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Prospects of green hydrogen in Poland: A techno-economic analysis using a Monte Carlo approach

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HIGHLIGHTS

- The prospects of green hydrogen production in Polish NUTS-2 regions are analyzed.
- A Monte Carlo-based model for the assessment of LCOH is proposed.
- With today's PEM technology, the LCOH could be in the range of €6.37 to €13.48/kg.
- By 2030, the LCOH of a 6-MW PEM electrolyzer could decrease to €2.33–4.30/kg.
- In 2050, the LCOH of a 20-MW PEM electrolyzer could fall to €1.23–2.03/kg.

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ABSTRACT

The European Commission's plan to decarbonize the economy using innovative energy carriers has brought into question whether the national targets for developing electrolysis technologies are sufficiently ambitious to establish a local hydrogen production industry. While several research works have explored the economic viability of individual green hydrogen production and storage facilities in the Western European Member States, only a few studies have examined the prospects of large-scale green hydrogen production units in Poland. In this study, a Monte Carlo-based model is proposed and developed to investigate the underlying economic and technical factors that may impact the success of the Polish green hydrogen strategy. Moreover, it analyzes the economics of renewable hydrogen at different stages of technological development and market adoption. This is achieved by characterizing the local meteorological conditions of Polish NUTS-2 regions and comparing the levelized cost of hydrogen in such regions in 2020, 2030, and 2050. The results show the geographical locations where the deployment of large-scale hydrogen production units will be most cost effective.

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Nomenclature

Abbreviations

CF	Capacity factor
CRiT	Coal regions in transition
EU	European Union
LCOE	Levelized cost of electricity
LCOH	Levelized cost of hydrogen
NUTS	Nomenclature of territorial units for statistics
PV	Photovoltaic
PEM	Proton-exchange membrane
TRL	Technology readiness level

Symbols

$C_{O\&M}$	Annual operation and maintenance costs, (€)
C_{REP}	Annual replacement costs, (€)
CRF	Capital recovery factor
c_e	Electricity price, (€/kWh)
E_{el}	Electrolyzer power consumption, (kWh/kg)
P_{el}	Electrolyzer rated capacity, (kW)
I_{el}	Electrolyzer specific investment cost, (€/kW)
γ	Electrolyzer water consumption to produce one kg of hydrogen, (L/kg)
φ	Fraction of capital cost
i	Interest rate, (%)
$LCOH$	Levelized cost of hydrogen, (€/kg)
c_w	Price of water, (€/L)
N	System lifetime, (yrs)
C_{CC}	Total electrolyzer capital cost, (€)
M_{H_2}	Total hydrogen produced by the electrolyzer in one year, (kg)
τ	Total number of hours in a calendar year, (h)
$C_{TotalRep}$	Total replacement cost, (€)
u_{el}	Utilization rate of the electrolyzer

Introduction

In recent years, considerable efforts have been focused on accomplishing the vision of a hydrogen economy in Europe. Despite the positive momentum towards the decarbonization process of the European Union (EU), some Member States face unique barriers —mainly due to their historical energy paths— that hinder their prospects for sustainable green economic growth. In 2020, for instance, nearly 85% of the electricity generated in Poland originated from fossil fuels, particularly from hard coal and lignite [1].

On the other hand, Poland is required —as a Member State of the EU— to meet the targets set out in the European Green Deal and which are essential to achieve climate neutrality by 2050 [2,3]. Consequently, Poland is now at a crossroads in terms of the strategic choices necessary for a sustainable and successful energy transition. To address some of the above-mentioned challenges, the Polish government has recently adopted the Energy Policy of Poland until 2040 and announced the Project of the Polish Hydrogen Strategy. These documents set the framework for the country's energy transition, and to some extent, position hydrogen as an important energy vector for the economy and multiple end-use sectors [4]. Furthermore, the European Commission's plan to decarbonize the economy using innovative energy carriers has brought into question whether the national targets for developing electrolysis technologies are sufficiently ambitious to grow a local hydrogen production industry. This has motivated much of the research on renewable hydrogen and its wide range of applications, including industrial processes, sustainable and smart mobility, electricity balancing, among others [5,6].

Zhang et al. [7] and Dong et al. [8] classified the utilization of hydrogen into three general categories. First, hydrogen in combustion processes—e.g., for small-scale heating, and after blending into natural gas networks, for electricity and heat generation at the grid-scale. Second, hydrogen in fuel cells, mainly used in the transportation sector. Third, the authors pointed out the application of hydrogen in chemical processes—e.g., methanol synthesis, oil and metallurgical industries. The opportunities and challenges for renewable Power-to-X, including solar and wind generation used for hydrogen production, are described in detail in the work of Dayian et al. [9]. In a more recent study, Cader et al. [10] assessed the impact of economic, energy, and environmental factors on the development of the hydrogen economies in nine countries. Their results indicated that the countries examined recognize the vital role of green hydrogen in their national energy and climate plans up to 2030.

In this context, Fragiacomo and Genovese [11] also conducted a techno-economic analysis of renewable hydrogen production in three Southern Italian regions and assessed its potential application in the mobility sector. The study found that depending on the level of hydrogen mobility and electricity prices, the levelized cost of hydrogen (LCOH) may range from €6.90 to €9.85 per kg. Doga et al. [12] investigated the integration of hydrogen-based dense energy carriers in renewable energy system networks. The study showed that managing renewable electricity surplus in Texas using dense energy carriers and subsequently transporting them to New York could significantly reduce the levelized cost of renewable electricity. Nadaleti et al. [13] considered one, two, and 3 h of surplus renewable electricity per day to produce hydrogen and convert it back to electricity in various regions of Brazil. Their findings indicated that the cost of hydrogen production for the base year of 2019 was $0.3 per kWh.

Bhandari and Shah [14] conducted a techno-economic assessment of hydrogen production in electrolyzers powered by solar PV in Cologne (Germany) and suggested that green hydrogen produced in this region is market competitive with fossil-based hydrogen. Minutillo et al. [15] carried out a techno-economic analysis of an on-site hydrogen refueling station integrated with a PV installation in Italy. The study concluded that the LCOH ranges from €9.29 to €12.48 per kg depending on the hydrogen production capacity and the fraction of renewable energy powering the electrolyzer. Ulleberg and Hancke [16] assessed the economic performance of small-scale hydrogen supply systems for zero-emission transport in Norway. The techno-economic calculations showed the importance of support schemes to reduce the cost of hydrogen for refueling stations. Franco et al. [17] analyzed different pathways for offshore wind-powered hydrogen production and transportation. The research pointed out that using pipelines to transport hydrogen can potentially reduce the LCOH to €2.17 per kg.

Recent pilot projects embracing higher electrolyzer capacities also highlight the increased interest in renewable hydrogen. The study carried out by Kopp et al. [18] presents a techno-economic analysis of the research facility "Energiepark Meinz" —a 6-MW Power-to-gas installation in Germany. Similarly, the project H2FUTURE assessed and tested a pilot plant with a 6-MW polymer electrolyte membrane in Austria [19]. In 2020, the Gigastack project, a 100 MW industrial-scale installation, entered the second phase of demonstration [20]. The commercial introduction of such a system is expected to help the United Kingdom achieve net-zero green gas emissions by 2050.

Although it is well established that renewable hydrogen is an effective solution for reducing carbon emissions [21], high electricity prices and capital costs are major barriers to the further development of electrolytic installations in Europe. While several research works have investigated the economic viability of individual hydrogen production and storage facilities in the Western European Member States, only a small number of studies have examined the future costs of hydrogen production systems in Poland. Moreover, to the best of our knowledge, no research has yet been carried to examine the technical and financial uncertainties that may impact the economics of green hydrogen production in Polish coal-dependent regions. Further, there is a gap in the literature in terms of prospective studies that offer a better understanding of the critical role that hydrogen will play in the diversification opportunities of Coal Regions in Transition. Hence, the motivation of this study is to provide timely and evidence-based knowledge to researchers and decision-makers on the economics of green hydrogen production in Poland at both national and regional levels.

With this in mind, the objectives of this study are threefold: (1) to characterize the local renewable energy resources that can be used to produce hydrogen through water electrolysis; (2) to conduct a quantitative analysis of the technical and economic feasibility of hydrogen production from solar photovoltaic and onshore wind potential at the NUTS-2 level[1]; (3) to examine, using a Monte Carlo approach, the underlying economic and technical factors that may impact the success of the Polish green hydrogen strategy. A comprehensive analysis of local technical, financial, and policy-related aspects of green hydrogen production is carried out to fulfill the abovementioned research objectives. Moreover, a Monte Carlo simulation framework is developed for the techno-economic assessment of large-scale hydrogen production systems in Poland.

It is important to emphasize that this research is the first to investigate the economic prospects of green hydrogen production in Poland at the NUTS-2 level using a Monte Carlo approach. The Monte Carlo-based framework proposed in the paper is a novel contribution since it allows to assess the economic viability of renewable hydrogen production considering the wide range of uncertainties that may impact this emerging industry. Further, the probabilistic approach employs the levelized cost of hydrogen as the metric for evaluating the economic performance of large-scale electrolyzers powered by solar and wind energy.

