to the fact that there are lots of consecutive and positive SCR calls, which overstrains the gas storage. Overall it can be said that the great majority of excesses and deficits doesn't rely on simulation. The participation in the control reserve market reinforces the excess- and deficit-effects but their occurrences

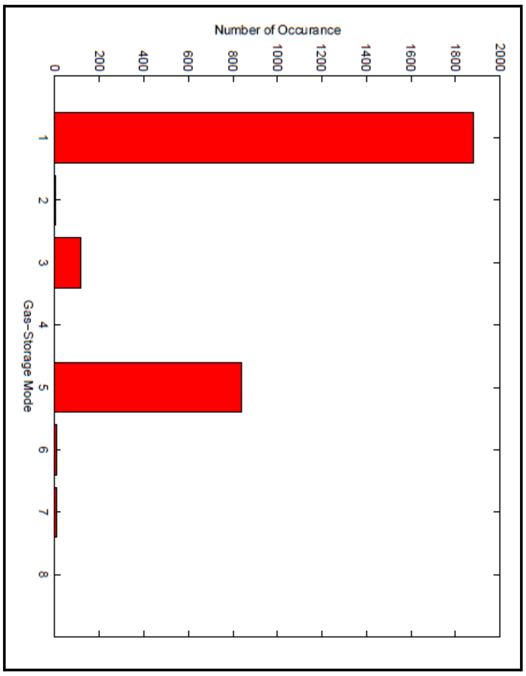

Figure 66: Gas storage mode: Scenario 1 (EEX)

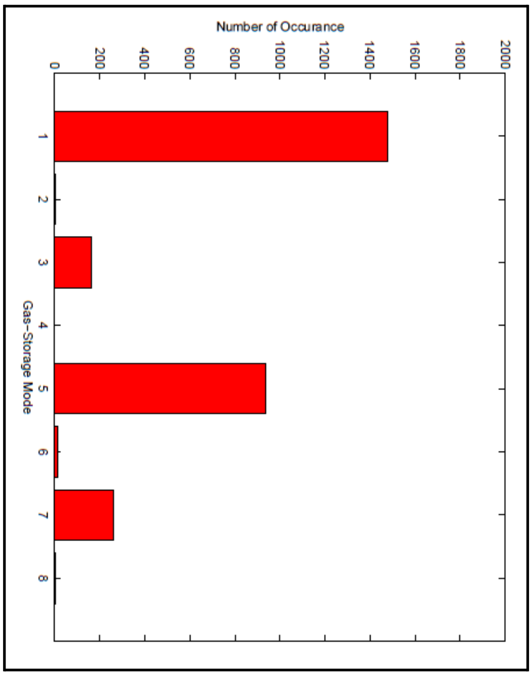

Figure 67: Gas storage mode: Scenario 2 (EEX & SCR)

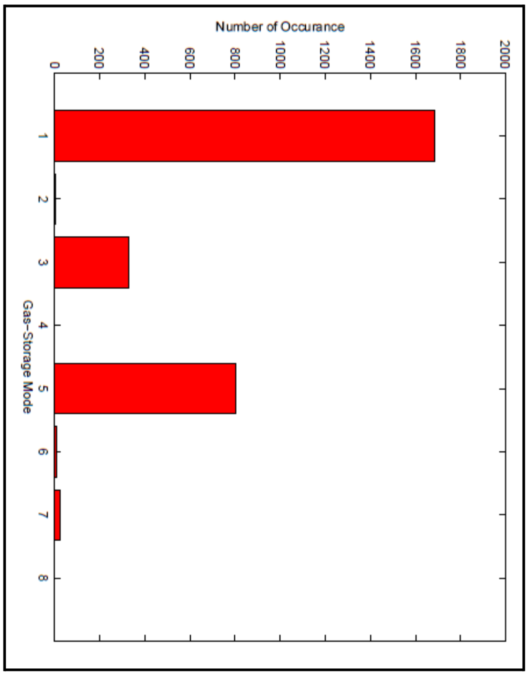

Figure 68: Gas storage mode: Scenario 3 (EEX & MR)

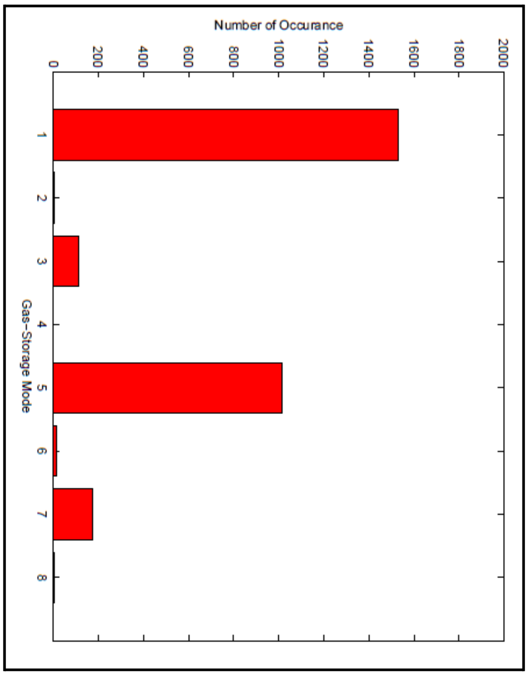

Figure 69: Gas storage mode: Scenario 4 (EEX & SCR & MR)

Summary of all EEX based scenarios				
Parameter	**EEX (MWh)**	**EEX+SCR (MWh)**	**EEX+MR (MWh)**	**EEX+SCR+MR (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	591,360	591,360	591,360
$\sum_{t=1}^{end} E_{SCR,RV}^{+}$	0	46,758.2	0	28,054.9
$\sum_{t=1}^{end} E_{SCR,RV}^{-}$	0	29,471.7	0	17,683.0
$\sum_{t=1}^{end} E_{MR,RV}^{+}$	0	0	4,873	2,197.2
$\sum_{t=1}^{end} E_{MR,RV}^{-}$	0	0	14,066.7	5,700.5
$\sum_{t=1}^{end} E_{deficit}$	658.2	7,681.8	1,417.7	3,832.2
$\sum_{t=1}^{end} E_{excess}$	114.1	203.3	127.2	163.6
$\sum_{t=1}^{end} E_{sale}^{Gas}$	1,987.9	3,197.1	2,690.4	1,750.8

Table 14: Overview over the technical results of all four scenarios. (Best value for energy deficit is marked green, worst value marked red)

Energy excess		
	Storage can deliver power	**Storage can not deliver power**
Storage can handle excess	1	2
Storage can not handle excess	3	4

Table 15: Overview of the different excess modes

Energy deficit		
	Storage can deliver power	**Storage can not deliver power**
Storage can handle deficit	5	6
Storage can not handle deficit	7	8

Table 16: Overview of the different deficit modes

are only varying to a negligible extent. The conclusion is that weather conditions rule the behavior of the gas storage in a significant manner, more than the use of control reserve. In order to minimize the deficits or respectively the not manageable overruns the capacity of the gas storage or/and the power input-output of the gas storage has to be increased.

7.3 Market-oriented scenarios only based on control energy market

Now, simulations based only on control energy market, more precisely on Secondary Control Reserve and Minute Reserve are investigated. Before introducing these simulations, some expected problems and some possible ways to handle these problems will be discussed. Due to the fact that there is no EEX trading anymore, the amount of provided control reserve has to be increased to achieve appropriate economical results. As can be seen in Figures 66, 67, 68 and 69 there are lots of deficit situations. A question arises here: How to handle these deficit periods in a meaningful way even with great amounts of provided control reserve? The main problem might be the limited gas storage capacity. The second one: How to handle the energy overrun in case of long term periods of negative control reserve calls?. Here again the limited gas storage capacity might be a problem. Furthermore the output performance should be increased to serve all requirements. In the next section the SCR based scenario will be introduced, then the MR based scenario will be discussed in more detail and at end a combination of SCR and MR will be investigated.

7.3.1 Scenario 5: Secondary Control Reserve

Figure 70 shows a 72 hours time period. It can easily be seen that huge amounts of correctional control energy are required due to a disproportionate capacity of the gas storage as well as a too small input performance of the methanation facility. In addition it can be seen that the positive Secondary Control Reserve retrievals can not be satisfied, due to an inappropriate gas storage capacity.

