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Spatially-resolved analysis of the challenges and opportunities of Power-to-Gas (PtG) in Baden-Württemberg until 2040

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Abstract

The increasing penetration of renewable energies will make new storage technologies indispensable in the future. Power-to-Gas (PtG) is one long-term storage technology that exploits the existing gas infrastructure. However, this technology faces technical, economic, environmental challenges and questions. This contribution presents the final results of a large research project, which attempted to address and provide answers to some of these questions for Baden-Württemberg (south west Germany).
Three energy scenarios out to 2040 were defined, one oriented towards the Integrated Energy and Climate Protection Concept of the Federal State Government and two alternatives. Timely-resolved load profiles for gas and electricity for 2015, 2020, 2030 and 2040 have been generated at the level of individual municipalities. The profiles include residential and industrial electrical load, gas required for heating (conventional and current-controlled CHP), as well as gas and electricity demand for mobility. The installation of rooftop PV-plants and wind power plants is projected based on bottom up cost-potential analyses which account for some social acceptance barriers. Residential load profiles are derived for each municipality. In times with negative residual load, the PtG technology could be used to convert electricity into hydrogen or methane.
The detailed analysis of four structurally-different model regions delivered quite different results. While in large cities, no negative residual load is likely due to the continuously high demand and strong networks, rural areas with high potentials for renewables could encounter several thousand hours of negative residual load. A cost-effective operation of PtG would only be possible under favorable conditions, including high full load hours, a strong reduction in costs and a technical improvement of efficiency. Whilst these conditions are not expected to appear in the short to mid-term but may occur in the long term in energy systems with very high shares of renewable energy sources.

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1. Introduction

Ambitious national and regional energy plans in Germany include a continued rapid expansion of renewable energy technologies. In order to efficiently integrate the electricity from these technologies into the energy system, several measures are required in parallel. These include network strengthening and expansion, much more flexibility in all areas of the energy system, a more extensive use of automation as well as information and communication technologies (smart grid) and large increases in storage capacities. The latter include pumped hydropower plants and batteries, as well as so-called sector-coupling approaches, whereby energy vectors such as electricity, heat and power, as well as sectors such as transport, domestic buildings and industry, are more strongly linked. Power-to-Gas (PtG) is one such technology, which involves the conversion of electricity into hydrogen and/or methane through electrolysis, which can then be locally stored or injected into the gas infrastructure.

Some of the technical, economic, and social questions surrounding the potential employment of this technology in Baden-Württemberg (BW) have been analyzed in the interdisciplinary research project "Power-to-gas concepts with high social acceptance for an efficient and flexible storage and energy infrastructure for the integration of renewable energies in Baden-Württemberg". In total, eight partners collaborated within this project, which ran from November 2013 to October 2016. The main goal was to carry out a detailed study of the challenges and opportunities for PtG in four model regions.

Assessments of the PtG technology from the technical and economic point of view can be found in [1–3]. Other studies address the topic from the market perspective [4–6].

This contribution summarizes the main results of the aforementioned research project relating to the potential and associated costs of PtG in four analyzed model regions. The paper is structured as follows. First, a methodology for the prediction of the residual load in BW in 2020, 2030 and 2040 is provided. The results, obtained with this methodology are given in the next section. This section also includes the evaluation of the market potential for hydrogen, generated with electrolyzer and synthetic natural gas (SNG), generated by a combination of electrolyzer and methanation. Finally, the results are shortly summarized.

Nomenclature

BW	Baden-Württemberg
CAPEX	Capital expenditure
CHP	Combined heat and power
CLC	Corine land cover
FLH	Full load hours
IEKK	Integrated climate protection concept
LCOE	Levelized cost of electricity
OPEX	Operational expenditure
OSM	Open street map
PtG	Power-to-Gas
PV	Photovoltaic
RES	Renewable energy sources
SNG	Synthetic natural gas
TRNSYS	Transient System Simulation

2. Methodology

2.1. General methodology

To study the challenges and opportunities of the PtG technology on a regional level, the following methodology is applied. Four model regions are selected in BW. The selected regions are supposed to cover a wide variety of regions in terms of energy supply and demand structure, from urban areas with high share of industry to rural areas with a high potential of RES.