Despite the growing body of literature that explores the future role of green hydrogen on European energy systems, the lack of prospective studies in Poland limits the space for a democratic debate about the technological options available for clean energy production. As a result, the present study attempts to fill this gap and contributes to the literature along four dimensions.

First, the study proposes a Monte Carlo-based model to estimate the levelized cost of hydrogen of large-scale production systems powered by onshore wind and ground solar PV. Second, the study shows the economics of renewable hydrogen in Poland at different stages of technological development and market adoption. This is achieved by considering the local meteorological conditions of Polish NUTS-2 regions and comparing the LCOH of large-scale PEM electrolyzers in different years (2020, 2030, and 2050). Third, the study exposes the key factors that drive risk in large-scale green hydrogen projects using a sensitivity analysis. Fourth, the findings provide invaluable insights to researchers and policymakers on the future trajectories of green hydrogen production costs in Poland, which ultimately may help the regional development of a green hydrogen economy.

The remainder of the paper is organized as follows. Section Materials and methods describes the characteristics of the quantitative approach employed in this study and the model used to examine the economic performance of green hydrogen production systems in Poland. The case study, including research scenarios, main assumptions, and data sources, is described in Section Case study. Section Results presents and compares the results of the different scenarios and the sensitivity analysis. Finally, Section Conclusions offers concluding remarks about the method and large-scale green hydrogen production in Poland.

Materials and methods

This section describes the method specifically developed to examine the complexities and uncertainties of large-scale green hydrogen production in Poland. As discussed in Section Introduction, this research focuses on the production of hydrogen via water electrolysis using onshore wind and ground solar PV resources. Although several electrolyzer technologies are available in the market or are under development, this study proposes a general model to determine the LCOH of off-grid stand-alone hydrogen production systems equipped with proton exchange membrane (PEM) electrolyzers. PEM electrolysis is a promising technology for future decentralized hydrogen production facilities due to its high flexibility, efficiency, and compact design [22]. Please note that because of the versatility of the model, other electrolyzers and power generation technologies could also be evaluated.

Unlike most studies that use simple sensitivity analyses (deterministic methods using point or expected values) to

[1] The NUTS classification (Nomenclature of territorial units for statistics) is a hierarchical system for dividing up the economic territory of the EU and the UK. NUTS-2 category is the basic one for the application of regional policies [44,95].

estimate the LCOH for planned or under construction hydrogen production systems, this study employs a probabilistic method to assess the effects of technical and economic uncertainties on the costs of hydrogen production in Poland. The techno-economic model proposed in this study incorporates a Monte Carlo approach to propagate the uncertainty of different inputs into the levelized cost of hydrogen. Fig. 1 presents a diagram of the approach proposed in this study.

Monte Carlo simulation is a computer-based method that estimates the expected value of an output function or a deterministic model using a set of inputs randomly generated from probability distributions [23,24]. Moreover, it is a methodological approach frequently used to analyze hypothetical scenarios and conduct what-if analyses in systems or processes for which experimental testing is too costly or simply not possible [25]. The method involves multiple steps that can be summarized as follows [26,27]:

- Identification of statistical distributions for model parameters that are subject to risk or uncertainty.
- Generation of N random samples from each probability distribution function, the random samples are transferred to the deterministic model as a set of input parameters.
- Computation of model outputs based on each set of input parameters.
- Statistical analysis of model outputs and approximation of probability density functions.

This probabilistic approach has been effectively used to conduct risk-based analyses of energy investments and project the cost performance of various energy technologies. In this context, Heck et al. [28] used a Monte Carlo approach to calculate the levelized cost of electricity (LCOE) of seven generation technologies and investigate the effects of location-based capacity factors (CF) on the LCOE of renewable technologies. Geissman and Ponta [29] calculated the LCOE of nuclear and gas projects with a Monte Carlo simulation technique and analyzed the impact of external costs like carbon intensity and carbon tax on LCOE density functions. Kryzia et al. [30] conducted a study using Monte Carlo simulations to determine the economic profitability of micro-cogeneration installations in Poland. More recently, Yates et al. [31] developed a Monte Carlo-based model to identify the key drivers of LCOH in off-grid stand-alone photovoltaic installations in five different locations around the globe.

To this date, however, no study has systematically examined the potential economic feasibility of green hydrogen production in Polish NUTS-2 regions with the aid of a Monte Carlo-based approach. For the abovementioned reasons and considering the uncertainty that exists in the strategic planning (long-term planning horizon) of green hydrogen production installations, the present study develops a static techno-economic model to estimate possible output values using random samples generated from probability density functions. In the approach, as it is commonly practiced, the probability density functions are constructed from subsets of

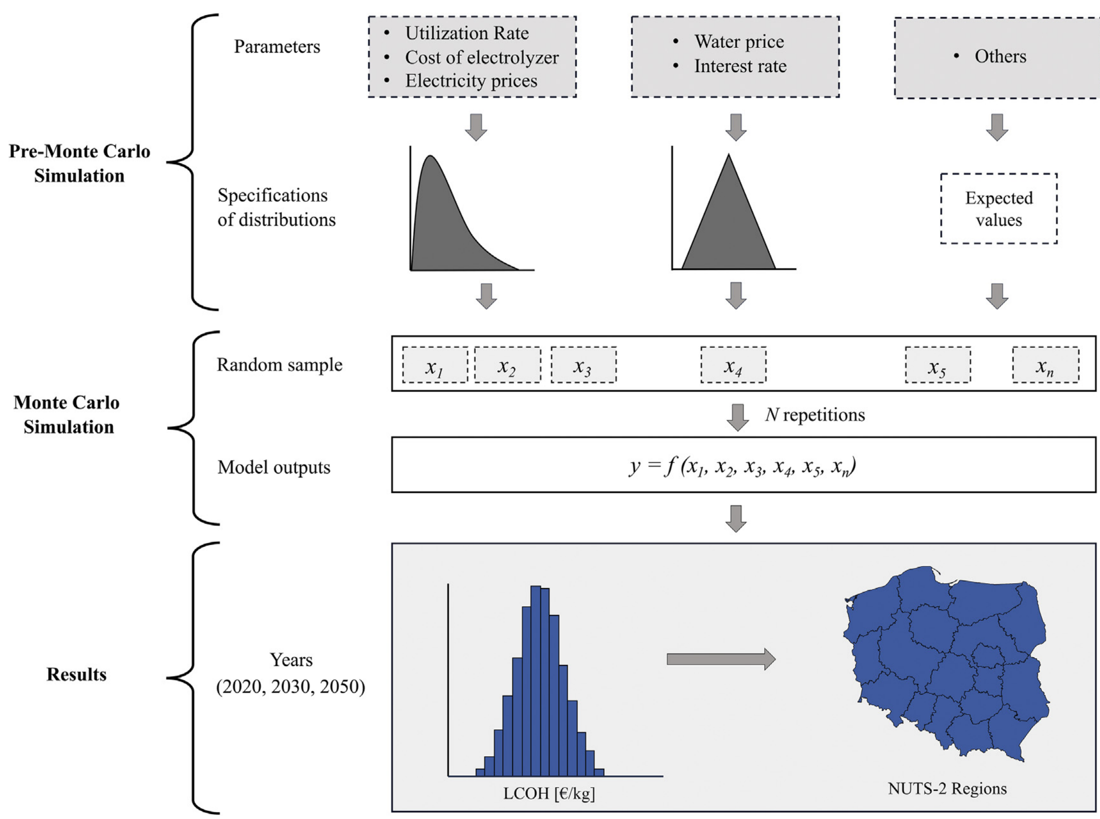

Fig. 1 – Overview of the Monte Carlo approach applied to estimate the LCOH of green hydrogen production systems in Poland. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

observed and projected data. Further, this study employs the levelized cost of hydrogen as the metric for evaluating the economic performance of large-scale PEM electrolyzers powered by solar and wind energy in various NUTS-2 regions.

The LCOH (€/kg) can be expressed as follows [15]:

$$LCOH = \frac{(C_{CC} \times CRF) + C_{O\&M} + C_{REP}}{M_{H_2}} \tag{1}$$

where C_{CC} is the total capital cost of the electrolyzer (€), CRF is the capital recovery factor, $C_{O\&M}$ is the annual operation and maintenance costs (€), C_{REP} is the annual replacement costs (€), and M_{H_2} is the total hydrogen produced by the electrolyzer in one year (kg).

CRF stands for the capital recovery factor, which converts the capital cost into a series of equivalent annual payments over the system lifetime N considering an interest rate i. It is defined using Eq. (2) [32]:

$$CRF = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{2}$$

The capital costs of the electrolyzer C_{CC} (€) can be calculated with Eq. (3) [33].

$$C_{CC} = P_{el} \times I_{el} \tag{3}$$

where P_{el} is the rated power of the electrolyzer (kW) and I_{el} the specific investment cost of the electrolyzer (€ $/kW$).