In contrast to further graphics the real power output of the wind farm is also visualized by the brown line. The green line indicates the overrun or respectively the deficit. $\Delta P_W(t_i)$ denotes the difference of produced and delivered power and $P_{M,max}$ describes the power input of the storage unit. If,

$$\Delta P_W(t_i) > P_M \qquad then \qquad \Delta P_W(t_i) - P_M = 0.5 \cdot (P^{-,max}_{SCR,PR}(t_i) + P^{-,max}_{MR,PR}(t_i)) \quad (7.6)$$

where $P^{-,max}_{SCR,PR}(t_i)$ and $P^{-,max}_{MR,PR}(t_i)$ denotes the maximum provided negative SCR or respectively negative MR. Figure 70 shows the same 72 hours time period as before. Obviously the amount of correctional control reserve has increased. To reduce this amount the gas storage capacity is increased up to 350% of the wind farm power output which results to an absolute value of 1,347.5 MWh. Figure 71 illustrates the achieved results.

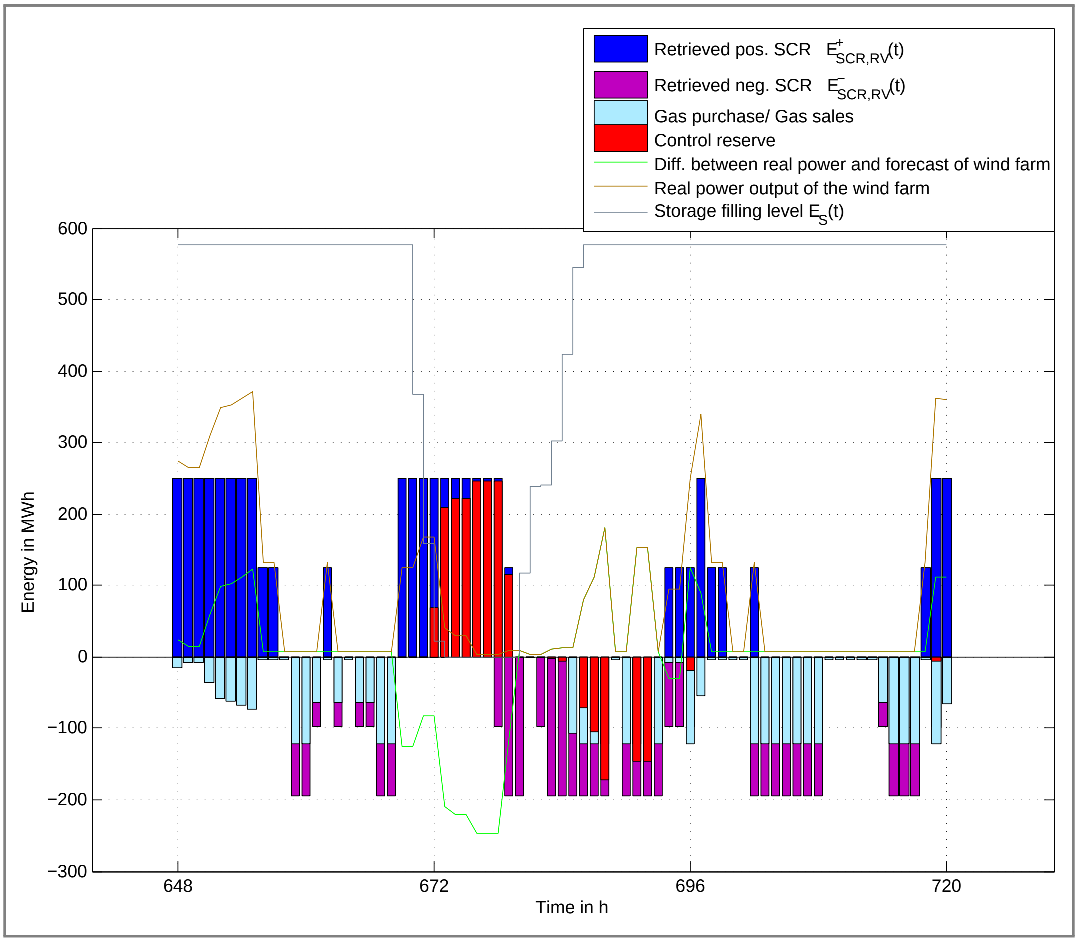

Figure 70: Visualization of Scenario 5 with the same parameter set as Scenario 1, but without EEX trading

It can be seen that the capacity has increased but the gas purchases in this time period are quiet similar to the previous simulations which is an indication of a a small gas storage capacity. Furthermore it can be noted that the positive correctional control reserve calls are less then the last time but there are still some left over. There are seven positive correctional control reserve calls. The call to the right is caused due to a nearly empty gas storage, the left ones are caused by an inadequate power output of the gas storage. Thus in the next step we will double the power input $P_{G,max}$ of the gas power plant from 128 MW to 256 MW. Figure 72 gives an illustration of the results. Only one call of control reserve is left. Nevertheless the gas storage capacity is not sufficient, even with an actual capacity of 1,347.5 MWh. Table 17 lists all technical parameters used for this simulation with modified gas storage capacity and increased power output $P_{G,max}$.

Table 18 lists the results to give an overview of some technical aspects. The first column (Reference) refers to the scenario EEX trading and provision of SCR (Section 7.2.2), the remaining three columns are labeled from (A) to (C). (A) stands for the simulation assigned to the scenario based only on provision of SCR (Figure 70), (B) denotes the simulation which belongs to Figure 71 (provision of SCR with increased gas storage capacity) and (C) is corre-

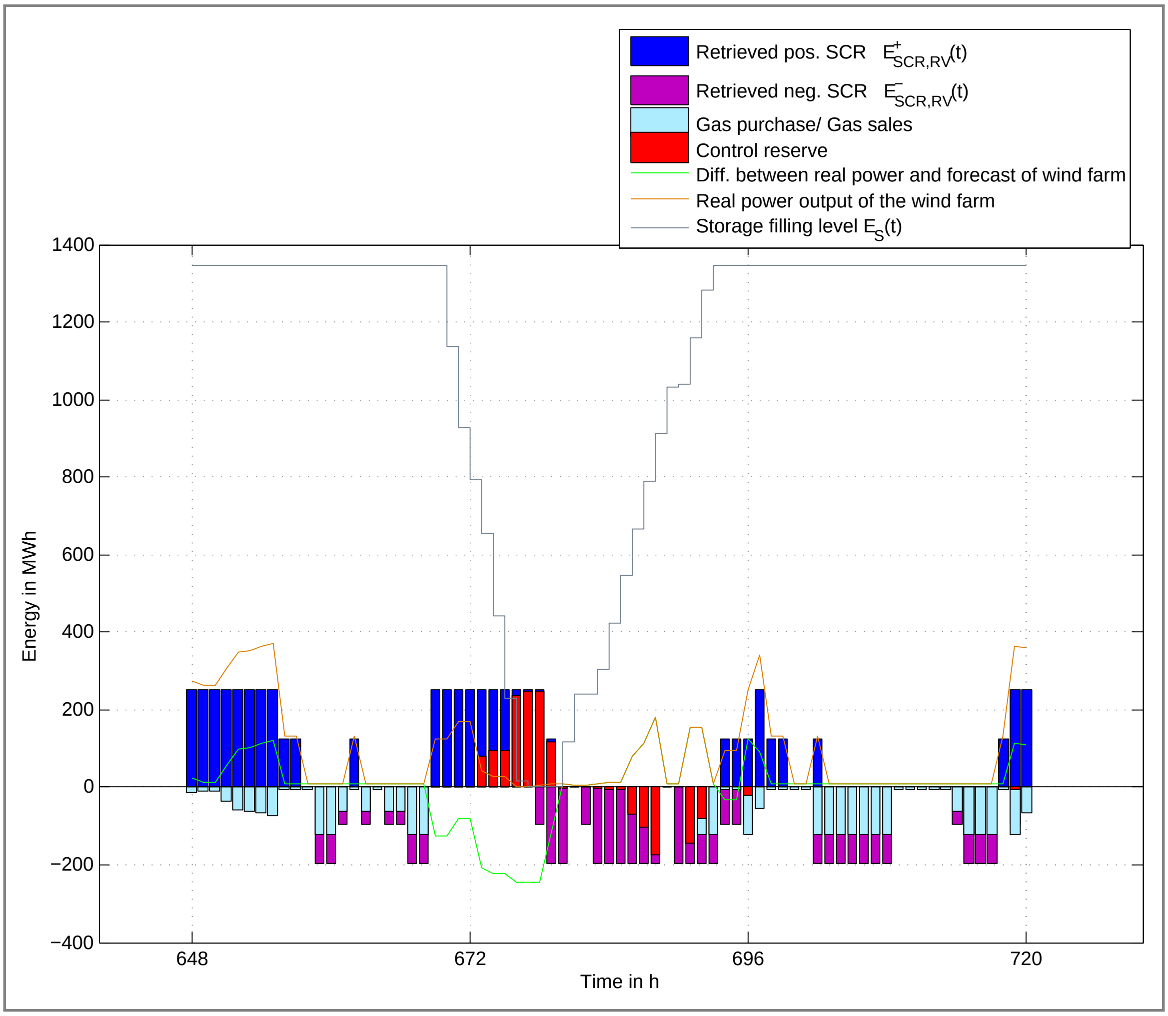

Figure 71: Visualization of Scenario 5 with same parameter set as Scenario 1, without EEX trading and increased gas storage capacity

