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Sensitivities of power-to-gas within an optimised energy system

E. Kötter[a,1,*], L. Schneider[a,2], F. Sehnke[b,3], K. Ohnmeiss[b,4], R. Schröer[c,5]

[a]*Reiner Lemoine Institut gGmbH, Ostendstraße 25, 12459 Berlin, Germany http: // www. reiner-lemoine-institut. de*
[b]*Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW), Industriestrasse 6, 70565Stuttgart, Germany*
[c]*juwi international GmbH, Energie-Allee 1, 55286 Wörrstadt, Germany*

Abstract

The storage of fluctuating energy production is a major challenge on the pathway to a fully renewable electricity supply. This paper investigates the role of Power-to-Gas (PtG) as a key storage technology in the fulfilment of the Energiewende. This study describesthe optimal composition and application of energy supply technologies using a detailed cost optimisation model based on data from an existing system in an actual German region. The region's electricity demand can be covered with 100% renewables at a levelised cost of electricity (LCOE) of 11 ct/kWhel. We found that the PtG capital expenditures (CAPEX) do not significantly affect the optimal system in terms of the installed capacity of PtG. Due to the high storage capacity of the existing gas grid, the use of PtG results in lower LCOE than the use of batteries. Alteration of system components towards greaterfluctuating energy production increases the need forlong-term energy storage, especially PtG, and results inhigher total costs. In summary, this investigation demonstrates the significance of Power-to-Gas.

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*Keywords:*Power-to-Gas; Energy System Optimisation; Energy Storage

1. Introduction

Storage of renewable energy (re) will pose a decisive challenge on the pathway to a fully renewable energy supply. The generation of synthetic methane from renewable electricity, Power-to-Gas (PtG), is considered a feasible

* Corresponding authorTel.: +49 30 53042002 Fax.: +49 30 53042010
E-mail address: editha.koetter@rl-institut.de

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storage solution with a high technical potential Sterner [41], Gahleitner [14]. Due to the limited potentials of pumped hydroelectric storage (PHS) [1, 7, 16, 31, 40] and biogas plants [42], PtG has the potential tobecome the principal energy storage concept for large-scaleimplemention. PtG is considered an appropriate long-term storage solution, since the productof the PtGprocess, Synthetic/Substitute Natural Gas (SNG), can be fed into the existing gas grid infrastructure. The capacity of natural gas reservoirs in Germany amounts to 219TWh [15], giving it the highestenergy storage capacity [41, 37, 32].

Since 2012, several implemented PtG-plants with sizes between 25 - 6,000kW$_{el}$ [8, 10] have provenitstechnical feasibility [14]. However, the economic potential of PtG to trade onthe energy exchange hasnot yet been demonstrated, asPtG competes for energy surpluses against energy export and Power-to-Heat (PtH) [3]. Other studies show that PtG becomes increasingly important, in scenarios with high re-shares. Within long-term scenarios, says Nitsch, it is conceivable to reach the goal of significantly reducing greenhouse gas emissions with PtG technology[24]. The optimisation of the entire energy system of the Berlin Brandenburg region by Möller shows that PtG is a main part of a cost optimal energy system with a high proportion, above 75 %, of re penetration [23].

However, the optimal usage of PtG within a dynamic and highly detailed power supply system, based on an existing model region has not yetbeen studied. This study investigates the role of PtG within a future energy system, via a complex dynamic optimisation model, including PHS, PtH and waste heat utilisation, using elaborateed potential analysis. The question has not yet been answered how the integration of PtG in an energy system with high shares of re is influenced by financial conditions or the interaction with additionaltechnology components. The following sensitivity analyses will investigate this questionin detail.

Theorem 1. PtG will prevail in dynamic energy systems against other innovative and favourable balancing components, such as PtH or lithium batteries, despite its comparatively low system efficiency.

2. Methods

2.1. Model Region

To investigate PtG in an energy supply system with 100% re, an appropriate model region in Rhineland-Palatinate is defined. The selected region already has a high share of re of 59% (calculated with [9]) and corresponds approximately to the power grid region “Trier-Amprion 5”. The geographical size corresponds to 1% of Germany. In general, it is a rural area with a high percentage of forests and agricultural areas. The map in figure 2.1 illustrates the position anddimensions of the model region including administrative borders, major cities and rivers.