The annual operation and maintenance costs $C_{O\&M}$ (€) include the costs of electricity, water, nonfuel variable operation and maintenance [34].

$$C_{O\&M} = (\tau \times P_{el} \times u_{el} \times c_e) + (\gamma \times M_{H_2} \times c_w) + (C_{CC} \times \varphi) \tag{4}$$

where τ is the total number of hours in the year (h), P_{el} is the rated power of the electrolyzer (kW), u_{el} is the utilization rate of the electrolyzer expressed as a fraction of 1, c_e is the price of electricity (€ $/kWh$), γ is the water required to produce each kg of hydrogen (L/kg), M_{H_2} is the hydrogen produced by the installation in one year (kg), and c_w is the price of water (€ $/L$). Similar to Refs. [35,36], maintenance costs are assumed to be constant throughout the system's lifetime and are estimated as a fraction (φ) of the electrolyzer capital cost.

The annual production of hydrogen using the PEM electrolyzer can be computed using Eq. (5) [34]:

$$M_{H_2} = \frac{\tau \times P_{el} \times u_{el}}{E_{el}} \tag{5}$$

In the equation above, E_{el} stands for the power consumption of the electrolyzer in (kWh/kg).

The replacement costs C_{REP} in year t can be converted into annual costs using the capital recovery factor [15], as shown in Eq. (6):

$$C_{rep} = \frac{i \times (1+i)^N}{(1+i)^N - 1} \times \frac{C_{TotalRep}}{(1+i)^t} \tag{6}$$

where $C_{TotalRep}$ stands for the total replacement cost of the system (€).

The Monte Carlo-based model described in this section was implemented in MATLAB using the Statistics and Machine learning toolbox. The simulations were run on a desktop computer with an Intel i7-8086, 4.0 GHz six-core processor, and 46 GB of RAM. The validation of the computational tool was performed by comparing the simulation results to those obtained with the H2A: Hydrogen Analysis Production Model, a widely used and accepted tool in academia and industry [37].

In addition, a sensitivity analysis was performed to supplement the Monte Carlo approach and identify the sources of uncertainty that affect the LCOH in Polish renewable hydrogen projects. Five input parameters (equivalent to the ones used for the probability distribution functions) were used to evaluate the sensitivity of the LCOH: electricity price, cost of electrolyzer, utilization rate, water price, and interest rate. The sensitivity analysis was performed by systematically varying the values of a single parameter within the same ranges used to define the probability distributions (Table 2). A particular case was the range selected for the electrolyzer utilization rate. The ranges for the utilization rates were selected from the annual average capacity factors presented in Table 4 (for solar ground PV and onshore wind). The median of the capacity factors was taken as the central value (nominal value), while the minimum capacity factor was adopted as the lower bound of the sensitivity range. The upper bound was computed by multiplying the maximum annual average capacity factor with an oversizing factor. The oversizing factor of 1.33 was taken from the study of Vartiainen et al. [38]. This factor reflects the common approach of oversizing the RES system, and it indicates that the electrolyzer has 33% more full hours. In order to achieve comparable results for systems powered by onshore wind, the factor of 1.33 was applied to all scenarios (ground solar PV and onshore wind). The results of the sensitivity analysis are reported in Section Main factors affecting the levelized cost of hydrogen.

Case study

The method proposed in Section Materials and methods was applied to examine the complexities and uncertainties of large-scale green hydrogen production in Poland. Looking to the future, it is expected that the Polish government will make an effort to prioritize low-carbon energy sources and ultimately move forward with a national hydrogen strategy. As mentioned in Section Introduction, the Polish power system remains heavily dependent on coal. Nonetheless, in recent years there has been a steady expansion of renewable capacity. As of September 2021, renewables accounted for nearly 29.6% of the total installed capacity in power generation units (13.3 GW), with record-high capacity additions of solar PV (3.4 GW) and wind power (6.6 GW) [39]. However, because of the intermittent and non-dispatchable nature of renewable energy (low capacity factors compared to thermal power plants), electricity generation from renewables provided only 21.7 TWh or 15.4 percent of the total electricity production in 2020 [1]. Fig. 2 shows the development of the installed capacity per technology since 2015.

A promising solution for the decarbonization of the European energy systems [40,41] and the long-term transformation of the Polish economy is the use of power-to-gas technologies [42]. In Poland, the high technical potential for onshore wind (concentrated in the northern areas of the

Table 1 – Potential of ground solar PV and onshore wind in the context of electricity consumption. Based on [43].

NUTS-2 2021	Region	Ground Solar PV [TWh/yr]	Onshore Wind [TWh/yr]	Consumption in 2019 [TWh]	Surplus/deficit [TWh/yr]
PL21	Małopolskie	10.70	2.90	15.12	−1.52
PL22	Śląskie	9.14	0.80	21.59	−11.65
PL41	Wielkopolskie	31.77	27.34	14.72	44.39
PL42	Zachodniopomorskie	13.57	28.34	7.22	34.69
PL43	Lubuskie	8.00	7.66	4.28	11.38
PL51	Dolnośląskie	18.79	13.42	12.93	19.28
PL52	Opolskie	11.75	6.13	4.62	13.26
PL61	Kujawsko-pomorskie	19.18	23.41	9.34	33.25
PL62	Warmińsko-mazurskie	17.56	39.28	6.17	50.67
PL63	Pomorskie	12.23	22.71	9.74	25.2
PL71	Łódzkie	20.48	14.40	10.97	23.91
PL72	Świętokrzyskie	10.44	1.80	5.61	6.63
PL81	Lubelskie	27.82	32.30	9.37	50.75
PL82	Podkarpackie	12.09	4.30	9.03	7.36
PL84	Podlaskie	15.37	21.4	5.06	31.71
PL91	Warszawski stołeczny	4.45	12.15	12.49	4.11
PL92	Mazowiecki regionalny	29.06	12.15	10.05	31.16
Total		272.40	270.49	168.31	374.58

Table 2 – Distributional assumptions.

Parameter	Unit	Scenario I	Scenario II	Scenario III
Cost of electrolyzer	€/kW	PERT (500.0; 1164.8; 2097.6)	PERT (315.6; 362.0; 403.4)	PERT (138.6; 174.5; 210.5)
Electricity price (onshore wind)	€/MWh	PERT (24.7; 53.1; 131.3)	PERT (25.4; 33.9; 42.3)	PERT (16.9; 21.1; 25.4)
Electricity price (ground solar PV)	€/MWh	PERT (28.7; 53.0; 145.7)	PERT (16.9; 42.3; 67.7)	PERT (8.5; 22.5; 42.3)
Price of water	€/kg	Tr (0.00094; 0.00098; 0.00103)	Tr (0.00106; 0.00113; 0.00118)	Tr (0.00143; 0.00150; 0.00158)
Interest rate	%	Tr (6.0; 8.0; 10.0)	Tr (6.0; 8.0; 10.0)	Tr (6.0; 8.0; 10.0)

Note: PERT(A; B; C) – Beta-PERT distribution with a λ (lambda) parameter of 4; Tr(A; B; C) – Triangular distribution; A – the lowest possible value, B – the highest probability value, C – the highest possible values.

Table 3 – Input parameters.

Parameter	Unit	Scenario I	Scenario II	Scenario III	Reference
Rated power of electrolyzer	kW	1000	6000	20000	[18,51]
Stack efficiency[a]	%	59.0	63.0	71.0	[59]
Power consumption	kWh/kg	51.0	46.0	44.0	[59]
Lifetime	yrs	20	20	30	[38,86–89]
Maintenance cost	% of electrolyzer cost	5.0	2.2	1.85	[89]
Replacement cost	% of electrolyzer cost	42.0	42.0	42.0	[14,31,90]
Replacement year	yrs	7.0	10.0	15.0	[91]
Water requirement	L/kg H_2	9.0	9.0	9.0	[31]
Lower heating value of hydrogen	kWh/kg	33.3	33.3	33.3	[89]

[a] Based on lower heating value (LHV).

country) and ground solar PV (central and southern areas of Poland) could be used to partially decarbonize the economy through the production of green hydrogen and synthetic fuels. Figs. 3 and 4 highlight the wind power and photovoltaic potential in Poland. Kakoulaki et al. [43] point out that Poland has a total renewable energy supply potential of 629.9 TWh, of which 272.4 TWh (43.7%) corresponds to ground PV, and 270.5 TWh (42.4%) to onshore wind.

To date, however, no study has systematically examined the economic competitiveness of future green hydrogen production in Poland at a basic regional level. Thus, this study covers the 17 NUTS-2 regions (according to the Eurostat NUTS 2021 classification [44]) and assesses the economic feasibility of large-scale hydrogen production in off-grid stand-alone installations using a Monte Carlo simulation method.

Besides analyzing the green energy potential (ground PV and onshore wind) at the NUTS-2 level, it is essential to take into account the local electricity consumption. In the future, the feasibility of converting renewable electricity from stand-alone installations to hydrogen would depend on the availability of energy resources, or put differently, on whether there are enough renewable energy sources to cover the local

Table 4 – Average capacity factors for ground solar PV and onshore wind.

