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Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario

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Abstract

In future energy systems with high shares of fluctuating renewable energy generation, electricity storage will become increasingly important for the utilization of surplus energy. The Power-to-Gas (PtG) technology is one promising option for solving the challenge of long-term electricity storage and is theoretically able to ease situations of grid congestion at the same time. This article presents the perspectives of PtG in an 85% renewable energy scenario for Germany, quantifying an economic optimum for the PtG capacity as well as an optimized spatial PtG deployment.

Keywords: Power-to-Gas, methane, long-term electricity storage, economic optimization, unit commitment

1. Introduction

The growing share of renewable power from wind and solar plants in Germany leads to an increasing balancing need in a temporal as well as a spatial dimension. On the time axis, the weather dependent renewable electricity production has to be kept in balance with the demand for electricity at any time using demand side management, additional flexible power generation, or energy storage systems. In the spatial dimension, the balancing need arises, because a substantial share of electricity from renewable energy resources has to be transported to distant load centers across Germany.

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The Power-to-Gas (PtG) technology is one promising option in the context of these multi-dimensional challenges because PtG enables a combined temporal and spatial balancing solution for a time when renewable energy will supply the major part of the electrical demand. The storage concept links power and gas networks by the conversion of power into gas by two major steps: hydrogen (H_2) production by water electrolysis and the following conversion of H_2 and carbon dioxide (CO_2) into methane (CH_4) in the Sabatier reaction [1,2]. In this way, renewable electricity can be stored in the natural gas infrastructure, accessing the large transport capacities of the natural gas network and gas storage sites that offer the largest storage capacities for energy in Germany. The storage gas is a sustainable and versatile energy carrier, which can be used for reconversion to electricity, for heating and cooling purposes or as an alternative fuel option for the transport sector (Fig. 1).

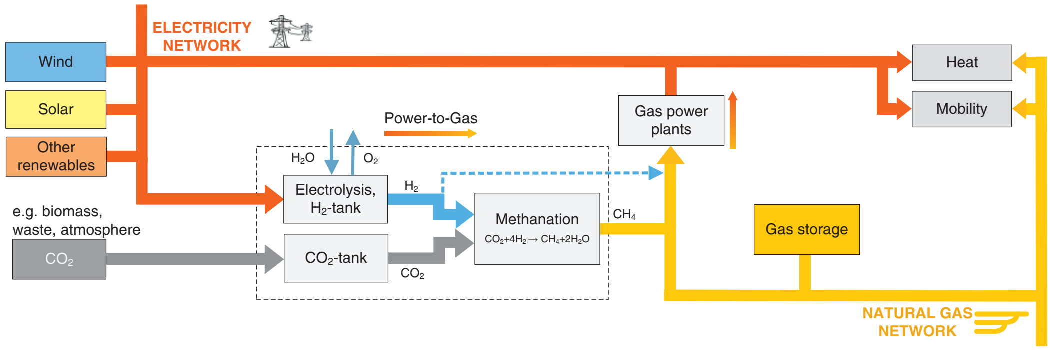

Fig. 1. The storage concept Power-to-Gas: storing renewable power as gas in the natural gas network for multiple use (based on [2]).

The conversion efficiency for PtG varies between 54 - 77 % for hydrogen and 49 - 65 % for methane, depending on the pressure level of the gas network or storage utility [3]. The feed-in of pure hydrogen into the gas infrastructure is possible but limited: todays feed-in limits of hydrogen are 2 – 5 vol% depending on the gas network and gas consumers; future limits can be up to 10 vol% [4]. In this paper PtG always means the production of CH_4, in order to fully access the gas infrastructure.

The objective of the research, presented in this paper, is to quantify an economic optimum for the PtG capacity as well as an optimized spatial PtG distribution in an 85% renewable energy scenario for Germany.