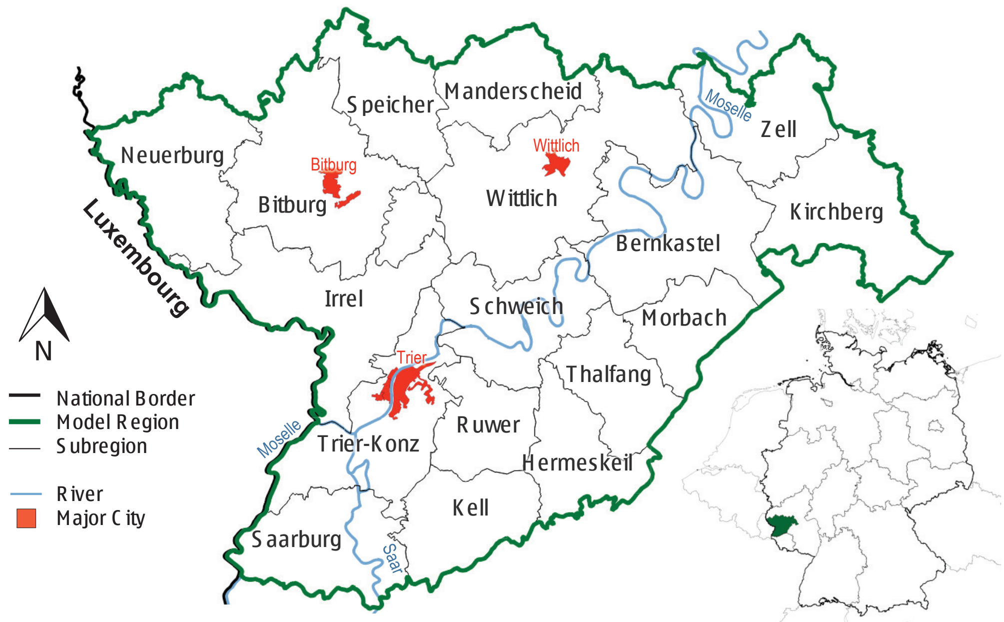

Fig. 1.General map of the model region [5]

2.2. Energy System Model

The model wasbuilt with P2IONEER [34], a component based energy flow simulation with a resolution of 15 minute time-steps, see figure 2. The analysed scenarios refer to a 100%re share in the year 2030. The electricity demand must be covered at any point in time. The operating order of the storage systems (pumped hydro storage, Li-ion batteries and the interaction of PtG, Biogas and CHP via the gas grid) depend on their efficiencies. Electricity surplus that cannot be stored is converted into heat via PtH, as long as the defined limits of the heat demand are not reached. Surplus of electric energy is allowed. Biogas is stored and can subsequently be converted into SNG via methanation or separated into CO2 and purified biogas, and afterwards fed into the gas grid.

The model is based on an optimisation approach to achieve the lowest LCOE possible by finding the installed capacity of wind power, PV, Li-ion battery, CHP, PtG, PtH, as well as the storage capacity of CO2 and crude biogas. The installed capacities are limited by the potentials shown in section 2.3. The objective function is described by minimal LCOE, based on CAPEX, OPEX, interest and depreciation, with specific depreciation periods and OPEX for each technology. The complexity of the optimisation problem is caused by a combination of many well-known properties which result in a flat solution space with frequent local minima. A further difficulty is the multimodality of the search space. Eventually, black box solvers with reinforcement learning wereselected over evolutionary algorithms, because they provedto be more efficient [36, 35].