Scenario 5: Provision of SCR			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	256	$P^{+,max}_{SCR,PR}$	308
$P_{M,max}$	-203	$P^{-,max}_{SCR,PR}$	200
$E_{S,max}$	1,347.5 (MWh)	$P^{+,max}_{MR,PR}$	0
		$P^{-,max}_{MR,PR}$	0

Table 17: Parameter set for simulation of Scenario 5: Provision of Secondary Control Reserve

sponding to Figure 72 (provision of SCR with increased gas storage capacity and the power output of storage unit). In these simulations the overall produced energy by the wind farm is limited by 396,967.5 MWh (- 32.9%) in comparison to the simulations based on EEX trading (Section 7.3). Now lets get a closer look on the retrieved negative/positive Secondary Control

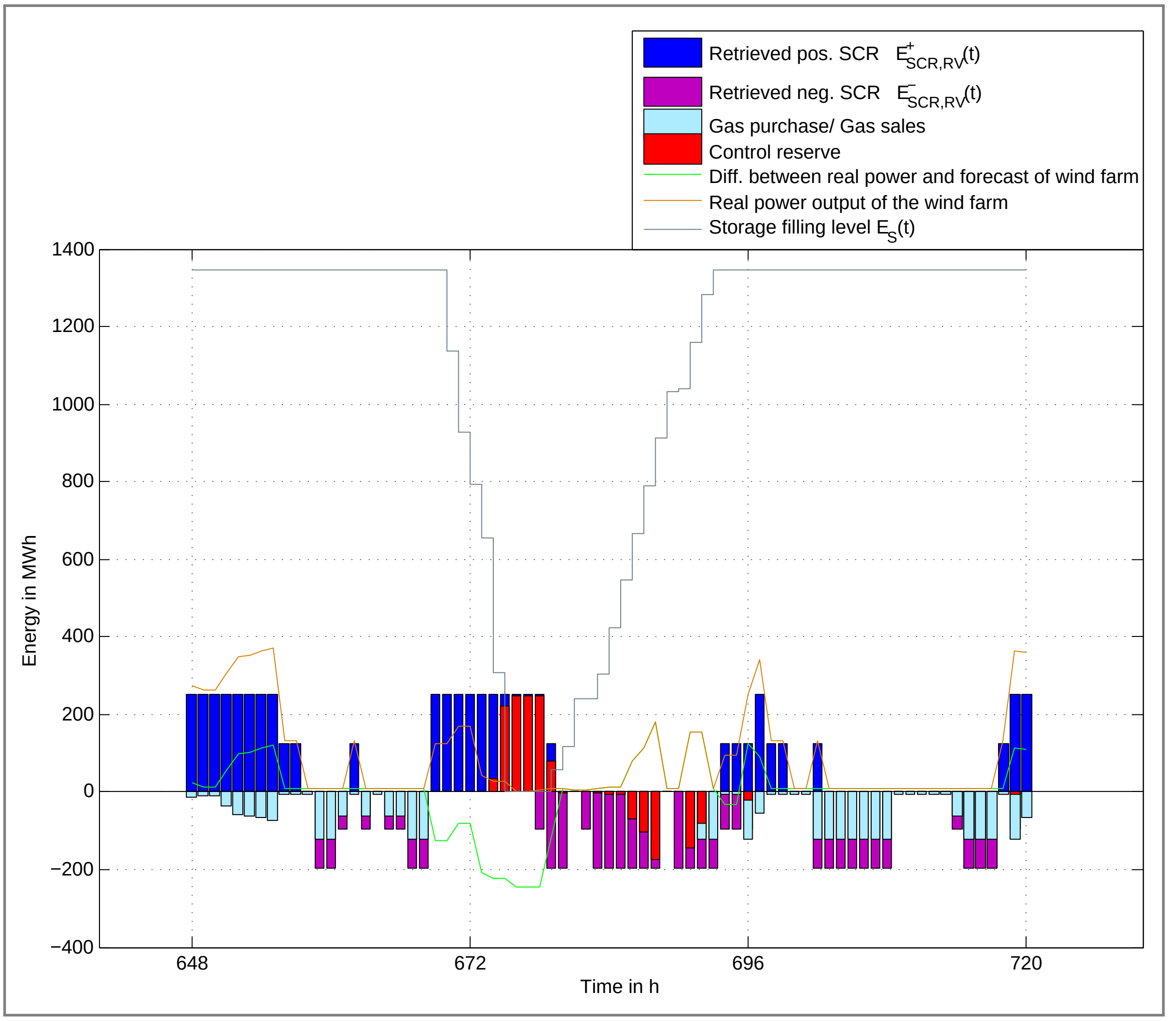

Figure 72: Visualization of Scenario 5 with same parameter set as Scenario 1, without EEX trading and increased gas storage capacity and power output of storage unit

Reserve in Table 18. In case of the combination of the EEX trading and SCR in first column (Reference), the sum of called positive SCR amounts to 46,758.2 MWh, the sum of called negative SCR amounts to 29,471.7 MWh. In case of only provision of Secondary Control Reserve these values change to 187,033 MWh for called positive SCR (+ 400%). The amount of retrieved negative SCR remains constant because the maximum provided negative SCR has not changed compared to the first simulation.

The presented values in Table 18 denotes the variation compared to the reference values in the first column. In addition to the result for the above explained simulation, the results for providing Minute Reserve and Secondary Control Reserve combined with Minute Reserve are presented.

Scenario 5: Provision of SCR				
Parameter	**Reference (MWh)**	**A (MWh)**	**B (MWh)**	**C (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	591,360	591,360	591,360
$\sum_{t=1}^{end} E_{SCR,RV}^{+}$	46,758.2	187,033	187,033	187,033
$\sum_{t=1}^{end} E_{SCR,RV}^{-}$	29,471.7	29,300	29,300	29,300
$\sum_{t=1}^{end} E_{MR,RV}^{+}$	0	0	0	0
$\sum_{t=1}^{end} E_{MR,RV}^{-}$	0	0	0	0
$\sum_{t=1}^{end} E_{deficit}$	7,681.8	54,255.7	47,327.9	47,129.7
$\sum_{t=1}^{end} E_{excess}$	203.3	161,734.9	338.1	338.1
$\sum_{t=1}^{end} E_{sale}^{Gas}$	3,197.1	181,421.3	149,404.5	149,259

Table 18: Technical results for simulation of the Scenario 5: Provision of Secondary Control Reserve

7.3.2 Scenario 6: Minute Reserve

Now the simulation based on Minute Reserve is presented. Table 19 gives an overview of the used paramterset (MR, large gas storage and high power output).

Scenario 6: Provision of MR			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	256	$P_{SCR,PR}^{+,max}$	0
$P_{M,max}$	-203	$P_{SCR,PR}^{-,max}$	0
$E_{S,max}$	1,347.5 (MWh)	$P_{MR,PR}^{+,max}$	308
		$P_{MR,PR}^{-,max}$	200

Table 19: Parameter set for simulation of Scenario 6: Provision of Minute Reserve

As can be seen in Figure 73 the offered Minute Reserve is based on the weather conditions. The blue line indicates the power output of the wind farm. The potential of Minute Reserve (green line) as well as the provided Minute Reserve (red line) follow the blue line. Thus offering Minute Reserve instead of Secondary Control Reserve allows the wind farm operator to adapt his energy schedule more precisely.

