Economic Potential of the "Power-to-Heat" Technology in the 50Hertz Control Area

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Abstract

Electricity generation through renewable energy sources (RES) in Germany has risen significantly in the last years. Specifically, the control area of "50Hertz Transmission GmbH" is confronted by a situation of high installed wind power capacities and simultaneously by a comparably low electricity demand. With already oversized conventional generation capacities with a high share of cogeneration plants, transfer capacities to neighboring control areas are even today often congested. Therefore, the introduction of new electricity consumers like the Power-to-Heat technology (P2H) may be useful in integrating increasing excessive amounts of RES and in supplementing system service provision. Furthermore, the tightening conflict between cogeneration and fluctuating RES could be defused through this technology. Compared to the often discussed Power-to-Gas technology, P2H is already available at comparably low costs.

This paper evaluates through an energy economic model the economic potential of the application of P2H in combination with heat storages in district heating grids as an additional flexibility option for combined heat and power plants. The model maximizes the possible profits of a district heating system consisting of cogeneration units, heating plants and heat storages combined with P2H applications on the day-ahead spot and balancing power market for a given heat demand on an hourly basis. Moreover, a case study analyzes several existing district heating grids in the 50Hertz control area for the years 2014 and 2020.

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As the P2H technology is well-suited for the provision of balancing power, P2H-plants can pay back investment costs in less than one year by just providing negative secondary reserve. The energy price for P2H-plants is mainly determined by state and other charges for the electricity consumption. Therefore, the cost efficient usage of P2H for heat provision via the spot market needs negative spot market prices in a considerable size. Only with a total exemption of the additional costs P2H-plants would be used for heat production.

Key words:
Power-to-Heat, combined heat and power, heat storage, renewable energy, control power.

1 Introduction

The expansion of generation capacities from renewable energy sources (RES) has made significant progress since the implementation of a Feed-In-Tariff (FIT) regulation in Germany in 2000. Foremost, the variable RES (vRES) have developed notably, though with a high regional differentiation. Whereas Photovoltaic (PV) is mainly installed in the southern parts of Germany – the area with high electricity consumption and low conventional generation capacity – wind energy has been developed mostly in the northern and eastern parts of Germany where comparably higher load factors for wind turbines can be achieved. (*DLR et al., 2012*)

The net electricity consumption especially in the control area of the transmission system operator (TSO) “50Hertz Transmission GmbH” (50Hertz) is comparably low while large base load capacities such as lignite-fired power plants have a high share in electricity production. (*50Hertz, 2012a*)

Furthermore, combined heat and power (CHP) associated with large district heating grids plays a major role in the control area of 50Hertz (*AGFW 2011*). On the other hand the transmission capacities of the interconnectors to neighboring control areas in Germany, Poland, Denmark and the Czech Republic are progressively not sufficient (foremost at times with high wind generation and a low load in the control area) to integrate all amounts of renewable generation. The incidence of single interconnection lines having been re-dispatched or that renewable generation has to be shut down is increasing. The situation becomes highly problematic because grid extension is not proceeding as fast as the RES capacities. Figure 1 illustrates the projections for the expansion of RES until 2020 in the 50Hertz control area. The capacities of onshore wind generators are expected to double as compared to 2010. Wind power is depicted to be the dominating electricity source (64 % of installed RES power) by 2020. PV capacities will have an annual growth rate of 25 %. The calculated RES-share on electricity demand will be 72 % in 2020. The installed capacities of all RES of 39 GW_{el} will be more than twice as high as the maximum net electricity load of 15 GW_{el} in the 50Hertz control area. Under certain conditions, the total demand in the control area will be covered by wind and PV systems – even today.