2. Methodology

A scenario simulation of the German electricity system is used to answer the given research objective. The 85% renewable energy scenario defined in [5] (scenario B) is used as data basis. The renewable power generation, the set of controllable power plants (fossil and biogas plants), electricity imports and exports, pumped storage power stations as well as the assumptions concerning the demand-side management applications in households (e.g. electric vehicles, electrical heat pumps and cooling) are taken from the scenario framework. Promising future flexibility options, especially the energy storage technology PtG but also the possible competing technologies Power-to-Heat (PtH) and typical short-term electricity storage systems, are varied within this research. The optimum dispatch of all controllable energy units is calculated by a unit commitment model, which solves linear mixed-integer problems [6,7].

Figure 2 shows the installed capacity as well as the electricity feed-in of all generation and storage technologies included in the base case calculation (Base). Apart from all existing and planned pumped storage power stations as well as demand-side management applications, the additional flexibility options mentioned above are not taken into account for the integration of surplus renewable energy in the base case.

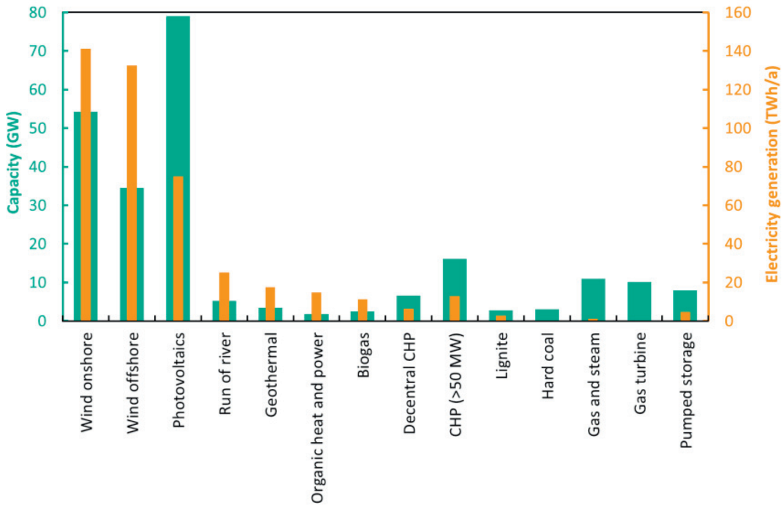

Fig. 2. Power generation capacities and electricity feed-in in the base case calculation.

In order to consider the spatial dimension of the electricity supply, a simplified representation of the German transmission network is included in the unit commitment model. At the one hand, the number of transmission lines is reduced to interconnectors between defined network regions (see Fig. 3); on the other hand, the calculation of the load flow is simplified by a linear description, using the so called 'direct current approximation'. This approach is able to generate the load flow distribution taken into account the given maximum transmission capacities for the defined interconnectors between different regions.

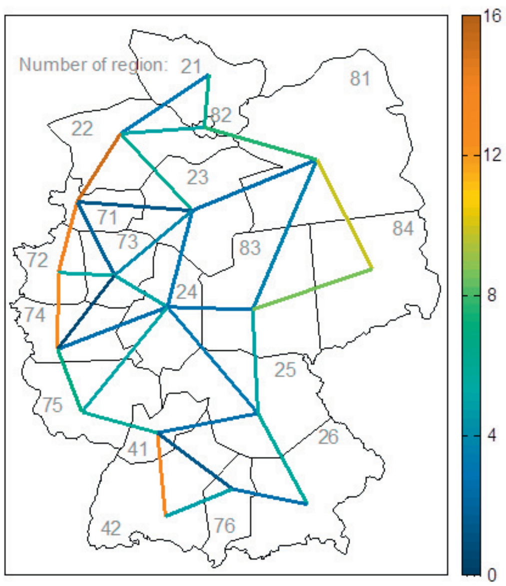

Fig. 3. Regional representation of the German transmission network for the 85% renewable energy scenario.

3. Economic optimum of Power-to-Gas capacity

For determining an economic optimum of PtG capacity (see also [8]), the optimal dispatch of several scenario variants is evaluated. The relevance of the additional flexibility options PtH and short-term storage systems is analyzed in a first step. In a second step, an increasing PtG capacity is modeled in interaction with the most relevant competitive option.