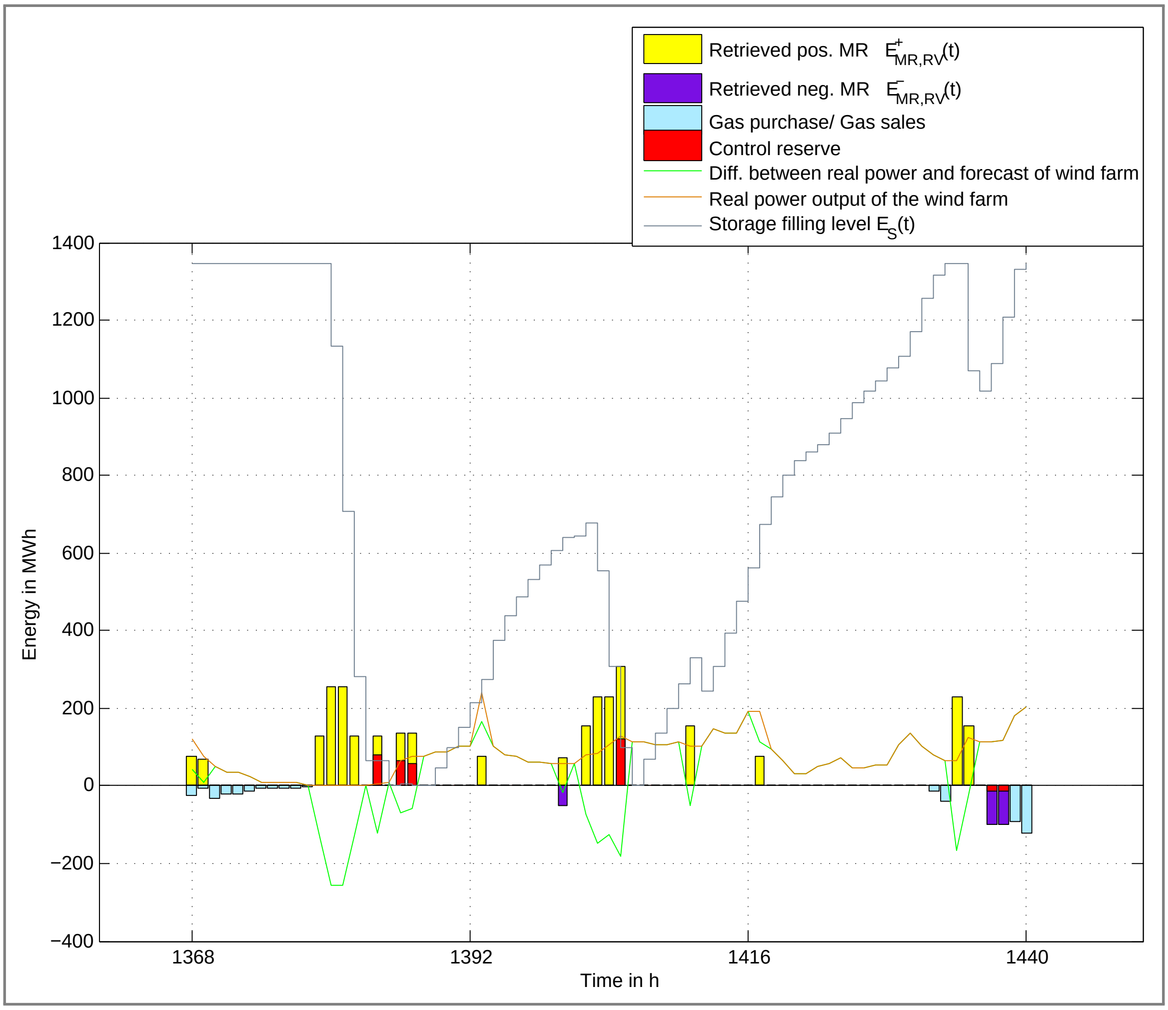

Figure 73: Visualization of Scenario 6: Minute Reserve. Furthermore the Minute Reserve potential and Minute Reserve offer are plotted.

Basically the same ideas as in the Section 7.3.1 apply to this simulation. Thus the results will be compared to those of the Scenario 5. As can be seen in Table 20, the energy excess has increased dramatically and consequently gas purchases increased as well.

When looking at the corresponding column of the Scenario 5, this is the main difference and can be explained with the ratio of positive and negative control reserve calls. In case of Minute Reserve there are nearly as much positive as negative retrievals. Thus the gas storage is not stressed in the same way. The amount of energy deficit reaches its minimum at column (B). Gas purchases are larger then to the reference values for all cases. Note that $E_{deficit}$ is also higher than the reference value, when increasing the power output of the storage unit column (C). In contrast to SCR, Minute Reserve can be adapted to weather conditions. Instead of having a fixed amount of maximum offered control reserve, it is allowed to adapt the Minute Reserve offer by using good weather forecasts.

Scenario 6: Provision of MR				
Parameter	**Reference (MWh)**	**A (MWh)**	**B (MWh)**	**C (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	591,360	591,360	591,360
$\sum_{t=1}^{end} E_{SCR,RV}^{+}$	0	0	0	0
$\sum_{t=1}^{end} E_{SCR,RV}^{-}$	0	0	0	0
$\sum_{t=1}^{end} E_{MR,RV}^{+}$	4,873	35,328.8	35,328.7	46,871.5
$\sum_{t=1}^{end} E_{MR,RV}^{-}$	14,066.7	28,220.5	28,220.5	28,220.5
$\sum_{t=1}^{end} E_{deficit}$	1,417.7	1,035.1	44.7	6,671.6
$\sum_{t=1}^{end} E_{excess}$	127.2	214,413.2	6257	6257
$\sum_{t=1}^{end} E_{sale}^{Gas}$	2,690.4	216,555	188,941.2	184,282.3

Table 20: Technical results for simulation of the Scenario 6: Provision of Minute Reserve

7.3.3 Scenario 7: Secondary Control Reserve and Minute Reserve

This section presents the results of the last scenario. Secondary Control Reserve is combined with Minute Reserve. Table 21 gives the used parameter set (large gas storage and high power output of gas power plant).

Scenario 7: Provision of SCR and MR			
Parameter	**Value (MW)**	**Parameter**	**Value (MW)**
$P_{G,max}$	256	$P_{SCR,PR}^{+,max}$	154
$P_{M,max}$	-203	$P_{SCR,PR}^{-,max}$	100
$E_{S,max}$	1,347.5 (MWh)	$P_{MR,PR}^{+,max}$	154
		$P_{MR,PR}^{-,max}$	100

Table 21: Parameter set for simulation of Scenario 7: Provision of Secondary Control Reserve and Minute Reserve

As might be expected the results of the scenario presented in Figure 74 are also a combination of SCR scenario and MR scenario results. Here again a limitation of the power output of storage unit is required to bring down $\sum_{t=1}^{end} E_{sale}^{Gas}$, $\sum_{t=1}^{end} E_{deficit}$ and $\sum_{t=1}^{end} E_{excess}$ to an acceptable level. It can be seen in column (B) and (C) in Table 22, acceptable results are achieved.

Scenario 7: Provision of SCR and MR				
Parameter	**Reference (MWh)**	**A (MWh)**	**B (MWh)**	**C (MWh)**
$\sum_{t=1}^{end} E_S^{Intra-Day}$	591,360	591,360	591,360	591,360
$\sum_{t=1}^{end} E_{SCR,RV}^{+}$	28,054.9	93,516.5	93,516.5	93,516.5
$\sum_{t=1}^{end} E_{SCR,RV}^{-}$	17,683	14,735.8	14,735.8	14,735.8
$\sum_{t=1}^{end} E_{MR,RV}^{+}$	2,197.2	11,618	11,618	22,308.5
$\sum_{t=1}^{end} E_{MR,RV}^{-}$	5,700.5	7,193	7,193	7,193
$\sum_{t=1}^{end} E_{deficit}$	3,832.2	18,456.6	14,345.5	17,756.1
$\sum_{t=1}^{end} E_{excess}$	163.6	182,214.6	494.7	466.8
$\sum_{t=1}^{end} E_{sale}^{Gas}$	1,750.8	197,629.2	168,276.7	162,017.2

Table 22: Technical results for simulation of the Scenario 7: Provision of Secondary Control Reserve and Minute Reserve