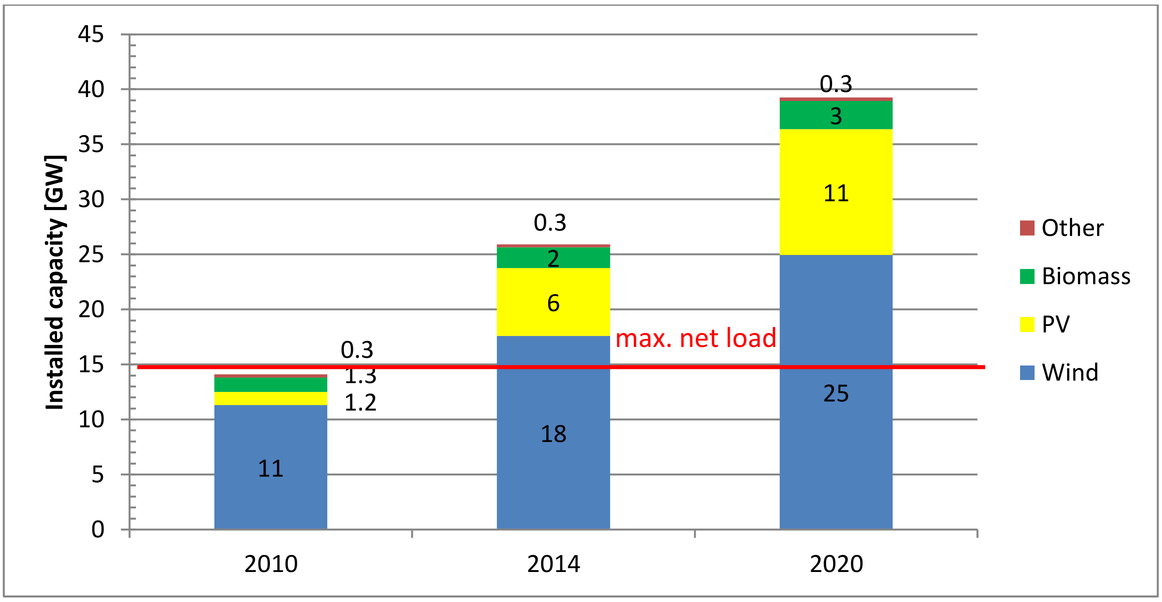


Figure 1: Projections of RES generation capacities until 2020 (Source: 50Hertz, 2012b)

In addition to measures to grid expansion and retrofitting, future flexibilities within the system can be identified and used. One possibility pertains to the use of excessive electricity from RES to generate heat in district heating systems. In this paper the economic potential of the Power-to-Heat technology in large district heating systems is assessed by using an economic model for CHP/district heating systems. The analysis of the technology encompasses various scenarios.

2 Methodology

The assessment of the theoretical potential of P2H in the control area of 50Hertz requires the analysis of the data of the local district heating systems as well as the development of synthetic heat demand curves. They base on historical district heating demand curves of the district heating systems of the cities of Würzburg (2001), Berlin (2007) and Leipzig (2010). Via the correlation between outside temperature, date and historical heat demand, synthetic heat profiles on the basis of local outside temperatures at the relevant district heating grids can be constructed.

Figure 2 manifests the calculation of the technical potential on the supply and demand side for the years 2014 and 2020. This is conducted by considering technical restrictions and the feed-in of RES.

The European power plant dispatch model *MICOES-Europe*[5] produces hourly price forward curves (HPFC) for the years 2014 and 2020 using assumptions on the development of the economic and technical parameters taken from the Network Development Plan (*Netzentwicklungsplan 2012; ÜNB (2012)*) and *DLR et al. (2012)*. The assumptions concerning fuel prices and net electricity consumption are summarized in Table 1. Together with historical control power prices from 2010 the HPFC serves as input parameter for the model "P2H". With the model "P2H" six large district heating systems, including CHP-plants, boilers, heat storages and P2H-systems, can be analyzed.

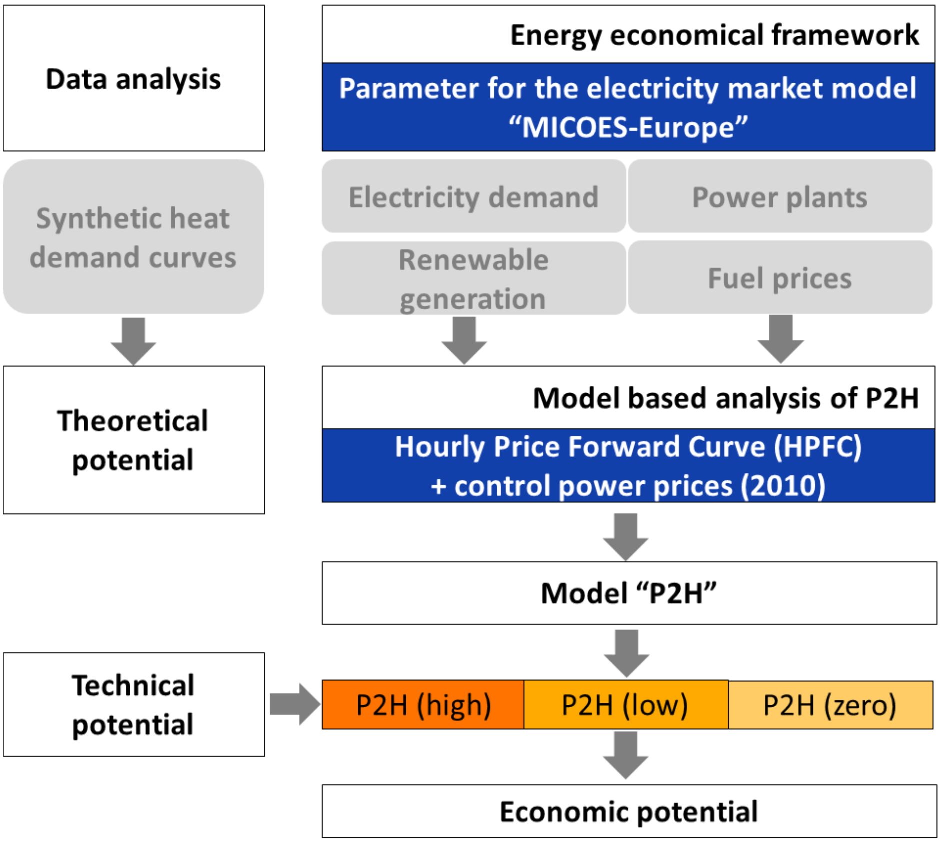


Figure 2: Methodology of assessing the economic potential of P2H

[5] A short description of the model *MICOES-Europe* can be found in the appendix.