3.1. Competing flexibility options

Figure 4 shows the influence of additionally installed PtG, PtH and short-term storage systems (8 GW in each case) on the electricity surpluses and on the variable costs of electricity and heat generation in comparison to the base case. The PtG option shows the highest flexibility and integrates most electricity surpluses. The PtH option is also very suitable to reduce long-term electricity surpluses of the 85% renewable energy scenario. PtH is modeled using electric heaters, which are used to provide further flexibility to the simulated combined heat and power plants (CHP). In hours with heating demand and concurring renewable energy surpluses, electric heaters are used instead of the fuel-based CHP operation. As the PtH operation is directly linked to a given heating demand, it cannot be used as flexible as the PtG option, but it shows the highest effect on reducing the variable system costs.

The additional short-term storage systems, which are modeled with a 5 hour ratio of storage volume to charging power, are not able to significantly reduce the long-term electricity surpluses or the variable system costs. These additional short-term electricity storages, which could represent a mix of battery and adiabatic compressed air storage systems, may be necessary to provide ancillary services (not analyzed in this work), but are not identified as relevant parameter concerning the main field of application of the PtG technology, which is long-term storage.

Therefore the following analysis, regarding the determination of an optimized PtG capacity, are done within the base case (Base) and within the PtH scenario variant (Base + PtH).

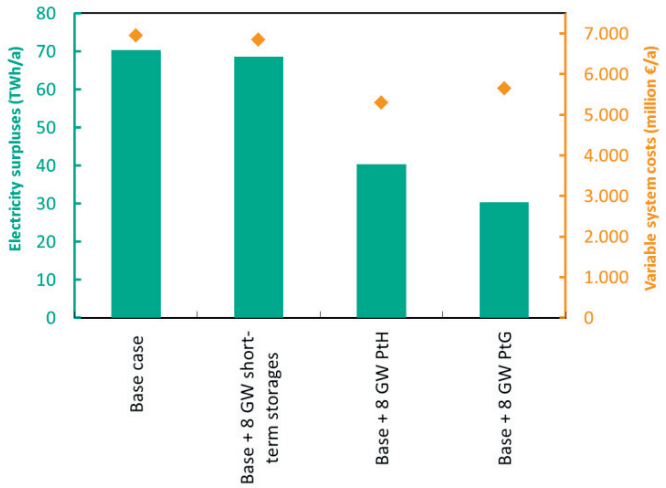

Fig. 4. Effects of different flexibility options on the surplus electricity generation and the variable system costs.

3.2. Benefit-cost-lines with an increasing PtG capacity

For determining a cost optimized PtG capacity within the two chosen scenario variants, benefits and costs related to the PtG technology are balanced for a series of model runs with an increasing PtG capacity.