For the four model regions, the residual load is computed, as explained in the respective section. The electrolyzers are supposed to use the hours with negative residual loads to convert electric energy into hydrogen, which can be further converted into SNG. The market potential of the production of hydrogen as an end product of a PtG plant is studied as an additional business model. Further, the potential for residential heating using micro-CHP plants is studied as a method of locally re-converting the gas to electricity and heat.

In the project, different scenarios are deployed. The presented results all base on the reference scenario, which is the official Integrated Energy and Climate Protection Concept (IEKK) for BW [7].

2.2. Model regions

The following model regions are chosen for the further analysis:

- City of Karlsruhe: High PV potential, high share of industry and good electricity and gas infrastructure.
- Municipality of Pfaffenweiler and Ebringen (Black Forest): High PV potential, rural area with moderate share of medium-sized companies.
- City of Aalen and surrounding area within a radius of 15 km: High PV and wind potential, medium-sized companies and good electricity and gas infrastructure
- Municipality of Leutkirch (Upper Swabia): High PV and moderate wind potential, little industry and relatively weak electricity and gas infrastructure.

2.3. Electricity demand

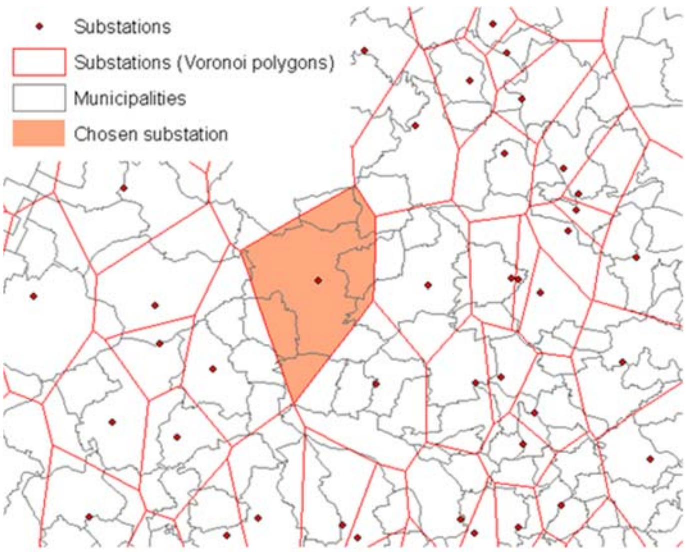

Fig. 1. Voronoi diagram of the substations in BW

In order to calculate the residual load in BW with a high spatial and temporal resolution, regionalized hourly profiles for the electricity demand are generated as shown in [8]. Herein, reference hourly load profiles for several sectors and sub-sectors are combined with yearly energy demand statistics of the lowest administrative areas available in order to generate specific hourly profiles for these areas.

The results obtained on different geographic levels are assigned to the distribution grid using a Voronoi partitioning based on 559 identified substations (110 kV) retrieved from Open Street Map (OSM) data. Profiles are created for three different sectors (industry, services and households) and for each substation. Here, the profiles created for 143 substations within the federal state of BW are considered. Using the values for the year 2012 as a basis, these profiles are adjusted for the year 2020, 2030 and 2040.

For this study, the load profiles which are now assigned to substations have to be re-assigned to the respective municipality. Hence, a Voronoi diagram of the substation positions is generated, as shown in Figure 1. By intersecting the area of the Voronoi elements with the area covered by the municipalities, the share of the substation profiles, whose Voronoi element intersects with the municipality, is assigned to this municipality.

2.4. Feed-in of RES

The electricity generation by wind turbines and PV plants is computed using wind and solar radiation data provided by the Anemos European Wind Atlas [9]. The temporal and spatial resolution of the data is 10 minutes and 20x20 km², respectively. The additional installation of wind turbines is computed considering the electricity generation costs (LCOE) of each potential location as well as the quality of the landscape [10]. Each wind turbine is clustered into a wind park and allocated to the nearest point of the Anemos grid and to the nearest grid substation, regardless of its assignment to a municipality. Using a Weibull distribution, the timely variable wind speed is derived from the average wind speed provided by the Anemos European Wind Atlas [9]. Taking into account the different efficiencies of the wind turbine (e.g., sub-optimal control, non-availability or wake effects), the annual energy yield by the wind turbine is calculated. A unique point of the study presented in [10] is the consideration of aesthetic aspects of the landscape in BW. The study uses the results published in [11], in which these aspects are rated by a test group of 400 participants. Areas, which have been identified as to have a high quality of landscape are subsequently excluded from the calculations. Hence, the feasible wind energy potential in BW is obtained and used in this work. Due to the additionally considered landscape aspects, it is about 50% smaller than the technical potential [10].