Table 1: Assumptions for fuel prices, CO_2 prices and the net electricity consumption

Fuel/Demand	Unit	2014	2020
Uranium	€/MWh_{fuel}	3.70	4.00
Lignite	€/MWh_{fuel}	4.51	4.69
Hard coal (import)	€/MWh_{fuel}	9.95	9.81
Natural gas	€/MWh_{fuel}	23.00	25.14
Light fuel oil	€/MWh_{fuel}	73.61	82.69
Heavy fuel oil	€/MWh_{fuel}	40.37	45.35
CO_2	€/t	10.00	20.00
Net electricity consumption (Germany)	TWh	548.2	548.2

3 Results and Discussion

3.1 Theoretical potential

The total district heat supply of all district heating grids in the 50Hertz control area in 2010 was about 38.6 TWh_{th} according to *AGFW (2011)*. The accumulated maximum load was approximately 11.7 GW_{th}. If P2H plants will be installed with a thermal output equal to the maximum total heat load of all district heating grids in the 50Hertz control area, the theoretical potential to increase the electrical load amounts to 12 GW_{el} (at a thermal efficiency of 98 %). The ten largest district heating grids already cover 76 % of the whole district heating demand in the control area (8.7 GW_{th}/29.4 TWh_{th}).

The technical potential of P2H is derived from the theoretical potential and is distinguished between the technical potential on the supply side and the one on the demand side. While the technical potential on the supply side is determined by the usable heat demand that is *provided* by the district heating system (dimension of the heat sink), the technical potential on the demand side is determined by the *need* of additional electrical load to integrate excessive amounts of RES.

3.2 Technical potential on the supply side

According to *Prognos (2011)* only district heating grids with an average thermal load higher than 10 MW_{th} are considered. Thereby, the simultaneous maximum heat load of these relevant grids decreases to 11 GW_{th} (equivalent 11.2 GW_{el}). This value also pays attention to the fact that the maximum thermal load in every single heating grid cannot be found at the same time. Figure 3 embodies the combined thermal load curve of the relevant district heating grids.

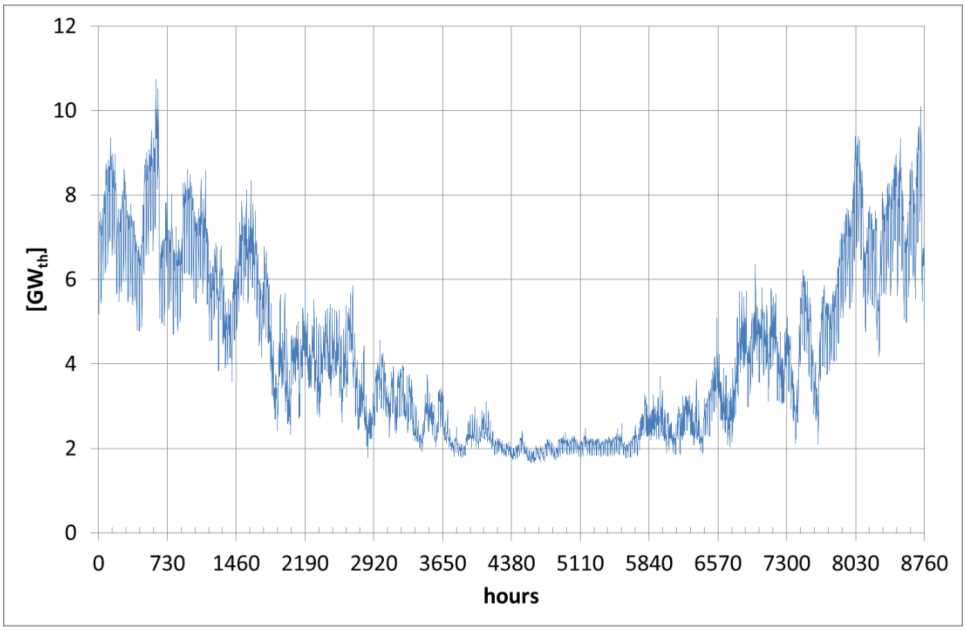


Figure 3: Combined thermal load curve of the relevant district heating grids in the control area of 50Hertz in 2010 (own calculation; AGFW (2011))

The technical potential of P2H on the supply side depends on the dimensioning of the P2H-systems. *Prognos (2011)* recommends a dimensioning of the P2H-systems for 30 % to 50 % of the maximum thermal load. Hence, the technical potential of P2H on the supply side is between 2.2 GW_{el} and 5.6 GW_{el}. Table 2 summarizes the regional distribution of the technical potential of P2H in the 50Hertz control area. The largest potentials are located in Berlin, Saxony and Hamburg.

Table 2: Regional distribution of the technical P2H-potential in the control area of 50Hertz

Area		Control area		Brandenburg	Berlin	Mecklenburg-West Pomerania	Saxony	Saxony-Anhalt	Thuringia	Hamburg
(thermal efficiency 98%)		**[MW_{th}]**	**[MW_{el}]**	[MW_{el}]	[MW_{el}]	[MW_{el}]	[MW_{el}]	[MW_{el}]	[MW_{el}]	[MW_{el}]
Dimensioning of the P2H-Systems in Percentage of the max. thermal load	20%	2,199	2,243	292	730	147	463	161	168	284
	30%	3,298	3,365	438	1,095	220	694	242	251	426
	40%	4,397	4,487	583	1,460	293	925	322	335	567
	50%	5,496	5,609	729	**1,826**	367	**1,156**	403	419	**709**

3.3 Technical potential on the demand side

The technical potential is further restricted by the amounts of excessive generation from RES. As it can be seen in Figure 4, mathematically, the demand for base load generation in the 50Hertz control area completely disappears by 2020 due to the expansion of RES generation. In 2014, the residual load is negative in about 700 hours. The value increases until 2020 to more than 2500 hours. The maximum potential that is needed for the integration of excessive RES generation culminates in -9 GW_{el} in 2014 and -17.7 GW_{el} in 2020.

