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Multi-criteria analysis framework for the optimal localization of power-to-gas plants: A case study for Germany

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ABSTRACT

A well-developed hydrogen infrastructure is a key element for the global energy transition. The strategic implementation of this infrastructure is challenging, due to the wide range of different criteria which need to be considered and analyzed. This paper presents a novel multi-criteria analysis framework for the optimal localization of power-to-gas (PtG) plants. The framework considers criteria such as renewable energy availability, hydrogen demand, proximity to existing gas infrastructure, and groundwater availability. A techno-economic model is integrated into the framework to evaluate the levelized cost of hydrogen (*LCOH*) for different electrolyzer technologies. Applying the developed framework to Germany, the potential of northern and northwestern Germany as suitable locations becomes apparent. In addition, *LCOH* for PtG plants at selected locations in Germany are evaluated depending on the year of commissioning. The large differences between present *LCOH,* ranging from 16.8 €/kg to 9.1 €/kg, illustrate the importance of an integrated techno-economic model.

1. Introduction

1.1. Motivation

Countries all over the world are facing the major challenge of decarbonizing their energy systems. In addition to the rapid expansion of renewable energy capacities, the development of hydrogen infrastructures is playing a key role in global energy transition strategies. Germany, for example, has set an ambitious expansion plan to realize this substantial transformation. The installed capacity of onshore wind and solar will be expanded from 60 GW to 74 GW in 2023 to 115 GW and 215 GW by 2030 [1,2]. In addition, the installed capacity of offshore wind farms will be increased from 8.4 GW in 2023 to 30 GW by 2030 [2,3]. Along with the rapid expansion of renewable energies, Germany is focusing on the power-to-gas (PtG) concept as a key technology for sector coupling. In this process, electricity is converted into the chemical energy carrier hydrogen through water electrolysis. A meta-study commissioned by the National Hydrogen Council shows, that the estimated demand for hydrogen and synthesis gas products in Germany in 2050 will be between 400 TWh and 800 TWh [4]. Germany has set the goal of installing an electrolyzer capacity of 10 GW until 2030 [5]. Furthermore, a hydrogen network will be established, both by repurposing the existing natural gas grid as well as installing new hydrogen pipelines.

The operation of large-scale PtG plants, however, poses major challenges for the future energy infrastructure. To avoid overloads in the electricity or gas grid, optimal localization of these plants is required, which depends not only on the impact on the energy infrastructure, but on several further criteria. For instance, environmental and economic factors need to be considered to achieve a holistic optimum.

1.2. Literature review

Some studies have already addressed the issue of the market ramp up and the spatial distribution of future PtG plants. The national grid development plan [6] and energy system studies [7–9] provide useful constraints for a detailed analysis of a subset of data. Depending on the scenario, up to 80 GW of domestic electrolyzer capacity will be installed in Germany until 2045 [6]. The proper localization of those capacities is rarely considered in general studies but poses a major challenge in the future. Due to a wide subset of boundary conditions, a multi-criteria

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Nomenclature

Symbol

a	Year of operation -
An	Annuity factor -
$Capex$	Specific capital expenditures €/kW
CF	Capacity factor -
F	Faraday constant A s/mol
FLH	Full load hours h
i	Interest rate -
I	Current A
$LCOH$	Levelized cost of hydrogen €/kg
LHV	Lower heating value kWh/kg
m	Mass kg
$\dot{m}$	Mass flow kg/s
$\dot{n}$	Molar flow mol/s
p	Pressure bar
P	Power in kW
$Opex$	Specific operational expenditures €/kW
R	Universal gas constant J/(mol K)
t	Year of commissioning -
T	Temperature K
U	Voltage V
W	Technical work kWh
Z	Compressibility factor -

Greek symbols

γ	Heat capacity ratio -
η	Efficiency -

Sub- and superscripts

1, 2, …	States 1, 2, …
AC	Alternating current
act	Activation
Aux	Auxillary
cell	Cell
compr	Compression
conc	Concentration
el	Electric
El	Electrolyzer
H_2	Hydrogen
i	Hourly
in	Input
me	Mechanical
O&M	Operation and maintenance
ohm	Ohmic
out	Output
r	Replacement
rev	Reversible
s	Isentropic
stack	Stack
tn	Thermoneutral
V	Voltage

Abbreviations

AEL	Alkaline electrolyzer
EEX	European Energy Exchange
EUEO	EU Energy Outlook
GIS	Geographic information system
MCA	Multi-criteria analysis
PEMEL	Polymer membrane electrolyzer
PtG	Power-to-gas
PV	Photovoltaic
RES	Renewable energy sources
SOE	Solid oxide electrolyzer
TSO	Transmission system operator

analysis (MCA) framework is necessary for the optimal localization of PtG plants. MCA is commonly used within decision-support tools to compare alternatives based on multiple criteria. It is particularly useful in contexts where cost-based and non-cost-based metrics need to be considered to support informed decisions. In this study, MCA is applied to provide a transparent framework that goes beyond a traditional cost comparison and supports holistic decision-making.

A comparison of the levelized cost of hydrogen (LCOH) for PtG plants based on PEM electrolysis in different locations in Switzerland was carried out by Gupta et al. [10]. The main results show that, at present, only hydrogen plants directly connected to run-of-river hydropower are economically viable, although there is significant potential for plants located near demand centers and powered by rooftop photovoltaic (PV). Alavipoor et al. [11] used the fuzzy set theory combined with geographic information system (GIS) data to evaluate potential locations for gas power plants in Natanz, Iran and found that the most suitable locations are the southern parts of the city. The work of Mokarram and Sythyamoorthy [12] also analyzed a region in Iran using multi-criteria decision making with GIS data to determine suitable locations for gas-fired power plants and demonstrate that only 9.57 % of the study area is unsuitable. Uyan [13] chose solar farm locations in Turkey using GIS data and multiple boundary conditions. The results show that 13.92 % of the study area is suitable and two candidate sites on public land were selected as most suitable. Schneider and Kötter [14] focused on the generation of synthetic methane within a German model region, using comprehensive spatial data. The study demonstrates that, due to CO_2 availability and limitations of suitable locations, the geographic PtG potential in the study area is reduced from estimated 1.2 GW to only 75.5 MW. Yum et al. [15], Ali et al. [16] and Amjad et al. [17] investigated suitable locations for solar-based hydrogen production plants using MCA and GIS data. The studies show that optimal locations require a combination of high solar energy availability, good access to the transmission grid, and favorable environmental conditions. The selection of wind farms for power and hydrogen production was carried out by Rezaei-Shouroki et al. [18] and Hosseini Dehshiri and Hosseini Dehshiri [19]. The results illustrate that, in addition to wind energy availability, the distance to urban areas is also a significant sub-criterion. The study by San Martin et al. [20] analyzed potential public areas for a possible hydrogen industry in Chile based on several technical criteria, e.g. availability of solar and wind energy, and socio-ecological parameters, where the solar powered scenario achieves the best results. La Guardia et al. [21] have implemented a MCA to select the best location for new PtG plants in Sicily, Italy, depending on several factors, such as the location of wind and photovoltaic plants as well as population distribution. The results show that most of the suitable locations are situated along the coastal areas. A spatial modeling process using a GIS tool was developed by Nielsen and Skov [22] to find optimal locations for PtG plants based on carbon source potential, proximity to the grid, grid transmission costs, and investment costs of the respective technology, with investment costs and proximity to the gas grid emerging as the most influential parameters. Soha and Hartmann [23] also worked on GIS-based site selection for PtG plants. In addition to considering factors such as power, gas and water networks, the focus was on the availability of biogas plants as a CO_2 source in Hungary. The study shows that only 2.5 % of the study area is suitable for potential locations, with infrastructure and agricultural activity identified as the most influential parameters. Denzihan and Özçelik [24] introduced a new approach for MCA to determine the location of hydrogen production plants in Turkey, depending on the surplus of renewable energy, proximity to industrial hydrogen demand and further criteria. The optimal location combines well-developed industrial infrastructure, reliable energy availability, and good logistics supported by port access. Recently, Fraunhofer ISE in cooperation with other partners developed an atlas of suitable electrolyzer sites in Germany [25]. The locations are determined by the economic optimum in terms of proximity to hydrogen consumers, possible usage of the byproducts waste heat and oxygen as well as wind and solar energy potential. The main results indicate that the most suitable locations are in northern Germany, with high wind energy availability, especially with proximity to offshore grid connection points and industrial centers with well-developed infrastructure. Brümmer et al. [26] investigated the optimal allocation of PtG plants in Germany with focus on the electricity transmission grid, highlighting the coastal areas in northern and northwestern Germany as most favorable locations for future PtG operation.