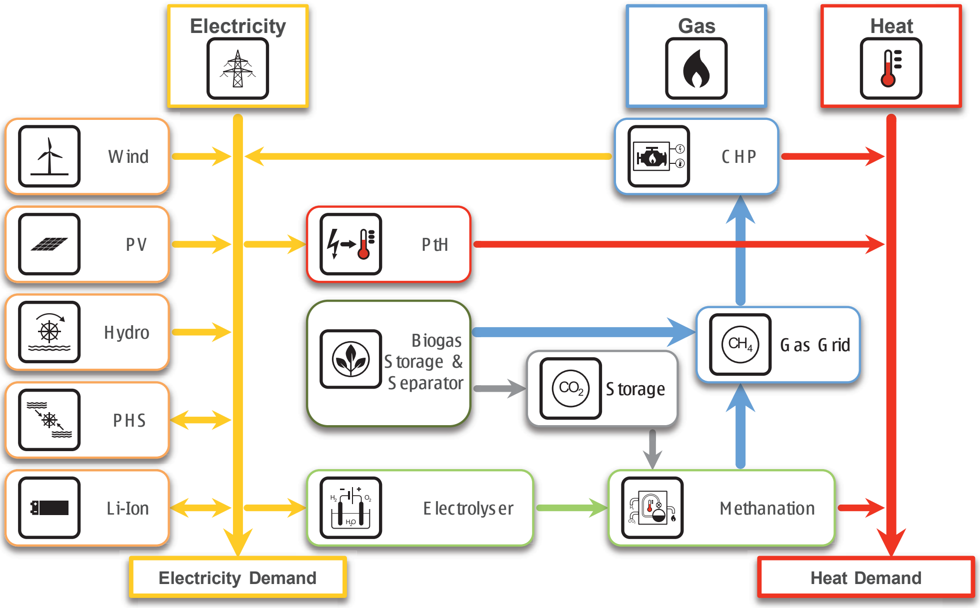

Fig. 2. Flow chart of the model

2.3. Input Data: Potentials, Parameters, Time Series

As a basis for the simulation, the existing energy system and its potentials configuration wasanalysed, see table 1. Comparatively high capacities of wind power (494MW$_{el}$), PV (259MW$_{el}$) and biogas (33MW$_{el}$) wereinstalled in the MR, leading tothe high reshare of 59% [9].

Table 1: Installed capacity and potential of re within the model region [2, 9, 20, 28, 29, 39]

re	Capacity (MW$_{el}$)	Potential (MW$_{el}$)
Wind Power	494	2,327
PV	259	13,475
Biogas	33	31
Hydropower	142	142

Furthermore, technical and financial parameters of all implemented technologies are determined for the year 2030 by efficiencies and costs, see table 2.3. All time series data arebased on the same meteorological conditions from the years 2011 and 2012. Wind: The potential of wind power depends on planning law and on-site wind conditions. It is assumed that adapted weak-wind turbines are used in 2030 and that typical hub heights will increase to 160 m due to future technical developments [24]. The energy output profile from wind power is based on meteorological satellite data (MERRA reanalysis), the roughness factor (Hellmann), and logarithmic profile calculations. Applying specific power curves results in reliable wind data with the influence of local site qualities (orology).

Table 2: Technical and financial parameters of the implemented components [4, 11, 12, 13, 18, 19, 21, 22, 24, 25, 26,30, 41]

Technology	CAPEX (€/kW$_{el}$)	OPEX (Invest./a)	Life Time(a)	Efficency
(Weak-) Wind Power	1,6	3.5%	20	
(High-) Wind Power	1	3.5%	20	
PV Rooftop	875	1.0%	25	
PV Ground Mounted	700	1.5%	25	
Hydropower	2,7	4.5%	40	
Biogas	1,35	6.0%	20	
CHP	900	2.8%	20	40%
PtG	900	2%	20	60% (24%)
Li-ion	350	1%	10	85%
PHS	160	1%	60	81%
PtH	100	1%	20	98%

PV: The rooftop PV potential is basedon the method of Lödl [20]. The ground-mounted PV potential is calculated usinggeographic analysis. The energy production profile from PV is calculated with satellite data of solar radiation, reference units, and cloud motion with the developedPV-model SolStEis (ZSW); the radiation calculations of Quaschning and Huld [27, 17]; system parametersby Schubert [33]; an analysis of yield data; and information aboutthe direction and velocity ofthe wind.