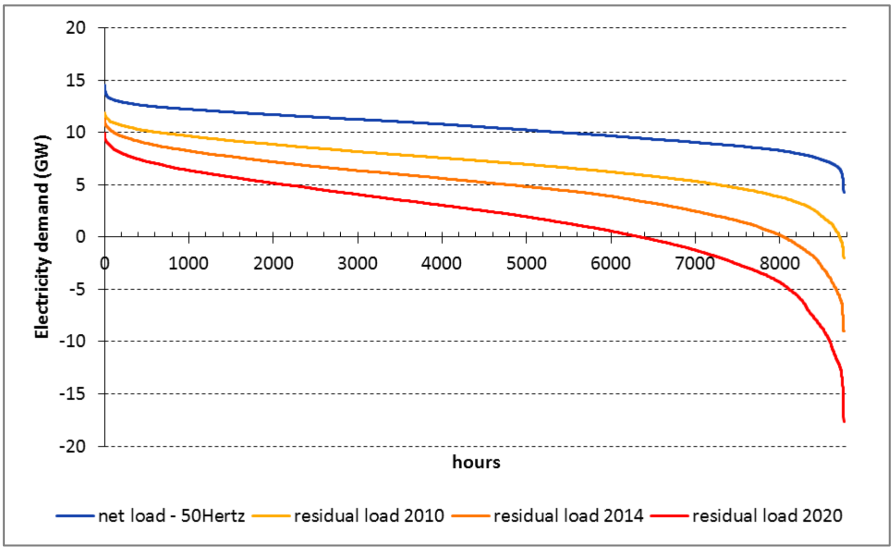


Figure 4: Development of the residual load duration curve in the contral area of 50Hertz for 2010-2020

In Figure 5 the heat demand curves and the residual load curves for 2014 and 2020 are combined. Every point represents the residual load and the heat load for a single hour out of the 8760 hours of the year. The area within the red rectangle shows the hours of the year when P2H can play a role. In this area, the residual load is negative and meets a certain heat demand. At points within the rectangle, which are situated above the diagonal line, the heat demand is higher than the residual load. Thus, the entire negative residual load can be absorbed, but additional heat producers (heat storages, boilers) are needed to fulfill the heat demand. Below the diagonal line the negative residual load exceeds the heat demand. In this case, the excessive heat production from P2H-systems could be stored in heat storages. In hours situated on the diagonal line the heat demand equals the negative residual load.

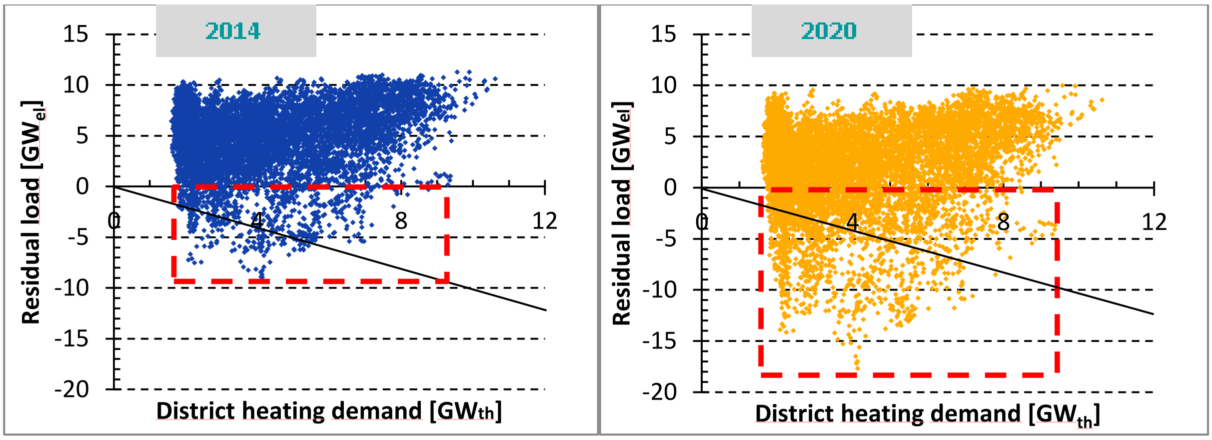


Figure 5: Simultaneous heat demand and residual load for 2014 and 2020

The following duration curve of the technical potential on the demand side is constructed by sorting all points in the red rectangle (Figure 6). It is determined by the minimum of the heat demand and the absolute value of the negative residual load. Hence, up to 5.6 GW$_{el}$ of the absolute negative residual load of 9 GW$_{el}$ in 2014 and up to 8 GW$_{el}$ of the absolute negative residual load of 17.6 GW$_{el}$ in 2020 could be used for P2H. All in all, the amount of excessive electricity that could be transformed to heat is 1.5 TWh$_{el}$ in 2014 and 5.9 TWh$_{el}$ in 2020.

