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Determination of photovoltaic hydrogen production potential in Portugal: a techno-economic analysis

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Hydrogen is expected to become a dominant energy vector in a scenario where renewable energies will prevail over other conventional sources. This suggests that beyond its conventional industrial applications, such as in the chemical industry, hydrogen is poised to find numerous additional uses, including serving as a fuel for internal combustion engines. Consequently, global demand is expected to surge significantly, necessitating the implementation of large-scale hydrogen production units from renewable sources. This is particularly pronounced in Europe, where recent energy directives have set ambitious targets in this regard. Consequently, it becomes imperative to evaluate potential locations suitable for hosting these hydrogen production facilities. In this study, particular attention is directed towards photovoltaic-fed water electrolysis as a method for hydrogen production. This choice is informed by the maturity and affordability of these technologies, coupled with the abundant solar energy resource available in Southern Europe. To this end, it is utilized 23 years of hourly meteorological data obtained from the Portuguese Meteorological Service. This dataset enables the development of typical meteorological year files for nearly 90 stations across mainland Portugal. These files were inputted into a model simulating a 120 MW_p photovoltaic plant, utilizing the System Advisor Model. The electricity generated by this plant was subsequently used to simulate the hydrogen production using an in-house developed model for the electrolyser. Finally, the simulation results were used to develop the first atlas for Solar Hydrogen production capacity and cost in Portugal. The techno-economic results indicate that annual specific hydrogen production can achieve values above 30 kg/kW_p, with the levelized cost of hydrogen below 4.0 €/kg, especially, in the southern regions (Alentejo and Algarve) and the central-east area (Beira Interior). This makes these regions highly attractive for hosting large-scale photovoltaic hydrogen production plants and very competitive in the hydrogen market, especially with neighbouring countries like Morocco and Spain.

KEYWORDS

meteorological data, separation model, typical meteorological year, photovoltaic power plant, water electrolysis, hydrogen production, levelized cost of hydrogen

Highlights

- This work uses 23 years of 1-h meteorological data from the Portuguese Meteorological Service to develop typical meteorological years for 89 stations in mainland Portugal.
- A separation model was calibrated for a reference station in the South of Portugal and used to determine diffuse horizontal irradiance and direct normal irradiance.
- A model of a 120 MWp photovoltaic power plant was used, System Advisor Model, to yield electricity production.
- The photovoltaic power production values were fed into a model of an electrolyser plant to determine the annual hydrogen production.
- The techno-economic analysis reveals annual specific hydrogen production values above 30 kg/kWp, and levelized cost of hydrogen below 4 €/kg, in the southern regions (Alentejo and Algarve) and the central-east area (Beira Interior)
- A benchmark analysis concludes that Portugal is very competitive in the “green” hydrogen market, when compared with neighbouring countries like Morocco and Spain.

1 Introduction

Combustion is a main source of atmospheric pollution (Conceição et al., 2016) producing both particulate and gaseous pollutants. These became prevalent in industrial and urban areas (Silva et al., 2014; Silva et al., 2016; Matthews et al., 2019). Since “green” hydrogen is a non-pollutant alternative, it is expected to become a dominant energy vector in the future, where pollution is being substantially reduced. In fact, hydrogen benefits from two advantages in comparison to conventional fuels: it has the highest gravimetric energy density, and (essentially) the only product of the combustion process is water (Sterner and Stadler, 2019). These bring advantages like higher autonomies, in comparison to battery run electric cars, at (almost) null levels of pollutants. Moreover, adaption of internal combustion engines running on conventional fuels to hydrogen is a common practice today. Such technology would then appear to solve the mobility problem, yet, it has its downfalls. For example, the low ignition energy that makes it a dangerous gas, and the low volumetric energy density that implies the use of very high pressures of up to 700 atm. Such challenges are expected to be overcome with significant research efforts being done in order to do so (Rasul et al., 2022). Moreover, the use of hydrogen is not restricted to internal combustion engines, but it has many additional applications. For example, plans are set in different countries to blend hydrogen into the natural gas grid as a transition measure (Rosenow, 2022). Hydrogen is also considered to store renewable energy avoiding curtailment in periods of significant production and reduced demand (Sterner and Stadler, 2019). Another example is synthetic fuels production via Fisher-Tropsch process (Partidário et al., 2020).

More fundamentally, hydrogen could provide sustainability and energetic independence to Europe, if it is produced from renewable sources and within European borders. In fact, from the different technologies able to produce hydrogen from renewable

energy (Holladay et al., 2009; Yue et al., 2021), water electrolysis (Schmidt et al., 2017; Bunge et al., 2022) combined with wind or photovoltaic power seem to be the most mature and affordable technologies. Thus, most of the investments expected on this field are considering those (Olabi et al., 2021). Relevant to this is the abundance of solar energy in the South of Europe (e.g., PVGIS, 2022). This makes photovoltaic power very suitable for hydrogen production. Obviously, the case can also be made for concentrated solar power (CSP) plants (Lopes et al., 2019; Lopes et al., 2020; Tavares et al., 2022). In which improvements, like the use of residual heat from the electrolysers to pre-heat the heat transfer fluid, could be implemented (Merrouni et al., 2016a; Merrouni et al., 2016b). But, this technology would certainly have a higher cost than photovoltaic power plants.

In this context, Portugal has excellent conditions to produce hydrogen from solar energy. Recent studies, focused on the assessment of solar resource in this country, have shown mean annual availabilities as high as 2,028 kWh/m²/year for global horizontal irradiance (GHI) (Silva et al., 2020) and 2,097 kWh/m²/year for direct normal irradiance (DNI) (Cavaco et al., 2021) for the South of the country. As a matter of fact, Portugal, relying on the National Energetic and Climate Plan for 2030 (PNEC 2030a, 2023), has set resolute targets for the integration of renewable energy into the energy production system. This plan aims at a goal of 47% of renewable energy by 2030 and 64% by 2040 (Partidário et al., 2020). In this scenario modest targets have been set for hydrogen production by water electrolysis that would have an installed capacity of only 160 MW by 2030 and 400 MW by 2040, while production by biomass gasification would have similar capacities and availabilities. Nevertheless, these targets are being updated to more ambitious ones (PNEC 2030b, 2023). In fact, the Portuguese National Strategy for Hydrogen (PNSH 2030, 2020) has set more assertive targets for 2030. By that year hydrogen should cover 5% of final energy use, 2 GW of electrolyser capacity should be installed, 15% of injection of hydrogen into the natural gas grid should be guaranteed, and 50 to 100 fuelling stations for mobility purposes should be installed. These targets make it indispensable to accurately evaluate the potential of hydrogen production and its costs for Portugal. These also require the development of an hydrogen capacity atlas to better visualise the results and encourage policymakers and stakeholders to invest in this promising energy sector.

In fact, mapping the potential of hydrogen is an interesting research subject that recently attracts the attention of researchers. For instance (Nasser and Hassan, 2024a; Nasser and Hassan, 2024b) evaluated and mapped the potential of hydrogen production in Egypt from solar and wind. Several scenarios of the renewables share were used, and the authors found that the hydrogen power density can reach 57.1 kg/m². On the same vein (Nasser and Hassan, 2024a; Nasser and Hassan, 2024b), assessed and developed an atlas of hydrogen production for the Middle East and North Africa (MENA) region. One of the pertinent results in this study is the cost of hydrogen that ranges between 2.12 and 3.89 \$/kg while hybridizing the solar and wind technologies.

Moreover, one of the main inconveniences related to the hydrogen atlas development (for a region or a country)- is the accuracy of the data used and the number of the points used to

generate the maps. Having access to a significant number of measurement points is usually a critical factor that impact the accuracy of the developed map (Azouzoute et al., 2019). Also, the measurement points should be very well distributed and covering the whole surface of the investigated country (Ouchani et al., 2021).