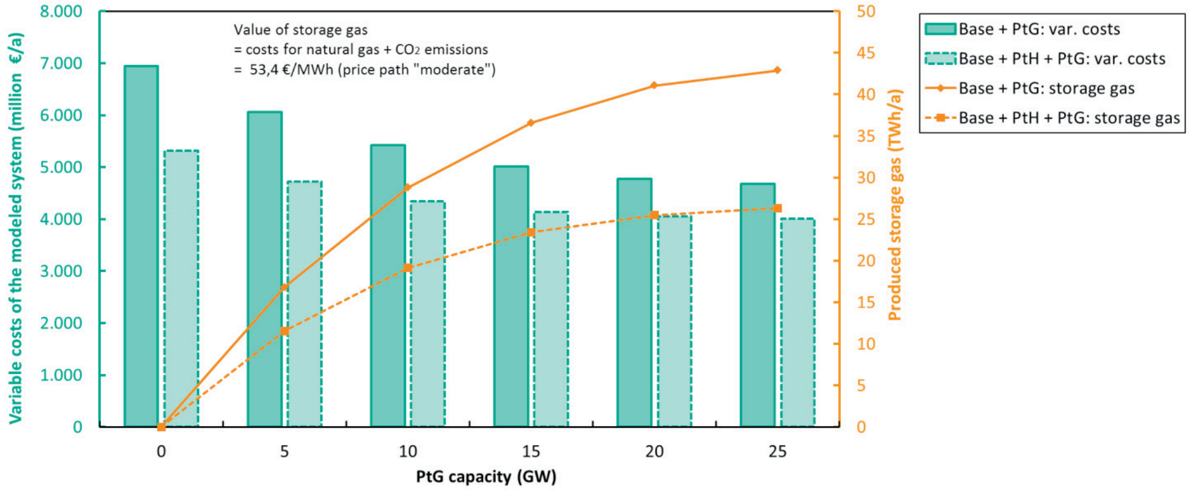

Fig. 5. Variable costs of electricity and heat generation as well as the produced storage gas in dependence of installed PtG capacity.

The result of the optimum dispatch of the modeled energy system provides the variable costs of electricity and heat generation (see Fig. 5). The variable costs decrease with higher PtG storage capacities. Additional PtG units offer the possibility to use higher shares of surplus electricity wherefore the value of the produced storage gas reduces the overall costs of the modeled system. In interaction with the balancing option PtH, the contribution of PtG decreases, but the overall effect on reducing system costs is at its maximum when the energy system includes a mix of both complementary balancing options.

The value of PtG storage gas is set to the value of natural gas including the costs for CO_2 emissions in the emission trading system as the storage gas substitutes the use of natural gas. For this calculation, the price path “moderate” with 53,4 €/MWh is used according to [5]. The difference between the variable system costs of the base cases and the calculations with increasing PtG capacity are used to quantify the economic benefit of PtG integration.

Table 1. Parameter of the PtG technology in the 85% renewable energy scenario.

Technical parameter		
Efficiency of the PtG process (electrolysis und methanation)	62	%
PtG technology costs		
Investment costs	750	€ / kW installed electrical power
Fixed operating costs	4	% / a of investment costs
Interest rate	6	%
Depreciation period	25	a
Fix annual costs (Annuity + fixed operating costs)	118	€ kW^{-1} a^{-1}
Price path / value of storage gas		
Energy costs for natural gas including costs for CO_2 emissions (according to [5])		
Price path “moderate”	53,4	€ / MWh
Price path “significant”	86,8	€ / MWh

The calculated benefit is set in relation to the costs for building up the PtG plants. It is assumed that the investment costs for future PtG plants, in the considered 85% renewable energy scenario, have decreased from about

3.000 €/kW (today) to 750 €/kW. The fixed annual costs are 118 €/kW when calculating the annuity and taking fixed operating costs into account (Tab. 1). In addition to the intended technology costs, the influence of lower and higher investment costs (500 and 1.000 €/kW) are also analyzed.

Finally, benefits and costs are combined by drawing lines that show the balance of benefits and costs for a PtG capacity range from 0 to 40 GW (Fig. 6). The benefit-cost-lines are shown for the intended technology costs of 750 €/kW as well as for a lower and higher sensitivity assumption (500 €/kW / 1.000 €/kW). The optimum PtG capacity for each calculated variant is reached at the maximum of the benefit-costs-lines. In case of assumed investment costs of 750 €/kW, the economic optimum of the PtG capacity is in a range of 6 to 12 GW (green lines), depending on the additional penetration of the PtH technology.