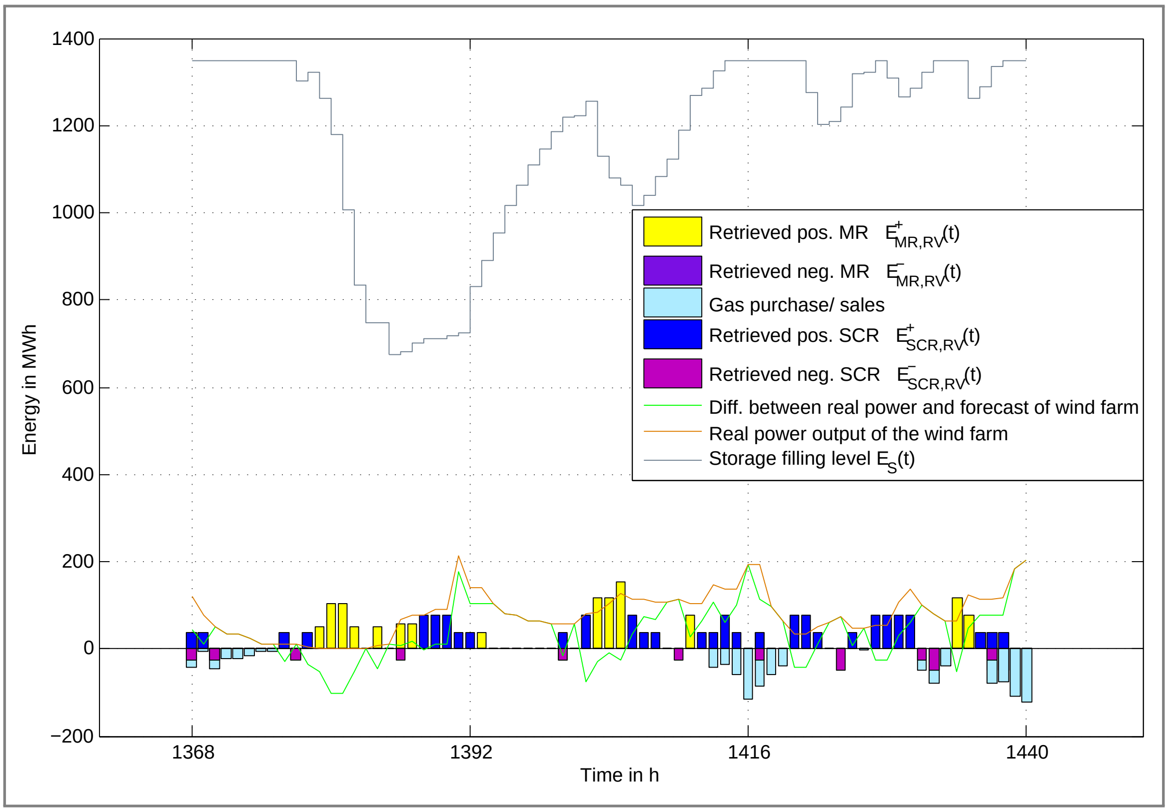

Figure 74: Visualization of Scenario 7: Provision of Secondary Control Reserve and Minute Reserve.

Thus improvements regarding the power output of storage unit or storage capacity are not absolutely necessary.

7.3.4 Summary of scenarios based on Secondary Control Reserve and Minute Reserve without EEX Trading

Finally all results of the last three scenarios are summarized. There are some conclusions which can be made on the basis of the results listed in Table 18, Table 20 and Table 22.

- **First:** An increase of the storage unit power output and the storage capacity are essential for a meaningful operation. As can be seen in column (C) the amount of energy overruns which can not be handled by the gas storage or respectively the methanation facility is decreased to an acceptable level.
- **Second:** Gas purchases have increased. Due to the fact that there are no EEX trading, energy excesses occur all the time which lead to huge amounts of produced gas. Even an expansion of the gas storage can not counteract this trend. Hence these gas purchases contribute to the profit.
- **Third:** Irrespective of whether these scenarios make sense or not in an economical manner, only providing Minute Reserve or respectively in combination with Secondary Control Reserve make sense from a technical point of view. It is because of the adaption of Minute Reserve to the weather conditions. In case of Secondary Control Reserve there are lots of correctional control reserve calls which may result in great deficits in case of windless time periods.

8 Conclusion

The aim of the presented work is to develop a concept for intelligent scheduling of a virtual power plant that consists of a wind farm and a methane-based storage unit, in order to allow the unit to participate in the free energy market and the balancing energy market. For this purpose, a time-domain simulation of energy flows within the unit was developed, processed and analyzed for different optimization approaches. The overall concept and every optimization step in this work are also done aiming at loss minimization through the required convention in the storage, and the deviation of the actual and reference feed-in power in the power network.

In this case, a few percentage reduction of the deviations from actual-to-reference feed-in was achieved. The main reason is the intelligent compilation of energy schedules, i.e. the target value of the VPP $P^{i}_{required}$ (Figure 26), which controls also the storage filling level so that the storage unit always remains operational and ready (correction of the difference between forecast and required power). The economic analysis also revealed, that not only the desired average electricity price/Megawatt-hour (which not surpassed the EEG-remuneration value) on the free energy market can be achieved, but also the energy losses will be covered. In total, the revenue towards the demand of the legal EEG-remuneration in the considered time period (in consideration of the current amount of energy trading in the free energy market) could increase by more than 10%.

Furthermore, the participation of the storage unit system in the control energy market was made possible through the virtual power plant concept that is designed in this work. And due to the legal basis, only offering positive and negative MR without EEX-trading could be considered useful. The offering of SCR must be combined with the EEX-trading, in order to avoid the payment of correctional control reserve. And although the data that where used for the MR and SCR in this simulation is based on statistical and simplified assumptions, the result still indicates that the participation of the proposed virtual power plant in the control energy market could be promising in technical and economical terms.

This work can be seen as a guideline to define the sizing of the storage unit of different wind farms based on the forecast and measurement data of the harvested energy, and also to determine the scheduling optimization of wind-farms in various sizes. It should be noted that the size of the optimization steps and the dimensioning of the storage unit are only valid for the wind-farm that is considered in this work. Hence, the further usage of this in another wind-farm has to undergo an additional adaptation process. Also note that further economical and profitability assessment in consideration of the necessary costs of investment, maintenance, and repair is beyond the scope of this work.

In addition, the combination of a methane-based energy storage and an intelligent schedule planning is to improve the yield of a wind farm with simultaneous stabilization of the energy supply behavior of the VPP.

Moreover, wind farm operators incur a remarkable financial risk, when they decide to commercialize the produced energy in a direct way. That could be energy trading at a EEX market, as well as taking part on the control energy market. Thus the question rises, whether this way is economical reasonable. There are two main kinds of simulations described in this work. First, the combination of EEX trading and control energy provision, secondly only provision of control reserve is analyzed. In case of combining EEX trading with control reserve, the tremendous investment costs can be compensated by clearly increased sales of energy. All in all this way of direct marketing makes sense regarding economical considerations as well as technical ones. Only providing control energy, is not economical and technical suitable.

Concluding it can be said, that conventional power plants as we know them today may not be necessary in the future anymore. A combination of different renewable energy sources with effective storage technologies could be capable to ensure a stable and reliable energy supply structure.

Appendix A

The tables in this appendix provide additional information to the Chapter 2.

Wind farm name	Nominal power [MW]	Water depth [m]	Distance from shore [km]	Area [km^2]	Status	Latest start of construction
alpha ventus	60	30	43	8	In operation	n.a
BARD Offshore 1	400	39 - 41	89 - 111	58.9	In operation	n.a
ENOVA Offshore Ems - Emden	4.5	0 - 2	0 - 0.6	n.a	In operation	n.a
Hooksiel	5	2 - 8	0.4	0.16	In operation	n.a
Riffgat	108	18 - 23	30 - 42	13.2	Completely installed	n.a
Borkum West II	200	28 - 33	65.6 - 66.3	56	Under construction	n.a
Global Tech I	400	38 - 41	109.4 - 115	41	Under construction	n.a
Innogy Nordsee Ost	295.2	22 - 25	51.4 - 57	24	Under construction	n.a
Dan Tysk	288	21 - 32	70 - 74	70	Under construction	n.a
Amrumbank West	288	19.5 - 24	36 - 55	32	Under construction	n.a
Borkum Riffgrund I	277.2	23 - 29	54	35.7	Under construction	n.a
Meerwind Süd / Ost	288	23 - 26	52.4 - 53	40	Under construction	n.a

Table 23: Overview of (installed, In operation and under construction) wind farms in the German region of the North Sea (status of Dec 2013). Data sources: [BSH,2013], [Fraunhofer, 2013]