1.3. Research gap and scientific significance

For comparison with the present work, a selection of the literature presented in section 1.2 is summarized in Table 1. The selection is limited to research papers focusing on the optimal localization of hydrogen production plants. The table categorizes individual studies based on the integration of various methodological elements and the consideration of evaluation criteria relevant to the present study.

Although spatial data analysis methods are well-documented in literature, to the best of the authors' knowledge, no comprehensive studies have addressed multiple critical boundary conditions in conjunction with detailed technical and economic models of PtG plants according to Table 1. The table also shows that none of the studies consider all the selected criteria. In addition, no study investigates groundwater availability as an assessment factor. This paper presents a MCA framework showing the potential locations for future PtG plant operation in Germany supported by analytical techno-economical models to strengthen the robustness and reliability of the presented results. Furthermore, the availability of renewable energy sources (RES), such as wind and solar energy, is not determined by the overall potential of specific areas, but by the expansion plans of the national grid development plan for multiple target years. Additionally, the analysis distinguishes between onshore and offshore wind potential, as well as rooftop and open-field PV systems. Another contribution of this work is the integration of a criterion regarding groundwater availability for large-scale electrolyzers. Some studies in literature have integrated the proximity to existing waterbodies, but do not consider the specific yield and recharge of groundwater at the respective locations. Addressing all the aforementioned aspects, this paper bridges the gap in current literature by extracting information from broad, national-level energy system studies with localized and regional considerations and introducing a novel methodology framework for the optimal localization of PtG plants.

The main contributions are summarized as follows.

- A criterion to address the problem of water availability, which may become relevant in the future for large-scale PtG plants, is integrated into the assessment.
- Aligning renewable energy availability to specific expansion plans in the national network development plan enables a detailed assessment with time-dependent scenarios according to the political framework.
- The novel MCA framework gives a high-level optimum for the localization of PtG plants due to the integration of a technical and an economic model.

2. Methodology

This section outlines the methodology developed in this study. It begins with an overview of the overall MCA framework. The subsequent

Table 1
Categorization of selected literature investigating the localization of hydrogen production plants based on different integrated methodology elements and assessment criteria of the present study.

Authors (alphabetical)	Case study	Integrated methodology element			Assessment criteria				
		GIS data	Technical electrolyzer model	Economic electrolyzer model	Solar energy availability	Wind energy availability	Industrial hydrogen demand	Proximity to gas grid	Groundwater availability
Ali et al. [16]	Thailand	x	x	x	✓	x	x	x	x
Amjad et al. [17]	Pakistan	✓	x	x	✓	x	x	x	x
Denizhan and Özçelik [24]	Turkey	✓	x	x	✓	✓	✓	✓	x
Hosseini Dehshiri & Hosseini Dehshiri [19]	Iran	✓	x	x	x	✓	x	x	x
La Guardia et al. [21]	Italy	✓	x	x	✓	✓	x	✓	x
Nielsen and Skov [22]	Denmark	✓	x	✓	x	x	x	✓	x
Rezaei-Shouroki et al. [18]	Iran	x	x	x	x	✓	x	x	x
San Martin et al. [20]	Chile	x	x	x	✓	✓	x	x	x
Soha and Harrtmann [23]	Hungary	✓	x	x	x	x	x	✓	x
Yum & Adhikari [15]	Korea	✓	x	x	✓	x	✓	x	x
Present work	Germany	✓	✓	✓	✓	✓	✓	✓	✓

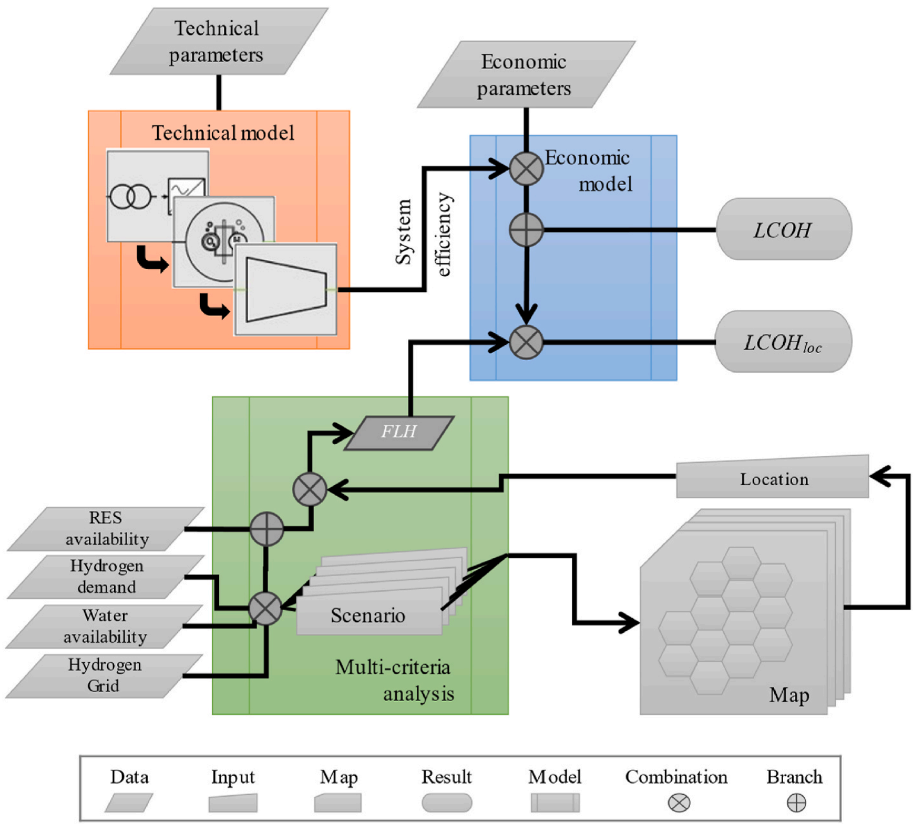

Fig. 1. MCA framework for the optimal localization of PtG plants.

subchapters provide a detailed description of the integrated technical and economic models. Finally, the study area and the scenarios considered are defined.

2.1. Multi-criteria analysis framework

The novel MCA framework presented in this study is visualized in Fig. 1. The MCA constitutes the key element of the framework and is combined with both a technical and an economic model.

The technical model determines the system efficiency of a PtG-plant, which serves as an input to calculate the produced hydrogen in the economic model. GIS-based data of renewable energy availability, hydrogen demand and proximity to the gas grid as well as water availability is used to perform a MCA for specified scenarios. Depending on different scenario sets, an evaluation of the different criteria is visualized in a map of the considered study area. The individual criteria are categorized on a scale from 0 to 10, where 0 is the minimum and 10 is the maximum value of the respective data set. The values in between are obtained by linear interpolation. When two or more evaluation criteria are combined, the weights are set to be equal. The generated maps are used to select specific locations. For each of these locations the full load hours (*FLH*) of a specified electrolyzer technology are calculated based on RES availability and fed into the economic model. The generated maps and the *LCOH* of specific locations are the main outputs of the MCA framework and can be used to identify optimal locations of PtG plants.

2.2. Technical model

2.2.1. Simulation model design

In the simulation model of the PtG plant, only the components with the highest electricity consumption are considered. These are the power electronics, the electrolyzer system and the compressor unit. The overall structure of the simulation model is illustrated in Fig. 2. The following sections describe the individual components in more detail.

2.2.2. Power electronics

The model receives a load profile (e.g. from a RES based power plant) as an input parameter. Before the electrical power is fed into the electrolyzer, the input current is adjusted based on the *U*–*I* characteristics of the electrolyzer stack. This is achieved by using power electronics to convert medium voltage AC into low voltage DC to supply the electrolyzer system. In this paper, the power electronics model consists of an operating point dependent efficiency curve of a thyristor based system according to the work of Rodriguez et al. [27]. The efficiency of the power electronics improves with increasing load, reaching a maximum of more than 96 % at full load operation.

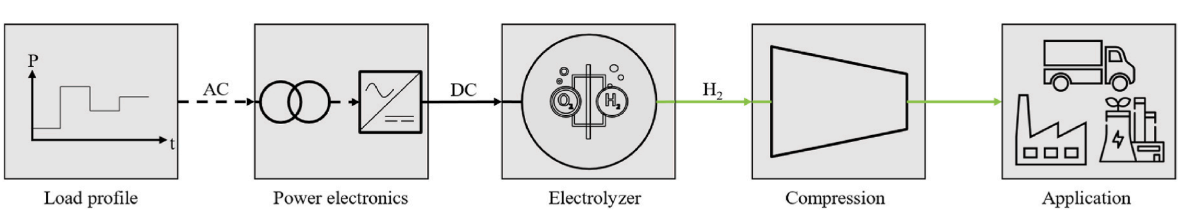

Fig. 2. Simulation model design of the PtG plant.

