Optimal Sizing of Solar/Wind–to–Hydrogen Systems in a Suitable Site Selection Geospatial Framework

— The case of Italy and Portugal —

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November 2022

Abstract

The growing global deployment of renewables has triggered an energy transformation with profound geopolitical implications. As an energy carrier, hydrogen is at the heart of this transformation, enabling international trade and facilitating decarbonisation. This research project aims to find eligible locations to install renewable systems dedicated to producing green hydrogen. These locations are restricted to onshore and offshore regions of Italy and Portugal. Moreover, the research focuses on identifying the optimal configurations of such systems that minimise the cost of producing hydrogen. The multi–criteria geographical model is built through standard–level procedures, with data collected from several prominent sources, while the optimisation algorithm expands from the detailed computation of the classic levelised cost of hydrogen. Key findings of this study include the acknowledgement that although having only a small percentage of their territory available, both countries can easily satisfy their annual hydrogen needs. Furthermore, the optimal configurations obtained by the algorithm offer reductions in costs to the order of 70%, depending on location in the countries; this can translate to millions of euros in savings. Such findings represent unprecedented achievements for both Italy and Portugal, and can serve as an essential asset to economic analyses performed on this subject by municipalities and even the central governments. Additionally, these results validate the initial premise of the optimisation model, significantly improving the credibility of this study by constructively challenging the standard way of assessing large–scale green hydrogen projects.

Keywords: hydrogen, GIS, economical analysis, LCOH, optimisation

1. Introduction

The world is changing. The expanding deployment of renewables has put in motion a global energy revolution with profound geopolitical implications. The coming of a new energy age will transform relationships between nations and communities and create a new world of power security, energy independence and human prosperity. Unlike fossil fuels, whose reserves are concentrated in specific regions, renewable energy sources (RES) are available in every country. Renewable energy can be produced everywhere and thus has the potential to significantly change how energy is traded [1]. Nonetheless, in recent times, no sustainable and cost–effective way has been developed to transport renewable electricity over long distances. The use of green–hydrogen could be an answer. As an energy carrier, hydrogen enables renewable energy to be traded across regional and continental borders, also facilitating the decarbonisation of harder–to–abate sectors (like the steel and cement heavy industries). Hence, hydrogen has been recognised as a leading study subject, driven by unprecedented policy focus and put on the spotlight to investors and other market players [2].
Stemming from and subsequent of this recent surge in interest, academia has seen a growing body of research being published containing hydrogen–related keywords. This thesis intends to contribute to said groundwork by exploring the feasible linkages of hydrogen systems directly coupled to RES.

Hydrogen technologies have gone through many cycles of expectation over the last decades. Although the vast majority of hydrogen produced to date has come from steam methane reforming, the production through green electrolysis has grown exponentially—mostly driven by hydrogen road–maps enacted by governments around the globe [3]. Efforts exist to ramp the up–scaling of electrolysers for high–purity hydrogen production, supported by recommendations by the International Energy Agency (IEA); some suggest that it is not beneficial to connect all this capacity to the electric grid, which is facing enough of a challenge keeping up with the increase in demand for electrification [4]. A solution could come from systems with increasing shares of variable renewable energy sources, where low–cost surplus electricity may be available.

Even so, relying solely on occasional curtailed electricity to produce hydrogen implies electrolysers having very low utilisation factors (and, ultimately, very high unit costs). Hereupon emerges the relevant argument for extensive, dedicated hydrogen projects directly coupled to renewable energy sources. As will be seen, these systems can be located onshore or offshore, and have single or hybrid RES–to–Hydrogen configurations [5].

This thesis is then rooted on the central purpose of contributing to the study of these important matters, with an article to be published hereafter. More clearly, the two–part question to be answered in this thesis is: *Which locations are available to install renewable energy systems dedicated to the production of green hydrogen, and which configuration results in the lowest hydrogen production cost?*

To answer this question, a series of three objectives have been explicitly established, which constitute the set of expected deliverables of this work. The following list details said objectives, also disclosing the novel contributions associated with each one:

1) Create a map of the eligible locations on which to install renewable systems dedicated to the production of green hydrogen. These maps are restricted to Italy and Portugal, and represent an unprecedented achievement for these two countries.

2) Obtain a ratio of the RES installed capacity to the electrolyser's nominal power, to apply on these extensive, country–wide systems. This innovative method may be used by the academia in subsequent research papers published on this topic, as a means to make estimations that better resemble reality.