Wind farm name	Nominal power [MW]	Water depth [m]	Distance from shore [km]	Area [km^2]	Status	Latest start of construction
MEG Offshore I	400	27 - 33	60	40	Approved	31.10.2013
Veja Mate	400	39 - 41	114	50	Approved	30.06.2014
Innogy Nordsee 1	332.1	26 - 35	44 - 47.3	34	Approved	01.07.2014
Butendiek	288	17 - 22	32	34	Approved	31.12.2014
Delta Nordsee 2	160	29 - 33	n.a	n.a	Approved	31.12.2014
Deutsche Bucht	210	39 - 41	98 - 117	22.6	Approved	31.12.2014
Albatros	474	39 - 41	75 - 113	39	Approved	01.06.2015
Gode Wind 01	330	26 - 35	40 - 42.1	37	Approved	30.06.2015
Gode Wind 02	252	26 - 35	33 - 34	29	Approved	30.06.2015
Borkum Riff-grund 2	349	25 - 30	40	43	Approved	31.12.2015
Gode Wind 04	252	30 - 34	33	29	Approved	31.12.2015
EnBW Hohe See	500	39 - 40	90 - 104	n.a	Approved	30.06.2016
Borkum Rif-fgrund West I	400	29 - 33	67 - 76	30	Approved	31.07.2016
Nördlicher Grund	384	25 - 38	84 - 88	55	Approved	31.12.2016
Sandbank 24	288	25 - 37	83 - 96	59	Approved	31.12.2016
EnBW HeDreiht (1)	400	39	97 - 104	62.49	Approved	30.06.2017
EnBW HeDreiht (2)	195	39	97 - 104	19	Approved	30.06.2017
Delta Nordsee 1	235	29 - 35	50 - 51.4	28	Approved	31.12.2017
Innogy Nordsee 2	295.2	26 - 34	47.3 - 48	36.45	Approved	01.07.2018
Innogy Nordsee 3	360	26 - 34	47.3 - 49	29	Approved	01.07.2019
Kaikas	415	39 - 41	110 - 125	65	Approved	n.a
Nordergründe	110.7	4 - 14	16 - 17.6	6	Approved	n.a

Table 24: Overview of approved wind farms in the German region of the North Sea (status of Dec 2013). Data sources: [BSH,2013], [Fraunhofer, 2013]

Wind farm name	Nominal power [MW]	Water depth [m]	Distance from shore [km]	Area [km^2]	Status	Latest start of construction
Breitling	2.5	2	0 - 0.3	0	In operation	n.a
EnBW Baltic 1	48.3	16 - 19	16 - 17.1	7	In operation	n.a
EnBW Baltic 2	288	23 - 44	32 - 35.4	27	Under construction	31.10.2013
Wikinger	400	36 - 40	35 - 39	35	Approved	31.12.2015
Arkona - Becken Südost	480	21 - 27	35 - 37	40	Approved	01.10.2016

Table 25: Approved wind farms in the German region of the Baltic Sea (status of Dec 2013). Data sources: [BSH,2013], [Fraunhofer, 2013]

Appendix B

The tables in this appendix are based on the simulations in accordance with the Chapter 5.

Excess ($\Delta P_{W,S} \geq 0$)		
	Methanation facility can take up completely the excess power ($\Delta P_{W,S}(t_i) < \lvert P_{M,max} \rvert$)	**Methanation facility can NOT take up completely the excess power** ($\Delta P_{W,S}(t_i) \geq \lvert P_{M,max} \rvert$)
Storage can absorb the excess energy $E_S(t_i) + \Delta P_{W,S} \cdot t_{int} \cdot \eta_M \leq E_{S,max}$ or $E_S(t_i) - P_{M,max} \cdot t_{int} \cdot \eta_M \leq E_{S,max}$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M$	$E_{CP}(t_i) = -(\Delta P_{W,S}(t_i) + P_{M,max}) \cdot t_{int}$ $E_S(t_{i+1}) = E_S(t_i) - P_{M,max} \cdot t_{int} \cdot \eta_M$
Storage can NOT absorb the excess energy $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M > E_{S,max}$ or $E_S(t_i) - P_{M,max} \cdot t_{int} \cdot \eta_M > E_{S,max}$	$E_{CP}(t_i) = (E_{S,max} - E_S(t_i)) \cdot (\eta_M)^{-1} - \Delta P_{W,S}(t_i) \cdot t_{int}$ $E_S(t_{i+1}) = E_{S,max}$	$E_{CP}(t_i) = (E_{S,max} - E_S(t_i)) \cdot (\eta_M)^{-1} - \Delta P_{W,S}(t_i) \cdot t_{int}$ $E_S(t_{i+1}) = E_{S,max}$

Deficit ($\Delta P_{W,S} < 0$)		
	Gas power plant can apply completely the required power ($\Delta P_{W,S}(t_i) > -P_{G,max}$)	**Gas power plant can NOT apply completely the required power** ($\Delta P_{W,S}(t_i) < -P_{G,max}$)
Storage can compensate the deficit: $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot (\eta_G)^{-1} \geq 0$ or $E_S(t_i) - P_{G,max} \cdot t_{int} \cdot (\eta_G)^{-1} \geq 0$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot (\eta_G)^{-1}$	$E_{CP}(t_i) = -(P_{G,max} + \Delta P_{W,S}(t_i)) \cdot t_{int}$ $E_S(t_{i+1}) = E_S(t_i) - P_{G,max} \cdot t_{int} \cdot (\eta_G)^{-1}$
Storage can NOT compensate the deficit: $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot (\eta_G)^{-1} < 0$ or $E_S(t_i) - P_{G,max} \cdot t_{int} \cdot (\eta_G)^{-1} < 0$	$E_{CP}(t_i) = -\Delta P_{W,S}(t_i) \cdot t_{int} - E_S(t_i) \cdot \eta_G$ $E_S(t_{i+1}) = 0$	$E_{CP}(t_i) = -\Delta P_{W,S}(t_i) \cdot t_{int} - E_S(t_i) \cdot \eta_G$ $E_S(t_{i+1}) = 0$

Table 26: The eight possible cases in the simulation according the Section 5.2

Evaluation of different methods for forecast adjustment as a function of $P_{W,max}$				
Forecast values	**Original**	**Mean value correction 24h**	**Mean value correction 12h**	**Mean value correction 2h**
Mean value $\mu_{\Delta P_{W,corr}}$	0.0372	-0.0035	0.0180	0.0342
Standard dev. $\sigma_{\Delta P_{W,corr}}$	0.1663	0.1512	0.1453	0.1563
Min values	-0.9899	-0.7412	-0.7841	-0.9204
Max values	0.8357	0.8135	0.8198	0.8209

Forecast values	**Exp. smoothing** $\delta = 0.7$	**Exp. smoothing** $\delta = 0.8$	**Mean value correction 24h + Exp. smoothing** $\delta = 0.75$
Mean value $\mu_{\Delta P_{W,corr}}$	0.0131	0.0101	0.0060
Standard dev. $\sigma_{\Delta P_{W,corr}}$	0.0940	0.0908	0.0925
Min values	-0.6268	-0.6553	-0.6932
Max values	0.5884	0.6023	0.5992

Table 27: Evaluation of different methods for forecast adjustment

Evaluation of the parameters S and V for polynomial and root functions					
Polynomial function					
S	$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 4$	$\beta = 5$
$\alpha = 0.2$	0.8613	0.8518	0.8436	0.8383	0.8342
$\alpha = 0.4$	0.9301	0.9189	0.9113	0.9049	0.8995
$\alpha = 0.6$	0.9569	0.9494	0.9439	0.9397	0.9355
$\alpha = 0.8$	0.9727	0.9654	0.9603	0.9574	0.9553
$\alpha = 1$	0.9822	0.9750	0.9712	0.9689	0.9677
V	$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 4$	$\beta = 5$
$\alpha = 0.2$	0.0753	0.0739	0.0727	0.0720	0.0715
$\alpha = 0.4$	0.0778	0.0769	0.0760	0.0752	0.0746
$\alpha = 0.6$	0.0777	0.0776	0.0774	0.0771	0.0766
$\alpha = 0.8$	0.0778	0.0781	0.0779	0.0779	0.0777
$\alpha = 1$	0.0781	0.0782	0.0783	0.0783	0.0783
Root function					
S	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$	$\gamma = 5$
$\alpha = 0.2$	0.8613	0.8700	0.8747	0.8779	0.8799
$\alpha = 0.4$	0.9301	0.9358	0.9376	0.9384	0.9389
$\alpha = 0.6$	0.9569	0.9630	0.9653	0.9650	0.9655
$\alpha = 0.8$	0.9727	0.9792	0.9783	0.9758	0.9748
$\alpha = 1$	0.9822	0.9855	0.9798	0.9765	0.9687
V	$\gamma = 1$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$	$\gamma = 5$
$\alpha = 0.2$	0.0753	0.0765	0.0769	0.0773	0.0776
$\alpha = 0.4$	0.0778	0.0778	0.0784	0.0785	0.0801
$\alpha = 0.6$	0.0777	0.0777	0.0792	0.0817	0.0852
$\alpha = 0.8$	0.0778	0.0788	0.0826	0.0896	0.0956
$\alpha = 1$	0.0781	0.0797	0.0884	0.0983	0.1054

Table 28: Results for S and V of polynomial and root functions with forecast correction

Evaluation of the parameters S and V for polynomial					
S	$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 4$	$\beta = 5$
$\alpha = 0.2$	0.8113	0.8027	0.7926	0.7869	0.7838
$\alpha = 0.4$	0.8746	0.8744	0.8610	0.8694	0.8532
$\alpha = 0.6$	0.9063	0.8948	0.8991	0.8870	0.8755
$\alpha = 0.8$	0.9212	0.9067	0.9011	0.8969	0.8903
$\alpha = 1$	0.9322	0.9144	0.9177	0.9139	0.9157
V	$\beta = 1$	$\beta = 2$	$\beta = 3$	$\beta = 4$	$\beta = 5$
$\alpha = 0.2$	0.0642	0.0633	0.0589	0.0622	0.0610
$\alpha = 0.4$	0.0651	0.0648	0.0618	0.0634	0.0614
$\alpha = 0.6$	0.0657	0.0654	0.0642	0.0651	0.0627
$\alpha = 0.8$	0.0643	0.0667	0.0679	0.0653	0.0651
$\alpha = 1$	0.0655	0.0693	0.0680	0.0679	0.0695

Table 29: Results for S and V of polynomial function without forecast correction

Appendix C

The tables in this appendix are based on the simulations according to the Chapter 6.