2.2.3. Electrolyzer

The electrolyzer unit represents the core of each PtG plant, transforming electrical energy into chemical energy and storing it in the form of hydrogen. Nowadays, three technologies are mainly used to produce green hydrogen by water electrolysis. They are divided into low-temperature alkaline electrolyzer (AEL) and polymer membrane electrolyzer (PEMEL) and the high-temperature solid oxide electrolyzer (SOE). The AEL is considered to be the most mature of the three technologies and is already used worldwide for industrial hydrogen production in the multi-megawatt range [28]. The PEMEL has gained interest in recent years due to various advantages over AEL, with operational flexibility being the most prominent [29–33]. This advantage plays a major role in RES coupled systems with highly intermittent load profiles. For the PEMEL, there are also various manufacturers worldwide which have developed large-scale systems up to several MW [34]. Although SOE currently has the least market penetration, its high efficiency makes it a promising alternative [35–37]. A major drawback is currently an insufficient long-term stability [35–38]. Nevertheless, substantial progress has already been made in extending the lifetime of SOEs, and further improvements are actively ongoing [38,39].

The technical model of the electrolyzer unit is based on an electrochemical model calculating the cell voltage

$$U_{\mathrm{cell}} = U_{\mathrm{rev}} + U_{\mathrm{act}} + U_{\mathrm{ohm}} + U_{\mathrm{conc}}, \tag{1}$$

where U_{rev} indicates the reversible cell voltage. The internal losses occurring during operation are known as overvoltage. They can be divided into activation (U_{act}), ohmic (U_{ohm}) and concentration losses (U_{conc}).

For each electrolyzer technology, the characteristic polarization curve is determined based on existing models from literature. The electrochemical model for the PEMEL and the AEL are implemented according to the work of Pfennig et al. [40] and Jang et al. [41], respectively. The analysis of Nasser and Hassan [42] is used to model the polarization curve of a SOE cell. Each model is based on analytical equations and can be adapted to specific cell geometries or operating conditions. The models calculate each contribution to the cell voltage as given in Eq. (1) and can thus estimate the efficiency of the electrochemical reaction depending on the operating point.

The voltage efficiency

$$\eta_{\mathrm{V}} = \frac{U_{\mathrm{tn}}}{U_{\mathrm{cell}}} \tag{2}$$

defines the efficiency of an electrolyzer cell, with U_{tn} representing the thermoneutral voltage. Typical voltage efficiency values range from 50 % to 68 % for PEMEL and AEL, and from 75 % to 85 % for SOE [43].

Using Faraday's law, the produced hydrogen flow rate

$$\dot{n}_{\mathrm{H_2}} = \frac{I}{2F} \tag{3}$$

is calculated, which is directly proportional to the current I. F represents the Faraday constant.

2.2.4. Gas compression

The gas compression unit is an important part of the system to obtain the operating pressure of downstream applications. The compression of hydrogen from pressure p_1 to pressure p_2 can be approximated as an isentropic process [44,45]. The required technical work of isentropic compression can be calculated by

$$W_{\mathrm{s}} = \frac{\gamma_1}{\gamma_1 - 1} \cdot n_{\mathrm{H_2}} \cdot R \cdot T_1 \cdot Z_1 \cdot \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma_1 - 1}{\gamma_1}} - 1 \right], \tag{4}$$

where T_1, $n_{\mathrm{H_2}}$ and R indicate the temperature at the initial state of the compression, the amount of hydrogen and the universal gas constant, respectively. The heat capacity ratio γ_1 and the compressibility factor Z_1 depend on the pressure and temperature of hydrogen during the compression process. Both values are taken from REFPROP 10.0 [46]. The resulting total work W_{Compr} for the compression can be determined by considering an isentropic efficiency $\eta_{\mathrm{s}} = 80$ % [44,45]. The mechanical efficiency of the compressor $\eta_{\mathrm{me}} = 90$ % [44,45] includes mechanical losses and losses due to electrical power conversion. For this study no specific compressor technology is selected, but rather a general approach is applied to account for the energy demand of the compression. To ensure comparability of the different electrolyzer technologies, the input and output pressure are specified. The electrolyzer is operated at an atmospheric pressure $p_{\mathrm{in}} = 1$ bar. The value of the outlet pressure p_{out} is set to 100 bar to ensure that the produced hydrogen can be fed into the gas grid [47].To minimize the compression work and limit the hydrogen temperature, the compression is carried out in five stages. This number of stages was selected to achieve the target outlet pressure of 100 bar using a typical pressure ratio of approximately 2.6 per stage [44]. After each stage the hydrogen is cooled down to the inlet temperature $T_{\mathrm{in}} = 40$ °C. The overall compression work is the sum of the total work of each compression stage.

$$W_{\mathrm{Compr}} = \frac{W_{\mathrm{s}}}{\eta_{\mathrm{s}} \cdot \eta_{\mathrm{me}}}, \tag{5}$$

2.2.5. System efficiency

A significant parameter for the evaluation of a PtG plant is the system efficiency. Using the power consumption of the components described, the overall system efficiency

$$\eta_{\mathrm{PtG}} = \frac{\dot{m}_{\mathrm{H_2}} \cdot LHV_{\mathrm{H_2}}}{P_{\mathrm{El,AC}} + P_{\mathrm{Compr}} + P_{Aux}} \tag{6}$$

is calculated. Here, $\dot{m}_{\mathrm{H2}}$ and LHV_{H2} indicate the mass flow rate and the lower heating value of hydrogen expressed in kWh/kg. Electrical power consumption consists of the AC power of the electrolyzer $P_{\mathrm{El,AC}}$ and the compressor P_{Compr}. The power of other auxiliary and ancillary units of the electrolyzer, such as pumps, ventilation or control technology, are represented by P_{Aux}. According to Kopp [48], the electrical consumption of these components is nearly constant. The considered PEMEL plant reported an average auxiliary power consumption of about 50 kW. Given a maximum electrolyzer power of 6 MW, this corresponds to roughly 1 %, which is assumed in this study for the calculation of η_{PtG}. For SOE, it is assumed that it will be operated close to industrial processes with high-temperature waste heat, which can provide thermal energy for steam production. The operating temperatures are defined as

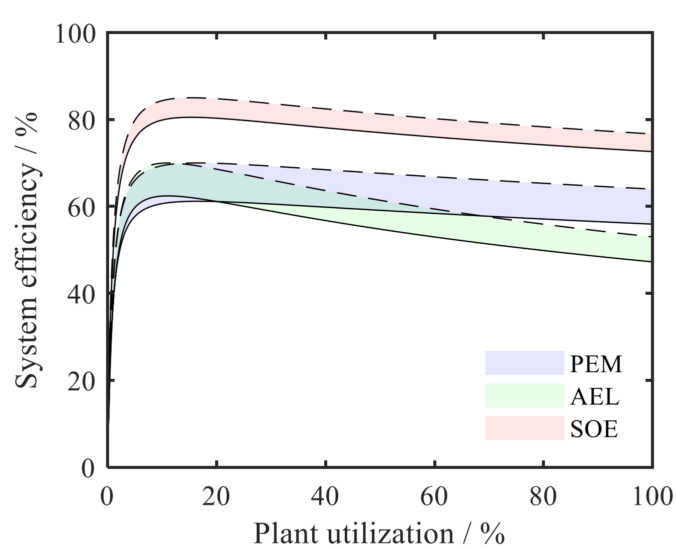

Fig. 3. System efficiency over plant utilization of various electrolyzer technologies; (–) calculated state of the art, (–) projections from [49,50].

80 °C for AEL and PEMEL, and 700 °C for SOE, while the operating pressure is assumed to be 1 bar according to the used electrochemical models from literature for all technologies.