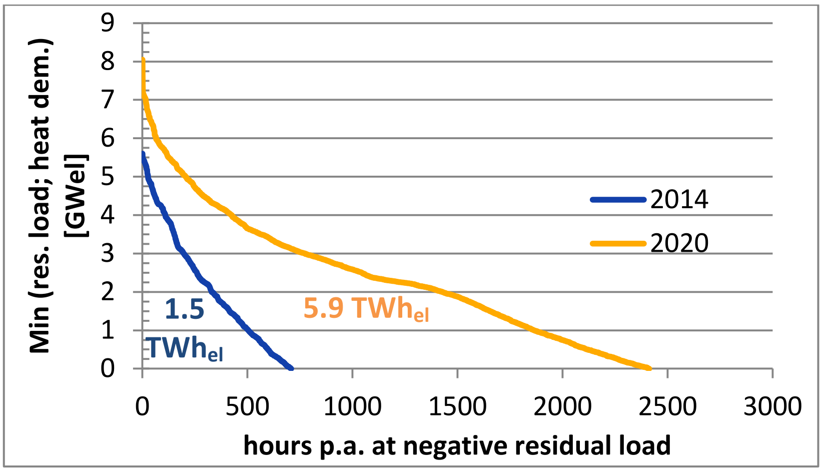


Figure 6: Technical potential of P2H on the demand side in 2014 and 2020

3.4 Variable costs of P2H-systems

In principle one would expect that P2H can be beneficial if the residual load of the control area is negative. But a negative residual load in the 50Hertz control area is not necessarily equivalent to a negative spot market price within the entire market area because of regional differences in the generation mix (foremost caused by RES), deviations of the load structure or the influence of the European market coupling. Furthermore, at the current regulatory framework P2H-systems need significant negative spot market prices to produce heat in a competitive way. Particularly the FIT surcharge (EEG-Umlage), the grid usage fees, the electricity tax and the compensation of the primary energy factor (PEF) lead to high variable costs. The PEF compensation is necessary because the production of heat by electricity deteriorates the PEF of the district heating system according to the German regulation for energy saving in buildings and building systems (“Energieeinsparverordnung” - EnEV). Compensation through the usage of renewable fuels from biomass or biogas would become necessary. The extent of the compensation varies and is dependent on the current PEF of the particular district heating system. For a P2H-system in an exemplary district heating grid the variable costs in a static consideration sum up to € 108.58/MWh_{el} in 2013 (Table 3). Therefore, P2H needs prices below € -108.58/MWh_{el} to work cost-effective.

Table 3: Variable costs of P2H in 2013

Variable costs	Unit	2013
FIT surcharge	€/MWh	52.77
Grid usage fee	€/MWh	25.20
Electricity tax	€/MWh	20.50
§19 StromNEV-surcharge	€/MWh	1.51
Concession levy	€/MWh	1.10
CHP-surcharge	€/MWh	0.50
Offshore-surcharge	€/MWh	0.00
PEF-Compensation	€/MWh	31.00
Displaced heat generation	€/MWh	-24.00
Sum	€/MWh	108.58

3.5 Model assumptions for heat storages and P2H

From a technical point of view it is recommendable to integrate P2H in district heating systems via heat storages. For modeling purposes, the output of the heat storages and P2H-systems are dimensioned for 50 % of the maximum thermal load of the particular grids. The heat storages are designed to absorb or release 50 % of the maximum thermal load for 10 hours. The data can be seen in Table 4. Approximately 60 % of the technical potential on the supply side of the 50Hertz control area can be covered by the modeled systems.

Table 4: Model assumptions for heat storages and P2H

	Unit	Berlin East	Berlin West	Leipzig	Dresden	Chemnitz	Halle	Sum
Max. thermal load 2010 (core grid)	MW_{th}	1,568	2,763	595	657	455	280	**6,003**
Heat demand 2010 (core grid)	GWh_{th}	5,500	5,258	1,812	1,890	1,116	948	**16,321**
Thermal output of CHP-plant	MW_{th}	651	2,024	534	265	475	140	**4,089**
Thermal output of boilers	MW_{th}	1,422	105	266	522	232	190	**2,737**
Modeled max. storage output (50% of max. thermal load)	MW_{th}	790	1,380	300	330	230	140	**3,170**
Modeled storage capacity (10h)	MWh_{th}	7,900	13,800	3,000	3,300	2,300	1,400	**31,700**
Modeled P2H-output (50% of max. thermal load)	MW_{th}	790	1,380	300	330	230	140	**3,170**

The following analysis is based on modeled spot market prices from *MICOES-Europe* for 2014 and 2020 (compare Figure 7) and historical control power prices from 2010. The CHP/district heating systems optimize their dispatch on the basis of the spot market, the control power market and the thermal load as price takers with perfect foresight.