NUTS-2 2021	Region	Ground PV CF	Onshore Wind CF
PL21	Małopolskie	12.64	17.12
PL22	Śląskie	12.65	17.12
PL41	Wielkopolskie	12.76	25.57
PL42	Zachodniopomorskie	11.92	33.10
PL43	Lubuskie	12.69	23.47
PL51	Dolnośląskie	12.82	26.58
PL52	Opolskie	12.95	26.38
PL61	Kujawsko-pomorskie	12.35	28.88
PL62	Warmińsko-mazurskie	11.82	29.58
PL63	Pomorskie	11.84	35.04
PL71	Łódzkie	12.70	23.62
PL72	Świętokrzyskie	12.94	20.77
PL81	Lubelskie	12.97	23.61
PL82	Podkarpackie	12.66	16.72
PL84	Podlaskie	12.23	28.15
PL91	Warszawski stołeczny	12.45	24.67
PL92	Mazowiecki regionalny	12.45	24.67

Source: Own work based on [80,81].

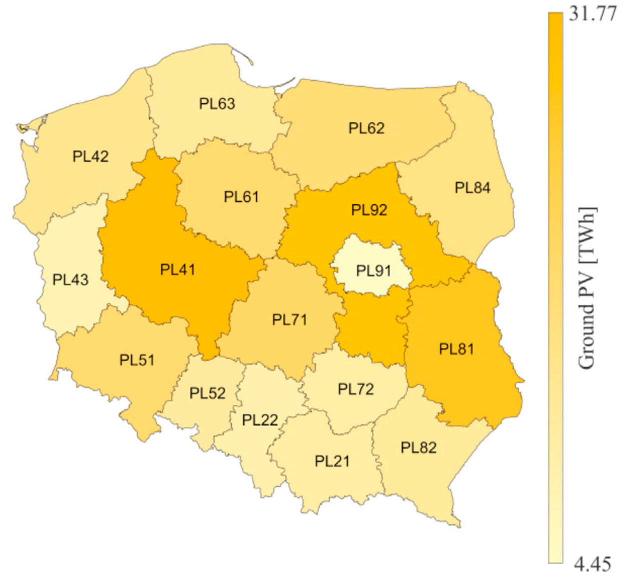

Fig. 3 – Potential of electricity generation from ground PV power plants. Based on [43].

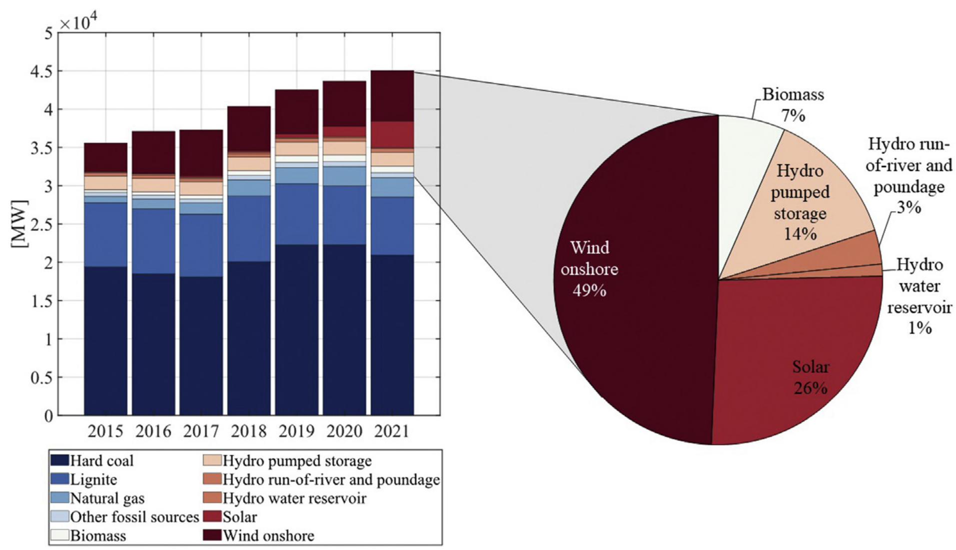

Fig. 2 – Installed generation capacity per technology in Poland (2015–2021). Based on: [39].

electricity demand and sufficiently low-cost electricity for hydrogen electrolysis.

In 2019, electricity consumption was almost 170 TWh, and it is expected to reach 225.7 TWh by 2040 [45]. As shown in Table 1, three regions (PL81, PL62, and PL41) have the highest amount of potential surplus green energy, with more than 40 TWh. Six regions (PL42, PL61, PL84, PL92, PL63, PL71) show a potential surplus between 20 and 40 TWh, and six regions with 0–20 TWh (PL51, PL52, PL43, PL82, PL72, PL91). Moreover, two regions could have an energy deficit in the future, where local renewable resources are unable to cover their electricity consumption (PL21, PL22). Note that the regions with a deficit of RES potential have been designated according to the European Commission as EU Coal Regions in Transition (CRiT) [46].

Current status and prospects of hydrogen production

In 2018, Poland ranked 5th among the top global hydrogen producers (3rd in Europe) with a production capacity of approximately 1.3 million Mg per year [47]. Most of the local hydrogen is produced either in refineries and chemical plants as a byproduct or using steam reforming processes, resulting in what is commonly known as gray hydrogen [48,49]. It should be noted that nearly 97% of the global hydrogen demand is met using processes that generate gray hydrogen [50]. Further, large-scale green hydrogen production systems are mainly considered emerging technologies, and no commercial plants are either in operation or under construction. Thus, the current methods used to produce hydrogen in Poland result in carbon emission at the level (a) of more than 5.8 kg CO_2

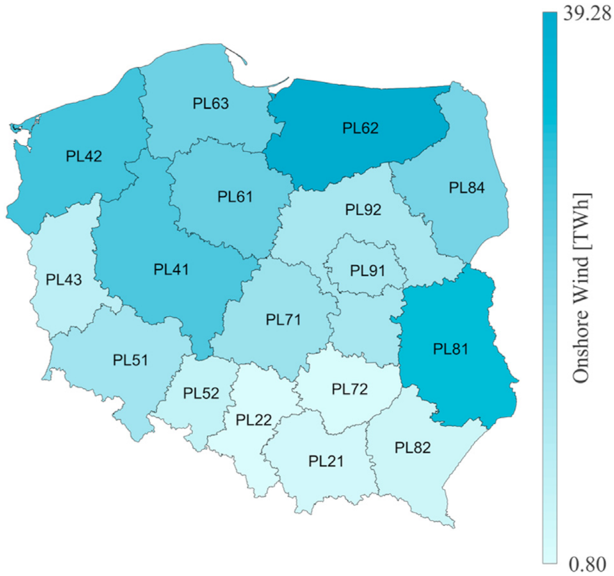

Fig. 4 – Potential of electricity generation from onshore wind power plants. Based on [43].

equivalent per kg H_2 when hydrogen is produced from natural gas, and (b) even more than 10 kg in the case of using coal as a primary energy source [49,51].

Since the current level of hydrogen production in Poland is far from being sustainable, policymakers and national regulatory bodies have laid some foundations for mid- and long-term strategies to support zero-emission energy carriers. The Polish Ministry of Climate and Environment, for instance, has recently proposed the "Polish Hydrogen Strategy until 2030 with a perspective until 2040" [51]. The strategy, aligned with the agenda of the European Green Deal, outlines several goals and activities primarily intended to support the establishment of low-carbon technologies in three sectors: energy, transport, and industry. Among the measures to support the development of a Polish hydrogen economy, the strategy proposed the deployment of 1-MW power-to-gas installations using Polish technologies within the next five years and potentially much larger installations (10–50 MW) in the next seven to ten years.

Consequently, considering the main targets of the proposed Hydrogen Strategy, the study analyses the economic performance of a 1-MW PEM electrolyzer relying 100% on wind or solar power in all of the 17 Polish NUTS-2 regions. This assessment is imperative for the development of the local hydrogen industry since the potential role of renewable energy varies significantly depending on the geographical conditions of the Polish territory. Moreover, to provide a much broader outlook of the trajectory of green hydrogen production in Poland, this study also analyzes the economic performance of 6-MW, and 20-MW PEM electrolyzers. Based on the strategy published by the Polish ministry, the present study assumes that electrolyzers with a capacity of 6-MW will be available in 2030, and electrolyzers of 20-MW in 2050. Additional information on the technical and economic assumptions of the three electrolyzers is provided in Section Techno-economic aspects of local green hydrogen production.

Techno-economic aspects of local green hydrogen production

Three research scenarios are designed and examined in the study. They are used to investigate the economic viability of green hydrogen production in Poland at different stages of technological development and market adoption. It is important to note that costs for hydrogen storage and transportation are not included in this study.

Scenario I considers the case of a 1-MW PEM electrolyzer deployed in 2020. The system operates independently from the transmission grid and is powered entirely by ground solar PV or onshore wind. In this scenario, data for a typical meteorological year (at the NUTS-2 level) is used to investigate the effects of different utilization rates on the levelized cost of green hydrogen.