Biogas: The potential of biogas power plants in the model region is estimated usinglocal substrateyield [2, 38] and the share of landuse [39].Hydropower: Furthermore, a large amountof hydropower (142MW$_{el}$) is installed [29, 28, 9], althrough itis assumed that the potential for major hydropower plants on the Moselle and Saar Rivers hasalreadybeen reached. The generated time series corresponds to the water-level of four measurement points ofthe Moselle river.

PHS &Li-ion: For the simulation, PHS capacity is set to the value of 248MW$_{el}$, scaled form the German PHScapacity to the model region via the energy demand. The parameters for PHS are based on the SRU data [30]. The efficiencies of Li-ion-batteries and PHS include losses for incoming and outgoing energy, and discharge rates are also considered in the simulation.

PtG: The potential of CO2 for the methanation process is composed of CO2 mainly from biogas heating plants. Further CO2-intense industry is not found in the model region. Due to the gas grid connection, the storage capacity of PtG is assumed to be almost infinitely high. The current electricity and natural gas grid are examined for the model. The efficiency of PtG includes the electrolyser (75 %) and the methanizer (80 %), resulting in a conversion rate of 60 %, as selected and discussed with the manufacturer ETOGAS, considering hydrogen efficiency between 40 and 80% [11, 12, 19, 21, 22, 25, 26, 41] and methanation efficiency in the range of 60-85% [19, 41]

Heat demand: The domestic heat demand for hot water and heating is calculated using the method of standard load profiles [43, 6].

Electricity demand: The electricity demand is based on measurements made of actual transformer substations. The included energy production from local PV, wind power, hydropower and biogas is deducted and specific filters are applied. In comparison with standard load profiles, this method leads to a more realistic and distinctive characteristic. The electricity demand accumulates to 2.88TWh$_{el}$/a with an average power demand of 328MW$_{el}$.

3. Results

In the base scenario, the optimal constellation results in a total energy production of 4.56TWh_{el}/a with wind energy as the main producer. The demand for the year 2030 amounts to 2.88TWh_{el}/a. Thus, the excess energy is 1.69TWh_{el}/a, which is mainly used in PtG and PtH. The installed capacity of PtG is 218MW_{el} at LCOE of 11.0 ct/kWh_{el}. The analysed scenarios can be separated into two groups, characterised by their character and their influence on the results. Firstly, there is the group of scenarios related to the PtGconditions such as the investment cost, resulting in higher LCOE and less installed PtGcapacity. Secondly, there is a group of scenarios which cause changes to the total system and increase the need for PtG, as shown in figure 3.