3) Develop an algorithm to compute the optimal size of pairs of renewable energy systems and electrolysers, in specific locations, considering single offshore and hybrid onshore configurations. A model with such characteristics has not been found in the literature.

Aside from these novel contributions, in the preparatory work for this thesis, two articles were published in scientific journals: *Recent Developments on Hydrogen Production Technologies: State–of–the–Art Review with a Focus on Green–Electrolysis* in MDPI's Applied Sciences, and *A Review of the Impact of Hydrogen Integration in Natural Gas Distribution Networks and Electric Smart Grids* in MDPI's Energies.

The remainder of this document is structured as follows: Section 2 clarifies the underlying concepts of the theoretical framework in study; Section 3 introduces the methods of investigation, elaborating on the different stages of designing the geographical model. The methodology extends to Section 4, where the numerical formulation of the economic models is described in detail. The discussion of results takes place in Section 5, and Section 6 provides the overall findings of this work, with its achievements and recommendations for future work.

2. Theoretical Framework

Standalone projects designed to produce green hydrogen always comprise two distinct systems. First, a RES system generates renewable electricity through green technologies; the two considered in this work are solar photovoltaic parks and onshore/offshore wind farms. Then, a hydrogen system converts this green electricity into gaseous hydrogen. The conversion is achieved by an electrolyser, that can be of different types; in this case, proton exchange membranes.

The competitiveness of renewable energy sources has improved greatly in the last decade, as shown by data from the International Renewable Energy Agency (IRENA) Cost Database. Between 2010 and 2021, reports indicate a decline of 88% in the cost of renewable electricity from utility–scale solar projects, 68% from onshore wind and 60% from offshore wind [6]. These costs are usually divided into capital expenses (CapEx) happening at the beginning of the project, and operational expenses (OpEx) taking place during its lifetime. In this work, CapEx includes hardware installation costs, balance of system (BOS) costs and soft financing costs, while OpEx includes fixed and variable operation costs and costs associated with maintenance and services. This distribution follows the suggestions of IRENA and the US Department of Energy's National Renewable Energy Laboratory [7].

Figure 1 presents a summary of up–to–date capital and operational expenditures for each of the four technologies in study, based on the most recent reports on the subject [7].

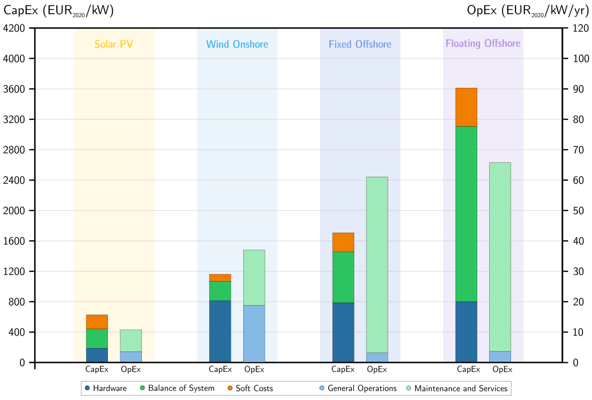

Figure 1: Cost analysis: overview of RES capital and operational expenditures.

The hydrogen feedstock industry is well established nowadays, having decades of experience in distinct sectors, from the production of ammonia to iron, steel, glass and electronics. Yet, the market is set to continue growing significantly in the coming years [8]. The large majority of hydrogen today is produced based on fossil–fuels, whether coal or gas. While efforts have been made to produce 'blue' hydrogen with carbon capture and storage (CCS) techniques, the hydrogen industry is still mostly polluting. However, the use of water electrolysis to produce 'green' hydrogen has been on the rise lately, with most of the research nowadays focusing on developing and improving electrolysis techniques. This production process is the one with the least life–cycle carbon intensity (measured in kilograms of carbon dioxide equivalent per kilogram of hydrogen), thus being the most sustainably alluring.

The first proton–exchange membrane electrolysers (PEMEl) were developed and commercialised in the 1960s, almost 200 years after the first alkaline electrolysers (AlkEl) [9]. PEMEls introduced some fundamental changes to overcome the drawbacks of AlkEls, offering a simpler and more compact system design and leading to fewer costs and maintenance [10]. PEM electrolysers use a solid polysulfated membrane as the electrolyte, working like a proton conductor through which the hydrogen atoms move during electrolysis. These membranes can operate at high differential pressures and ambient temperatures, enabling the production of highly pure hydrogen with low environmental impact. Other promising advantages include high net production rates, sizeable operating load ranges and fast response times—making this technology ideal to couple directly with renewable energy sources and produce green hydrogen in a flexible way. Table 1 presents a summary of the aforementioned features.