Scenario II explores the case of a 6-MW stand-alone green hydrogen production system. It assumes that by 2030 water electrolysis technologies have reached the necessary technology readiness level (TRL) for large-scale deployment in Poland. Additionally, in this scenario, the levelized cost of electricity (LCOE) of utility-scale solar PV and wind is significantly lower than in 2020.

Scenario III examines the economic performance of a 20-MW PEM electrolyzer powered by ground solar PV or onshore wind in 2050. This scenario assumes that RES capacity factors increase with time (due to technological improvements) and that learning curves and economies of scale will drive major cost reduction in PEM, wind, and solar technologies.

Note that each scenario is calculated under distinct economic and technical assumptions, including different levelized costs of renewable electricity (separately for ground solar PV and onshore wind installations), electrolyzers investment costs, efficiencies, lifetimes, maintenance costs, replacement costs, and replacement years. Moreover, future changes in the capital costs of renewable technologies are reflected in the scenarios with the variation of the levelized cost of electricity. The scenarios explored assume that new ground solar PV and onshore wind systems will be installed in 2030 and 2050 to tap the potential of renewable energy sources and power the electrolyzers.

The electrolyzers considered in this study are described by the following technical and economic parameters: rated power, energy consumption for producing 1 kg of hydrogen, utilization rate throughout the year, maximum hydrogen production in a year, efficiency of PEM electrolysis (including losses coefficient), water requirement to produce 1 kg of hydrogen at 25 °C and 1 atm, lifetime, replacement intervals, capital expenditures, maintenance, and replacement costs.

Because renewable hydrogen production in Poland is at a fairly early stage of development, the LCOH at the national and local levels is influenced by a large number of independent parameters that display high uncertainty. Therefore, this work applies a Monte Carlo approach to account for the uncertainty associated with the above-described parameters. The inherent uncertainties of the input parameters in the techno-economic model are expressed by probability distributions. It is important to emphasize that two types of continuous probability distributions are selected for the

Monte Carlo analysis: (a) triangular distributions and (b) beta-PERT distributions. These distributions are chosen since they may be estimated from limited sample data and are characterized by three parameters: lower bound or minimum value, upper bound or maximum value, and most likely value or median [52,53]. Consequently, the bounds of the abovementioned distributions can be defined from data specific to long-term scenarios reported by academic, governmental, and international organizations. The present study follows the approach of [29,54,55] and models control variables like capital costs, electricity prices, and electrolyzer utilization rates using beta-PERT distributions. Prices of water and interest rates are modeled by triangular distributions, as in prior studies [56–58]. The different distribution types and parameters used in this study are presented in Table 2.

The data employed to estimate the distributions were gathered from multiple data sources (available in the public domain). Data of electrolyzer technologies were extracted from IRENA [59], IEA [60,61], Bloomberg [62], Deloitte [63], Postdam Institute for Climate Impact Research [64], and others [18,65–70]. In the case of the current and future values of LCOE for onshore wind and ground solar PV technologies, the data were acquired from IRENA [71–73], IAE [74], NREL [75], Bloomberg NEF [76], Fraunhofer [77], Lazard [78], and other [79]. It is worth highlighting that some of the projected values reported in the abovementioned data sources are the outcomes of different works and methods that consider potential cost reductions based on experience curves or economies of scale. Water prices for hydrogen production were estimated from historical data sets of seventeen Polish municipal companies (operating in each NUTS-2 region). The projected prices of water used in Scenarios II and III take into account the observed upward trend in Poland of the last eight years. The input data used to estimate the distributions and their references are presented in detail in the Supplemental Information.

Additionally, Table 3 shows the values characterized as constant parameters in Eqs. (1)–(6). Note that the vast majority of data sources used in the present study cover the years 2018–2021. This is intended to provide an up-to-date perspective on the economics of green hydrogen production in Poland.

The parameters for the PERT probability distributions of the PEM electrolyzer utilization rates in individual Polish NUTS-2 regions were determined using the EMHIRES datasets (European Meteorological derived high resolution RES generation time series for present and future scenarios) [80,81]. Statistical analyses were performed to estimate the monthly average capacity factors of solar ground PV and onshore wind at the NUTS-2 level from the hourly datasets. Gonzalez-Aparicio et al. [82], Monforti and Gonzalez-Aparicio [83] provide detailed information about the method employed to validate these databases. The upper limits, lower limits, and most likely values of the PERT distributions were determined directly from the monthly average capacity factors of each NUTS-2 region. The maximum monthly average capacity factor in the year was used as the upper limit of the PERT probability distribution. Similarly, the minimum and mean values of the monthly average capacity factors were selected as the lower limit and most likely value of the distribution. This approach was considered the most appropriate way to model PEM electrolyzer utilization rates since several studies in the literature have reported that PERT probability distributions are less sensitive to extreme values and constructs as smooth curve that emphasizes the values closer to the distribution's mean [29,55,84,85].

Table 4 provides the values of the annual average capacity factors used in Scenario I. For Scenario II and Scenario III, the capacity factors are assumed to improve with time due to technological developments. The capacity factors of ground solar PV and onshore wind increase by 0.14% and 0.15% per year, respectively [62].

Results

This section summarizes the results and discusses the future LCOH developments in Poland. First, it presents —at a NUTS-2 level— the LCOH in 2020, 2030, and 2050 of large-scale PEM electrolyzer systems powered by local renewable energy sources. As the model is based on a Monte Carlo Simulation approach, it generates probability distributions of multiple outcomes for LCOH; therefore, this section also compares the LCOH distributions of three selected regions (favorable, unfavorable, and average CF locations). Finally, this section discusses the results of the sensitivity analysis used to identify the key factors that drive risk in Polish renewable hydrogen projects.

Levelized cost of hydrogen in NUTS-2 regions

The LCOH distributions of seventeen NUTS-2 regions for the target years, i.e., 2020, 2030, and 2050 were computed with the simulation model proposed in Section Materials and methods. In this study, the median was selected to characterize the central tendency of the probability distributions. Hence, the maps presented in Fig. 5a–f shows the median values of the levelized cost of hydrogen in each region. All monetary amounts are provided in real terms (€2020).

The median values of LCOH for Scenario I, which considers the deployment in 2020 of a 1-MW PEM water electrolyzer system powered by ground solar PV, are presented in Fig. 5a. Depending on the geographical locations of the NUTS-2 regions, the LCOH ranges from €12.64 to €13.48 per kg. The lowest LCOH values are observed in the southern parts of Poland, mainly due to the slightly higher solar radiation levels in these areas. Although higher radiation levels translate to higher electrolyzer utilization rates, the hilly landscapes of the southern NUTS-2 regions and the significant number of excludable areas (e.g., Natura 2000 protected areas, non-agricultural vegetated areas, among others) limit the potential of large-scale renewable and green hydrogen projects. In contrast, the highest overall LCOH values are observed in the northern parts of the country. This is caused by the marginal decrease in solar radiation levels and the lower electrolyzer utilization rates (Table 4).

Based on the outcomes of Scenario II (2030), Fig. 5b presents the levelized cost of hydrogen produced from ground solar PV. The LCOH values range from €4.12 to €4.30 per kg. As the land available for renewable projects is assumed to remain