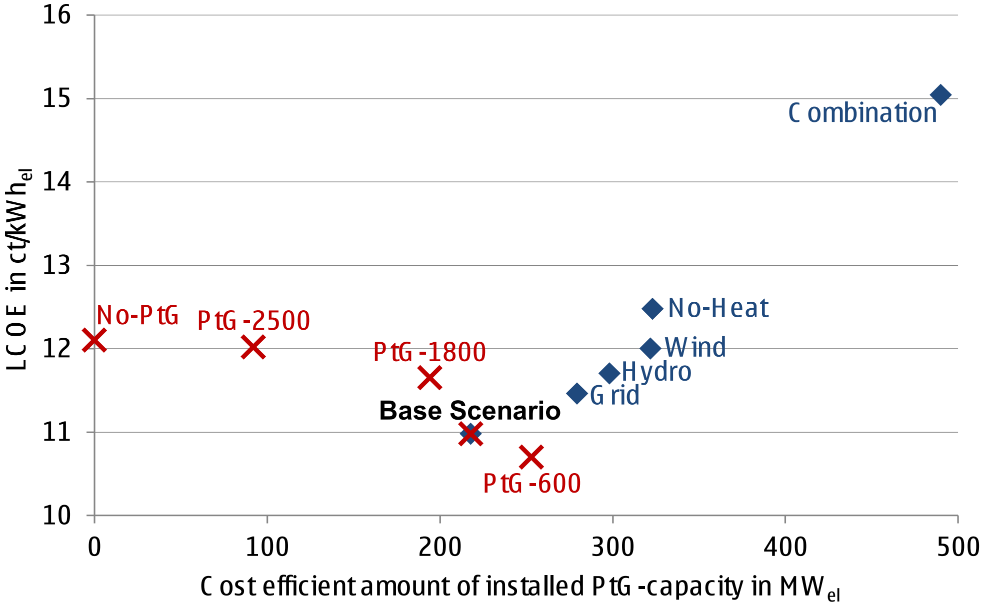

Fig 3: LCOE and PtG-capacity related to all scenarios

CAPEX of PtG: A higher CAPEX of PtG increases the LCOE, although it influences the composition of the energy system only slightly. Of course, with increasing CAPEX less PtG capacity is installed. Consequently, the system produces more fluctuating energy for direct supply. Thus, there is more surplus energy, causing higher Full Load Hours (FLH) of PtG, see table 3.

Table 3: Result of the CAPEX scenarios

Scenario	P_{PtG} (MW_{el})	FLH (h)	$P_{Li\text{-}ion}$ (MW_{el})
PtG-900	218	4,040	0
PtG-1200	209	4,112	0
PtG-1500	205	4,152	0
PtG-1800	194	4,245	0
PtG-2500	92	4,125	716
No-PtG	0	-	1,831

The results of the scenarios with modified PtG-CAPEX illustrate the correlation between increasing investment costs and increasing load factors. This changes at an assumed CAPEX of 2500 C/kW_{el}, because Li-ion batteries with better transformation efficiencies become pricecompetitive . Within the Base Scenario, the Li-ion battery is not cost efficient for the system, although its CAPEX is only 350 C/kW_{el}. Comparing the PtG-2500 to the Base Scenario, about 126MW_{el} capacity of PtG is replaced by 716MW_{el} Li-ion. For PtG, a huge storage capacity and a maximal power charge rate according to the installed capacity of the electrolyseris assumed within the model. However, for the Li-ion battery the storage capacity is limited. Thus it is obvious, when comparing the Base, PtG-2500 and No-PtGscenarios, that a lot of Li-ion battery installation is required in order to ensure the energy supply. Based on evaluation of the results of the CAPEX scenarios, it turns out that there is annearly linear relationship between LCOE and PtG-CAPEX: An increase of 300 C/kW$_{el}$ increases the LCOE by about 0.24 ct/kWh$_{el}$. Considering the LCOE of the No-PtG Scenario with 12.14 ct/kWh$_{el}$, Li-ion batteries become competitive as soon as the PtG-CAPEX is higher than 2,453 C/kW$_{el}$,, as proven by the scenario PtG-2500. This is the precise transition point at which the mixture of technologies in the system changes from an adaptation to PtG to an adaptation to batteries as the primary energy storage, see figure 4.

Fluctuating Load: Initially, weak-wind turbine technology is assumed for the simulation. The model region also has a considerable amount of hydropower installed. Both improve the electrical load curve and hence the performance of a 100%re energy system. Less hydropower leads to decreased energy production and must be compensated for using other energy producers, especially wind power and PV. Due to the fluctuating energy production of PV and wind turbines, however, more storage capacity is required to balance production and demand. Analogous to the Hydro Scenario, high-wind turbine technology causes fluctuating production time series so more producer and storage capacities are installed. This causes higher LCOE compared to the base scenario: +7% (wind) and +10% (hydro). It also causes higher PtG installations in both cases.