The PV potential is aggregated to the municipality level, which complicates its assignment to the correct point within the Anemos grid. The suitable area for the installation of PV plants is determined using the Corine Land Cover (CLC) database. For each building in the model regions, potential electricity generation costs with PV are computed. In addition, socioeconomic factors relating to the likelihood of households to invest in PV are considered [12]. E.g., it is more likely that PV plants are installed in rural areas than in cities. In addition, there is an 'imitation' effect. It is most likely that hot-spots with a high PV penetration arise in the vicinity of the location in which the first PV plant is installed in a particular area [12].

The identified areas for PV plants are intersected with a Voronoi diagram of the Anemos grid. Each municipality now consists of several sub-municipalities, which most likely are assigned to different points of the Anemos grid. The electricity generated by the PV plants in each sub-municipality is summarized to obtain the total PV generation of the municipality. The weather data of 2012 is used for all computations and no curtailment is considered. Further, the roof top orientation of the PV plants is neglected, instead a distribution of azimuth and inclination angles is assumed based on building statistics.

In a final step, the residual load for each of the four model regions is calculated as the net sum of local generation from wind and PV and demand, for each hour of the year. Negative residual load thereby implies a generation excess and therefore a necessary storage within or distribution beyond the region. A positive residual load implies a required import of electricity to, or an emptying of storage units in, the respective region.

2.5. Feed-in of combined heat and power generation

The electricity feed-in is investigated and calculated for micro-CHP units, used to supply residential buildings with heating energy. The executed simulations are based on a grid supportive operating mode (i.e. feed-in when prices are high etc.) of the CHP unit. The interactions between the requirements of the electricity grid, the CHP unit, the heat storage and the heating demand of a building are modeled using the TraNsient System Simulation (TRNSYS) software by Transsolar Energietechnik GmbH [13].

For the calculation of the building's heat energy consumption, three different energetic states (basic, conventional and innovative insulation) are investigated for a typical detached house and a typical multiple apartment block, respectively. The buildings are chosen according to the German building topology [14]. The heat load profiles are generated from the annual heat energy demand of these typical buildings by using the methodology described in [15]. The load profiles are used as input data for the simulation. The heat storage is modeled as a stratified storage tank, which is used to decouple the heat energy consumption of the building and the heat energy production by the CHP. The CHP itself is modeled in a simple equation using the thermal and electrical efficiency according to characteristic curves calculated from data provided in [16].

To determine the operation times of the CHP, two aspects have to be taken into account: the available capacity of the heat storage tank and a signal from the electricity grid requesting the electricity production by the CHP. The CHP runs if there is a request from the electricity grid and the available capacity of the heat storage tank is larger than the minimum heat production of the CHP according to its minimum running time. Otherwise the remaining heating energy is produced by an additional heat generator like a gas boiler. No thermal energy produced by the CHP is wasted. The signal from the electricity grid requesting the electricity production by the CHP is derived from the residual load of BW and the merit order. The residual load projected for the years 2015, 2020, 2030 and 2040 is calculated from historical data for the electricity demand of BW and the electricity production by volatile, renewable energies (photovoltaic, wind) of 2013 [17]. Their development is described in [7].

The CHP unit and the heat storage tank are dimensioned to reach an availability (running time divided by the time of request) of the CHP higher than 90% and a CHP cover ratio for the heat energy demand of the corresponding building higher than 50%. The remaining heat energy demand is covered by a typical gas boiler. The electricity production and gas consumption profiles of the CHP unit and the profile of the remaining heat energy demand are generated by the TRNSYS model for a period of one year.