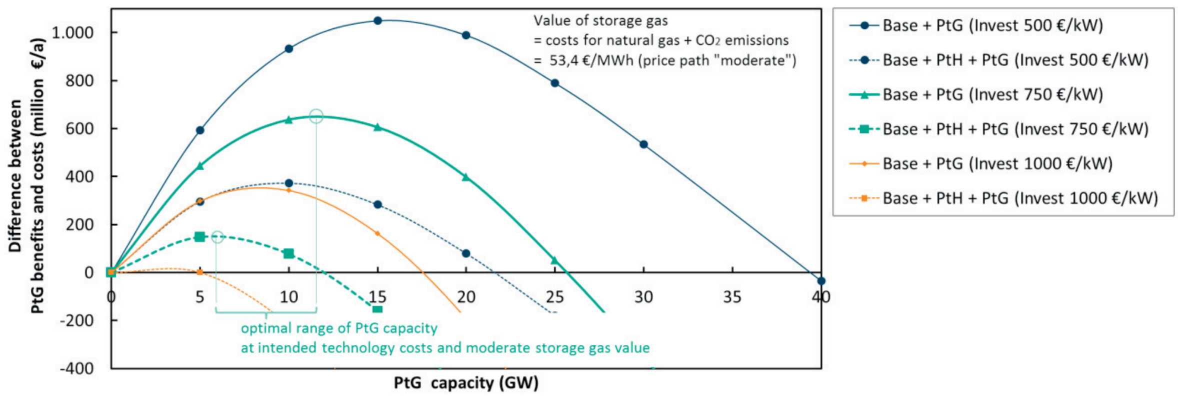

Fig. 6. Benefit-cost-lines for determining an economic optimum of PtG capacity in the 85% renewable energy scenario.

With lower technology costs (blue lines) the economic optimum of PtG capacity shifts to a higher level, while with more expensive investment costs (orange lines) the economic optimum moves to a lower PtG capacity need. Another very important factor that influences the result of optimal PtG capacity is the assumed storage gas value. A higher value for the renewable energy carrier leads to additional economic benefits, which will shift the economic optimum of PtG capacity to a higher need as well. When assuming a storage gas value according to the price path “significant” (see Tab. 1), the economic benefits lead to a similar effect on the economic optimum of PtG capacity as lower technology costs.

Altogether, the PtG technology leads to a reduction on economic costs, to a higher integration of renewable energy, and reduces the CO_2 emissions in all analyzed cases in the 85% renewable energy scenario.

4. Spatial distribution of Power-to-Gas plants

In order to achieve the economic benefits of PtG as energy storage option, described in section 2, and to enable a grid-compliant operation at the same time, it is not only necessary to analyze the temporal dimension, but also the spatial distribution of PtG plants. As part of this analysis, the spatial distribution is optimized with the objective to place a predefined PtG capacity, so that in times of grid congestions a high share of the surplus energy can be stored by using PtG, which otherwise could not be transported or used. The second aim is to place the PtG plants so that energy transport and related costs are reduced. Therefore, the optimization of the spatial PtG distribution takes maximum transport capacities into account as well as the specific costs for the use of the transport lines (see section 2).

Fig. 7 shows the annual electricity of the controllable power generation units and balancing options as well as the sum of energy exchange (positive and negative) between the modeled regions. In this exemplary simulation both complimentary balancing options (10 GW PtG and 8 GW PtH) are assumed. Taking into account the transmission network and related transmission costs, most of the PtG deployment is located in the two northern regions (21, 22) where most of the electricity of offshore and onshore wind power is fed into the grid. Especially the highly concentrated renewable power in the north-west of Germany (almost 35 GW offshore wind turbines) influences the result. When supposing less offshore capacities but higher power generation from inland wind energy plants, the spatial distribution of PtG would be spread on a larger area.

Besides the deployment of temporal balancing options, a strong need for electricity transmission between the regions can be observed.