Fig. 3 shows the system efficiency of a PtG plant over the plant utilization for each of the three electrolyzer technologies. The individual curves are illustrated as efficiency ranges. The lower limit of each curve represents today's efficiency and is calculated by the technical model. The model results show good agreement with efficiencies given in literature [49,50]. The results also show the typical trend of an electrolyzer efficiency curve with a maximum between 10 % and 20 % of the plant utilization, as illustrated for example in the work by Kopp et al. [51], who analyzed real operational data from a PEMEL plant in Germany. This is mainly caused by high electrolyzer efficiencies and a high share of P_{Aux} in the overall power consumption at low plant utilization. The upper limit in Fig. 3 represents the expected efficiency for 2050, based on an expert survey [49] and estimations from literature [50]. This work assumes that the future efficiency curve will follow the same trend, with absolute efficiency increasing due to technological advancements in cell design. This approach ensures that the maximum efficiency aligns with the value reported in literature (see Table 2). Some examples for these improvements are optimizations of membrane technologies or improved activities and durability of the catalysts [35,52]. The SOE achieves the highest efficiency because part of the energy required for water splitting can be provided by the high-temperature process heat. The AEL and the PEMEL are considered to have comparable maximum efficiencies, both today and in the future. The efficiencies calculated in this paper are based on assumptions from the implemented electrochemical models in literature and depend on cell design and operating conditions.

2.3. Economic model

To calculate the LCOH, the capital expenditures (*Capex*), the operational expenditures (*Opex*) as well as the electricity costs c_{el} should be considered. Also, the lifetime of an electrolyzer depending on degradation effects and the overall system efficiency must be included. The effect of stack changes after a few operational years can be significant [53]. Therefore, stack replacement costs $c_{\mathrm{stack,r}}$ are included in this model.

The initial investment costs $c_{\mathrm{stack,in}}$ of a PtG plant is mainly influenced by research and development and economies of scale. Multiple review articles developed equations to assess the future expenditures based on existing data and cost projections [54–56]. These can be used to estimate not only the future costs of a PtG plant installation, but also the stack replacement costs. The operation and maintenance costs $c_{\mathrm{O\&M}}$ are typically assumed to be a constant fraction of the *Capex* and can include small maintenance work, labour, insurance, lighting, communal fees/taxes and other extra costs. In this study, 2 % of *Capex* is assumed. It is expected that short-term electricity price fluctuations will align with long-term expectations and predictions based on the ongoing energy transition across the world [57,58].

The following equations are used to determine the *LCOH* for the respective year of commissioning *t*:

$$LCOH_t = \frac{LHV_{\mathrm{H_2}}}{\eta_{\mathrm{PtG}}} \cdot \sum_a (Capex_a \cdot An) + \sum_a (Opex_a), \tag{7}$$

$$Capex = \frac{(c_{\mathrm{stack,in}} + c_{\mathrm{stack,r}})}{FLH}, \tag{8}$$

$$Opex = \left(\frac{c_{\mathrm{O\&M}}}{FLH} + c_{el}\right), \tag{9}$$

$$An = \frac{(1+i)^a \cdot i}{(1+i)^a - 1}. \tag{10}$$

Here, *An* and *i* indicate the annuity factor and the interest rate, respectively. This calculation assumes a steady cash flow by discounting all costs over the system lifetime in years of operation *a*. The stack replacement costs are included in the *Capex* and have been adjusted for inflation with the set reference year 2024. Inflation is considered to maintain price stability in the European System of Central Banks, which is defined as a 2 % [59] symmetric target by the strategy review of the European Central Bank.

The electricity costs in this study are derived from electricity prices given in literature. Historical data are taken from the European Energy Exchange (EEX) [60], while future projections are based on the EU energy outlook (EUEO) [57,58]. The different considered electricity price scenarios are illustrated in Fig. 4. For the evaluation of plants which are built close to the target year 2045/2050, the data needs to be extrapolated even further than the long-term perspective. It is assumed that the prices will remain at the level of 2050/2060 in the distant future based on a highly sophisticated and interlinked energy system.

Table 2 gives an overview of parameters which are considered in the calculation of the *LCOH*. The stack replacement costs in literature vary from 5 % to 40 % [61] of the costs for a newly installed system. In this

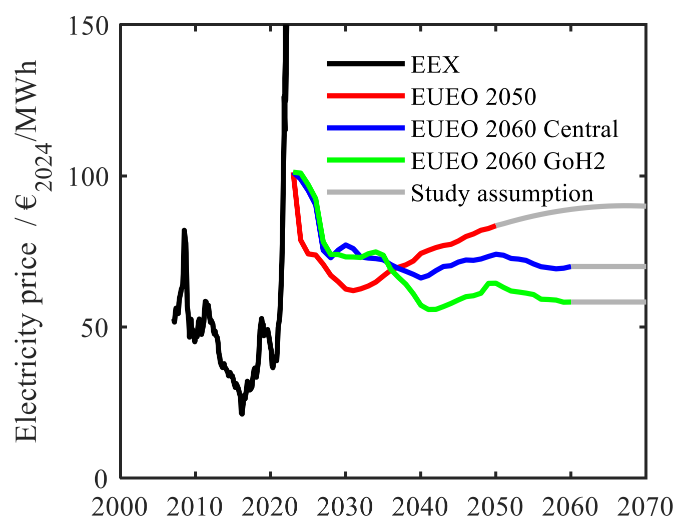

Fig. 4. Electricity prices, based on historic data and price projections.

Table 2
Input parameters for the economic model.

Parameter	Reference	AEL	PEM	SOE
			2022–2045	
Initial investment costs (€$_{2024}$/kW)	[54–56]	1268–444	2068–300	2285–527
Stack lifetime (h)	[63–66]	30,000–98,000	20,000–83,000	5000–52,000
Efficiency (%)	Technical model	47–53	56–64	73–77
Operation and maintenance costs (€$_{2024}$/kW)	[67]	2 % *Capex*		
Plant lifetime (a)	[65]	30		
Interest rate (%)	Study assumption	7		
Stack replacement costs (€$_{2024}$/kW)	Study assumption	30 % *Capex*		

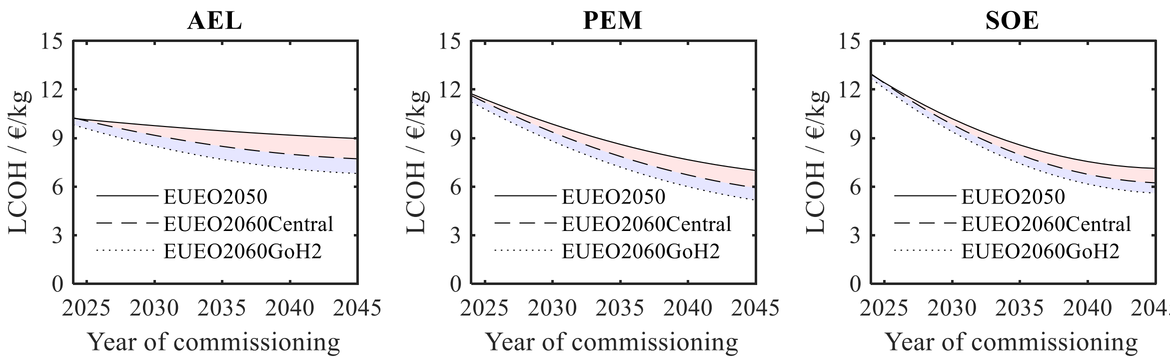

Fig. 5. *LCOH* depending on year of commissioning for different technologies and electricity price scenarios.

study, a value of 30 % in the corresponding year is assumed and discounted to the reference year. The costs for the purchase of electricity are also discounted to the year 2024 to avoid inaccurate results when summarizing the average costs of hydrogen production over the whole life cycle of the plant. According to Agora [62], the *FLH* of electrolyzers will remain around 3000 h in 2030. The efficiency values from the technical model are based on maximum plant utilization as well as the year of commissioning, and account for the technological advancements in the upcoming years. The techno-economic model was implemented using MATLAB/Simulink. The economic model interpolates between the specified value ranges and assigns values based on the year of commissioning, reflecting historical data and future projections. The amount of stack changes during the lifetime of the plant depends on the degradation of the stack and its lifetime [49]. Additional costs for the deconstruction of the plant are not explicitly included.

The *LCOH* are visualized in Fig. 5 depending on the technology and the year of commissioning. Based on cost projections for the electricity price in the future (Fig. 4), a range is given. Additionally, a variation of $c_{\text{stack,in}}$ is integrated, where mean values are derived from a linear scaling between a high cost projection for 2024 and a low cost projection for 2045. This can be assumed by technological advancements and economies of scale in the future. It must be emphasized, that the projected costs of hydrogen production are mean values over the whole lifetime of the PtG plant installation (up to 30 years with stack replacement). The *LCOH* has risen sharply in the last two years due to inflation and volatile electricity prices in the European Economic Area and is expected to settle down in the coming years [57,58].