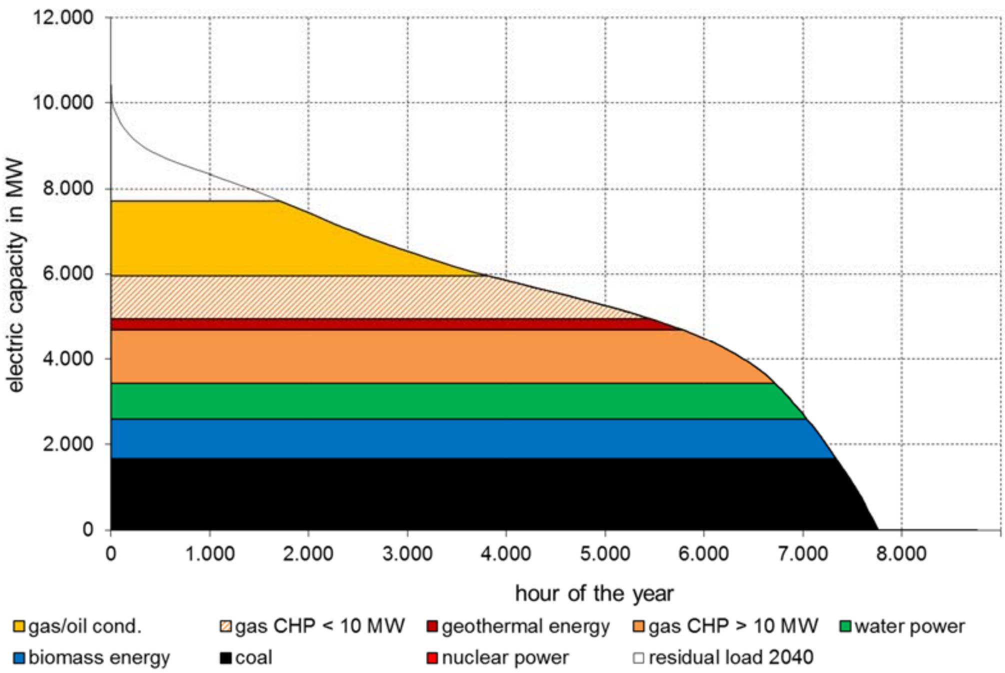

Fig. 2. Sorted annual residual load curve of BW and merit order of the controllable electricity producers for the year 2040

The generated electricity production and gas consumption profiles were supposed to be used in the calculations for the model regions. However, the contribution of the micro-CHP to the electricity supply is not significant, if the expansion rate of [7] is taken into account. In Figure 2, CHP units with a rated power of less than 10 MW contribute approximately 1 GW to the electric power generation in BW. However, within this portfolio, a significant number of multi-MW CHPs exist. Hence, only a low share of this power is actually generated by micro-CHP. However, if the expansion of power-led CHP plants would be accelerated, their contribution to meet the residual load can be more significant.

3. Results

3.1. Residual load

The residual load curves of the model regions reveal that it is absolutely reasonable to study the opportunities and challenges of the PtG technology on a regional level. Not a single hour of negative residual load is expected in Karlsruhe and Paffenweiler/Ebringen until at least 2040. The high PV potential in this region is completely used locally, as shown in the Figures 3 and 4. However, in the northern and south-eastern part of BW, represented by the city of Aalen and the municipality of Leutkirch, the high wind potential leads to a significant amount of time, in which the residual load is negative. In Aalen, more than 3.500 hours of negative residual load are expected in 2040.