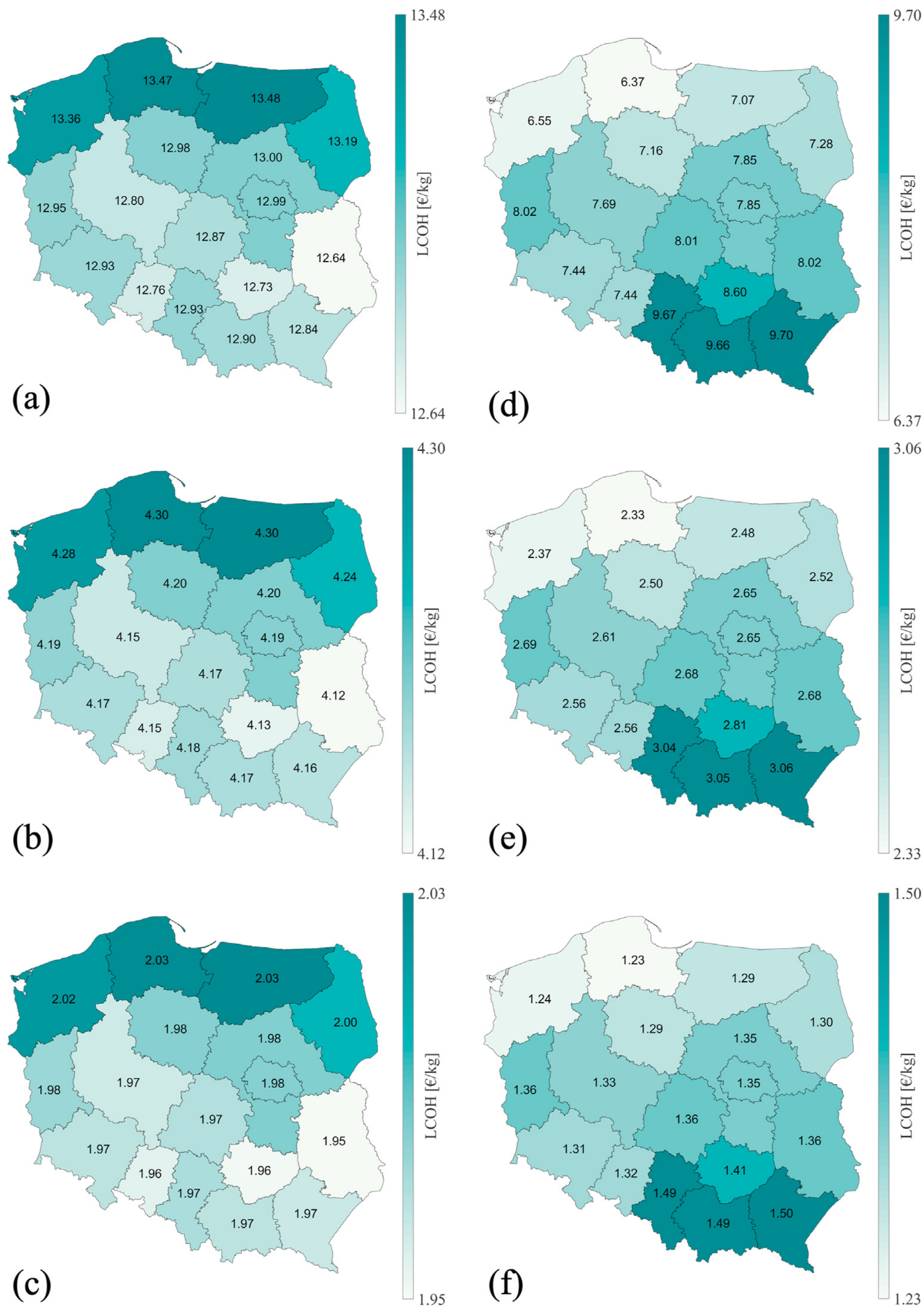

Fig. 5 – LCOH at the NUTS-2 level for: (a) ground solar PV (2020), (b) ground solar PV (2030), (c) ground solar PV (2050), (d) onshore wind (2020), (e) onshore wind (2030), (f) onshore wind (2050).

constant in all three scenarios, the geographically distributed LCOH estimates are primarily affected by changes in technical and economic factors such as reduced capital costs of PEM electrolyzers and lower generation costs from ground solar PV systems. Consequently, it can be observed from Fig. 5b that the levelized cost of hydrogen production decreases in all NUTS-2 regions by approximately 67–68% within a period of 10 years. Fig. 5c shows the levelized cost of green hydrogen produced from ground solar PV in 2050 (Scenario III). Although the spatial distribution of the LCOH is similar to the previous two scenarios, the LCOH drops to €1.95–2.03 per kg. This represents a decline of nearly 53% with respect to Scenario II (2030) and 85% when compared to Scenario I (2020).

Due to Poland's geographic and climatic characteristics and proximity to the Baltic Sea, the spatial distribution of the LCOH estimates of onshore wind in 2020 (Scenario I) is markedly different from the LCOH estimates computed for ground solar PV, as shown in Fig. 5d. The highest LCOH

Table 5 – Ranges of levelized costs of hydrogen for each scenario.

	Ground solar PV	Onshore wind
Scenario I (2020)	€12.64–13.48/kg H_2	€6.37–9.70/kg H_2
Scenario II (2030)	€4.12–4.30/kg H_2	€2.33–3.06/kg H_2
Scenario III (2050)	€1.95–2.03/kg H_2	€1.23–1.50/kg H_2

values are observed in the southern parts of Poland, whereas the lowest LCOH values are found in the northern regions, particularly in NUTS-2 regions closest to the Baltic Sea. The LCOH ranges from €6.37 to €9.70 per kg, approximately 49.6% lower than the costs expected for hydrogen produced from solar energy. The difference in LCOH can be attributed to the considerably higher annual average capacity factors of wind generating resources in Poland. Annual average wind capacity factors range from about 16.72 to 35.04%, whereas solar ground PV capacity factors vary from 11.82 to 12.97%.

Fig. 5e shows the levelized cost of green hydrogen produced from the onshore wind in Scenario II (2030). The LCOH ranges from €2.33 to €3.06 per kg, representing a decline of approximately 63.4–68.5% from the LCOH levels in Scenario I (2020). With a progressive decrease in the LCOE of wind technologies in the coming years, the economics of green hydrogen production improves. By 2050 (Scenario III), the computed LCOH values range from €1.23 to €1.50 per kg (Fig. 5f). These values are almost 47.2–51.0% lower than those estimated for 2030, or 80.7–84.5% to the values in 2020.

Table 5 summarizes the computation results for the levelized costs of hydrogen based on the type of renewable technology used to power the electrolyzer. Detailed results of the merit order ranking of Polish NUTS-2 regions (sorted from the lowest to the highest LCOH values) for each scenario are presented in Tables B1–B6 in Appendix B.

Location-adjusted LCOH distributions

The LCOH formula given in Eq. (1) considers various input parameters that are characterized by change and uncertainty. Therefore, the present study incorporates a Monte Carlo approach to propagate the uncertainty of different inputs into the levelized cost of hydrogen. As described in Section Materials and methods, the numerical procedure consisted of

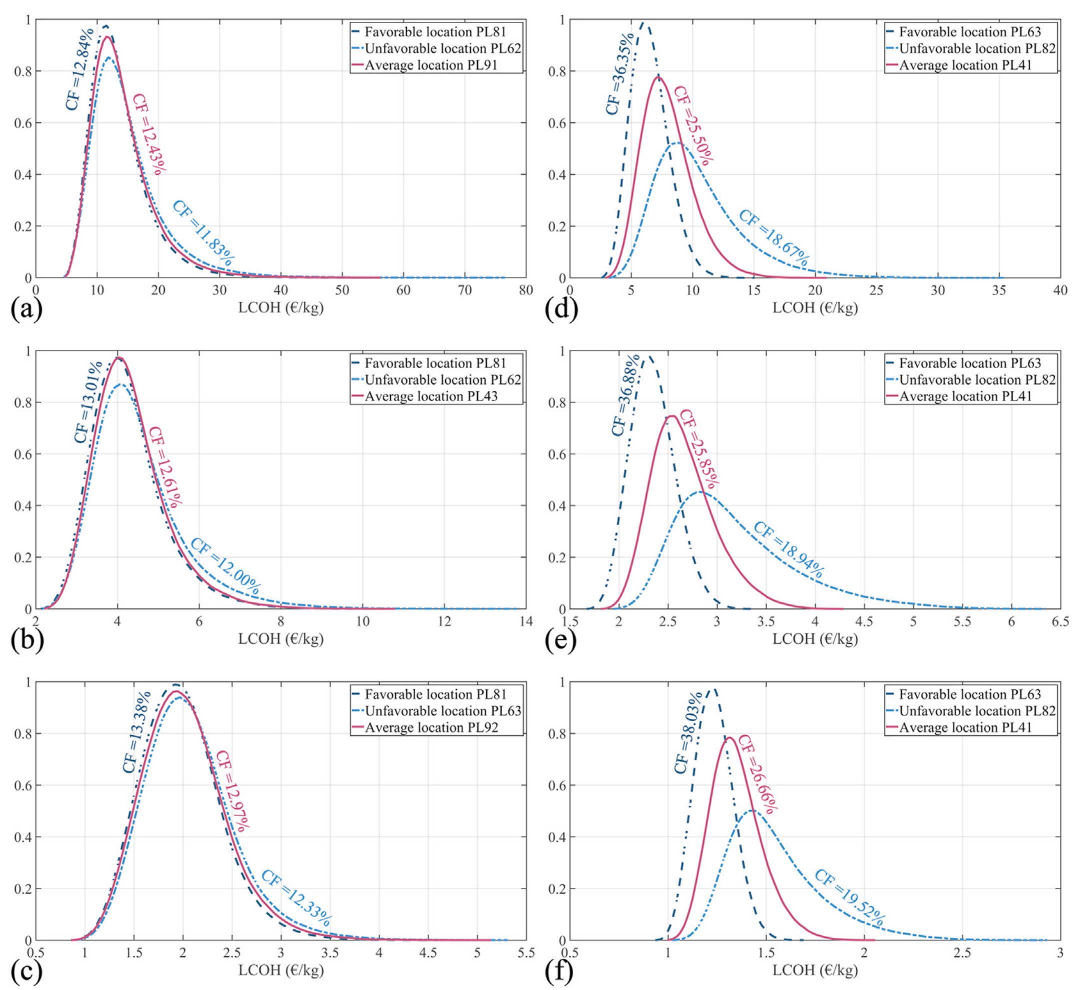

Fig. 6 – Uncertainty distributions for the NUTS-2 regions with the highest and lowest electrolyzer utilization rates, and the region with the utilization rate closest to the national average: (a) ground solar PV (2020), (b) ground solar PV (2030), (c) ground solar PV (2050), (d) onshore wind (2020), (e) onshore wind (2030), (f) onshore wind (2050).

selecting the variables considered uncertain in the LCOH formula, commonly referred to as “transfer equation,” and generating independent random values from the probability distributions listed in Table 2. The built-in functions in MATLAB were used to generate the random samples and perform the simulation. Although the vast majority of studies follow rules of thumb or adopt a standard number of replications, in this study, the number of replications was inferred following the procedure proposed by Geissmann and Ponta [29]. It was found that $2.9 \cdot 10^5$ replications achieve an accurate representation of the LCOH without having a negative impact on the computational time.