As such, this work uses 23 years of 1-h meteorological data from the Portuguese Meteorological Service (*Instituto Português do Mar e da Atmosfera* - IPMA) covering 89 stations in mainland Portugal. The data is employed to develop Typical Meteorological Years (TMY), according to the method explained in (Kalogirou, 2014), for each station. In terms of radiation the meteorological data only has GHI and no DNI nor diffuse horizontal irradiance (DHI) measurements are available, thus there was the need to estimate them. At this point a decision was made to use the separation model developed by (Abreu et al., 2019) to determine DHI and from it DNI. This model was developed for 1-min data, but is also suitable for 1-h data, as shown below, as data noise is reduced by the averaging process. Moreover, the model parameters were calibrated for a reference station in the South of Portugal, operated by the Portuguese Institute for Earth Sciences (*Instituto de Ciências da Terra* - ICT). This station measured simultaneously DNI, GHI, and DHI, using a standard Sun Tracker equipment, for 4 years. This calibration process leads to a good agreement between the modelled and the measured data, where the error is 2.5% for the DNI and 3.9% for the DHI. More details about this can be found in the methodology section. Furthermore, a model of a 120 MWp photovoltaic power plant was developed using the PVWatts (no financial model) option of System Advisor Model (SAM, 2024). SAM was developed by the National Renewable Energy Laboratory in the United States (Blair et al., 2014). The power plant model was fed with the TMY from the 89 stations in mainland Portugal. The resulting 1-h photovoltaic power production values were subsequently fed into a model of an electrolyser plant previously developed (Touili et al., 2018; Touili et al., 2022). This allowed to determine the annual hydrogen production on each station. The results are presented in annual mass of hydrogen produced per installed nominal power (annual specific hydrogen production) and leveled cost of hydrogen (LCOH₂). These are mapped using a geographical information system (GIS) software to identify suitable places to install these facilities. Finally, the techno-economic analysis reveals annual specific hydrogen production values above 30 kg/kWp, and LCOH₂ below 4 €/kg, in the southern regions (Alentejo and Algarve) and the central-east area (Beira Interior). This makes these regions very attractive and competitive in the hydrogen market, especially when compared with neighbouring countries like Morocco and Spain.

It is important to highlight that this study not only presents the first atlas for Solar Hydrogen production capacity and cost in Portugal, but it is developed with high accuracy. In fact, the simulations are done using high quality *in-situ* GHI data for a long-term period (that reduces the impact of inter-annual variation, Tavares et al., 2024) and a good land coverage with 89 measurement locations. This may be of high interest for the policymakers and the investors to boost “green” hydrogen projects in Portugal.

The paper is organized as follows: in Section 2 the methodology implemented is described; in Section 3 the results of the analysis are presented and are discussed in Section 4; finally, in Section 5 conclusions are drawn.

2 Methodology

This section is dedicated to present and discuss the different methods used in this study. The first part will discuss the technique used to model DNI and DHI data. While the second part will discuss the models used to simulate the electricity production as well as the hydrogen production and cost.

2.1 Measurements and filters

In this study it is considered the meteorological data from IPMA’s national network. This comprises more than 90 stations, well distributed across Portugal, and having a large data coverage period, reaching 23 years. Out of those stations, 89 were selected as having more than 5 years of data. Details on the stations can be found in Supplementary Appendix Table SA1 in the appendix and (Silva et al., 2020; Tavares et al., 2022). As mentioned before, the network measures only the GHI component and did not measure DHI nor DNI. Thus, these parameters have been estimated, as described below.

Measurements of GHI were performed every hour using Kipp&Zonen CM11 and Hukseflux LP02 pyranometers, with the CM11 model being used in most of IPMA’s stations. Both pyranometers are secondary standard instruments according to the International Organization of Standardization (ISO 9060:1990, 2018). It is worth mentioning that detailed information regarding the pyranometers calibration and maintenance is not available, due to the large number of stations and their spatial distribution. Thus, in some cases, measurements might be affected by absence of calibration, malfunction, or soiling (Conceição et al., 2018; Merrouni et al., 2020). Regarding other meteorological variables measured at IPMA’s stations, air temperature and relative air humidity were recorded at a height of 1.5 m, from which the corresponding hourly averages are utilized for the analysis. Wind speed is recorded at a height of 10 m, with the averages of the last 10 min of each hour utilized (IPMAa, 2024). Air temperature and relative humidity measurements were made mainly with both Vaisala HMP45 (humidity accuracy at +20°C ± 1% RH, temperature accuracy at 20°C ± 0.2°C) and HMP155 sensors [humidity accuracy at +15 ... +25°C - ±1% RH (0 ... 90% RH), temperature accuracy ±(0.1 + 0.0017 × |temperature|) °C]. Whereas wind speed was mainly measured with both Vaisala WAA 151 cup anemometer [accuracy with characteristic transfer function (standard deviation) ± 0.17 m/s (0.38 mph), with simple transfer function $U_f = 0.1 \times R \pm 0.5$ m/s (1.12 mph)] and Gill ultrasonic sensors Windsonic 75 (accuracy ± 2% at 12 m/s) (IPMAb, 2024).

Among the meteorological network, a high precision meteorological (HPM) station is used as reference. This station is located at the ICT observatory (University of Évora – lat.: 38.567676; lon.: -7.911757). The HPM is able to measure the three components of solar irradiation simultaneously and separately with high accuracy. The GHI and DHI were both measured using Kipp&Zonen CMP11 pyranometer. This is a secondary class instrument with an average accuracy of ± 2% (ISO 9060:1990, 2018). For DNI measurements a Kipp&Zonen CHP1 pyrliometer mounted on a SOLYS2 Sun-Tracker (from Kipp&Zonen) was used. This sensor is a World Meteorological

Organization first class instrument standard with an estimated uncertainty on a daily basis of < 1% (ISO 9059:1990, 2014).

To ensure that the used irradiation measurements have high quality, a quality control procedure was performed for all the available measuring stations from IPMA's network, as well as the ICT station. Data points that do not follow the proposed filters, as described in (Gueymard and Ruiz-Arias, 2016), were rejected:

1. $Z < 85^\circ$;
2. $GHI > 0$, $DHI > 0$, $DNI \geq 0$;
3. $DNI < 1100 + 0.03 \times Elev$;
4. $DNI < DNI_{toa}$;
5. $DHI < 0.95 \times DNI_{toa} \times \cos^{1.2} Z + 50$;
6. $GHI < 1.50 \times DNI_{toa} \times \cos^{1.2} Z + 100$;
7. $DHI/GHI < 1.05$ for $GHI > 50$ and $Z < 75^\circ$;
8. $DHI/GHI < 1.10$ for $GHI > 50$ and $Z > 75^\circ$.

In these equations, Z is the solar zenith angle, $Elev$ is the elevation of each station, and DNI_{toa} is the direct irradiance at the top of the atmosphere. Both Z and DNI_{toa} were calculated based on the formulas proposed by Kalogirou (2014), i.e., Eqs (2.12), (2.77), respectively. Following the application of proposed filters on the observed HPM data, the remaining data were used to calibrate the separation model parameters, this is the same procedure done by Tavares et al. (2022).

2.2 Data gap filling

Data gaps in time series are frequent as a consequence of equipment malfunction (e.g., datalogger failure, electrical supply shot-down) or maintenance works. Hence, gap filling methods are required. In this study the gap filling method follows previous work done by the authors, details can be found in Silva et al. (2020); Tavares et al. (2022). Thus, data gaps of one or 2 h are filled by linear interpolation from the non-missing values. For missing periods of more than 2 h in a day, a geographical interpolation is made. In this interpolation, the algorithm selects the four closest neighbouring stations of the station to which data gaps are being filled and determines the long-term linear regression coefficients (slope and interception) between this station and the neighbouring ones. With those long-term linear regressions, up to four data points can be determined for each data point missing. The final value that will fill the data gap will be the average value of those four values. For example, for a missing GHI value in one station, the GHIs from the other four stations allow the determination of four GHI values for that station, through the long-term linear regression, which are averaged to estimate a value for the missing GHI. Differently to what was done in Silva et al. (2020); Tavares et al. (2022), after the geographical interpolation a new linear interpolation for data gaps of one or 2 h was performed. It should be said that interpolation of wind data was accomplished by the projection of wind speed and direction into its x and y components.

2.3 Typical meteorological year

Similarly to what was done in Tavares et al. (2022) the method developed in Hall et al. (1978) is followed. It estimates TMY by

concatenating twelve typical meteorological months (TMM) from the complete time-series comprising 23 years of data. The determination of the TMM, from each calendar month, is accomplished by the use of Finkelstein-Schafer (FS) daily values (Finkelstein and Schafer, 1971). These coefficients compare cumulative frequency distribution functions (CDFs) of different meteorological parameters: mean, maximum and minimum daily value of air temperature, mean daily relative humidity, maximum and mean daily values of the wind speed, and daily global horizontal solar irradiation availability; for every month of every year to their long-term distribution. Comprehensive details for this method can be found in chapter two of Kalogirou (2014) and in Abreu (2016); Abreu et al. (2018).

2.4 Separation model

To simulate the DHI and DNI data a separation model is used, where the DHI is estimated from GHI, and these two parameters are used to assess DNI. According to the recent work (Yang, 2022), a considerable amount of separation models exists in the literature that can be used for that purpose. Out of these, the model by Abreu et al. (2019) is highlighted by the fact that it only uses one parameter, the clearness index - k_t , to estimate the diffuse fraction:

$$K_d = DHI/GHI. \quad (1)$$

This is a considerable improvement in relation with other models that include more parameters like Engerer2 (Engerer, 2015) and Yang4 (Yang, 2022). Because it simplifies the procedure to obtain K_d while retaining good accuracy in the determined DHI and DNI (Yang, 2022). Considering that the main objective of this study is to estimate the potential production of hydrogen and not a detailed mapping of solar irradiance, the choice of Abreu's model (Abreu et al., 2019) is completely justified.