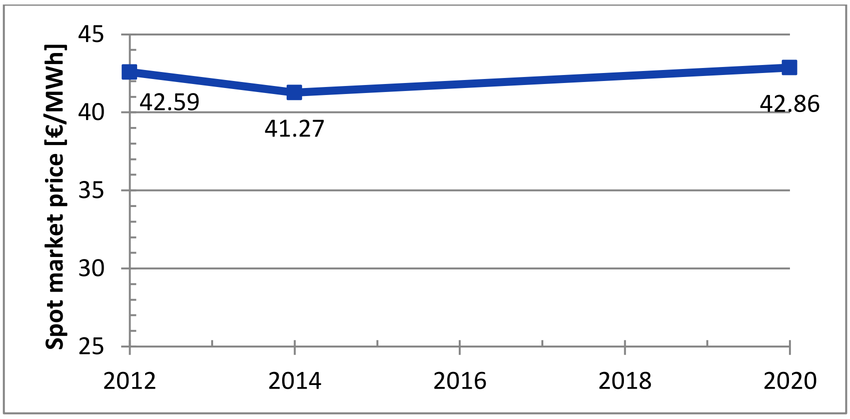


Figure 7: Development of spot market prices until 2020 (Source: MICOES-Europe)

As said before, the economic potential is assessed for three different scenarios (compare Table 5). In the base scenario "P2H (high)" the systems run at expected variable costs of € 124.16/MWh in 2014 and € 148.25/MWh in 2020. The costs displayed in Table 5 do not include the opportunity costs of displacing the conventional heat production because they are calculated endogenously in the model for every modeled grid. Compared to 2013 all cost elements are assumed to be constant besides the FIT surcharge. Based on the published data of the German TSOs in 2011 and the development of the spot market prices (Figure 7) assessed by *MICOES-Europe* the FIT surcharge has been calculated to fall to € 44.38/MWh in 2014 and to increase to € 68.47/MWh in 2020. In the scenarios "P2H (low)" and "P2H (zero)" a partly (FIT surcharge, PEF-compensation) and a fully exemption from all government induced cost elements is assumed.

Table 5: Scenario description for the modeled P2H systems

Scenario	**P2H (high)**	**P2H (low)**	**P2H (zero)**
Description	Full technical potential of 50 % of the max. heat load	Full technical potential of 50 % of the max. heat load **with exemption from FIT-surcharge and PEF-compensation**	Full technical potential of 50 % of the max. heat load **with full exemption** of government induced cost elements
Variable costs 2014 (w/o opportunity costs)	€ 124.16/MWh	€ 67.96/MWh	€ 0.00/MWh
Variable costs 2020 (w/o opportunity costs)	€ 148.25/MWh	€ 92.05/MWh	€ 0.00/MWh

3.6 Model results for 2014

Figure 8 summarizes the aggregate heat production via the spot market, the average thermal full load hours (FLH) and the additional average specific contribution margin over all modeled P2H-systems in 2014.

As a result, the P2H-systems are not used for heat production via the spot market in the scenarios with current or low variable costs in 2014 ("P2H (high)" and "P2H (low)"). Only in hours with very low spot market prices at a full exemption from government induced variable costs ("P2H (zero)") does P2H contribute to heat production via the spot market. The modeled P2H-systems provide only negative secondary control power. This business case has a much higher profitability than the heat production itself. Producing heat via the spot market and providing *negative* control power are mutually exclusive. However, producing heat via the spot market and providing *positive* control power at the same time is possible. Heat production also takes place, if the P2H-systems provide negative control power and are scheduled by the TSO. The scheduling of control power and the equivalent heat production is not assessed by the model and therefore not included in the depicted results.

The main component of the additional specific contribution margin is the benefit from providing negative control power. The low heat production in scenario "P2H (zero)" hardly increases the additional specific contribution margin.