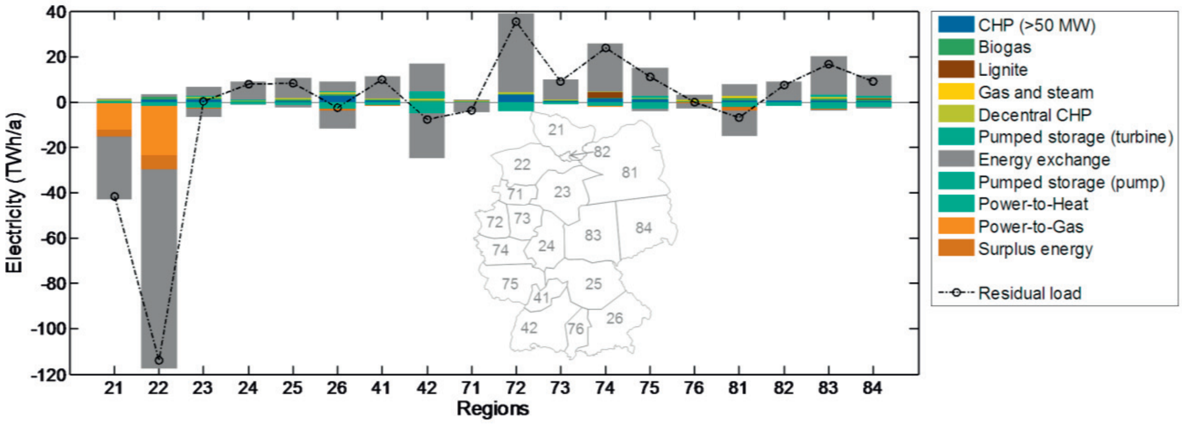

Fig. 7. Spatially resolved controllable power generation and energy exchange between regions taking into account 10 GW PtG and 8 GW PtH.

Other aspects influencing the spatial deployment of PtG plants in the future are additional requirements from lower network levels, the availability and the cost of CO_2 for the methanation process, the capacity and proximity of the gas network, as well as local advantages to generate synergies using the waste heat of the PtG process or the oxygen of the electrolysis process (see also [9]). As those effects were not part of this analysis, the spatial deployment of PtG plants might be different taking further parameters into account. Nevertheless, regions in the north of Germany seem to be highly suited for future PtG plants for the reasons described above.

5. Conclusion and outlook

The presented scenario simulations have shown that the PtG technology is able to significantly integrate surplus feed-in power in an 85% renewable energy scenario for Germany. In interaction with the balancing option PtH the contribution of PtG becomes smaller, but the overall effect on reducing economic costs as well as CO_2 emissions is at its maximum, when the energy system includes a combination of both complementary balancing options.

The economic optimum of the PtG capacity is within a range of 6 to 12 GW in the case of future average technology costs for building up the PtG plants and the moderate price path for storage gas assumed in the scenario. Taking into account the transmission network and related costs, most of the specified PtG capacity should be located in the north of Germany in order to achieve the highest benefit in storing surplus energy and reducing power flows in the transmission network at the same time.

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References

[1] Specht M, Brellochs J, Frick V, Stürmer B, Zuberbühler U, Sterner M, Waldstein G. Storage of Renewable Energy in the Natural Gas Grid. In: *Erdöl Erdgas Kohle 126*, no. 10, 2010, pp. 342-346.

[2] Sterner, M. Bioenergy and renewable power methane in integrated 100% renewable energy systems. Limiting global warming by transforming energy systems. Dissertation, University of Kassel; 2009.

[3] Sterner M, Jentsch M, Holzhammer U. Energiewirtschaftliche und ökologische Bewertung eines Windgas-Angebotes. Fraunhofer IWES expert report for Greenpeace Energy; 2011.

[4] Müller-Syring G, Henel M, Köppel W, Mlaker H, Sterner M, Höcher T. Entwicklung von modularen Konzepten zur Erzeugung, Speicherung und Einspeisung von Wasserstoff und Methan ins Erdgasnetz. Final Report DVGW Project G1-07-10, DVGW e.V. Bonn; 2013.

[5] DLR, Fraunhofer IWES, IfnE. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Expert report for the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety; 2012.

[6] Von Oehsen A. Entwicklung und Anwendung einer Kraftwerks- und Speichereinsatzoptimierung für die Untersuchung von Energieversorgungsszenarien mit hohem Anteil erneuerbarer Energien in Deutschland. Dissertation, University of Kassel; 2013.

[7] Jentsch M. Further development of unit commitment model presented in [2], not yet been published; 2013.

[8] Jentsch M. Perspektiven der Langzeitspeicheroption Power-to-Gas. In: *BWK* 65, no. 10, 2013, pp. 54-56.

[9] Trost T, Horn S, Jentsch M, Sterner M. Erneuerbares Methan: Analyse der CO_2-Potenziale für Power-to-Gas Anlagen in Deutschland. In: *Zeitschrift für Energiewirtschaft* 36, no. 3, 2012, pp. 173-190. doi: 10.1007/s12398-012-0080-6.