Moreover, Abreu's model was originally developed for 1-min solar irradiation data but in our case is applied to 1-h data. This is feasible due to the averaging procedure acting as a low-pass filter. Therefore, if the model demonstrates proficiency with 1-min data, as demonstrated in (Yang, 2022), it is expected to perform even better with 1-h data. This is due to noise reduction resulting from the averaging process. Below, it will be discussed the accuracy of the modelled DNI for the HPM reference station in Évora.

According to Abreu's model (Abreu et al., 2019) the diffuse fraction is defined as:

$$K_d = \left\{ 1 + \left[A \times (k_t - 0.5)^2 + B \times (k_t - 0.5) + 1 \right]^{-n} \right\}^{-\frac{1}{n}}. \quad (2)$$

In which, the clearness index is defined by:

$$k_t = \frac{GHI}{GHI_{toa}}, \quad (3)$$

and

$$GHI_{toa} = DNI_{toa} \cos Z. \quad (4)$$

In Eq. 2 A , B and n are constants that can be calibrated for a specific region if GHI and DHI measurements are available. Additionally, DNI can be estimated from the clearness index and the diffuse fraction using the closure equation:

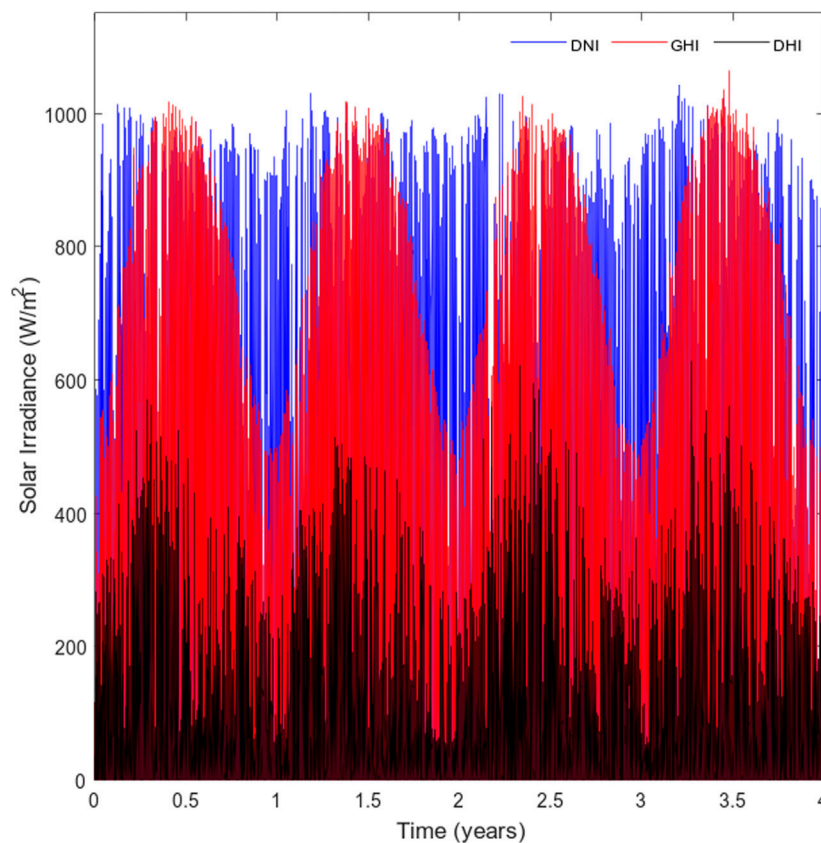


FIGURE 1 Hourly radiation data: DNI, GHI, and DHI (W/m^2); used to calibrate de separation model. It was measured in Évora and comprises the years 2016–2019.

$$k_b = k_t (1 - K_d), \tag{5}$$

and

$$DNI = DNI_{tot} k_b. \tag{6}$$

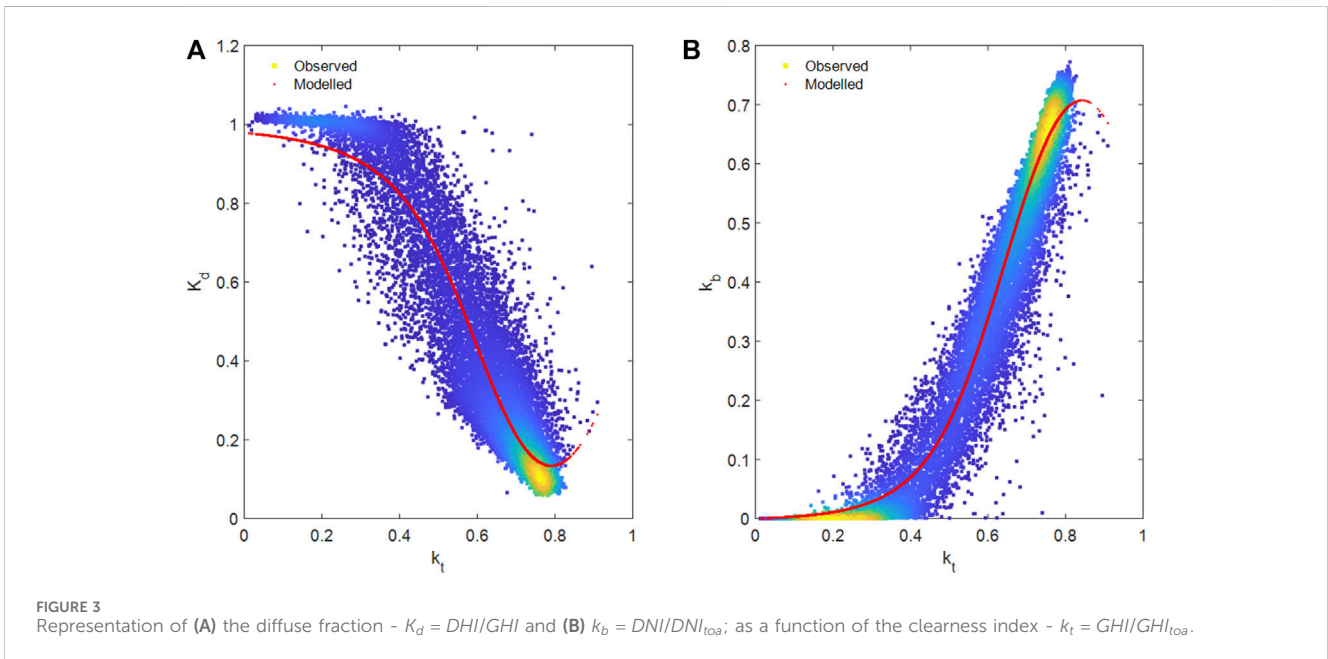
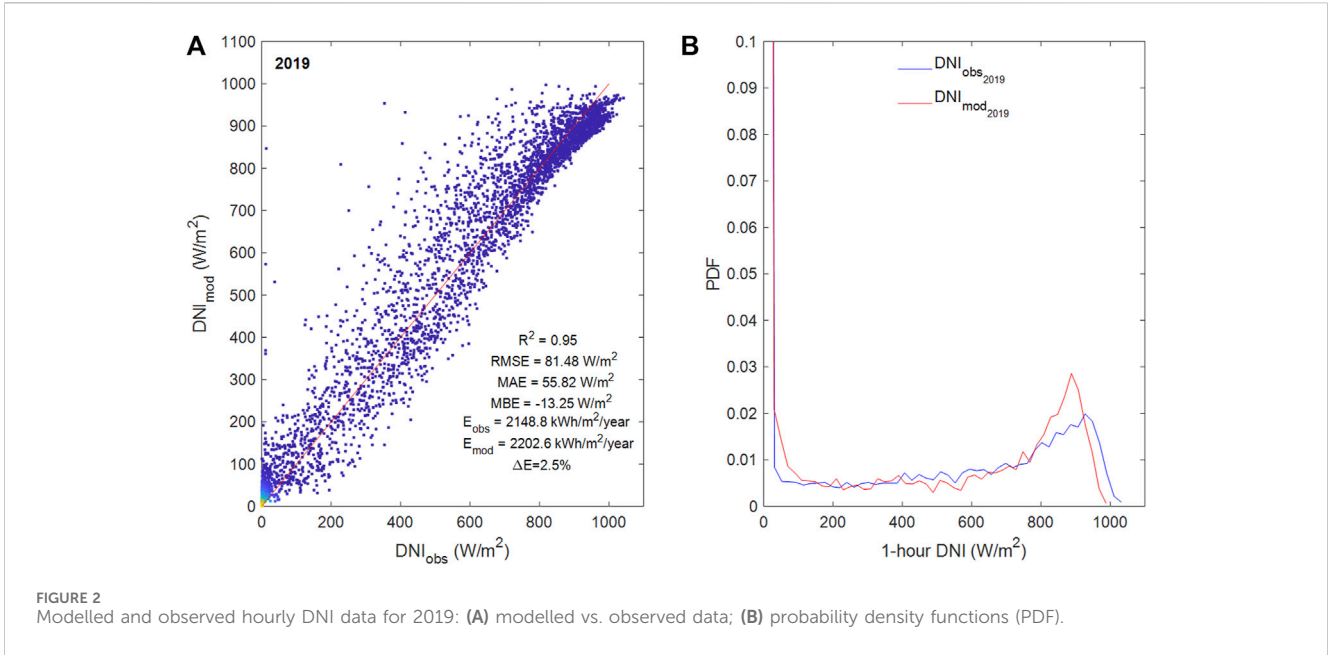
With this set of equations (Eqs 1–11), it is possible to estimate both DHI and DNI from GHI. Furthermore, 4 years of solar irradiation, from 2016 to 2019, recorded at the HPM, are used to validate and calibrate the separation model. In Figure 1 DNI, GHI and DHI measurements at this station are presented.