Excess ($\Delta P_{W,S} \geq 0$)		
	Methanation facility can take up completely the excess power ($\Delta P_{W,S}(t_i) < \lvert P_{M,max} - P^{-}_{CP,PR}(t_i)\rvert$)	**Methanation facility can NOT take up completely the excess power** ($\Delta P_{W,S}(t_i) \geq \lvert P_{M,max} - P^{-}_{CP,PR}(t_i)\rvert$)
Storage can absorb the excess energy $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M \leq E_{S,max}$ or $E_S(t_i) - (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M \leq E_{S,max}$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M$ $E_{GN}(t_i) = 0$	$E_{CP}(t_i) = (-\Delta P_{W,S}(t_i) + P^{-}_{CP,PR}(t_i) - P_{M,max}) \cdot t_{int}$ $E_S(t_{i+1}) = E_S(t_i) - (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M$ $E_{GN}(t_i) = 0$
Storage can NOT absorb the excess energy: $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M > E_{S,max}$ or $E_S(t_i) - (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M > E_{S,max}$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_{S,max}$ $E_{GN}(t_i) = (E_{S,max} - E_S(t_i)) - \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M + E^{+}_{CP,RV} \cdot (\eta_G)^{-1} - E^{-}_{CP,RV} \cdot \eta_M$	$E_{CP}(t_i) = (-\Delta P_{W,S}(t_i) - P_{M,max} + P^{-}_{CP,PR}(t_i)) \cdot t_{int}$ $E_S(t_{i+1}) = E_{S,max}$ $E_{GN}(t_i) = (E_{S,max} - E_S(t_i)) + (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M + E^{+}_{CP,RV} \cdot (\eta_G)^{-1} - E^{-}_{CP,RV} \cdot \eta_M$

Table 30: The four possible cases in the simulation with consideration of the control power and positive $\Delta P_{W,S}(t_i)$ according to the Section 6.1

Deficit ($\Delta P_{W,S} < 0$)

	Gas power plant can deliver completely the required power ($\Delta P_{W,S}(t_i) > -P_{G,max} + P^{+}_{CP,PR}(t_i)$)	**Gas power plant can NOT deliver completely the required power** ($\Delta P_{W,S}(t_i) \geq -P_{G,max} + P^{+}_{CP,PR}(t_i)$)
Storage can compensate the deficit: $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot (\eta_G)^{-1} \geq 0$ or $E_S(t_i) - (P_{G,max} - P^{+}_{CP,PR}(t_i)) \cdot t_{int} \cdot (\eta_G)^{-1} \geq 0$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot (\eta_G)^{-1} - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M$ $E_{GN}(t_i) = 0$	$E_{CP}(t_i) = -(P_{G,max} + \Delta P_{W,S}(t_i) - P^{+}_{CP,PR}(t_i)) \cdot t_{int}$ $E_S(t_{i+1}) = E_S(t_i) - (P_{G,max} - P^{+}_{CP,PR}(t_i)) \cdot t_{int} \cdot (\eta_G)^{-1} - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M$ $E_{GN}(t_i) = 0$
Storage can NOT compensate completely the deficit: $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot (\eta_G)^{-1} < 0$ or $E_S(t_i) - (P_{G,max} - P^{+}_{CP,PR}(t_i)) \cdot t_{int} \cdot (\eta_G)^{-1} < 0$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = 0$ $E_{GN}(t_i) = -\Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_G^{-1} - E_S(t_i) + E^{+}_{CP,RV} \cdot (\eta_G)^{-1} - E^{-}_{CP,RV} \cdot \eta_M$	$E_{CP}(t_i) = -(\Delta P_{W,S}(t_i) + P_{G,max} - P^{+}_{CP,PR}(t_i)) \cdot t_{int}$ $E_S(t_{i+1}) = 0$ $E_{GN}(t_i) = (P_{G,max} - P^{+}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_G^{-1} - E_S(t_i) + E^{+}_{CP,RV} \cdot (\eta_G)^{-1} - E^{-}_{CP,RV} \cdot \eta_M$

Table 31: The four possible cases in the simulation with consideration of the control power and negative $\Delta P_{W,S}(t_i)$ according to the Section 6.1

	$P_M^{max} = -0.3\ P_W^{max}$ $P_G^{max} = 0.2\ P_W^{max}$ $E_S^{max} = 1.5h\ P_W^{max}$	$P_M^{max} = -0.35\ P_W^{max}$ $P_G^{max} = 0.26\ P_W^{max}$ $E_S^{max} = 2.7h\ P_W^{max}$	$P_M^{max} = -0.4\ P_W^{max}$ $P_G^{max} = 0.33\ P_W^{max}$ $E_S^{max} = 3.9h\ P_W^{max}$	$P_M^{max} = -0.45\ P_W^{max}$ $P_G^{max} = 0.39\ P_W^{max}$ $E_S^{max} = 5.1h\ P_W^{max}$	$P_M^{max} = -0.5\ P_W^{max}$ $P_G^{max} = 0.45\ P_W^{max}$ $E_S^{max} = 6.2h\ P_W^{max}$
No control power	$S = 97.62\%$ $V = 5.96\%$	$S = 98.66\%$ $V = 5.78\%$	$S = 99.26\%$ $V = 5.84\%$	$S = 99.55\%$ $V = 5.96\%$	$S = 99.73\%$ $V = 6.08\%$
$P_{CP}^{+,max} = 0.05\ P_W^{max}$ $P_{CP}^{-,max} = -0.05\ P_W^{max}$	$S = 97.51\%$ $V = 5.94\%$ $\varnothing E_{CP,PR}^{+} = 10.92$ $\varnothing E_{CP,PR}^{-} = 9.60$	$S = 98.59\%$ $V = 5.78\%$ $\varnothing E_{CP,PR}^{+} = 12.11$ $\varnothing E_{CP,PR}^{-} = 10.50$	$S = 99.23\%$ $V = 5.83\%$ $\varnothing E_{CP,PR}^{+} = 13.45$ $\varnothing E_{CP,PR}^{-} = 11.39$	$S = 99.51\%$ $V = 5.95\%$ $\varnothing E_{CP,PR}^{+} = 14.35$ $\varnothing E_{CP,PR}^{-} = 12.24$	$S = 99.70\%$ $V = 6.07\%$ $\varnothing E_{CP,PR}^{+} = 15.43$ $\varnothing E_{CP,PR}^{-} = 12.91$
$P_{CP}^{+,max} = 0.1\ P_W^{max}$ $P_{CP}^{-,max} = -0.1\ P_W^{max}$	$S = 97.39\%$ $V = 5.94\%$ $\varnothing E_{CP,PR}^{+} = 20.44$ $\varnothing E_{CP,PR}^{-} = 18.30$	$S = 98.43\%$ $V = 5.77\%$ $\varnothing E_{CP,PR}^{+} = 23.26$ $\varnothing E_{CP,PR}^{-} = 20.12$	$S = 99.16\%$ $V = 5.83\%$ $\varnothing E_{CP,PR}^{+} = 26.23$ $\varnothing E_{CP,PR}^{-} = 21.90$	$S = 99.47\%$ $V = 5.94\%$ $\varnothing E_{CP,PR}^{+} = 27.97$ $\varnothing E_{CP,PR}^{-} = 23.65$	$S = 99.65\%$ $V = 6.06\%$ $\varnothing E_{CP,PR}^{+} = 29.98$ $\varnothing E_{CP,PR}^{-} = 25.15$
$P_{CP}^{+,max} = 0.15\ P_W^{max}$ $P_{CP}^{-,max} = -0.15\ P_W^{max}$	$S = 97.12\%$ $V = 5.94\%$ $\varnothing E_{CP,PR}^{+} = 28.50$ $\varnothing E_{CP,PR}^{-} = 25.95$	$S = 98.28\%$ $V = 5.76\%$ $\varnothing E_{CP,PR}^{+} = 33.06$ $\varnothing E_{CP,PR}^{-} = 28.84$	$S = 99.01\%$ $V = 5.82\%$ $\varnothing E_{CP,PR}^{+} = 37.71$ $\varnothing E_{CP,PR}^{-} = 31.54$	$S = 99.38\%$ $V = 5.94\%$ $\varnothing E_{CP,PR}^{+} = 40.96$ $\varnothing E_{CP,PR}^{-} = 34.19$	$S = 99.59\%$ $V = 6.05\%$ $\varnothing E_{CP,PR}^{+} = 43.74$ $\varnothing E_{CP,PR}^{-} = 36.58$
$P_{CP}^{+,max} = 0.2\ P_W^{max}$ $P_{CP}^{-,max} = -0.2\ P_W^{max}$	$S = 90.69\%$ $V = 5.75\%$ $\varnothing E_{CP,PR}^{+} = 35.25$ $\varnothing E_{CP,PR}^{-} = 30.57$	$S = 98.01\%$ $V = 5.75\%$ $\varnothing E_{CP,PR}^{+} = 41.86$ $\varnothing E_{CP,PR}^{-} = 36.87$	$S = 98.86\%$ $V = 5.81\%$ $\varnothing E_{CP,PR}^{+} = 48.67$ $\varnothing E_{CP,PR}^{-} = 40.70$	$S = 99.24\%$ $V = 5.93\%$ $\varnothing E_{CP,PR}^{+} = 53.27$ $\varnothing E_{CP,PR}^{-} = 44.33$	$S = 99.51\%$ $V = 6.04\%$ $\varnothing E_{CP,PR}^{+} = 57.58$ $\varnothing E_{CP,PR}^{-} = 47.67$