Table 1: PEM electrolyser: summary of features

PEMEl Features	2020	2050	Ref
Operational parameters			
Temperature (°C)	20–100	80	[9]
Pressure (bar)	30–80	>70	[4]
Nominal attributes			
Production rate (Nm^3/h)	$\approx$ 5000	$\approx$ 5000	[11]
Load range (%rnl)	0–160	5–300	[4]
System characteristics			
Consumption (kWh/m^3)	$\approx$ 4.60	<4.04	[11]
Efficiency (%LHV)	56–60	>80	[4]
Stack Lifetime (kh)	30–90	100–150	[4]
Cold start (min)	<20	<5	[10]

Note: features whose predictions for 2050 are not found in the literature remain the same as 2020. Nevertheless, improvement in the coming decades is always expected. rnl = relative to nominal load; LHV = lower heating value; kh = thousands of hours.

PEMEl costs have fallen over time, following progressive learning rates. Concerning this topic, numerous recent articles and reports [12] have published different values based on different assumptions. A meticulous reasoning is performed upon consulting the literature to ensure the credibility and validity of results. Data is first gathered from IRENA [10] to draw a detailed cost breakdown of a 1 MW PEM electrolyser (assumed to be the same for larger stacks). Further research from issued papers and technical reports put current PEMEl capital expenditures at 1136 EUR$_{2021}$/kW and operational expenditures at 38 EUR$_{2021}$/kW/yr. Here, OpEx is mainly defined by fixed and variable water consumption costs. These typically vary across the country's regions since each administrative division refers to its own water company; for the sake of generality, an average value is used from the Italian company ABC, following the procedure of M. Minutillo et al. [13].

After establishing the electrolyser technology for the methodological analysis, the geographical model design is presented in the next section.

3. Geographical Model Design

This section describes the distinct stages of material work undertaken to design and develop the geographical model. Subsection 3.1 presents the main characteristics of both study areas and Section 3.2 explains the data collecting and handling. Sections 3.3 and 3.4 present the diverse set of criteria used for the exclusion and evaluation phases, respectively; lastly, Section 3.5 discusses the final eligible locations.

3.1. Study Area

This work focuses on two similar but different countries located in Europe, to enable a comparative analysis of the potential for hydrogen production. The following is a brief description of the physical characteristics of Italy and Portugal.

The Republic of Italy is a country located in the Southern part of Europe between latitudes 35°–47° N and longitudes 6°–19° E. To the North, Italy borders France, Switzerland, Austria, and Slovenia and is delimited by the Alpine watershed; to the South, it consists of the entirety of the Italian Peninsula and the two Mediterranean islands of Sicily and Sardegna, in addition to many smaller islands. The country has a total inland area of 301,230 square kilometres, comprising 21 regions grouped into five major territories, and an exclusive economic zone (EEZ) of 541 915 square kilometres that extends 200 nautical miles ($\sim$370 km) from its shores within the Ligurian and Tyrrhenian seas to the west, the Ionian Sea to the South and the Adriatic Sea to the east.

The Portuguese Republic is a country whose mainland is located on the Iberian Peninsula of Southwestern Europe, between latitudes 36°–42° N and longitudes 9°–6° W. It is bordered to the West and South by the Atlantic Ocean and to the North and East by Spain; its territory also includes the Atlantic archipelagos of the Azores and Madeira, which form two autonomous regions with their regional governments—they are left out of this analysis for this particular reason and the fact that thousands of kilometres separate them from the continent (making it extremely difficult to visualize the results clearly). The country occupies a total inland area of 92 090 km^2, divided into 18 districts, and a North–Atlantic EEZ of 327 667 km^2.

3.2. Data Collection and Handling

A geographical framework begins with establishing its coordinate reference system (CRS). This process is required to avoid angular, length or area distortions on the imported data, enabling precise algebraic computation of acceptable regions and the creation of buffer zones. The native geographic coordinate reference system of QGIS is the World Geodetic System 1984 (commonly referred to as WGS 84). Upon projection to the Universal Transverse Mercator (UTM) CRS, latitudes, longitudes and degrees are respectively converted to northing values, easting values, and distances. Since map projections never represent the sphericity of the Earth exactly, the appropriate UTM zone should be used as CRS for each area of interest to minimize distortion and get correct analysis results. In this case, Italy employs the projected CRS of UTM zone 32N, while Portugal's is UTM zone 29N.