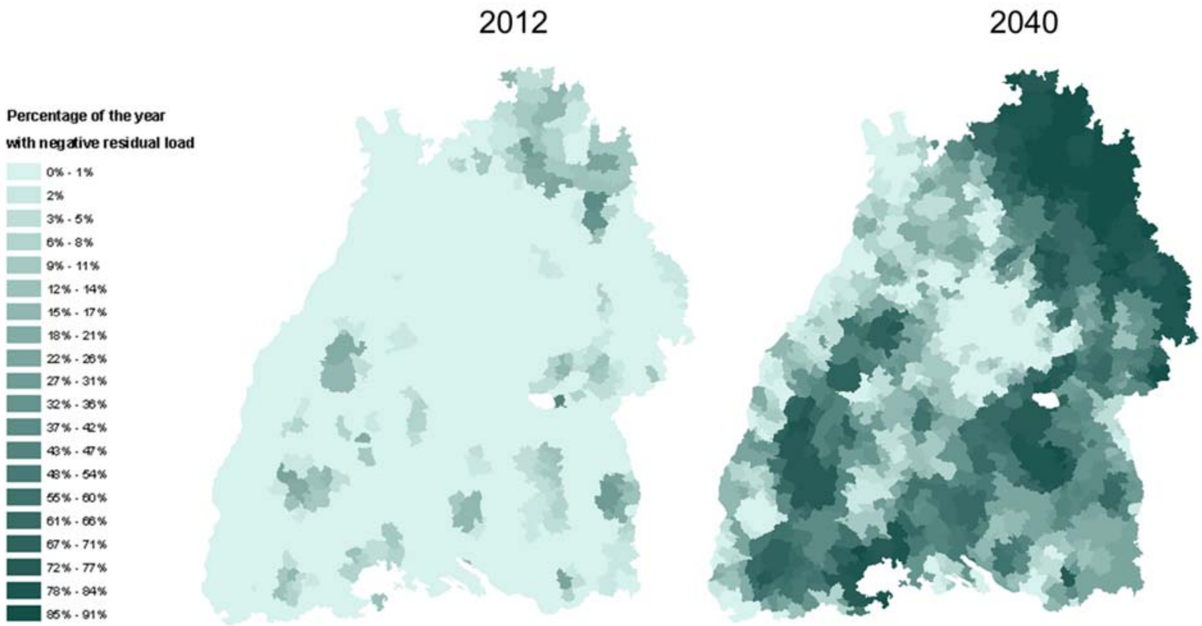

Fig. 3. Percentage of the year during which the residual load is negative in BW [7]