2.4. Definition of the study area

For the evaluation of the future potential of PtG plants the study area is divided into hexagons. Drezner and Zemel [68] demonstrated, that a hexagonal grid is the optimal layout for spatial coverage, outperforming square and triangular grids. Iravani [69] also used a hexagonal grid plane for his work and summarized the results of Drezner and Zemel [68] as follows: The main advantage of hexagons is that regular hexagons are closest to a circle and offer additional symmetry compared to squares. Therefore, they have the lowest perimeter-to-area ratio among geometrical shapes, which reduces edge effects and leads to more efficient space utilization. Additionally, each hexagonal cell has six neighboring cells with equal-length shared sides, and the centroids of all neighbors are equidistant, ensuring uniform connectivity and interaction across the grid. A hexagonal grid allows for an aggregated assessment of smaller regions without losing too much information, while simplifying the result for a better understanding of overall trends.

In the German case study in section 3, hexagons with a length and width of 50 km are used. The GIS data sources contain more detailed information, which is aggregated into a mean value for each hexagonal shape. To reflect real world conditions, data points located just outside of a hexagon's boundary are included in the evaluation of that hexagon. This accounts for situations where relevant factors, such as nearby infrastructure, lie nearby but outside of the spatial limits of the hexagon. The boundaries are therefore treated as analytical aid rather than a rigid spatial limitation. The centroid of the hexagon covering Berlin is located at 52.64° N and 13.42° E. In these details are illustrated using results of the applied case study.

2.5. Definition of assessment criteria

2.5.1. Renewable energy availability

The generation of renewable electricity is the prerequisite for carbon neutral hydrogen production. Therefore, PtG plants should be operated in regions with high availability of RES. For the case study in section 3, the two energy sources with the highest share of renewable electricity generation in Germany are considered: Wind and solar [70]. Wind energy is further divided into onshore and offshore production. The current expansion targets for the installed capacity of onshore wind and solar are obtained from supplementary studies of the German network development plan from 2019 [71], 2021 [72] and 2023 [73]. The specific power densities for open field and rooftop PV as well as onshore wind can be derived from the heat maps presented in the accompanying studies. The offshore wind energy potential of a specific location is defined as the distance to the respective grid connection points. The locations of the grid connection points for offshore wind production are taken from the German network development plan from 2019 [74], 2021 [75] and 2023 [6]. The data has been collected for the years 2025, 2030, 2035 and 2040.

Different RES for the same location are weighted according to their *FLH*. *FLH* of solar and onshore wind energy were aggregated based on the installed capacity *P* and the capacity factors *CF* for each hour *i* based on data from the Renewables.ninja model [76,77] of the respective RES:

$$FLH = \frac{\sum_i \max\left(CF_{\text{PV},i} \cdot P_{\text{PV}}, CF_{\text{Onshore},i} \cdot P_{\text{Onshore}}, CF_{\text{Offshore},i} \cdot P_{\text{Offshore}}\right)}{\max\left(P_{\text{PV}}, P_{\text{Onshore}}, P_{\text{Offshore}}\right)}. \quad (11)$$

This simplified function provides a straightforward approach and offers a general estimate of the available renewable resources in each region.

2.5.2. Hydrogen demand

As long as the hydrogen gas network is not sufficiently developed, long distances between hydrogen production and consumption should be avoided, as this results in high transportation costs. Therefore, the localization of PtG plants is significantly influenced by industrial locations with high hydrogen demand.

For the case study, information on the projected future hydrogen demand in Germany, published in the gas network development plan of the German transmission system operators (TSO) [78], is used. In addition to on-site production, the future hydrogen supply can also be ensured by a direct connection to the gas infrastructure. For this reason,

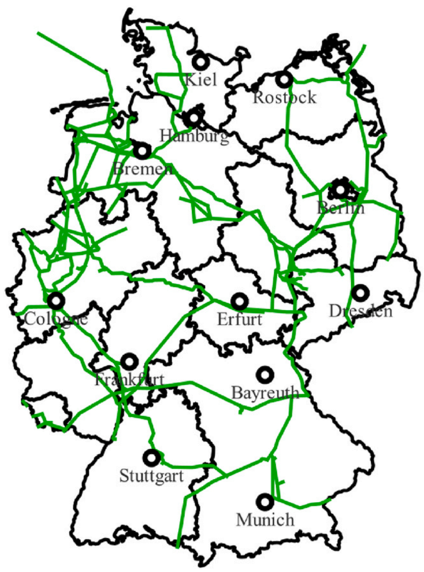

Fig. 6. Hydrogen core network, based on the present planning of the gas TSO's in Germany (adapted from Ref. [79], status October 2024).

the proximity to the gas infrastructure, expressed by the distance to the planned hydrogen core network in Germany for 2032 (see Fig. 6), is included in the evaluation of this study.

2.5.3. Groundwater availability

Water is still a critical resource in many countries around the world. Even Germany has experienced an increasing number of droughts in recent years and is among the countries with the highest water losses in the world losing 2.5 cubic kilometers of water per year since 2000, according to a monitoring report by the Interministerial Working Group on Adaptation to Climate Change [80]. Although the availability of groundwater is currently not a problem in Germany, the German Association of Energy and Water Industries (BDEW) emphasized the urgency of water-related aspects in PtG plant localization [81]. The following example should give an idea of water demand of a large-scale PtG plant. The PEMEL Siemens Elyzer P-300 produces 335 kg/h of hydrogen with an electrical input power of 17.5 MW, using around 10 L of demineralized water per kilogram of hydrogen produced [82]. To obtain 10 L of demineralized water, about 12 L–13 L [81,83] of groundwater is required. In addition to the water consumption for hydrogen production, there are other system-specific water requirements, e.g. for cooling. Just the hydrogen production leads to an annual groundwater consumption of over 38 million liters at maximum capacity corresponding to approximately 826 German households with an average water consumption of about 126 L per person per day [84]. At this scale, the consumption may not appear significant, but a large-scale plant with an electrical input power of around 1 GW would meet the entire water demand of a town with approximately 50,000 residents, assuming linear scalability.

To consider a possible future water shortage due to scale-up, groundwater availability is defined as an assessment criterion. It reflects the potential of groundwater yield and recharge, with both components being equally weighted in the assessment. Groundwater potentials can be extracted from the datasets of the Federal Institute for Geosciences and Natural Resources [85]. The database provides information on groundwater share in water supply, its regional distribution, and geological occurrences. Groundwater recharge indicates the average annual renewal rate in mm/a, while the deposits of major and minor aquifers are expressed as groundwater yield in l/s.

To provide an overview of the different evaluation criteria and to ensure transparency and reproducibility, Table 3 presents the minimum and maximum values of the applied criteria.

Table 3
Overview of minimum and maximum values of the different evaluation criteria.

Criteria	Min	Max
Renewable energy availability 2030		
Open field PV (kW/km^2)	≤10	≥720
Roof top PV (kW/km^2)	≤10	≥720
Wind onshore (kW/km^2)	≤10	≥720
Wind offshore (GW)	0	4
Industrial hydrogen demand		
Relevant to transmission grid (TWh/a)	<0.1	>5
Relevant to distribution grid (TWh/a)	<0.0001	>5
Proximity to hydrogen core network (km)	4	158
Groundwater availability		
Groundwater yield (l/s)	<2	>40
Groundwater recharge (mm/a)	0	>500

2.6. Scenario definition

For a detailed analysis of the different potential factors and their influence on the location of future PtG plants, several scenarios can be defined. An overview of selected scenarios, which are considered for the case study, is given in Table 4.

2.6.1. Scenario 1: Renewable energy production

This scenario focuses exclusively on assessing the potential for renewable energy production. It compares the potential for PV and wind energy for the years 2025, 2030, 2035, and 2040 to provide an overview of the planned expansion capacity.

2.6.2. Scenario 2: Year 2030

In addition to the availability of renewable energy in 2030, this scenario considers the future demand for hydrogen. A comparison is made between the representation of demand via actual industrial demand and proximity to the hydrogen gas grid. It is assumed that groundwater scarcity does not influence the site selection.

2.6.3. Scenario 3: Year 2040

This scenario shows possible potentials for a high expansion rate of renewable energy and gas infrastructure. It is assumed that the gas infrastructure is fully developed, the hydrogen demand can be met everywhere and therefore, does not influence the localization of production sites. However, the possible limited availability of groundwater is included in this analysis.