The proper land–eligibility operation starts with setting the working resolution. Both countries have thousands of square kilometres in area, whilst some polygons of the datasets have just a few square meters; so, even with the data divided into regions, this would mean evaluating several million points each time an operation is made—resulting in extra hours of wasted time. For simplicity's sake, yet without compromising the good accuracy of results, a general resolution was defined as 1 km^2. All the steps described below are performed in a batch sequence for every dataset. In general, the first procedure is to add geometry attributes to each layer (area and perimeter of the polygons or length of the lines); then, a minimum threshold is applied, the values below which are selected and deleted—in this case, an area smaller than 1 km^2 or a length less than 1 km. This process eliminates several tiny polygons and lines that would otherwise be requesting computing power unnecessarily, considering they are smaller than the set resolution. Secondly, most holes left within the layers are erased after applying the same area limit. Finally, a merge and dissolve processing tool is used to aggregate all layers that overlap but are not unified. It is often needed to correct geometries before applying further processing, and create spatial indexes that increase the performance of the operations.

3.3. Data Exclusion

The second stage of the methodology consists of the actual exclusion of unsuitable sites for the installation of RES. This operation starts with setting a buffer over the constraints previously categorized into four main restriction criteria—environmental, legislative, safety and technical—following the distribution established in literature [14].

Any environmental criterion is generally characterised by zones of recognised ecological value and beauty, where the viability and conservation of biodiversity are ensured through legislation. These include forests, parks and beaches, natural or artificial large lakes and glaciers, and residential, commercial or industrial areas and agricultural fields. Offshore nature conservation sites may include the Natura 2000 Network, the Common Database on Designated Areas, the *Posidonia Oceanica* meadows and other seabed habitats and biotopes.

A legislative criterion is provided by law and intends to define acceptable regions through a safe distance from terrestrial and maritime infrastructure. This analysis divides terrestrial infrastructure into transport facilities and general buildings. Regarding offshore locations, the safe distance to fishing areas and island settlements is typically absorbed by the broad 'Shore' buffer. This distance is the advisable radius to abide by the law and compensate costs, considering the increasing route expenses to and from the offshore location as it moves away from the coast.

Safety criteria encompass those related to the safe operation of transport activities, whether on land (rail or road), air or sea. Railways include operational regular and light tracks for trains, subways and trams, while major roads combine highways and primary national roads. Regarding airports, a buffer zone of 3000 meters from all major international airports is selected to avoid potential collisions with aircraft and to reduce the possible interference with radar systems. Shipping routes comprise a 0.5 nautical miles buffer from routes above 1000 units per km^2 in one year.

Finally, a technical criterion regards fixed infrastructure that has already been deployed in a potentially admissible area. For instance, the main oil and gas large–pipe network, and cables from the electric transmission grid. Concerning offshore regions, exclusions include telecommunication lines and internet optical fibres, submarine energy interconnections, and existing wind farms and oil and gas platforms.

3.4. Data Evaluation

Following the creation of acceptable areas through data exclusion, the last step of the methodology consists of their evaluation through characteristic criteria. These parameters concern region–specific physical attributes, on which limits are imposed to maximise energy production.

Mean elevation is included in this analysis on the premise that RES suitability decreases at extreme altitudes, mainly due to diminishing resources (like lower air density or increased cloud coverage) and increased inaccessibility, leading to higher installation costs. The exclusion threshold is set to 2000 meters, following the literature review by D. Rayberg [14].

The average terrain slope is used to evaluate the terrain's angle and orientation. Most studies in the literature [14] typically set a threshold on average terrain slopes above 10° since steeper topographies are found to cause problematic installation of solar panels and wind turbines. Note that this attribute should not be confused with the tilt of the solar modules; generally, fixed panels are installed with a tilt angle approximately equal to the latitude of the place where they are located.

The impact of temperature on the performance of photovoltaic modules is a well–known phenomenon in which increasing air temperature leads to a decrease of the module's voltage output. Typically, manufacturers define the nominal peak power of a solar panel at 25 °C (module temperature), but this temperature can vary significantly during operation. The panels used in this work require air temperatures between –10 °C and 50 °C for regular operation.