A validation of the separation model is performed by adjusting the model parameters to the HPM data of 2016, 2017 and 2018, and use GHI from 2019 to model DNI. The modelled DNI is then compared with the measured DNI for 2019. In Figure 2A the modelled DNI and the observed DNI are represented against each other, showing good agreement between both. As a matter of fact, the linear regression shows a R^2 -coefficient of 0.95, which confirms such agreement. Moreover, the root mean square error (RMSE) is equal to $81 W/m^2$, the mean bias error (MBE) is equal to $56 W/m^2$, and the mean absolute error (MAE) equal to $-13 W/m^2$, which are all small values. Comparing the modelled and observed DNI annual availabilities, $E_{b,mod} = 2,202 kWh/m^2/year$, and $E_{b,obs} = 2,149 kWh/m^2/year$, respectively, it is found that they differ of only 2.5%. In Figure 2B is represented the

probability density function (PDF) of modelled and observed DNI. It shows good agreement between modelled and observed DNI for values between 100 and $800 W/m^2$. While the PDF for the modelled data has a higher peak than the one for observed data and at a lower DNI value. The peak for the modelled data occurs roughly at $880 W/m^2$, while for the observed data it happens approximately at $920 W/m^2$. The higher peak for modelled data means that the modelled DNI tends to have more values between 800 and $880 W/m^2$ than the observed ones. This explains why the modelled data tends to overestimate DNI annual availabilities as seen before. Similar conclusions might be drawn when comparing modelled and measured DHI. The good agreement between modelled and observed DNI validates the use of Abreu’s model and justifies its use in the present analysis.

To calibrate the model, the 4 years (2016–2019) of common GHI, DHI and DNI data of the HPM reference station are used, Figure 1. The observed K_d is represented as a function of k_t and the parameters of Eq. 2 are adjusted by a least-square fit of the modelled K_d to the observed one. The parameters obtained are: $A = 10.1437$, $B = -5.9233$ and $n = 1.7264$, and the R^2 is equal to 0.92. For the sake of comparison in Figure 3 the modelled and observed K_d (Figure 3A) and k_b (Figure 3B) are represented as a function k_t .

Finally, the calibrated parameters are used to estimate DHI and DNI from the GHI in the TMY, these are then used to simulate the power production as described below.



It should be said that the methodology developed in this section has two limitations: only 4 years of data were used for the model calibration, and the calibration parameters are assumed to be valid for the entire country. Both limitations should not impact in the results found for hydrogen production. On the one hand, the interannual variability of solar radiation is low in Portugal (Silva et al., 2020; Tavares et al., 2024). Therefore, the inclusion of more years of data should not change considerably the model calibration. On the other hand, Portugal is a small country having a similar climate throughout its mainland region. Thus, it is not expected that the calibration parameters should vary significantly over it.

2.5 Power plant model

To simulate the electricity production of the selected power plant it is used SAM software (SAM, 2024). This is a freely available financial and performance model designed to facilitate decision making in renewable energy system projects (Blair et al., 2014). The simulated PV power plant is a fixed module with a nominal capacity of 120 MWp. The PVWatts (no financial model) option was selected. The simulation details are listed below:

1. Nominal power: 120 MWdc;
2. Module type: standard;

3. DC to AC ration: 1.2;
4. Rated inverter size: 100 MWac;
5. Inverter efficiency: 96%;
6. Array type: fixed open rack;
7. Tilt angle: optimum tilt angle is determined by equation 22.48 of (Lorenzo, 2011) for each latitude (L) - $\beta_{opt} = 3.7 + 0.69 L$;
8. Azimuth: 180;
9. Ground coverage ratio: 0.3;
10. System loss: soiling - 2%; shading - 1%; mismatch - 2%; connections - 0.5%; light-induced degradation 1.5%; nameplate - 1%; age: 1%; availability - 3%; total system losses - 13.18%.

The TMY for each station is fed into the simulator and hourly electricity production values from the photovoltaic power plants are achieved. The following parameters are recorded and passed to the electrolyser model: AC inverter output power; DC inverter input power; system power generated; ambient temperature; DNI; DHI; GHI.

It is worth mentioning that SAM software is one of the most widely used simulation tool for PV applications. Additionally, it was shown to have a very low average deviation from real measurements of only 0.75%, according to Umar et al. (2018).

2.6 Electrolyser techno-economic model

To simulate the hydrogen production, the electrolysis script is executed using the electricity production data as input from all the locations. The used electrolyser is based on Proton Exchange Membrane (PEM) technology. This decision is grounded on numerous advantageous attributes of this technology. These include durability, high efficiency, and, most notably, its compatibility with electricity fluctuations from intermittent sources. As this is the case for PV plants (Touili et al., 2018). The calculation of hydrogen production is performed using the following formula (Touili et al., 2022):

$$M_{H_2} = \frac{E \times \eta_{ele}}{HHV_{H_2}}, \quad (7)$$

here E represents the annual DC electricity production from the PV plant in (kWh), η_{ele} is the electrolyser efficiency considered as 75%, while HHV_{H_2} is the hydrogen higher heating value (39.4 kWh/kg). It is worth to mention that the assumptions used to calculate hydrogen production take into consideration the electrolyser overall energy requirement, including the system losses (Touili et al., 2020).

On completion of the calculation of the hydrogen production, the economic analysis can be performed. One of the most used metrics for similar studies is the LCOH₂ production. The LCOH₂ accounts for the project expenses through its lifetime as well as its technical aspects. This allows a fair assessment and comparison of the economic viability of hydrogen production projects between different technologies and locations. The LCOH₂ is expressed as follows (Amrani et al., 2024):

$$LCOH_2 = \frac{\sum_{i=0}^N [(C_{PV} + C_{elec})(1+T)^{-i}]}{\sum_{i=0}^N [M_{H_2,i}(1+T)^{-i}]} \quad (8)$$

In which N and T represents the project lifetime and discount rate taken as 20 years and 6%, respectively. Whereas $M_{H_2,i}$ is the annual hydrogen production in the year i discounted through the project lifetime. No degradation in the production is included in the model because a replacement of the electrolyser is accounted for (see below).

The investment cost associated with the electrolyser C_{elec} is expressed as follows:

$$C_{elec} = C_{el} + C_{O\&M} + C_{rep}. \quad (9)$$

The electrolyser capital cost C_{el} is directly proportional to the electrolyser size and it is calculated with equation:

$$C_{el} = C_{el,u} \times \left(\frac{M_{H_2} K_{el,th}}{8760 \eta_{ele}} \right). \quad (10)$$

In this equation $C_{el,u}$ represents the electrolyser unit price taken as 368 \$/kW, and $K_{el,th}$ accounts for the electrolyser theoretical energy requirements, which is 52.5 kWh per 1 kg of hydrogen produced (Valeria et al., 2022; Achour et al., 2023). The replacement cost (C_{rep}) is taken in consideration since the electrolyser lifetime is 7 years. Such replacement is estimated as 25% of the capital cost. While the operation and maintenance costs ($C_{O\&M}$) are taken as 2% of the installed capacity (Amrani et al., 2023).

Regarding the investment cost of the PV plant (C_{PV}), it is calculated with the following formula:

$$C_{PV} = C_{panels} + C_{BOS} + C_{O\&M}. \quad (11)$$

Here C_{panels} accounts for the PV panels cost considered as 0.84 \$/Wp (Allouhi, 2020). While C_{BOS} and $C_{O\&M}$ represent the costs associated with the PV plant installation, and operation and maintenance, respectively. These are taken as 50% and 5% of the total cost of the installed PV capacity (Amrani et al., 2023).