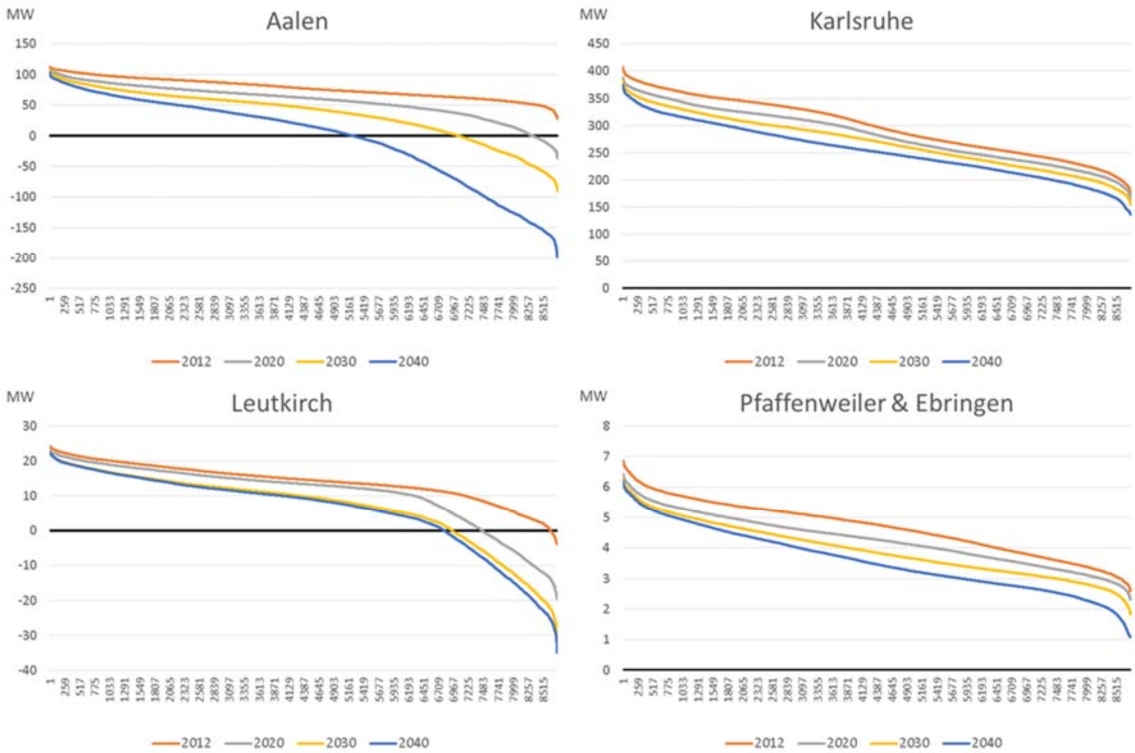

Fig. 4. Sorted annual residual load curves of the model regions

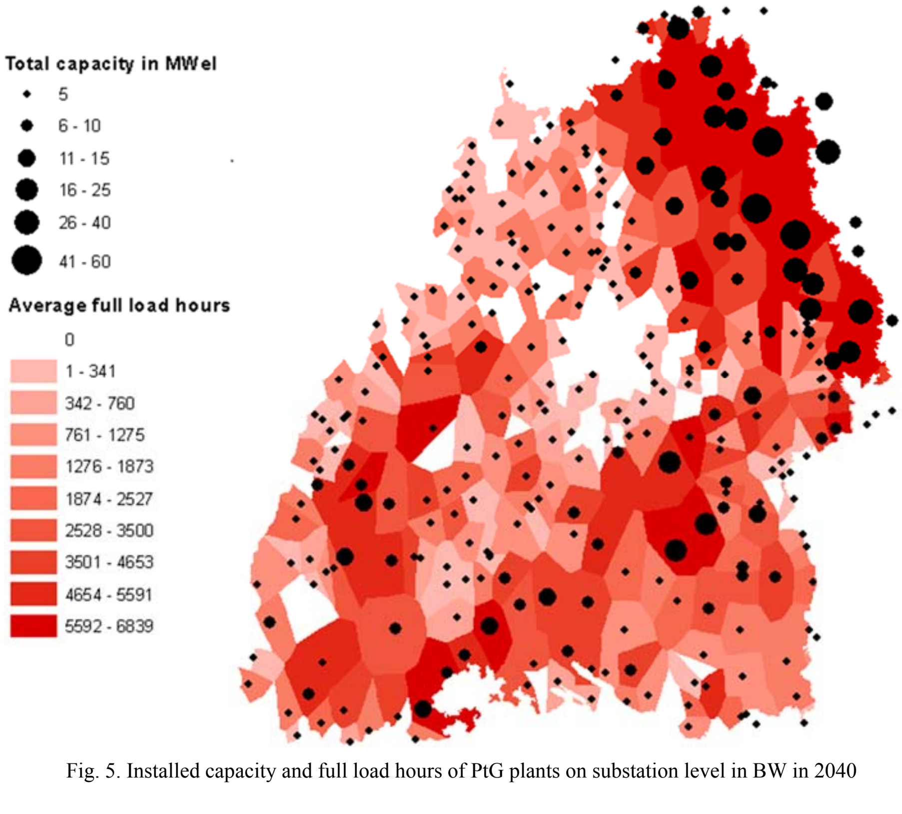

Fig. 5. Installed capacity and full load hours of PtG plants on substation level in BW in 2040

3.2. Installed PtG capacity

The results regarding the capacity needed to cover 10% of the electricity surplus for each substation and the resulting average full load hours are shown in Figure 5. As expected, the highest potentials for PtG, both in terms of capacity and full load hours, are mostly located in north-eastern BW. Overall, considering the particular assumptions explained above, full load hours reach more than 4000 hours.

3.3. Regional potential for SNG generated during hours with negative residual load

Among the four model regions, Aalen is the most suitable location for PtG plants. Hence, the full load hours of the PtG infrastructure and the corresponding SNG production costs are calculated for this model region. Only hours of negative residual load are used for generating SNG. The number of full load hours of the PtG infrastructure decreases with an increasing installed PtG capacity, as shown in Figure 6 a).