$E_{CP,PR}^{+}$ and $E_{CP,PR}^{-}$ in $[P_W^{max}\frac{h}{Month}]$, $P_W^{max} = P_{W,max}$,$P_G^{max} = P_{G,max}$, $P_M^{max} = P_{M,max}$, $E_S^{max} = E_{S,max}$, $P_{CP}^{+,max} = P_{CP,max}^{+}$ and $P_{CP}^{-,max} = P_{CP,max}^{-}$

Table 32: Evaluation of the results of the simulation with provision of control power for different Storage parameter values

Excess ($\Delta P_{W,S} \geq 0$)		
	Methanation facility can take up completely the excess power ($\Delta P_{W,S}(t_i) < \lvert P_{M,max} - P^{-}_{CP,PR}(t_i)\rvert$)	**Methanation facility can NOT take up completely the excess power** ($\Delta P_{W,S}(t_i) \geq \lvert P_{M,max} - P^{-}_{CP,PR}(t_i)\rvert$)
Storage can absorb the excess energy $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M \leq E_{S,max}$ or $E_S(t_i) - (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot (\eta_G)^{-1} \leq E_{S,max}$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M$ $E_{GN}(t_i) = 0$	$E_{CP}(t_i) = (-\Delta P_{W,S}(t_i) + P^{-}_{CP,PR}(t_i) - P_{M,max}) \cdot t_{int}$ $E_S(t_{i+1}) = E_S(t_i) - (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot \eta_M$ $E_{GN}(t_i) = 0$
Storage can NOT absorb the excess energy: $E_S(t_i) + \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M - E^{+}_{CP,RV} \cdot (\eta_G)^{-1} + E^{-}_{CP,RV} \cdot v_E M > E_{S,max}$ or $E_S(t_i) - (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M > E_{S,max}$	$E_{CP}(t_i) = 0$ $E_S(t_{i+1}) = E_{S,max}$ $E_{GN}(t_i) = (E_{S,max} - E_S(t_i)) - \Delta P_{W,S}(t_i) \cdot t_{int} \cdot \eta_M + E^{+}_{CP,RV} \cdot (\eta_G)^{-1} - E^{-}_{CP,RV} \cdot \eta_M$	$E_{CP}(t_i) = (-\Delta P_{W,S}(t_i) - P_{M,max} + P^{-}_{CP,PR}(t_i)) \cdot t_{int}$ $E_S(t_{i+1}) = E_{S,max}$ $E_{GN}(t_i) = (E_{S,max} - E_S(t_i)) + (P_{M,max} - P^{-}_{CP,PR}(t_i)) \cdot t_{int} \cdot \eta_M + E^{+}_{CP,RV} \cdot (\eta_G)^{-1} - E^{-}_{CP,RV} \cdot \eta_M$

Table 33: The four possible cases in the simulation with consideration of the control power and positive $\Delta P_{W,S}(t_i)$ according to the Section 6.2

Deficit ($\Delta P_{W,S} < 0$)

	Storage can apply completely the required power ($\Delta P_{W,S}(t_i) > -P_{G,max} + P^{+}_{CP,PR}(t_i)$)	**Storage can NOT apply completely the required power** ($\Delta P_{W,S}(t_i) \geq -P_{G,max} + P^{+}_{CP,PR}(t_i)$)
Storage can compensate the deficit: $E_S(t_i)+\Delta P_{W,S}(t_i)\cdot t_{int}\cdot(\eta_G)^{-1}-E^{+}_{CP,RV}\cdot(\eta_G)^{-1}+E^{-}_{CP,RV}\cdot\eta_M \geq 0$ or $E_S(t_i)-(P_{G,max}-P^{+}_{CP,PR}(t_i))\cdot t_{int}\cdot(\eta_G)^{-1}-E^{+}_{CP,RV}\cdot(\eta_G)^{-1}+E^{-}_{CP,RV}\cdot\eta_M \geq 0$	$E_{CP}(t_i)=0$ $E_S(t_{i+1}) = E_S(t_i)+\Delta P_{W,S}(t_i)\cdot t_{int}\cdot(\eta_G)^{-1} - E^{+}_{CP,RV}\cdot(\eta_G)^{-1}+E^{-}_{CP,RV}\cdot\eta_M$ $E_{GN}(t_i)=0$	$E_{CP}(t_i) = -(P_{G,max}+\Delta P_{W,S}(t_i)-P^{+}_{CP,PR}(t_i))\cdot t_{int}$ $E_S(t_{i+1}) = E_S(t_i)-(P_{G,max}-P^{+}_{CP,PR}(t_i))\cdot t_{int}\cdot(\eta_G)^{-1}-E^{+}_{CP,RV}\cdot(\eta_G)^{-1}+E^{-}_{CP,RV}\cdot\eta_M$ $E_{GN}(t_i)=0$
Storage can NOT compensate completely the deficit: $E_S(t_i)+\Delta P_{W,S}(t_i)\cdot t_{int}\cdot(\eta_G)^{-1}-E^{+}_{CP,RV}\cdot(\eta_G)^{-1}+E^{-}_{CP,RV}\cdot\eta_M < 0$ or $E_S(t_i)-(P_{G,max}-P^{+}_{CP,PR}(t_i))\cdot t_{int}\cdot(\eta_G)^{-1}-E^{+}_{CP,RV}\cdot(\eta_G)^{-1}+E^{-}_{CP,RV}\cdot\eta_M < 0$	$E_{CP}(t_i)=0$ $E_S(t_{i+1})=0$ $E_{GN}(t_i) = -\Delta P_{W,S}(t_i)\cdot t_{int}\cdot\eta_G^{-1} - E_S(t_i) + E^{+}_{CP,RV}\cdot(\eta_G)^{-1}-E^{-}_{CP,RV}\cdot\eta_M$	$E_{CP}(t_i) = -(\Delta P_{W,S}(t_i)+P_{G,max}-P^{+}_{CP,PR}(t_i))\cdot t_{int}$ $E_S(t_{i+1})=0$ $E_{GN}(t_i) = (P_{G,max}-P^{+}_{CP,PR}(t_i))\cdot t_{int}\cdot\eta_G^{-1} - E_S(t_i)+E^{+}_{CP,RV}\cdot(\eta_G)^{-1}-E^{-}_{CP,RV}\cdot\eta_M$

Table 34: The four possible cases in the simulation with consideration of the control power and negative $\Delta P_{W,S}(t_i)$ according to the Section 6.2

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