3 Results

3.1 Typical meteorological years

Following the procedure explained in Section 2.3, TMY are determined for each station considered in this study. After that, the calibrated Abreu's model, Section 2.4, is used to estimate DHI and DNI from GHI data in the TMY. Irradiance values below a solar zenith angle of 85° were considered in this analysis, despite their small contribution to electricity production. Such values were obtained by interpolation between the last point before sunrise and the first point with solar zenith angle above 85° in the morning, and the last value with solar zenith angle above 85° and the first value after sunset in the evening. With this procedure it is guaranteed that there are no data gaps in the TMY file, which is a necessary condition to use these files in SAM. The final .csv files contained rows with the following data (in the same order as in the file): GHI, DNI, DHI, ambient temperature, relative humidity, and wind speed.

For the sake of clarity DNI, GHI and DHI from TMY of selected stations (Lisboa – LIS, Sines – SIN, Beja – BEJ and Pampilhosa da Serra – PAM) are represented in Figure 4. The three components of solar irradiance follow the expected patterns observed in Portugal, e.g., in the HPM station at Évora, Figure 1. Detailed discussion of

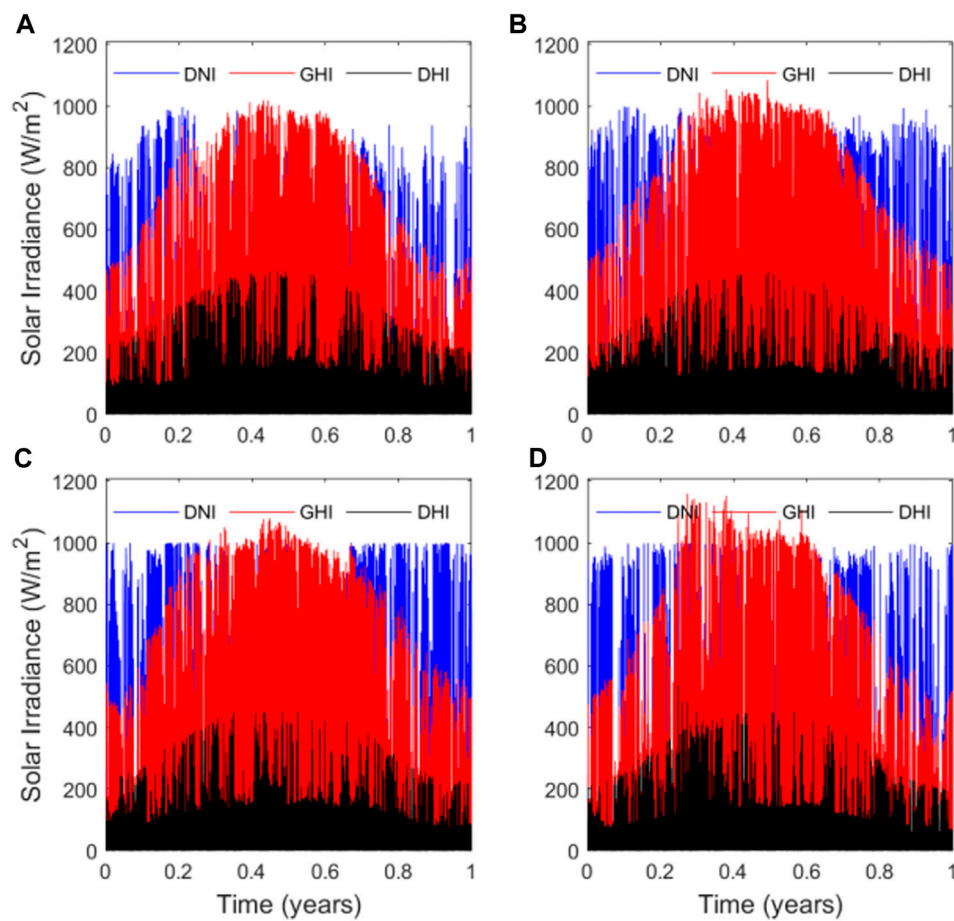


FIGURE 4
Hourly radiation data: DNI, GHI and DHI (W/m²) for the Typical Meteorological Year (TMY) on selected stations: (A) LIS; (B) SIN; (C) BEJ; (D) PAM; for sake of comparison.

similar data can be found in (Silva et al., 2020; Tavares et al., 2022). Moreover, GHI and DNI availability maps were already presented in those works and for that reason these will not be represented here.

3.2 PV plant simulation

The TMY files are now fed into the SAM photovoltaic power plant simulator described in Section 2.5. As it was done in the previous section the hourly PV production, inverter power: DC input and AC output, for the four selected stations are represented in Figure 5. The data shows a reduction in production in the Winter months followed by maxima in Spring and Fall. A shallow reduction is observed in the Summer months, as a consequence of the high temperatures felt in that time of the year.

The important variable for hydrogen production is the DC input inverter power. Thus, annual electricity production values are presented in Supplementary Appendix Table SA1 of the appendix and represented in a map in Figure 6. It can be realised that there is a tendency for an increase in electricity production following the north-west to south-east direction, with higher values being found in the south (in the regions of Alentejo and Algarve)

and in the central-east area (in the region of Beira Interior). Making these regions attractive for PV investments in Portugal. As expected, this tendency for increase is similar to what was found in solar irradiance (Silva et al., 2020; Tavares et al., 2022) and CSP production (Tavares et al., 2022; Tavares et al., 2024).

Furthermore, as can be concluded from the analysis of Supplementary Appendix Table SA1 the highest values of annual electricity production are found in Sagres (south-west) and Faro (south-east). In these locations the production is as high as 230 GWh and 224 GWh per year, respectively. These correspond to capacity factors of 21.9% and 21.3%, which are very attractive figures.

3.3 Hydrogen production

Additionally, electricity production is used to estimate hydrogen production following the procedure described in Section 2.6. Similarly to what was done in previous sections, the hourly hydrogen production is represented for the four selected stations in Figure 7. As presumed, the hydrogen production follows the same tendency of the DC input inverter power, since the electrolyser model is linear.

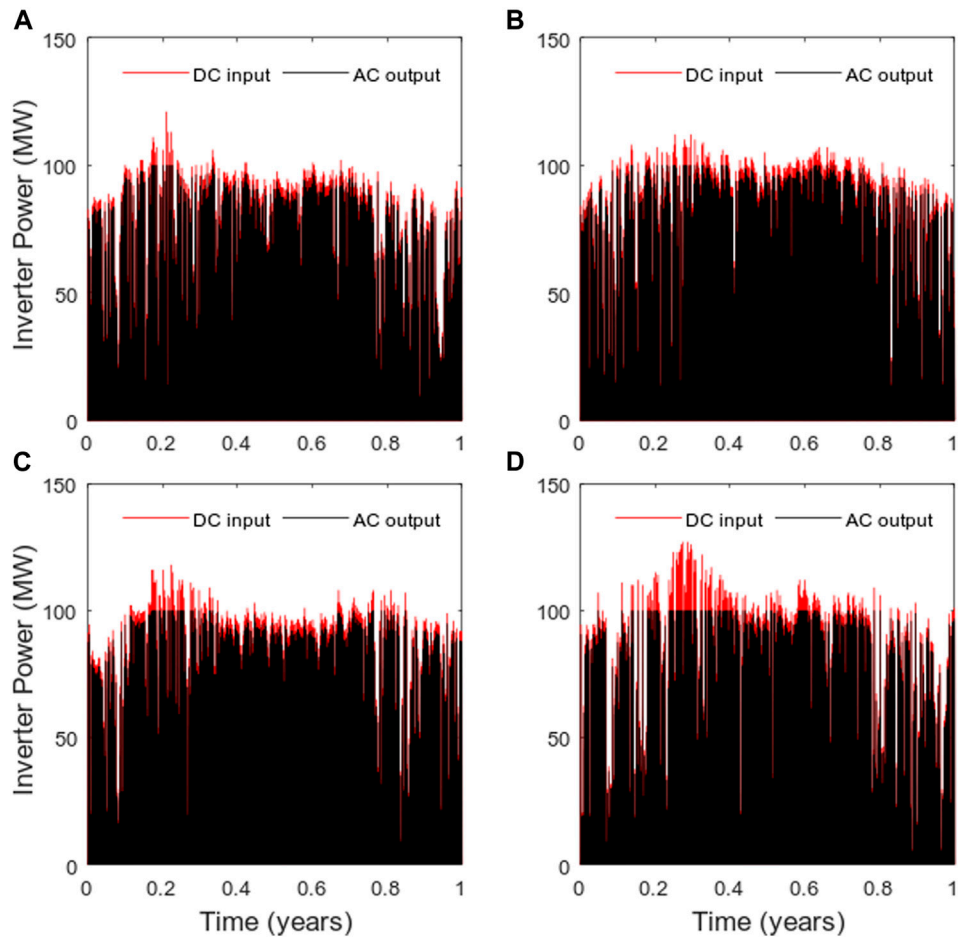


FIGURE 5
Hourly inverter power: DC input (in red) and AC output (in green) on selected stations: (A) LIS; (B) SIN; (C) BEJ; (D) PAM; for sake of comparison.