Fig. 6a–f presents the distributions for the NUTS-2 regions with the highest and lowest electrolyzer utilization rates, and the region with the utilization rate closest to the national average. As previously mentioned, the geographical location of the green hydrogen production system has a significant impact on the LCOH since the electrolyzer's utilization rate is directly proportional to the capacity factor of the renewable generator. Note that the y-axes of the uncertainty distributions were re-scaled between 0 and 1, with the highest frequency of the three NUTS-2 regions adopted as 1. The abovementioned adjustments were made for visual comparison and to show the effects of location on the LCOH distributions.

The results under Scenario I (Fig. 6a) for ground solar PV indicate that the most favorable location for green hydrogen production is region PL81 (situated in the eastern part of Poland). The LCOH values for this region generate a narrow distribution, showing that uncertainties and risk considerations are the lowest among the regions assessed. The distributions for regions PL62 (unfavorable location) and PL43 (average CF location) are wider, and exhibit longer tails than the distribution for PL81, indicating a higher uncertainty level. Further, the LCOH values for region PL81 are clustered closer together around the mode (€11.55 per kg), which indicates that this value is most likely to be found. Table 6 provides the 5th, 50th, and 95th percentiles of the distributions.

Even though Scenarios II and III (2030 and 2050) adopt different assumptions for some economic and technical parameters, the uncertainty distributions of all three NUTS-2 regions (identified as favorable, unfavorable, and average CF locations) are very similar (Fig. 6b and c). This can be attributed to the marginal change of ground solar PV capacity factors within the country. The most frequent LCOH values are €4.03 per kg for 2030 and €1.95 per kg for 2050.

Fig. 6d–f shows the uncertainty distributions of the scenarios considering large-scale PEM electrolyzer systems powered by wind energy sources. Unlike the distributions for ground solar PV, the shape and skewness of the uncertainty distributions for the levelized cost of hydrogen produced from the onshore wind vary between regions. In the case of Scenario I (Fig. 6d), the distribution of the favorable location (region PL63, situated in the northern part of Poland) is shifted to the left, indicating the higher economic efficiency of the green hydrogen production system (LCOH values clustered around €5.97 per kg). Moreover, the low uncertainty level of the LCOH values in this region is reflected by the narrow shape of the distribution and the short right tail. In contrast, the wider shape and lower peaks of the distributions corresponding to the unfavorable (PL82) and average CF (PL41) locations indicate the significantly higher level of uncertainty.

Table 6 – 5th, 50th, and 95th percentiles of the LCOH distributions.

LCOH [€/kg H_2]	Percentiles P5	P50	P95
PV (2020)			
Favorable location (PL81)	7.87	12.64	22.17
Average CF location (PL92)	8.02	12.99	23.38
Unfavorable location (PL62)	8.19	13.48	25.46
PV (2030)			
Favorable location (PL81)	3.04	4.12	5.90
Average CF location (PL43)	3.11	4.19	6.00
Unfavorable location (PL62)	3.14	4.30	6.60
PV (2050)			
Favorable location (PL81)	1.37	1.95	2.70
Average CF location (PL92)	1.39	1.98	2.79
Unfavorable location (PL63)	1.42	2.03	2.90
Wind (2020)			
Favorable location (PL63)	4.24	6.37	9.22
Average CF location (PL41)	5.02	7.69	11.75
Unfavorable location (PL82)	5.96	9.70	17.02
Wind (2030)			
Favorable location (PL63)	1.99	2.33	2.74
Average CF location (PL41)	2.19	2.61	3.26
Unfavorable location (PL82)	2.42	3.06	4.40
Wind (2050)			
Favorable location (PL63)	1.08	1.23	1.40
Average CF location (PL41)	1.16	1.33	1.59
Unfavorable location (PL82)	1.24	1.50	2.01

Fig. 6e presents the uncertainty distributions of the LCOH for onshore wind under Scenario II (2030), whereas Fig. 6f displays the distributions under Scenario III (2050). The local maxima of the distributions are affected by the assumption that learning curves and economies of scale will drive major cost reductions in renewable power technologies and PEM electrolyzers. The overall shapes of the distributions are comparable to the results of Scenario I (2020); however, the distributions shift further to the left with the increase in economic efficiency. The figures also suggest that green hydrogen production systems in unfavorable locations will need additional policy instruments to de-risk such investments in Poland.

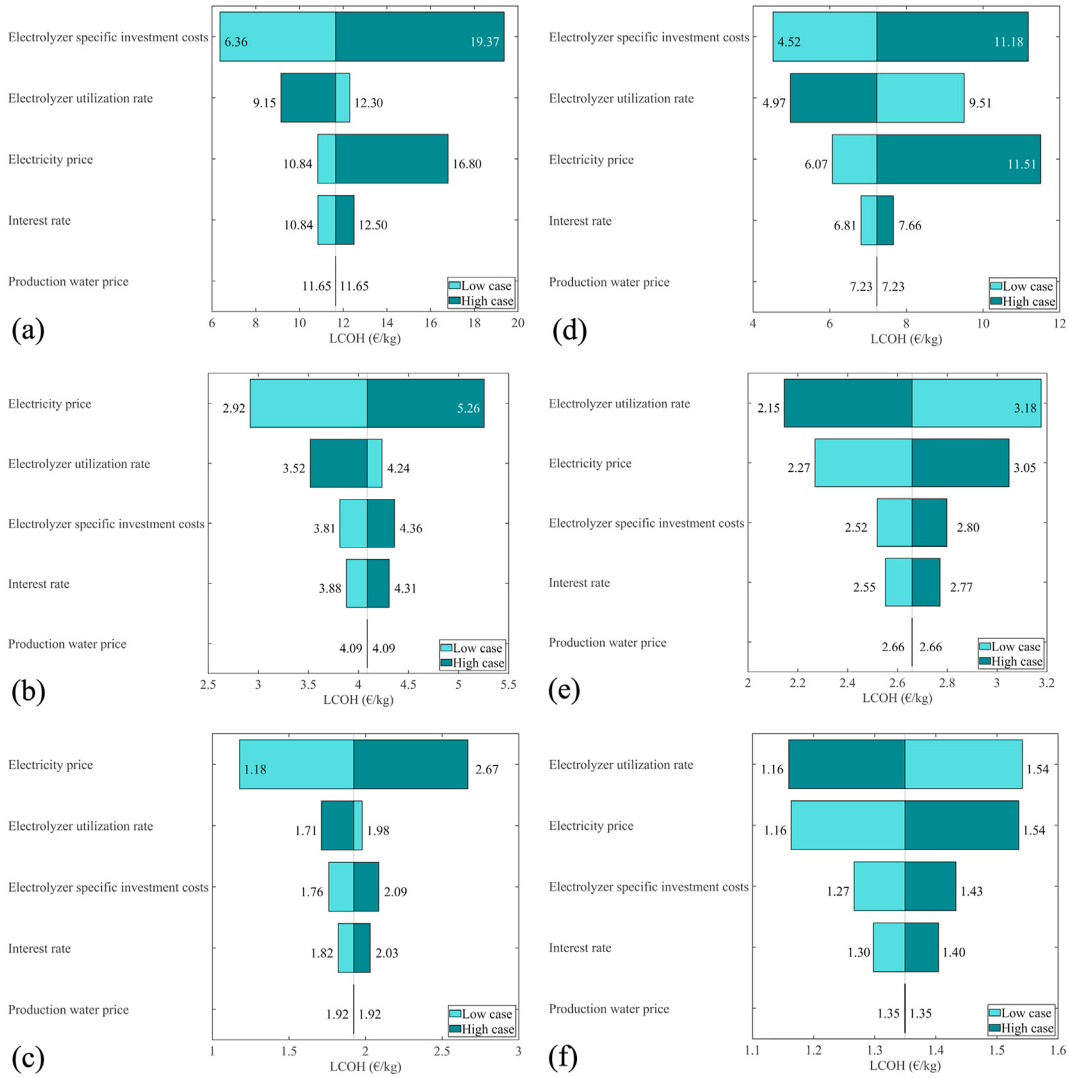

Fig. 7 – Key cost drivers of LCOH for: (a) ground solar PV (2020), (b) ground solar PV (2030), (c) ground solar PV (2050), (d) onshore wind (2020), (e) onshore wind (2030), (f) onshore wind (2050).

Main factors affecting the levelized cost of hydrogen

Fig. 7a–f presents the results of the sensitivity analysis for each of the renewable energy technologies studied. Note that the central lines in the tornado diagrams indicate the levelized costs of hydrogen at the nominal values (central values of the beta-PERT and triangular distributions). The horizontal bars are sorted in descending order by their outcome impact on the LCOH (from those with the greatest effect on the LCOH reduction to those with the least).