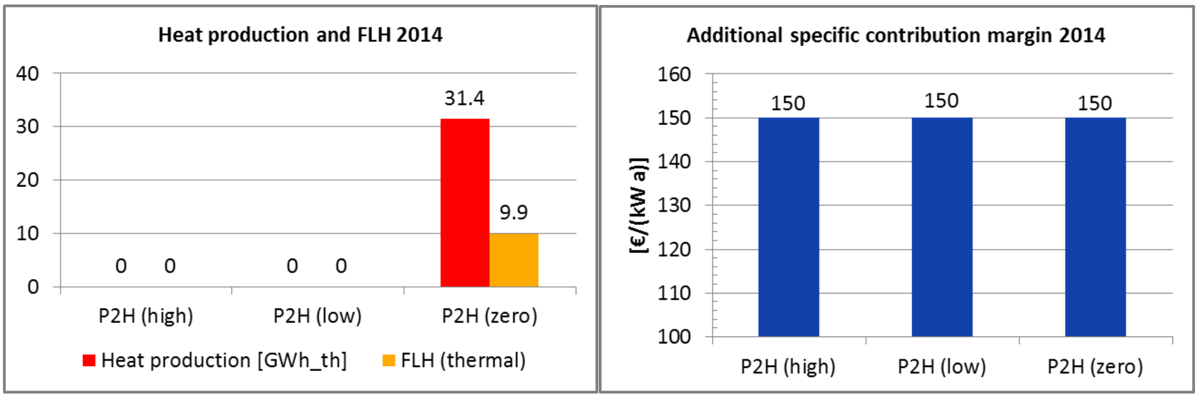


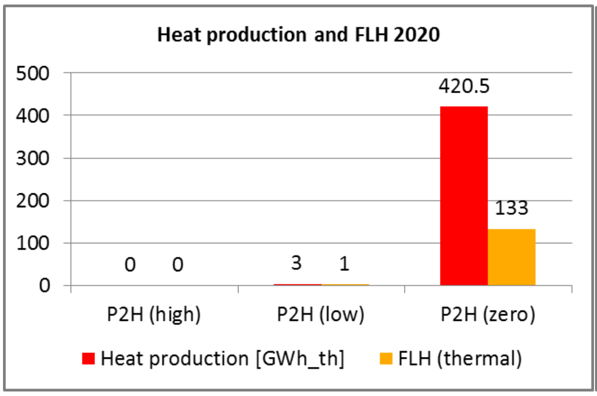
Figure 8: Heat production (sum), full load hours (avg.) and additional specific contribution margin (avg.) over all modeled P2H-systems in 2014

Within another sensitivity analysis, not shown in the figures, the P2H-systems were oversized to 60 % of the maximum thermal load. In result that does not lead to higher specific contribution margins for the whole CHP/P2H-system.

3.7 Model results for 2020

In 2020, P2H-systems are neither used for heat production via the spot market in the scenarios with current variable costs (Figure 9).

The higher contribution of P2H to the heat production in the scenario "P2H (zero)" is caused by a higher number of hours with very low or negative spot market prices in 2020. In cases of heat production P2H-systems further provide positive secondary control power. In this way the heat production is cost efficient. Compared to 2014, the heat production in scenario "P2H (zero)" slightly increases the additional specific contribution margin of the whole CHP/P2H-system.



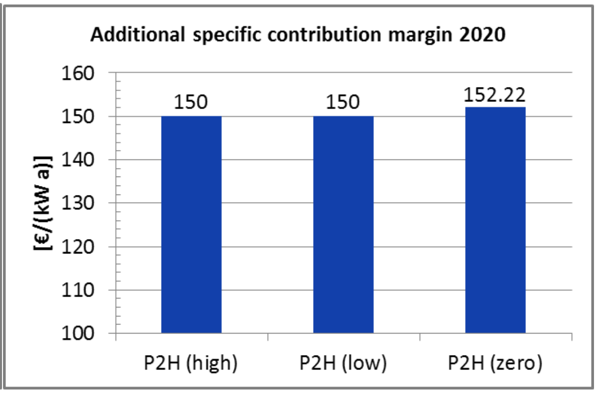


Figure 9: Heat production (sum), full load hours (avg.) and additional specific contribution margin (avg.) of the modeled P2H-systems in 2020

The high profitability by providing negative control power can lead to an extremely short payback period. This is caused by comparably high historical control power prices in 2010. By comparing the additional contribution margin of € 150/(kW a) with current specific investment costs of € 109.10/kW, the payback period is shorter than a year. Table 6 displays the payback periods for alternative investment costs and specific contribution margins. The data is calculated for an economic lifetime of 10 years and Weighted Average Costs of Capital (WACC) of 7 %. As it can be seen, the larger the output capacity of P2H-systems is, the shorter the payback periods are. This is due to high once-only costs of installation as they are independent from the output. Even at half specific contribution margins due to fallen control power prices the payback period does not exceed the duration of a year in case of large P2H-systems with prospective investment costs of € 45/kW.

Table 6: Payback periods of P2H systems for different investment costs and specific contribution margins

		Output [MW_{th}]					
		2.5	5	7.5	10	30	100
		Capacity costs €/(kW a)					
Specific contribution margin [€/(kW a)]		103.07	56.87	41.69	34.19	20.16	11.47
	20					5.9	3.0
	40			7.7	5.1	2.1	1.3
	60		6.2	3.5	2.6	1.3	0.8
	80	16.9	3.5	2.2	1.8	0.9	0.6
	100	7.6	2.5	1.7	1.3	0.7	0.5
	120	4.9	1.9	1.3	1.1	0.6	0.4
	140	3.6	1.5	1.1	0.9	0.5	0.3
	160	2.9	1.3	0.9	0.8	0.4	0.3
	180	2.4	1.1	0.8	0.7	0.4	0.3
	200	2.0	1.0	0.7	0.6	0.3	0.2

4 Conclusions

The basic requirements for using P2H in the control area of 50Hertz are existing. The maximum theoretical potential to increase the load with the P2H technology is 11.8 GW_{el}. The ten largest district heating systems in the control area provide more than ¾ of the heat sink.

Given a suitable design of the heat storages and P2H plants of 20-50 % of the maximum thermal load the aggregated technical potential on the supply side would be at 2.2 to 5.6 GW_{el}. This will eventually require investments of € 0.2 to 1.7 billion.

The technical potential at the demand side is characterized by low or negative residual power demand in the control area and by a simultaneously sufficiently high heat demand. It accounts for 5.5 GW_{el} resp. 1.5 TWh_{el} in 2014 and 7.8 GW_{el} resp. 5.6 TWh_{el} in 2020 at the maximum.

The working price for P2H-plants is mainly determined by state charges for the power consumption (FIT surcharge, CHP surcharge, electricity tax, grid levies etc.). Furthermore, there are additional costs for alternative fuel usage due to a probably necessary compensation of an increasing primary energy factor of the district heating grids. For a cost-efficient usage of

P2H-plants wholesale power prices below € -98.60/MWh in 2014 and below € -120.31/MWh in 2020 are necessary.