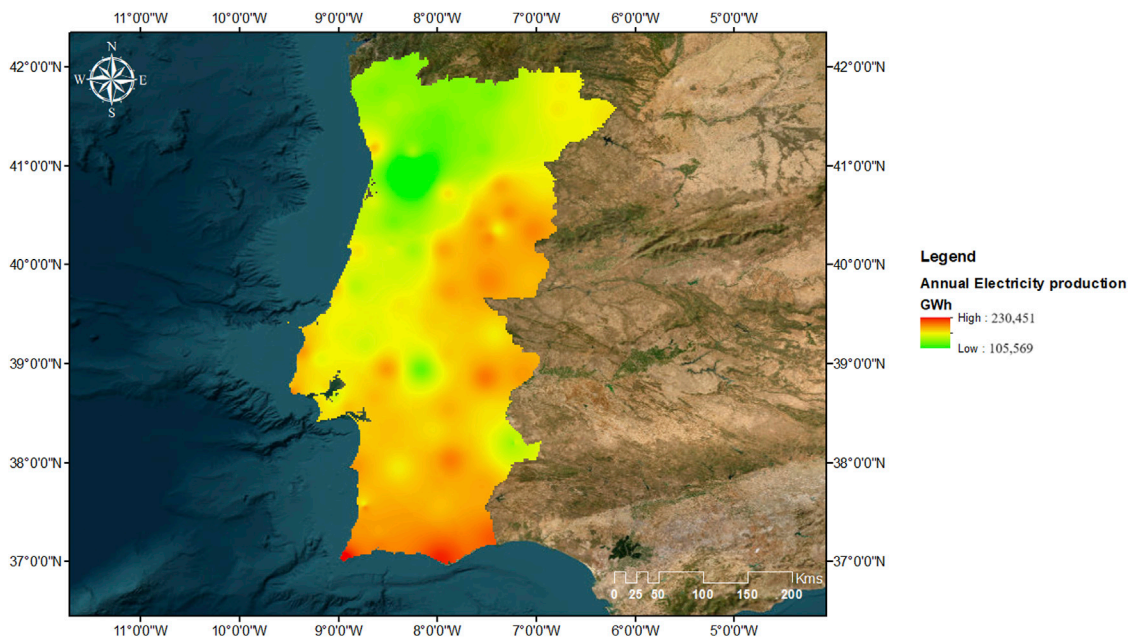
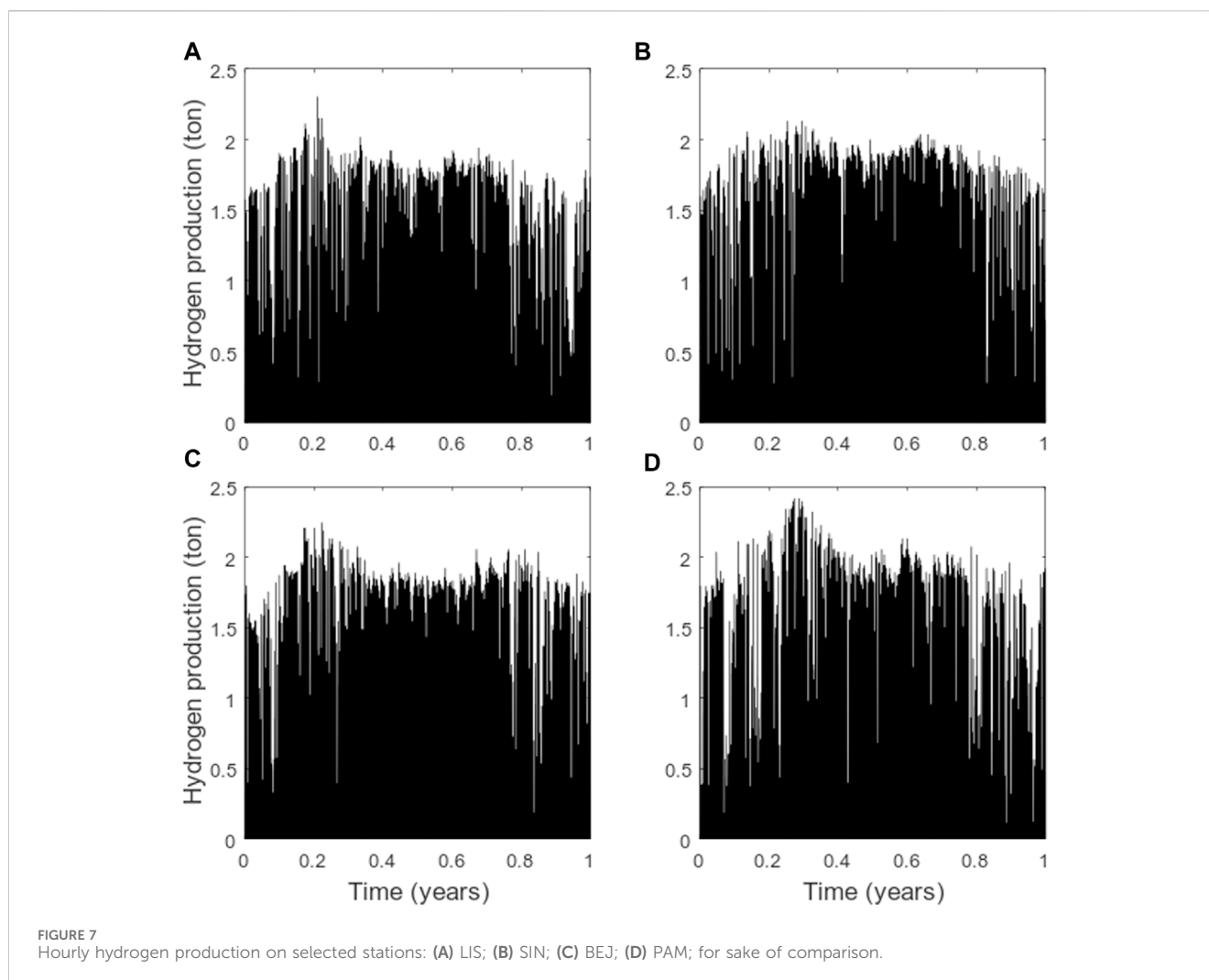


FIGURE 6
Annual electricity production (GWh) map for continental Portugal simulated from the IPMA's ground stations TMY using System Advisor Model (SAM).



Interestingly, in the annual hydrogen production map, [Figure 8](#), it is evident the north-west to south-east direction of production increase. It is further highlighted that the higher values of production are found for the same regions as electricity production: the south (in the regions of Alentejo and Algarve) and the central-east area (in the region of Beira Interior) of the country. This means that these regions have the potential for the lowest values of LCOH_2 , as will be discussed in the next section.

In fact, [Supplementary Appendix Table SA1](#) shows again that the highest values of annual hydrogen production are found in Sagres (south-west) and Faro (south-east) with values as high as 4 387 tons and 4,265 tons per year, which reveal to be very attractive figures.