2.6.4. Scenario 4: Copper plate

The copper plate assumption implies that the German electricity grid has no spatial limitations, meaning there are no regional constraints related to infrastructure or transmission in the electricity supply. The evaluation of beneficial locations only depends on the availability of groundwater and the future hydrogen demand supplied by the gas grid.

2.6.5. Scenario 5: Combination

In the final scenario, the influence of all factors is considered. The individual assessment criteria are weighted equally to achieve a valid comparison. In contrast to the previous scenarios, the final scenario includes a combined hydrogen demand factor, which weights the actual industrial demand and the proximity to the hydrogen backbone equally.

3. Case study for Germany

In this section the developed MCA framework illustrated in Fig. 1 is applied to Germany. The evaluation of the gathered information regarding renewable energy availability, hydrogen demand and groundwater availability are visualized hereinafter on a German map. Defined hexagons show the mean values for the area, while marked

Table 4
Scenario overview.

Scenario	Criteria			
	Renewable energy availability	Industrial hydrogen demand	Proximity to hydrogen core network	Groundwater availability
1: Renewable energy production	✓	x	x	x
2: Year 2030	✓	✓	✓	x
3: Year 2040	✓	x	x	✓
4: Copper plate	x	✓	✓	✓
5: Combination	✓	✓	✓	✓

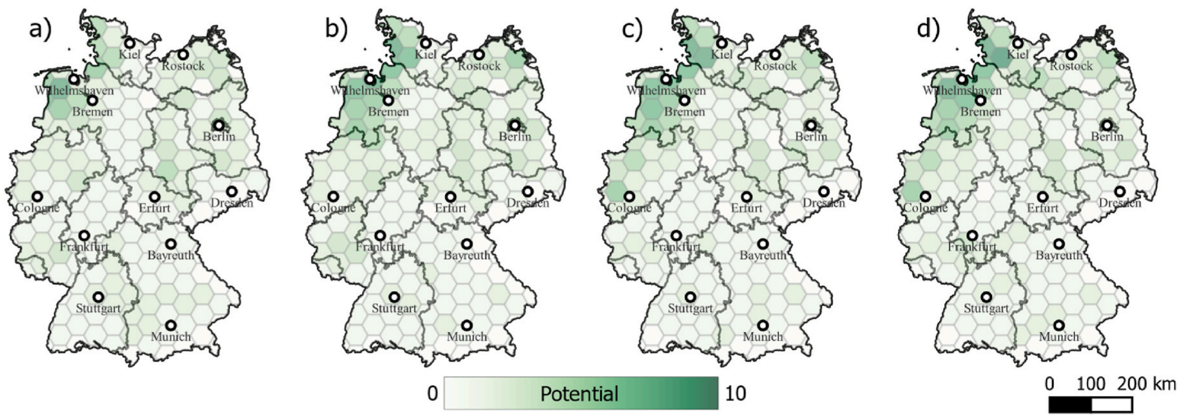

Fig. 7. MCA results of renewable energy production for a) 2025; b) 2030; c) 2035; d) 2040.

cities provide reference points within the grid. Based on the results of the MCA, the *LCOH* for three selected sites are determined using scenario 5: Combination as an example.

3.1. Scenario 1: Renewable energy production

The results for the availability of onshore and offshore wind as well as photovoltaic generation based on installed capacities and expected *FLH* are plotted for 2025 until 2040 (Fig. 7). Significant impact on the

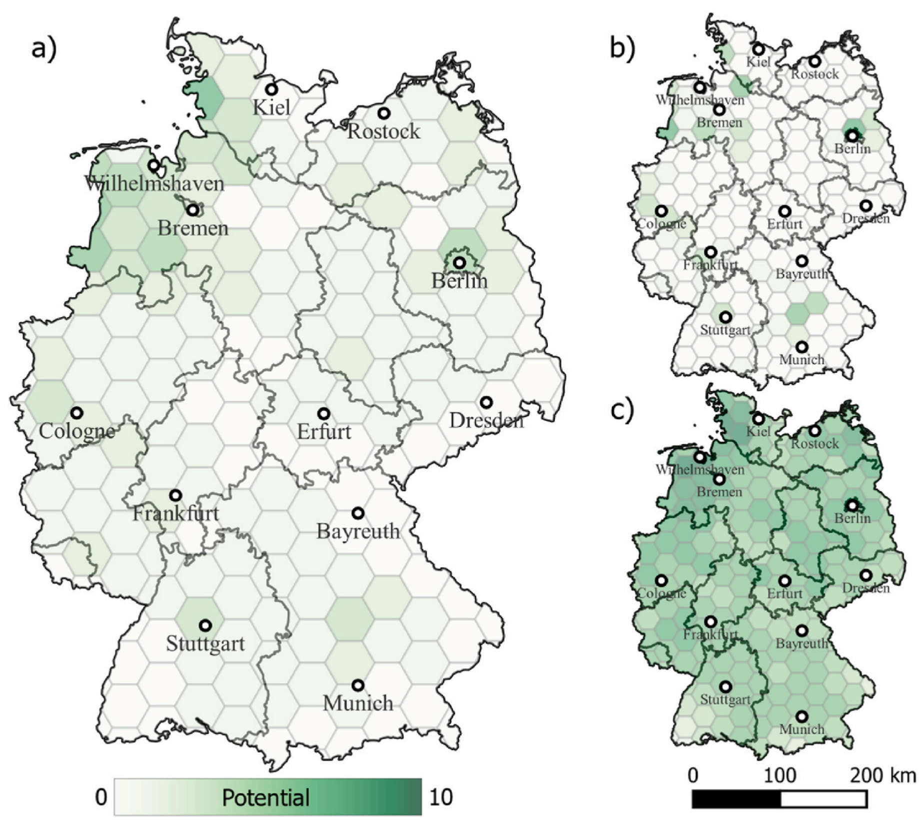

Fig. 8. MCA results for a) Combination of hydrogen demand and renewable potential for 2030; b) Industrial hydrogen demand; c) Hydrogen backbone + EE 2030.

results can be outlined for wind generation, especially near the North Sea coast. Offshore wind connections (HVDC) ranging as far as Cologne have a significant impact on the evaluation of hexagons. Furthermore, slightly higher wind and solar photovoltaic potential can be observed for the north-eastern national states. While high installed solar generation is projected in the south of Germany, it has less impact on the evaluation, due to low *FLH*. The PV-based potential for PtG plants can rise in the future for the south as well, when lower *FLH* are becoming economically feasible with lower investment costs. The south-west of Germany shows a lot of rooftop PV in the datasets while the north-east will get more and more permeated by land-based large photovoltaic arrays. Overall, northwestern Germany offers the most favorable conditions and highest potential for the production of green hydrogen.

3.2. Scenario 2: Year 2030

By 2030, the first segment of the planned hydrogen grid is expected to be completed, and major green hydrogen consumers should begin operations. Key demand hubs are projected near large cities and industrial complexes, such as Hamburg, Bremen, Cologne, Frankfurt, Stuttgart, Ingolstadt, and Berlin. The alignment of these demand hubs with the availability of renewable energy in 2030 indicates significant overlaps, particularly in the northwestern part of Germany. This region hosts substantial onshore and offshore wind farms, alongside heavy industries such as steel and chemicals. Additionally, the Ruhr area and parts of Bavaria, with their industrial complexes, and Berlin are noteworthy regions. Berlin, in particular, is projected to have significant hydrogen demand, according to datasets from gas TSOs [78], and will benefit from the increasing installation of RES in the surrounding areas in the upcoming years. The high potentials in Fig. 8 a) indicates a surplus of renewables as well as proximity to the customer. If the refitting of the gas network in Fig. 8 c) is assumed and included in the analysis, it becomes apparent, that the northern part of Germany is more suitable for hydrogen production. However, due to the equal weighting of renewable electricity production potential and the availability of a gas connection point, larger areas become suitable for the installation of PtG plants.

3.3. Scenario 3: Year 2040

Fig. 9 shows the result of a possible scenario for the year 2040, when Germany is moving towards climate neutrality. The hydrogen infrastructure is fully developed, and the location of PtG plants depends only on the availability of groundwater and renewable wind and solar energy. Due to the continuous expansion of large PtG plants, the availability of water may become more important. Fig. 9 b) and c) show the results for geological conditions of each region in terms of water yield and recharge. Due to the strong influence of wind production on the northern coasts, the highest potential in this scenario can also be found in north-west Germany (see Fig. 9 a)). In addition, high water yields in the north-east around Berlin and Brandenburg and high water recharge rates in southern Germany increase the potential of these particular areas. For coastal regions, there is also the possibility of meeting future water demands through seawater desalination. However, this adds another cost factor and reduces the overall system efficiency of hydrogen production [86]. Seawater desalination is not considered in this study but can play a key role in meeting future water requirements.