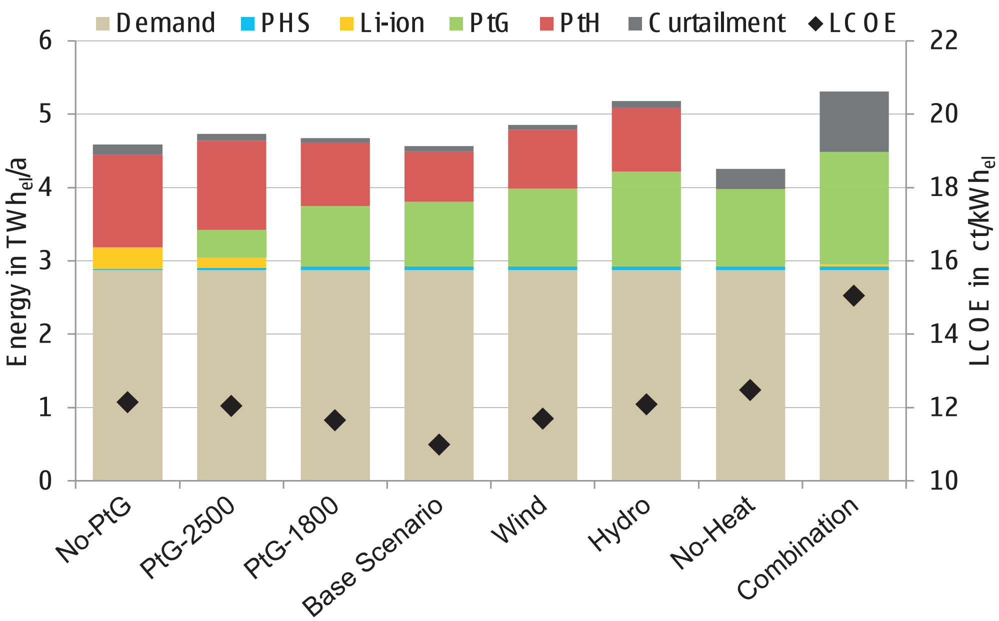

Fig 4: Usage of excess energy (storage, PtH and curtailment) in relation to the electrical demand

Heat: There is no installation of PtH withinthe No-Heat Scenario, and noother financial benefit from heat production. Because PtH is an inexpensive method to compensate power surpluses theyhave no in the No-Heat Scenario. This changes the technology composition, because powersurpluses are avoided to a greater degree, see figure 4. This surplusdecreases while the energy curtailmentsubstantially increases. Within the No-Heat Scenario more storage capacity and less productioncapacity is installed,and these additional expenses are the main reason for the higher LCOE of +14 %,compared to the base scenario.

Combination of Influences: The combination of the influence of less hydropower, the use ofhigh-wind turbine technology, and no benefits from heat sale, intensifies the challenges of the Energiewendedisproportionally. The LCOE of the combination scenario increases by 37%, comparedto the base scenario. However, the rise of the LCOE due to the isolated influences adds upto only 30% higher LCOE accompanied by an increasing amount of curtailment, see figure 4. Due to this interdependence of the influences, detailed simulations similar to the one completed inthis project are required for the investigation of the energy system. This means that a simpletransfer of results to other regions or differently composed systems is only possible under proviso. It is alsoapparent that a compensation of produced heat and waste heat has an explicit impact on the cost ofthe energy system.

4. Conclusion

PtG will probably be the main energy storage technology and thus a key technology for the Energiewendein Germany. An electrical energy supply based on a 100%re can be realised with or withoutPtG,but to achieve the most economical energy system, PtG is the optimal choice as the long-termenergy storage technology.It can lower the LCOE by 10 %, or more than one ct/kWh$_{el}$. An increaseof the LCOE by one ct/kWh$_{el}$ corresponds to an increase in the total cost of the energy system of28.76 million C/a, only for the model region.

On the one hand, only scenarios with 100 % re were analysed in this study, which realistically might not be implementedin Germany in the very near future. On the other hand, the high level of impact of PtG for future energy systems is highlighted.Thus other applications could serve as a launching platform for PtG, such as the mobilitysector. In conclusion, the analyses of the selected scenarios clarify some key findings about thePtG-technology within a simulated energy system. The total future need for PtG depends on thetechnological development of re, tested using technical sensitivity scenarios. Never the less, evenwithin the base scenario 218MW$_{el,}$ PtG is needed. Scaled to Germany, the energy consumptionamounts to 46GW$_{el}$. Taking the combined influences into account, the German need for PtGwould even be 102GW$_{el,}$ which is more than 14 times the level of current installations of PHS,which is around 7GW$_{el}$.

Even if the economic potential of PtG is not yet obviousthe impact of PtG on theenergy systemis so greatthat its CAPEX only slightly influences the requirement forPtG. At a battery-CAPEX of 350 C/MW$_{el}$,PtG would be prefered over batteries even at a high CAPEX up to 2,453 C/kW$_{el}$. Therefore,the PtG technology should not only be valued as a participant in the energy economy, but also as anvaluablesystem component for our future energy system.

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