Besides, warmer air is less dense than cold air; so in hotter locations, there is a decrease in the turbine's electricity yield since there is a lower energy extraction from the wind. Consequently, in this analysis, cooler air is always preferred for renewable electricity generation.

Bathymetry describes depth variations in the ocean's seabed. Water depth is a crucial criterion for assessing the siting of offshore wind farms since, typically, these require less than 50 meters of water depth for fixed foundation turbines. On the other hand, floating wind technologies are currently estimated to be economically feasible for water depth down to 1000 meters, mainly due to the mooring, anchorage and cabling works used.

Mean wind speed is one of the primary ways to measure wind energy resources. In general, the wind velocity profile in the atmosphere increases with height, which is why turbines have steadily become taller and taller over the years. At greater heights is also where the air is less dense, which in turn causes diminishing energy resources since the power of a wind–stream is directly proportional to air density. However, it varies to the cube of wind velocity; so higher wind speeds correspond to higher energy.

Average wind speeds are commonly measured from meteorological observations at 10 metres above ground level and then converted to the desired rotor height. Turbine manufacturers determine cut–in and cut–out speeds at those heights to protect the turbine from damage, usually fixating them between 3 m/s and 25 m/s. These limits are also applied in this analysis, serving as an evaluation criterion.

3.5. Eligible Locations

With the exclusion and evaluation criteria defined, their respective restricted zones are merged to create a layer of 'incompatible locations'. Afterwards, a geometric subtraction of these polygons is executed from the country's total surface, creating the data layer of the 'eligible locations'. Contrary to the previous ones, these are the available suitable areas for developing green hydrogen projects today—constituting one of the objective deliverables of this thesis. Figure 2 illustrates the aforementioned information, depicting both countries in a bicolour way of either *eligible* (in blue) or *incompatible* (in red) locations.

4. Numerical Model Layout

Every economic assessment requires the development of a numerical model that computes the outcome predictions from the input data. This section minutely describes the development of the two numerical models used in this economic analysis. Subsection 4.1 first addresses the broad calculation of the levelised cost of hydrogen, while Subsection 4.2 takes this calculation and employs it into a generalised model to be applied to the whole set of locations of both countries. Finally, Subsection 4.3 improves on the generalised model and describes the entire development of a specific optimisation model.

4.1. Hydrogen Economic Fairways

In this work, the pathway to define the economic viability of the hydrogen projects is based on the method recently employed by S. Walsh et al. [15]. Likewise, this analysis applies a sub–model developed in Microsoft Excel, which considers all the distinct parameters essential to compute the cost of hydrogen production in the eligible locations obtained in the previous section.

The levelised cost of hydrogen is a benchmark commonly used to determine the feasibility of a hydrogen project. Above all, it measures the cost of producing one unit of hydrogen during the lifetime of the project. Equation 1 presents the generalised formulation used in this thesis.

$$\mathtt{LCOH}^{(*)} = \frac{\mathtt{K_{RES}} + \mathtt{K_{H_2}}}{\mathtt{Y_{H_2}}} \tag{1}$$

Note: $^{(*)}$ is replaced according to the RES associated with the calculation: **(pv)** for solar photovoltaic parks, **(wd)** for onshore wind farms, **(fx)** for offshore fixed wind farms or **(ft)** for offshore floating wind farms.

where: $\mathtt{K_{RES}}$ is the overall cost structure of the RES power plant, in EUR; $\mathtt{K_{H_2}}$ is the overall cost structure