The tornado diagrams presented in Fig. 7a–c shows the key drivers of LCOH in systems powered by solar energy. As can be observed from the figures, the relative importance of the parameters changes depending on the year analyzed. In 2020, movements in the investment costs of electrolyzers have the most significant impact on the levelized cost of hydrogen (Fig. 7a). The results of the sensitivity analysis indicate that a reduction of this parameter from €1150 to €500 per kW (56.5%) may decrease the LCOH from €11.65 to €6.36 per kg, whereas a rise in investments costs by 82.4% could increase the LCOH to €19.37 per kg.

In 2030 and 2050 (Scenario II and III), the LCOH is most sensitive to changes in electricity prices. In 2030, the LCOH ranges from €2.92 to €5.26 per kg when electricity prices vary from €0.017 to €0.068 per kWh (Fig. 7b). In 2050, at a reduction in electricity prices of 66.7%, the LCOH drops from €1.92 to 1.18 per kg (Fig. 7c). In contrast, an increase in electricity prices of 66.7% leads to a rise in the LCOH (€2.67 per kg). Note that changes in electrolyzer utilization rate have a major impact on the economic performance of green hydrogen production systems.

Fig. 7d–f presents the results of the sensitivity analysis of LCOH produced by onshore wind energy. In 2020 (Scenario I), the order of the key cost drivers is the same as for ground solar PV, with electrolyzer specific investment costs having the greatest impact on the LCOH values. A reduction of this parameter by 56.6% causes the LCOH to drop from about €7.23 to €4.52 per kg (Fig. 7d). The results also show that movements in electricity prices may cause a significant change in the LCOH. For instance, a substantial increase in electricity prices (from €0.047 to €0.131 per kWh) leads to a steep rise in the levelized cost of green hydrogen (€11.58 per kg).

In 2030 and 2050 (Scenario II and III), the LCOH values are considerably affected by the variation in electrolyzer utilization rates. Note that in 2050 (Fig. 7f), the variation in electricity prices has the same effect on the LCOH as the variation in utilization rates. For example, a reduction of 32.2% in the electrolyzer utilization rate has the same effect on the LCOH as a 20% decrease in electricity prices (from €1.35 to €1.16 per kg). Additionally, the increase in utilization rate by 88.9% and electricity price by 20.0% lead to similar changes in LCOH (from €1.35 to €1.54 per kg.)

Conclusions

The study analyzed the economic performance of large-scale PEM electrolyzers relying on wind or solar power in all of the 17 Polish NUTS-2 regions. To this end, a Monte Carlo-based approach was developed to calculate the LCOH of decentralized (1-MW, 6-MW, and 20-MW) water electrolysis systems. The analyses were conducted separately for three target years, e.g., 2020, 2030, and 2050. This was done to investigate the economic viability of green hydrogen production at different stages of technological development and market adoption.

The study shows that in 2020 the LCOH of a 1-MW PEM electrolyzer system may have ranged between €12.64 to €13.48 per kg (using solar energy) and €6.37 to €9.70 per kg (using onshore wind energy). By 2030, the LCOH of a 6-MW PEM electrolyzer system could decrease to about €4.12–4.30 per kg (solar PV) and €2.33–3.06 per kg (onshore wind). In 2050, the levelized cost of green hydrogen of a 20-MW PEM electrolyzer system in Poland could fall to €1.95–2.03 per kg (solar PV) and €1.23–1.50 per kg (onshore wind) —mainly due to the advances in wind and solar technologies and major cost reductions in PEM technologies. Regardless of the year and the electrolyzer capacity, Poland's central and southern regions have the lowest LCOH values for solar-based hydrogen. For wind-based hydrogen, however, the lowest LCOH values are in the northern areas of the country.

To the best of our knowledge, there are no studies regarding the long-term prospects for green hydrogen production in Poland. However, a report published by BloombergNEF states that the cost of renewable hydrogen in Europe could be as low as $2 and $1 per kg in 2030 and 2050, respectively [92], which is in line with the results presented in this paper. The work performed by Kapłan and Kopacz [93] indicates that the levelized cost of hydrogen in Poland for hard coal gasification with carbon capture and storage (CCS) may range between €2.96 and €3.18 per kg, while for lignite coal gasification with CCS the LCOH may be around €3.93 to €4.17 per kg. In the case of hydrogen created using steam methane reformation ("blue hydrogen"), the International Energy Agency estimated the production cost in Europe to be around $1.7 to $2.4 per kg [61]. Considering the information available on the LCOH for different technologies, the results of this research indicate that the production of green hydrogen in Poland could become economically competitive with gray hydrogen by 2030 and blue hydrogen by 2050.

The study shows that the shape and skewness of the LCOH uncertainty distributions for ground solar PV (favorable, unfavorable, and average CF locations) are remarkedly similar. This is due to the marginal change in annual average capacity factors of solar generating resources. However, the shape and skewness of distributions for wind-powered hydrogen production systems vary significantly between favorable, unfavorable, and average CF regions. This suggests that in 2030 and 2050, some areas in Poland present significantly higher levels of uncertainty and may require additional support policy mechanisms to reduce or mitigate risk in hydrogen energy investments. Furthermore, the sensitivity analysis indicates that in 2020 the key cost drivers of hydrogen productions systems are electrolyzer investment costs and utilization rates. However, in 2030 and 2050, the LCOH of large-scale PEM electrolyzer systems will be significantly impacted by changes in electricity prices and utilization rates.

Policy implications

The findings of this study provide essential information on the structural changes that the Polish energy sector may experience in the following decades. The outcomes point out the geographical locations (a) where the deployment of large-scale PEM hydrogen production installation will be the most cost-effective and (b) where additional policy instruments will be needed to de-risk hydrogen investments. Consequently, the results contribute to a debate about the technological options available for clean energy production and provide timely and evidence-based knowledge on the economics of renewable hydrogen in Poland.

The study indicates that policymakers and regulators should formulate strategies considering the local conditions of a specific region. It is observed from the present study that new policy instruments will be needed to support the production of renewable hydrogen in the Polish areas with high levels of uncertainty and risk, especially in the next ten years. The critical success of such policies would lay strong foundations for the decarbonization of the energy sector and help the economic competitiveness of the Polish industrial sector, which is highly dependent on fossil fuels compared to the industrial sectors of neighboring countries.

Moreover, the findings contribute to the ongoing discussion on the need for policy interventions to develop hydrogen technologies and infrastructure in Poland. The results show that some regions will need a hydrogen grid and supply chain in the following decades. As the levelized cost of green hydrogen in Poland becomes more competitive over time, this clean fuel may become an alternative to natural gas. Thus, it is imperative that policymakers concentrate their efforts on the development of strategic plans for establishing a hydrogen supply chain considering the location of production facilities and the availability of renewable sources. Moreover, the policies and strategies for a hydrogen supply chain should not be developed independently from public policies supporting renewables. The increase in renewable capacity should go together with the development of the hydrogen economy.

The findings presented in this research may also be useful for developing regional innovation strategies for coal regions in transition. Since Poland still intends to produce energy from coal, addressing the challenges related to decarbonization requires the consideration of different solutions from multiple perspectives. Information on the renewable potential and the long-term prospects of green hydrogen production in these regions can provide new and valuable insight into the future directions of hydrogen storage and wind and solar energy applications.

Limitation of the study and future research

The present study provides a theoretical assessment of the levelized cost of hydrogen production through PEM electrolyzers powered by wind and solar energy. Although the approach developed in this study can be used to assess the LCOH in other countries and regions, further research is needed to fully understand the opportunities associated with the production of renewable hydrogen. In view of this, future research could expand and refine the Monte Carlo approach by considering the effects of storage and transportation on the LCOH of green hydrogen. Moreover, future research may focus on combining the proposed method with mathematical programming. An optimization model can provide detailed information on the dynamic behavior of energy systems for sustainable hydrogen production (PV-only, wind-only, or hybrid) and indicate the most cost-effective system configuration at a specific location (power capacity of the electrolyzer, solar photovoltaic, and wind power capacity). This would be particularly valuable in countries like Poland, where the renewable hydrogen industry and infrastructure are relatively underdeveloped. Such tools could provide new evidence on whether Poland will play a major role in the European Union, either as an importer or exporter of green hydrogen. Additionally, findings from such studies can be an important guide for policymakers and may help accelerate the decarbonization of coal-dependent economies.

An important area of research worth further work is the investigation of the optimal system configuration (e.g., electrolyzer and renewable technologies capacities) in relation to its location. In this study, the capacity of the renewable power system is considered directly proportional to the capacity of the electrolyzer. However, recent research findings suggest that the characteristics of the location have a significant effect on the optimal configuration of hydrogen production systems [31,94]. Largely motivated by this, our future work will concentrate on optimizing hybrid installations considering the characteristics of some locations in Poland. Furthermore, the method proposed in this study will be further developed to include the indirect costs associated with the construction, installation, and operation of green hydrogen systems. As pointed out by Khan et al. [94], these cost components have a considerable impact on the economics of electrolyzers and the levelized cost of hydrogen.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2021.12.001.

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