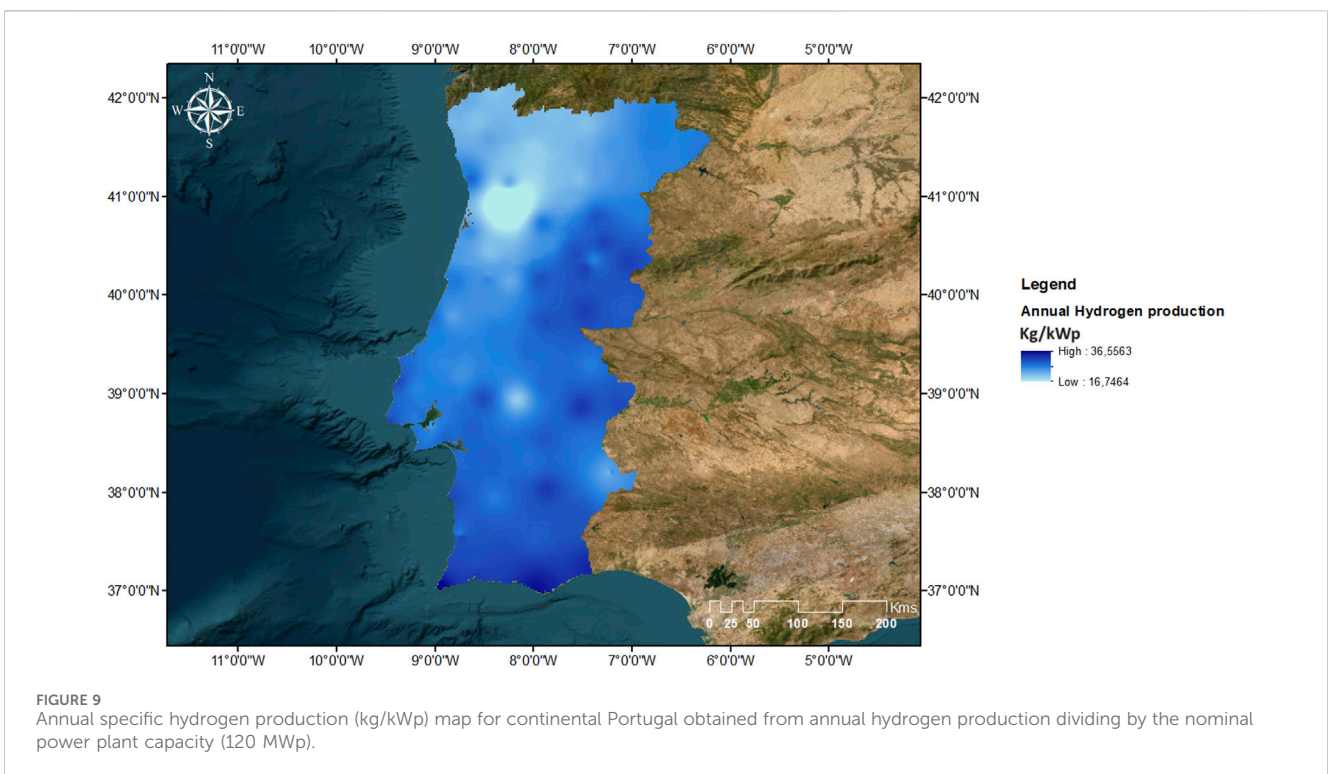
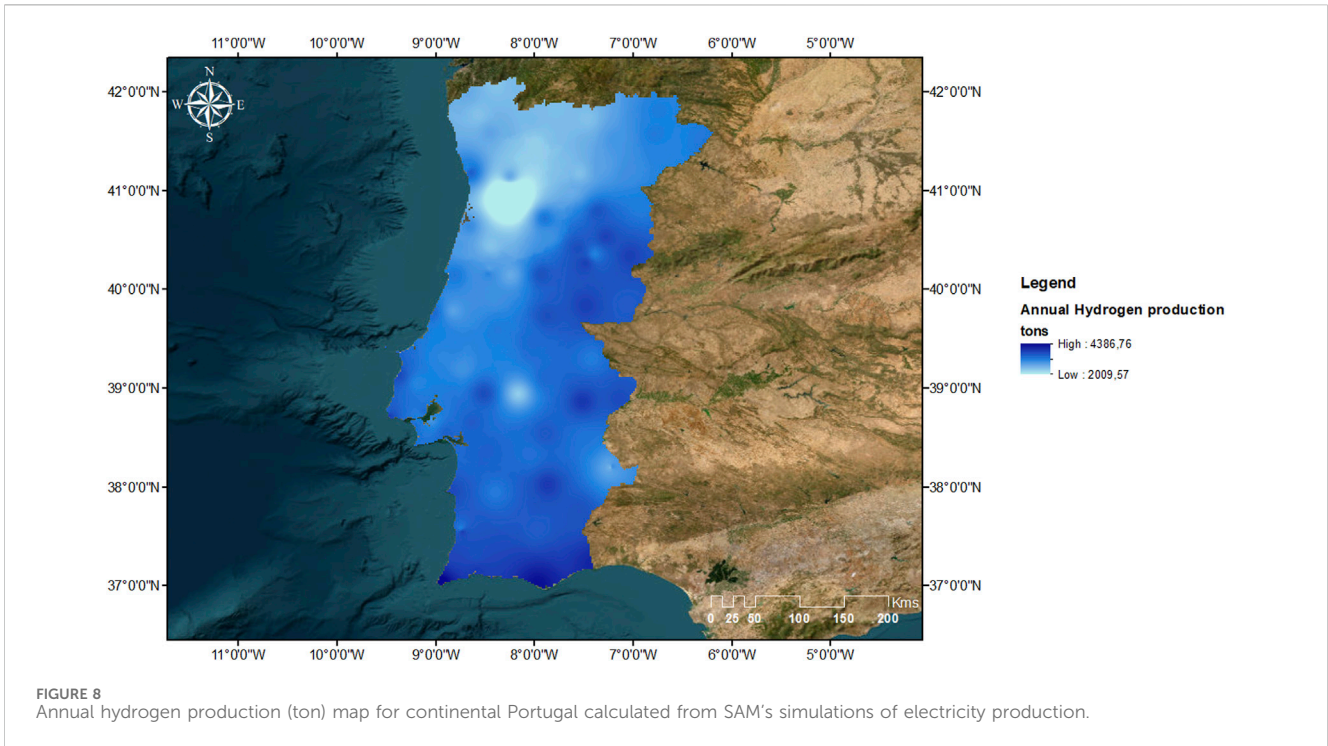
4 Discussion

To further extract information from these results the techno-economic analysis is here discussed.

First, to extract information independent of the PV power plant capacity, the annual hydrogen production values found in this study are divided by the nominal capacity of the simulated power plant to

determine the annual specific hydrogen production. It is defined as the annual mass of hydrogen produced per installed nominal power. This estimation gives the interested reader reliable figures for future investments in Portugal. They are presented in [Tabel 1](#) of the appendix for each station considered in this study and are mapped in [Figure 9](#). As it would be expected there is again an increase in the annual specific hydrogen production in the north-west to south-east direction following the same trend as both electricity and hydrogen production. The regions with the higher annual specific hydrogen production are, as expected, the south (in the regions of Alentejo and Algarve) and the central-east area (in the region of Beira Interior) of Portugal. These regions show benchmark values of annual specific hydrogen production above 30 kg/kWp per year. In fact, Sagres (south-west) and Faro (south-east), have the higher annual specific productions of 36.56 kg/kWp and 35.54 kg/kWp, respectively.

Second, a map of the LCOH_2 for Portugal is presented in [Figure 10](#) and the values related to each location are presented in [Supplementary Appendix Table SA1](#) of the appendix. As it can be noticed there is a north-west to south-east trend for LCOH_2 reduction. Some locations in Portugal, especially, the regions of Alentejo and Algarve and the Beira Interior, have the potential to



produce hydrogen with $LCOH_2$ below 4.0 €/kg. This is very interesting as these locations are considered as highly suitable for implementing solar-driven hydrogen production units. As a matter of fact, Sagres (south-west) and Faro (south-east), have the lower $LCOH_2$ of 3.476 €/kg and 3.562 €/kg, respectively.

To better evaluate the position of the Portugal on the “green” hydrogen market, a benchmark of the $LCOH_2$ has been made with

reference countries in the world, see Figure 11. In the plot the lowest $LCOH_2$ values found for each country are represented. As illustrated, Portugal has the potential to become a key player in solar hydrogen production, as the €/kg is the lowest in Europe. Moreover, it is very close to the prices determined for the northern African countries. The comparison is made with the following countries: Nederland (Roest et al., 2020), Spain (Matute et al.,