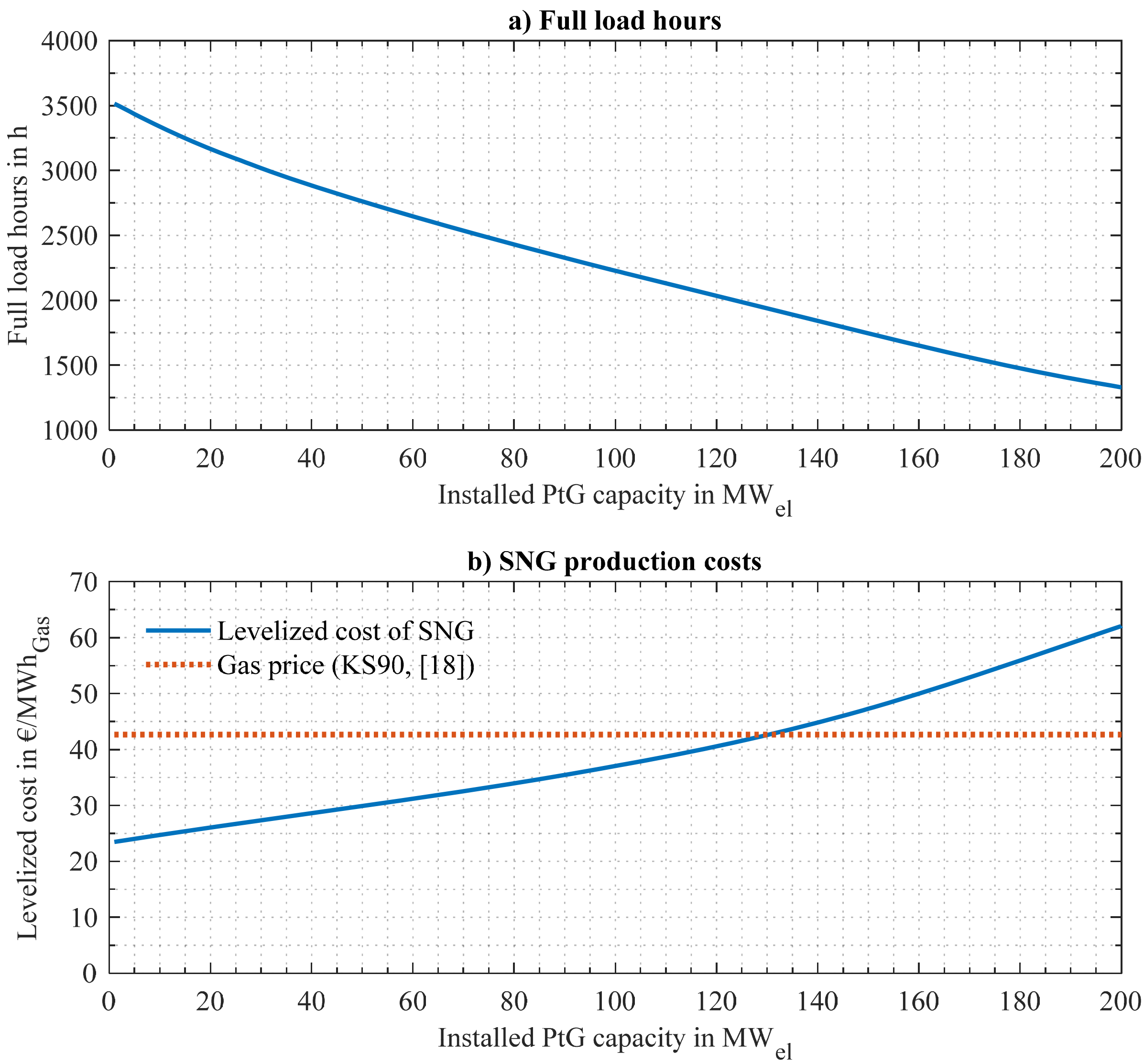

Fig. 6. Full load hours of the PtG infrastructure and levelized cost for SNG, generated with PtG in Aalen in 2040

The levelized cost of the generated SNG, LC_{SNG}, is calculated as shown in Equation (1). Herein, η_{Total} is the plant efficiency (electricity to SNG), which is assumed to be 68 %. CAPEX of 850 k€/MW$_{el}$, OPEX of 1.6% of CAPEX are taken into account. A depreciation period of 20 years and a gas price of 42.64 €/MWh$_{CH4}$ is assumed [4,18]. The electric energy, W_{el}, is taken out of the power grid by the PtG plant to generate the SNG.

$$LC_{SNG} = \frac{\frac{Capacity \cdot CAPEX}{20} + OPEX}{\eta_{Total} \cdot W_{el}} \quad (1)$$

As shown in Figure 6 b), a PtG capacity of 130 MW$_{el}$ could be installed in Aalen in 2040 to obtain parity with the expected price of natural gas in 2040 [18]. A larger PtG infrastructure will obtain lower full load hours. No economy of scale for larger plants is considered here. Thus, the levelized cost of SNG increases with increasing PtG capacity, as shown in Figure 6 b).

3.4. Market potential for hydrogen production with PtG

Besides using PtG on a local level for integrating the negative residual load, it can participate in national electricity markets in order to purchase electricity at low prices for gas production. As electricity prices are not spatially resolved, the market potential for this business case is studied Germany-wide. The economic evaluation of the PtG operation is mainly driven by efficiency and investment of the electrolysis, electricity costs, capacity utilization (full load hours) and the market value of hydrogen or methane respectively [4]. However, the electrolysis is a very flexible technology that can be ramped up and down within seconds to minutes. This flexibility allows the operator of a PtG plant to participate in different electricity markets e.g. the spot market and the balancing market. In the balancing market, the provision of capacity is remunerated in order to increase or reduce the electricity consumption when required. The operator of a PtG plant can decide to offer balancing power but must ensure that the operation schedules of the PtG plant can be adapted if a short-term call occurs. In the spot market, electricity is offered by producers and bought by consumers. Due to an hourly resolution, price fluctuations occur that are mainly influenced by the actual situation of electricity demand and supply. If the feed-in of RES is high or electricity demand is low, prices are generally low. The operator of a PtG plant can take advantage of these price changes and purchase electricity especially during the hours with low prices.