3.4. Scenario 4: Copper plate

In addition to the consideration of a fully developed hydrogen infrastructure, an assessment of the future potential for PtG plant locations is carried out in a further scenario, assuming an electricity grid with no spatial limitations. Wind and solar power are available all over Germany and therefore do not affect the choice of location. It is worth mentioning that the scenario implementation depends on fast electricity grid expansion without delay. The site of PtG plants is determined only by the demand of hydrogen represented by the hydrogen backbone and

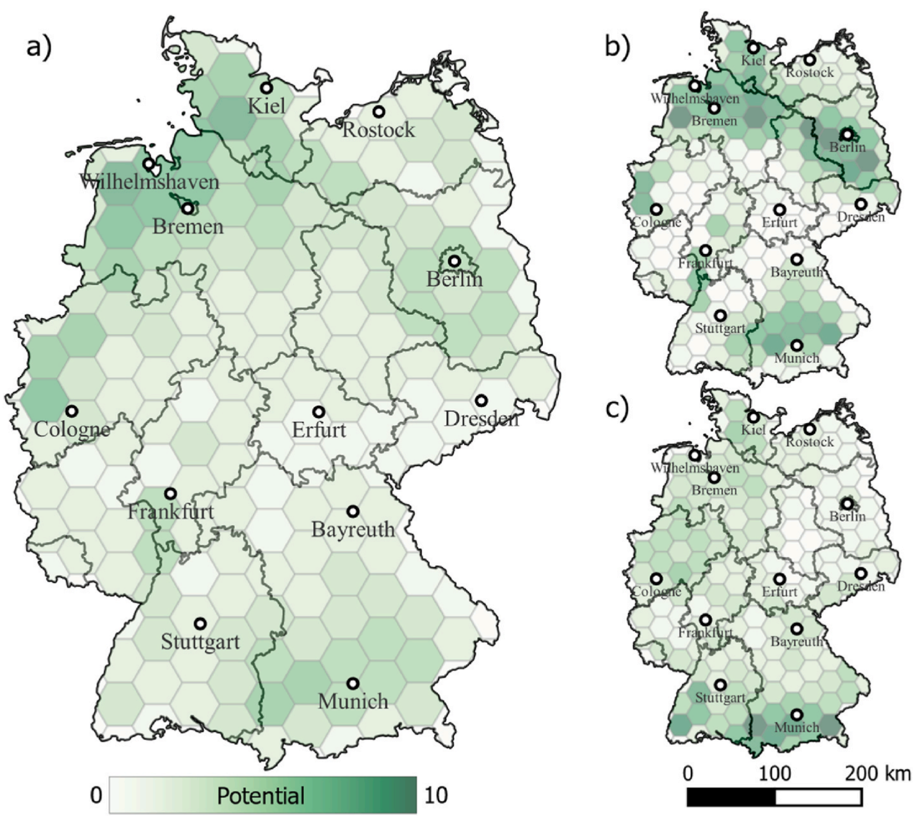

Fig. 9. MCA results for a) Combination of water availability and renewable potential 2040; b) Water yield; c) Water recharge.

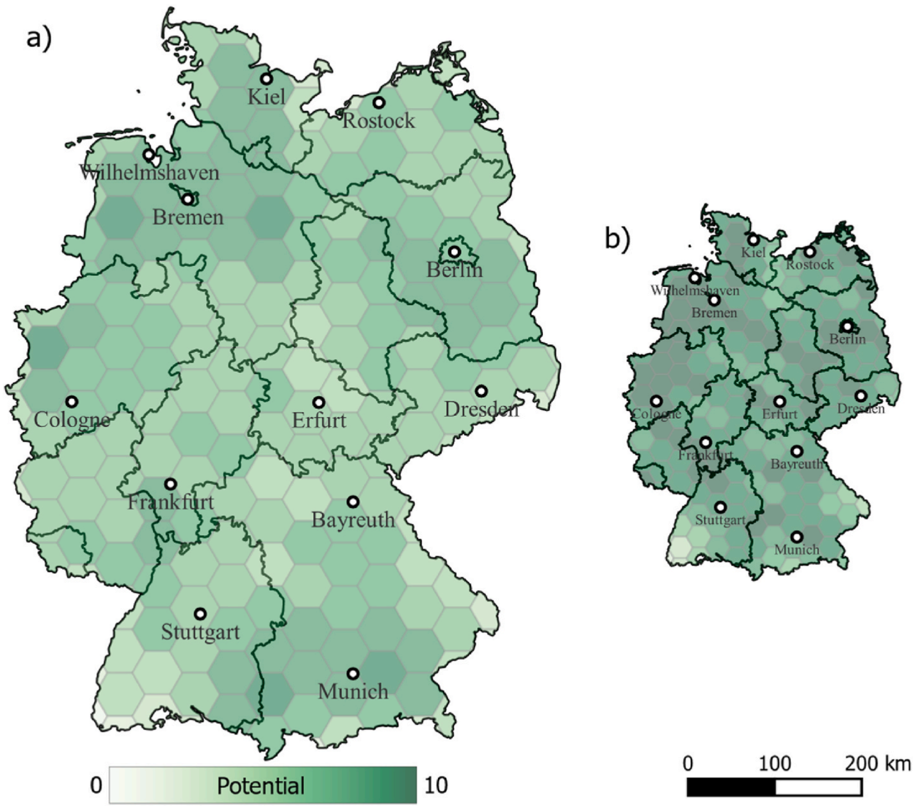

Fig. 10. MCA results of a) Combination of water availability and the planned hydrogen backbone; b) Hydrogen backbone.

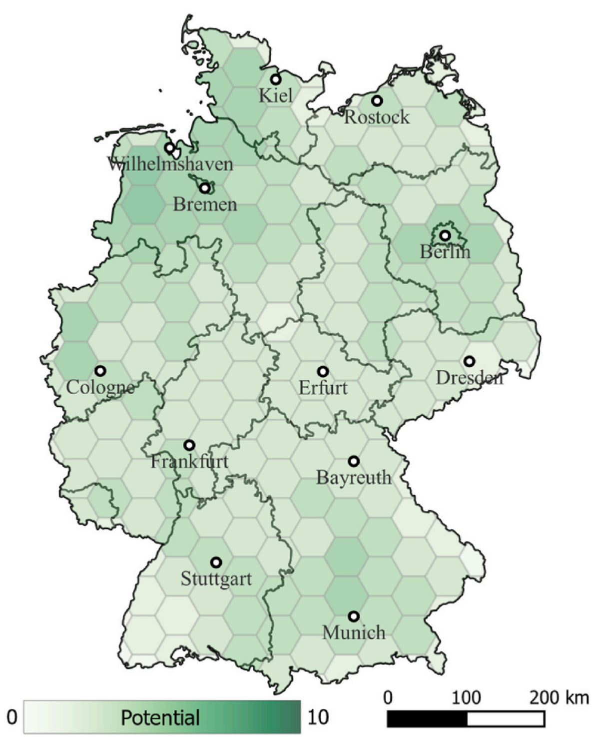

Fig. 11. MCA results for the combination of all the factors weighted uniformly.

the availability of groundwater. The hydrogen network extends along industrial complexes around major cities such as Cologne, Frankfurt or Berlin with significant hydrogen demands (see Fig. 10 b)). The results of the combined assessment in Fig. 10 a) also reveal an increased potential in northern and south-eastern Germany due to the availability of groundwater. By neglecting renewable energy production, the deviations between the individual hexagons decrease, as the differences between the factors considered are significantly smaller than between the availability of renewable energy across the country. For this reason, the potential in this scenario appears to be higher. However, an absolute comparison between scenarios is not possible, only relative differences can be used for further evaluation.

3.5. *Scenario 5: Combination*

In the last scenario, all factors presented are included in the analysis and weighted equally to ensure that the individual influences can be differentiated in a comparable manner. The MCA results in Fig. 11 show that the highest potential is in northwest Germany. It is not only the large capacities and full-load hours of wind production that play a vital role in this case, but there are also industrial centers with a large demand for hydrogen and a high groundwater yield. The potential in southern Germany is primarily characterized by the demand of hydrogen and thus the proximity to the hydrogen network as well as the large groundwater recharge rates around the area of Munich. The northeast of Germany is also interesting because of a good combination of renewable energy production from wind and solar.