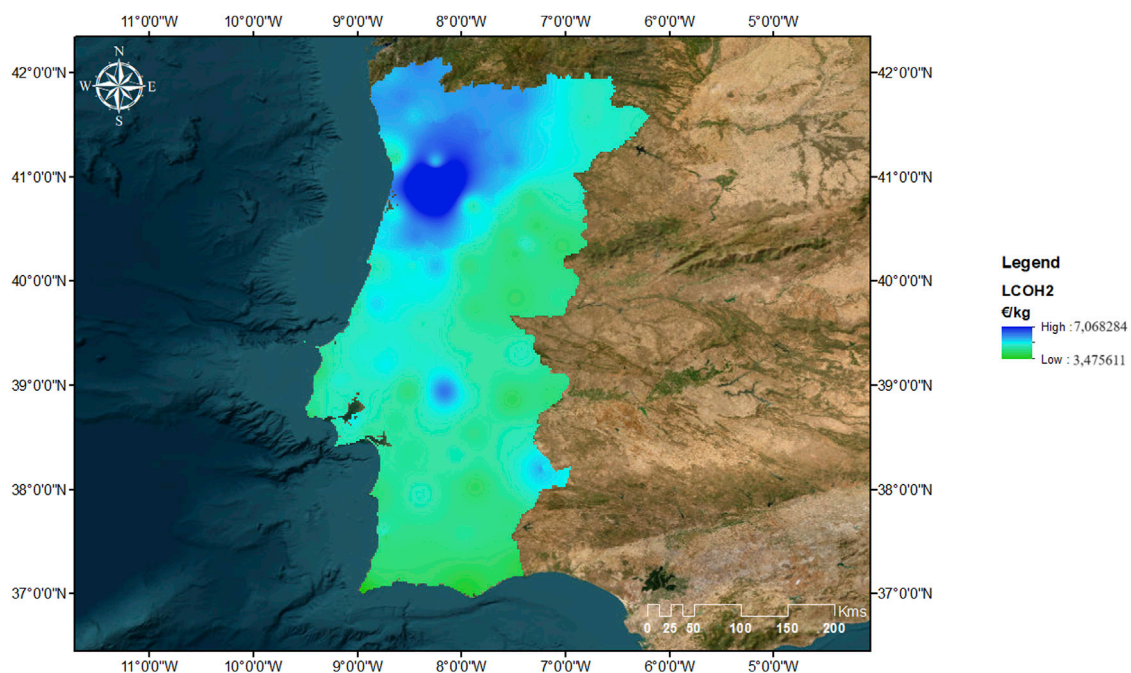


FIGURE 10 Levelized Cost of Hydrogen (LCOH₂) map continental Portugal obtained from techno-economic analysis of hydrogen production. *Conversion between dollars and euros updated on 30 of November 2023.

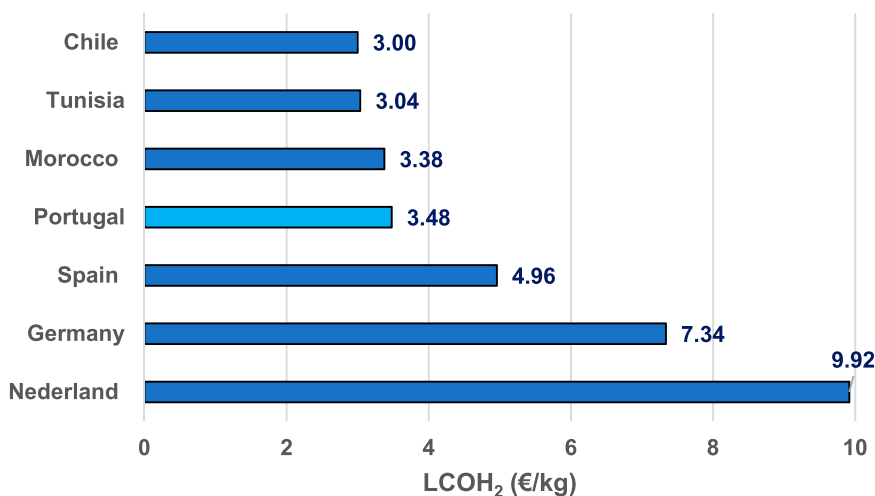


FIGURE 11 Benchmark of Levelized Cost of Hydrogen (LCOH₂) in Portugal compared with reference countries in the world. The lowest LCOH₂ values found for each country are represented.

2022), Tunisia (Barhouni et al., 2022), Chile (Garcia and Oliva, 2023), Germany (George et al., 2022), and Morocco (Amrani et al., 2023).

Besides, it should be said that intensive research is going on related with the techno-economic analysis of production of hydrogen from renewable sources, mainly, solar and wind. For that reason, a substantial amount of works is being published in the literature recently on this subject. Among the most recent are (Al-Ghussain et al., 2024); that used PVGIS data to perform a

techno-economic analysis of production of hydrogen in California (USA) (Fabianek and Madlener, 2024); that used reanalysis data to compare the “green” hydrogen capabilities in two different sites, one in California and other in Northern Germany (Mansir et al., 2024); that used meteorological data from NASA database to do a techno-economic analysis of photovoltaic and wind energy based hydrogen production for three cities in Saudi Arabia (Baghel et al., 2024); that performed the analysis for five different locations using meteorological data in India (Hussam et al., 2024); that used

meteorological data from NASA database to perform a techno-economic analysis of “green” hydrogen production in a single location in Kuwait.

These studies highlight the uniqueness of the present study. This is because it reveals that most studies involving hydrogen production from renewable sources can be basically divided into two categories: mapping of hydrogen production using satellite and simulations derived data; using meteorological data to study only several case studies and do not perform the mapping. Nevertheless, the present work uses ground measured meteorological data from an extensive network, 89 stations, with nearly 23 years of 1-h records. What, in the one hand, allows for an accurate mapping of the hydrogen production from solar energy. And, in the other hand, brings value to the meteorological data.

Additionally, this work allows to draw some conclusions in terms of energy policy and decision making. As it was mentioned in the introduction the Portuguese National Strategy for Hydrogen (PNSH 2030, 2020) has set the goal of 15% of injection of “green” hydrogen into the natural gas grid until 2030. Considering the natural gas yearly consumption in Portugal and the differences in the heating values due to the blend, the amount of hydrogen required per year can be calculated. In fact, it can be found that it is required nearly 82,500 000 kg of hydrogen per year to fulfil the 15% objective. Thus, according to the findings of this study, such objective will require the installation of approximately 2.75 GWp in photovoltaic power plants in the best performing regions (Beira Interior, Alentejo and Algarve) that have a “green” hydrogen potential of production above 30 kg/kWp. Moreover, according to the Portuguese General Directorate of Energy and Geology (in Portuguese “Direção Geral de Energia e Geologia”) in 2023 there were 3.9 GWp of photovoltaic power installed (DGEG, 2024). This means that this capacity would have to increase in 70% only to satisfy the “green” hydrogen production needs until 2030. This is a relevant figure that policymakers should have to have in consideration while making strategic decisions in the national energy transition.

Furthermore, it should be added that while the results found in this study cannot be directly used to draw conclusions to other regions. This is because the results depend considerably on the regional meteorology. The methodology developed in this work can be easily replicated to other regions supporting decision making there.

To wrap up, this study assessed the techno-economic potential of PV hydrogen production for Portugal. As a result it publishes the atlas of the hydrogen potential in this country for the first time. This can be considered as a first phase of the project implementation, but, several challenges and deeper analysis should be considered for a better and optimal implementation of “green” hydrogen production units. First thing that must be assessed is the site selection where land occupation, slope and proximity to cities should be evaluated among other site selection criteria (Jbahi et al., 2021; Dehshiri and Firoozabadi, 2023). In addition to that and after selecting the best location for the hydrogen project implementation, a feasibility analysis should be conducted by evaluating the meteorological parameters influencing the operation of the PV modules, like soiling (Merrouni et al., 2017) and high temperature values (Merrouni et al., 2016a; Merrouni et al., 2016b; Perraki and Kounavis, 2016; Ammari et al., 2022). Finally, durability of the PV modules (Aghaei et al., 2022) and the electrolyser (Zhang et al., 2022; Norazahar et al., 2024) should be assessed to have a more

precise economical model. This would lead to a better project bankability and profitability (Mehdi et al., 2023).

5 Conclusion

The main conclusion of this study is that the south (in the regions of Alentejo and Algarve) and the central-east (in the region of Beira Interior) areas of Portugal have benchmark techno-economic values for “green” hydrogen production. In terms of mass of hydrogen produced per installed nominal power, these regions have annual values above 30 kg/kWp. In terms of levelized cost of hydrogen they have values below 4.0 €/kg. These values make these regions highly attractive for hosting large-scale photovoltaic hydrogen production plants and very competitive in the hydrogen market, especially with neighbouring countries like Morocco and Spain.

To accomplish the 15% of injection of “green” hydrogen into the natural gas grid until 2030 this work predicts the need to install approximately 2.75 GWp in photovoltaic power plants in the best performing regions just mentioned. This means that the installed photovoltaic capacity in Portugal would have to increase in 70% only to satisfy the “green” hydrogen production needs until 2030.

Future work would cross geographical information on road accesses, land availability (besides natural reserves and urban zones) and surface inclination, with the techno-economic results presented in this study to pin-point locations for “green” hydrogen production in Portugal.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HGS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Writing—original draft, Writing—review and editing. AA: Data curation, Formal Analysis, Investigation, Methodology, Validation, Writing—original draft, Writing—review and editing. ST: Formal Analysis, Investigation, Methodology, Writing—review and editing. JN: Data curation, Investigation, Resources, Writing—review and editing.

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superior upscaling/replicability". It has the reference: HORIZON-JTI-CLEANH2-2023-06-02; and Grant Agreement n. 101137611.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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