Figure 7 shows the production costs of hydrogen that is produced with electricity bought at the spot market. The techno-economic input values are listed in Table 1. The future spot market prices are modeled for the AMS scenario from [18] with an electricity market simulation model. The lowest possible prices of one year are used for the hydrogen production, e.g. for 3.000 hours of operation, the 3.000 smallest spot market prices are included in the calculation of hydrogen production costs. For a better interpretation of the results, the hydrogen production costs of steam gas reformation via natural gas with 8.000 full load hours are illustrated as well. The steam gas reformation is a widespread technology that is currently mainly used for hydrogen production, so it is appropriate as reference technology for the evaluation of PtG.

It is apparent that the operation of PtG is not profitable in 2014 because of the high specific investment and relatively low efficiency. The hydrogen production costs of the electrolysis exceed those of the steam gas reformation at any time. In 2030, hydrogen production costs of electrolysis decrease but still lie above the reference technology. In 2050, the smaller investment costs and the higher efficiency of the electrolysis result in an operation at lower costs than the steam gas reformation, if 1.000 to 5.000 full load hours are obtained. The reason for the minimum at 2.000 operation hours is that in these hours, spot market prices are negative or close to 0 €/MWhel. As soon as electricity costs are higher, hydrogen production costs increase as well.

Table 1. Assumptions for the calculation of hydrogen production costs [18–21]

Year	2014	2030	2050
Specific investment in €/kW$_{el}$	1.500	900	500
Efficiency in %	70	75	80
Average spot market price in €/MWh$_{el}$	33	70	100

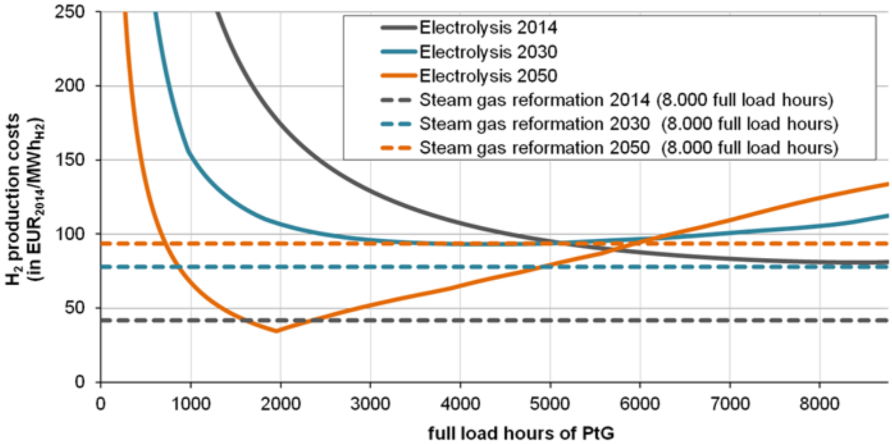

Fig. 7. Hydrogen production costs of electrolysis compared to the steam gas reformation

4. Summary

For generating hydrogen, a cost-covering operation of PtG in Germany is not possible at least until 2030. In the future, the situation may change if there is a progress in R&D concerning investment and efficiency of electrolysis and high shares of RES lead to situations with low electricity prices. However, these must occur in a greater number, as PtG plants need a capacity utilization of approximately 2.000 operation hours or more to be competitive with other hydrogen production methods. Additional profit opportunities like the participation of the electrolyzer in the balancing market could help to improve the economic result of the PtG plant, but these earnings are hard to predict because the price development in this market is driven by many factors.

The generation of SNG on a local level is expected to be an option by about 2040, if the development of the RES proceeds as quickly as expected in the baseline scenario. In this case, a significant PtG capacity could be installed at locations that show high RES feed-in and low electricity demand. However, the study reveals large inhomogeneities in terms of spatial distribution of the infrastructure. Hence, a significant gas transport capacity is required in these regions, if the SNG is not stored and used locally.

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