The results of the case study show good agreement with findings from the literature review in section 1.2. Similar to the work of [22–24], high potential is identified in industrial centers with good access to infrastructure. Furthermore, the most suitable locations are consistent with the German studies of the Fraunhofer ISE [25] and Brümmer et al. [26], which highlight the northern and northwestern regions of Germany due to their high availability of wind energy.

3.6. *Sensitivity analysis*

To assess the influence of each factor on the overall MCA results, a

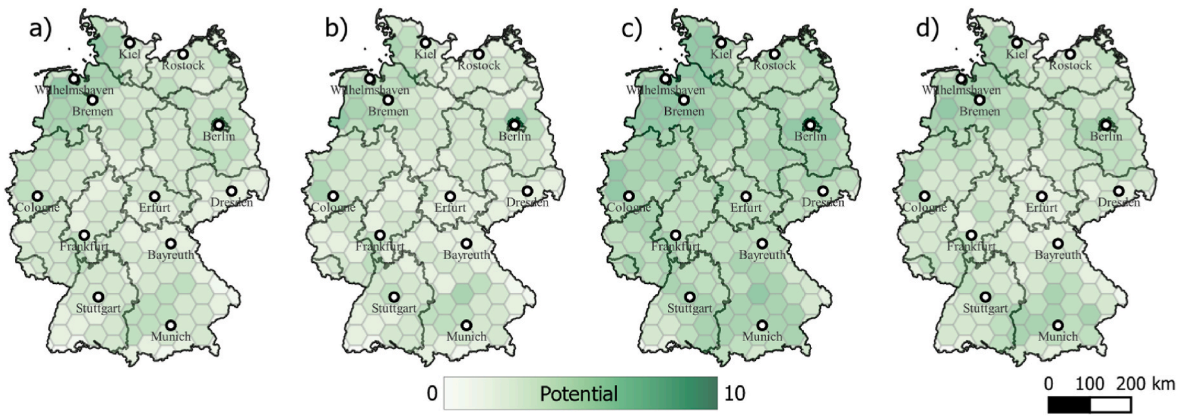

Fig. 12. Sensitivity analysis for scenario 5: Combination with double weighting for a) Renewable energy availability; b) Industrial hydrogen demand; c) Proximity to hydrogen core network; d) Groundwater availability.

sensitivity analysis for Scenario 5: Combination was performed. For this purpose, individual maps were generated in which the respective factor is assigned with a double weight in the MCA.

Fig. 12 illustrates that increasing the weight of individual evaluation factors highlights their respective characteristics. With a stronger emphasis on one factor, the maps become more similar to the corresponding single-factor maps shown on the right side of Figs. 7–10. The sensitivity analysis demonstrates that the results can be adapted to specific boundary conditions and to those evaluation factors considered most relevant by the applicant.

3.7. Techno-economic analysis

To integrate technical, economical, and GIS-based evaluations, three regions in Germany with significant differences in the availability of RES were selected. Wilhelmshaven near the North Sea was chosen due to its substantial contribution of offshore wind energy to the grid. A second location in central Germany (Erfurt) was selected for its mix of onshore wind and solar energy. Finally, Munich as example of a location in southern Germany was chosen to illustrate the impact of high PV infeed on the grid, in the absence of significant wind energy. The economic evaluation of the chosen locations was based on differences in the capacity factor of the renewable energies, as well as their installed capacity. This information was used to calculate the *FLH* according to Eq. (11). Also, for comparison purposes, PEMEL technology was selected, as it is expected to be one of the primary technologies utilized in the short to medium term for utilizing volatile energy sources. Consistent with the analysis presented in section 2.3, the *LCOH* was calculated and plotted for various price scenarios from the EU Energy Outlook [57,58] in Fig. 13. As anticipated, *FLH* have a substantial impact on hydrogen production costs, highlighting a significant advantage in regions with high operating hours. Depending on the location considered, the present *LCOH* show major differences, ranging from 16.8 €/kg to 9.1 €/kg. In the future, with lower *Capex* and longer stack lifetime, this effect may become less pronounced, leading to more uniform costs across regions. For PEMEL commissioned in 2045, the *LCOH* are projected to decrease well below 10 €/kg, and can even drop below 5 €/kg considering low electricity prices and high capacity factors of RES.

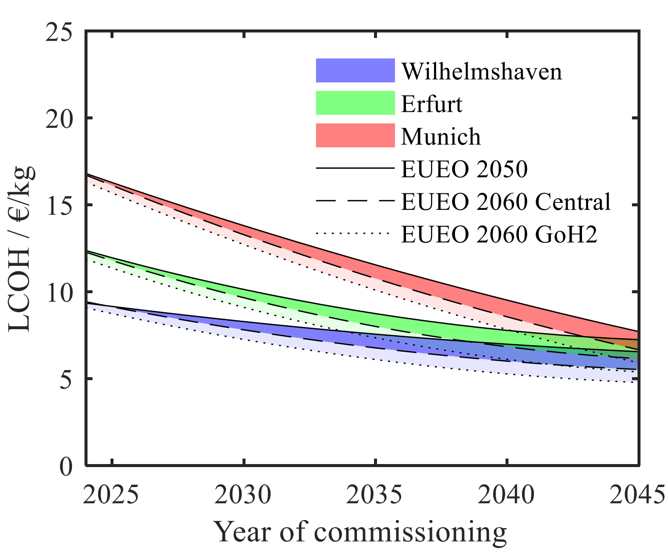

Fig. 13. *LCOH* for PEMEL in three different locations (Munich, Erfurt, Wilhelmshaven) based on electricity price and year of commissioning.

4. Conclusion

Many countries around the world are developing large-scale hydrogen infrastructures. To ensure their efficient operation, a proper selection of plant locations is essential. This paper presents a novel comprehensive MCA framework for the optimized localization of PtG plants in Germany. A technical model, based on established literature, is integrated to calculate the system efficiency of different electrolyzer technologies, providing crucial input for the economic model used to estimate the *LCOH*. The assessment of potential locations considers various criteria based on GIS data, including renewable energy availability, hydrogen demand, proximity to gas infrastructure, and groundwater availability.

In addition to the technical and economic analysis, multiple scenarios are explored to evaluate the potential of different regions in Germany, each based on varying weights assigned to the influencing factors. These scenarios allow for a nuanced understanding of regional variations in renewable energy, hydrogen demand, and water resources, that will impact the site selection of PtG plants. The results highlight northern and northwestern Germany as having the highest potential due to the abundant offshore wind resources, industrial hydrogen demand, and favorable groundwater conditions. Southern regions also show potential, particularly around Munich, due to high groundwater recharge and proximity to hydrogen infrastructure. However, the availability of wind energy and the resulting *FLH* are significantly lower compared to northern regions. The economic analysis confirms that regions with higher *FLH* of renewable energy, such as those near the North Sea, offer a significant cost advantage for hydrogen production. The present *LCOH* in the northern region around Wilhelmshaven are projected at approximately 9.1 €/kg, compared to 16.8 €/kg in Munich. However, as electrolyzer technologies evolve, resulting in improved efficiencies, reduced *Capex*, and longer operational lifetimes, *LCOH* is expected to converge across different regions. The *LCOH* for future years of commissioning is projected to decrease well below 10 €/kg, and may even drop under 5 €/kg for low electricity prices and high availability of RES.

Overall, this study emphasizes the importance of integrating technical, spatial, and economic factors in the localization of PtG plants. By considering a range of scenarios and site-specific conditions, this work provides valuable insights for decision-makers to optimize the deployment of PtG infrastructure, ensuring both economic viability and environmental sustainability as Germany moves towards an energy system in which hydrogen plays an increasingly important role. The new framework can be used as a benchmark to evaluate further regions and identify potential cross-country optima. Future work in this field could expand the geographical scope of the study to include the broader European region, where varying renewable energy potentials and hydrogen demands could provide new insights into optimal PtG plant localization. In addition, future methodological developments could incorporate alternative weighting schemes to reflect different strategic priorities, such as economic efficiency, environmental impact, or energy system resilience. Although plant size is indirectly considered in the analysis by different investment price projections, the explicit modeling of capacities and economies of scale can further refine the calculated *LCOH* values. Expanding the methodology itself, e.g. through dynamic scenario analysis, improved spatial resolution, or integration with (electricity) energy system models would further enhance its applicability and robustness across different regional und policy contexts.

CRediT authorship contribution statement

Tim Herrmannsdörfer: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christoph Linhardt:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matthias Welzl:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Andreas Jess:** Writing – review & editing, Supervision, Funding acquisition. **Dieter Brüggemann:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL and ChatGPT in order to improve the language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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