The negative wholesale power prices in the base scenario are not sufficient for the usage of the P2H-plants for heat production via the spot market in 2014 at current variable costs. Nevertheless, the P2H-plants are able to generate high returns with the provision of negative secondary control power (additional specific contribution margin of about € 150/(kW a)).

Possible exemptions from the network usage fees and the compensation of the primary energy factor are not sufficient to use the P2H systems for heat production via the spot market. Only with a total exemption of the additional costs (grid usage fees, electricity tax, FIT surcharge, the compensation of the primary energy factor etc.) would P2H-plants be used for heat production. Nevertheless, a wide exemption from state charges should be discussed and considered due to the superior importance of P2H for the entire system.

5 References

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6 Appendix

Description of the power market model *“MICOES-Europe“*

The power market model “MICOES” which is used at the Chair for Energy Management and Sustainability at the University of Leipzig is based on a Master´s Thesis supervised by Prof. Bruckner at the TU Berlin (Theofilidi, 2008) from 2008. Since then it was further improved at the University of Leipzig. In 2012, it was expanded from a national model for Germany to a model which covers most European countries.

The electricity market model used for the investigation is a fundamental model of the European power plant fleet, which uses a mixed-integer optimization to calculate estimates for the day-ahead spot market prices for each modeled country. For every hour of the analyzed years the model identifies those power plants that cover the electricity demand and the demand for balancing power at minimum cost.

Figure 10 illustrates the used power market model schematically. As input data for the model the hourly electricity demand of each modeled country and the demand for balancing power as well as a database with the European power plants is used. This database contains in particular the efficiency, maximum power and minimum load, as well as maximum power rate of change (“ramp rates”) and minimal operation and downtime for conventional power plants. Furthermore, it integrates the start-up costs (taking into account the time a plant was offline) as well as the cost of fuel beyond additional variable costs. In addition, the database contains the installed capacity of renewable energies. The power supply of fluctuating renewable energy (wind, solar) in the model is based on synthetically generated time series based on weather data for the year 2010 for all the countries, which are scaled according to the future expansion, if necessary. Since, besides Germany, 15 other European countries are included in the model, the power transfer between single European countries is model-endogenously possible, taking into account the capacity of the interconnections. All power plants available in the database of the model are dispatched with the aim of minimizing costs to meet the current power demand as well as the demand of balancing power. As a result, "MICOES Europe" provides hourly day-ahead spot market prices for each country and also the hourly schedules of all operating power plants as well as their CO_2-emissions and contribution margins. For the balancing power market the reserved capacities of all power plants as well as their opportunity cost in terms of capacity charges are determined.

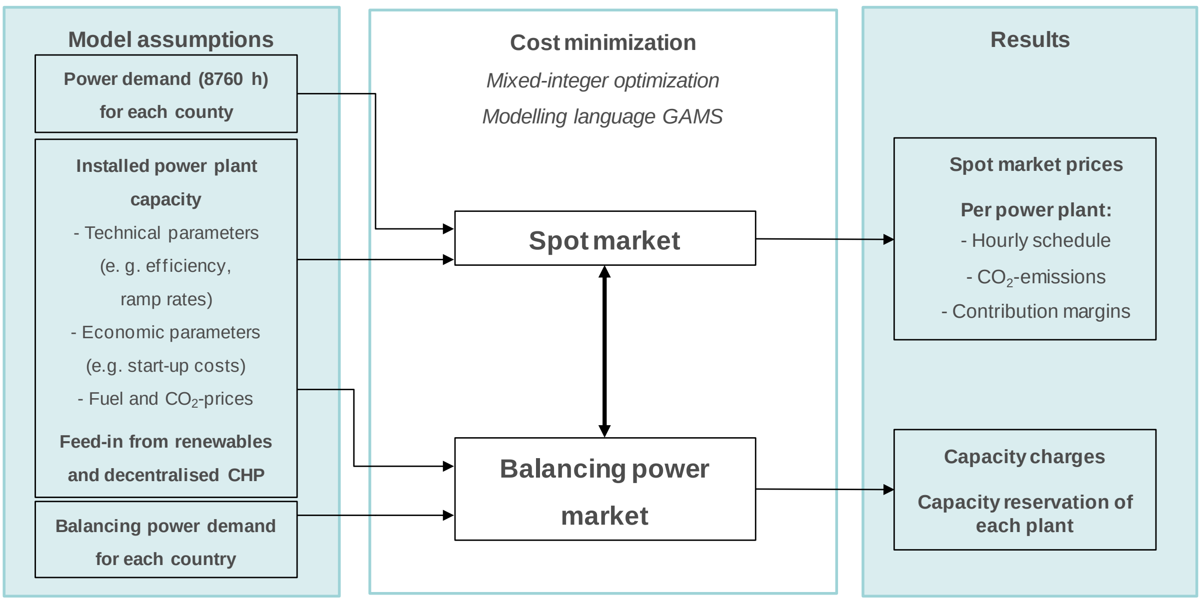

Figure 10: Model scheme of power market model "MICOES Europe", Source: Own presentation