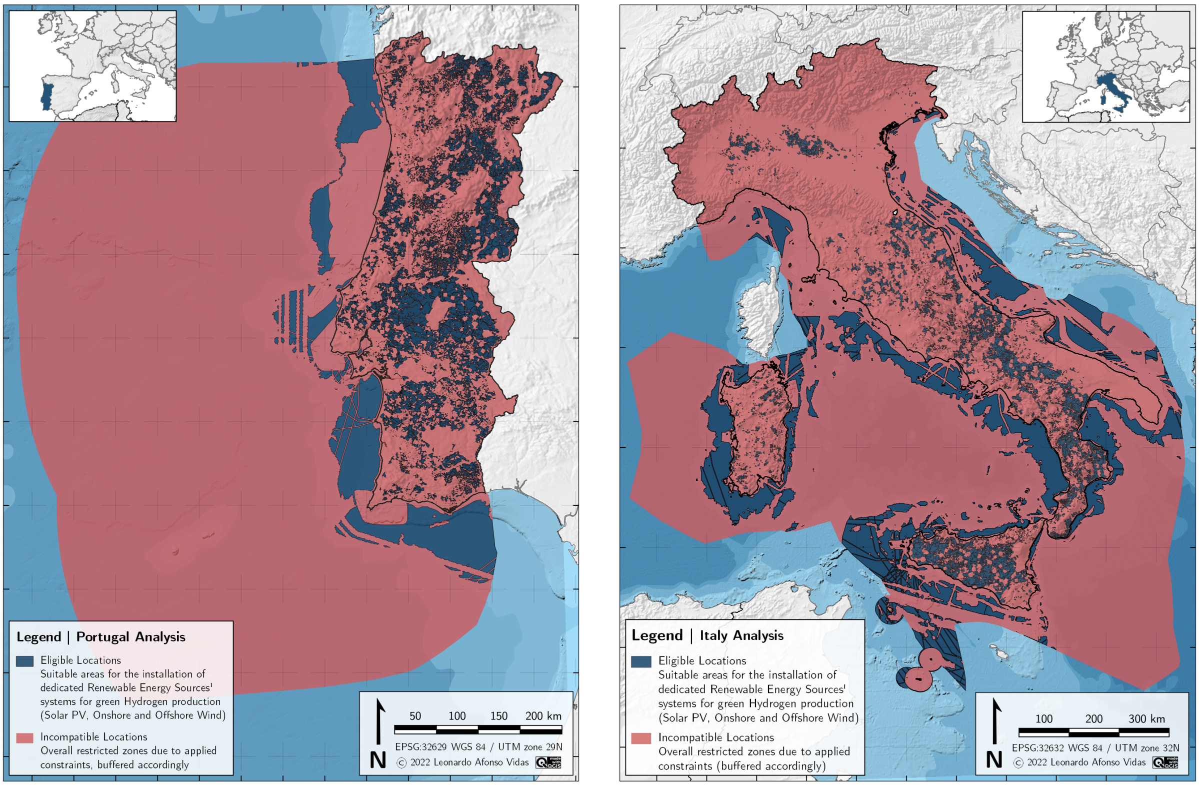

Figure 2: Country analysis: total eligible locations.

of the electrolyser, in EUR; Υ_{H_2} is the global hydrogen yield, in kg.

The generalised formulation has other several sub–components aggregated into progressively broader concepts. These concepts are based on the works of M. Minutillo et al. [13], L. Viktorsson et al. [16] and T. A. Gunawan et al. [17].

4.2. Simplified General Model

Many articles have been published in the literature where the global hydrogen yield is assumed to be converted directly from the electricity generated by the renewable energy source, usually using the net production rate of the electrolyser or the lower/higher heating value of hydrogen. This section describes the creation of the simplified general model (SGM), starting by explaining how to determine the upper–limit of the RES installed capacity for a given available area and then discussing the definition of the localised LCOH computation.

The process begins with choosing a generic utility–scale module. Next, the ground cover ratio (GCR) is obtained to compute the virtual area of the module, taking into account the row space that minimises shading; with the specific data of this analysis, GCR = 0.42. So, dividing the calculated real area of the modules by this ground cover ratio gives the module virtual area. The choice of the total available area per pixel (α) refers back to Section 3.2, where the spatial resolution of the geographical model is defined. This available area is then divided by the module's virtual area to give the maximum number of panels allowed in each pixel. Finally, the same datasheet states a module's nominal power of 600 W under Standard Test Conditions. Multiplying this value by the number of modules, leads to the solar PV installed capacity upper–limit.

For wind turbines, the process starts with establishing a common diameter size for the turbine rotor. The International Electrotechnical Commission Class II is used as reference, where 3.45 MW turbines have a diameter of 126 meters and a hub height of 100 meters.Nowadays, most sources agree on placing onshore turbines seven rotor diameters away from each other downwind and five rotor diameters sidewind. Regarding offshore farms, both these numbers increase to eight since turbines spaced further apart have been found to improve their efficiency and lifetime. Multiplying these two quantities gives a virtual rectangle with a turbine on one of its corners. The subsequent procedure is the same as for the solar parks: the number of turbines in each pixel is the quotient between this area and the turbine's virtual area. Finally, the upper–limit wind installed capacity is computed by multiplying the maximum number of turbines in each farm by the nominal power of one said turbine.

With the fundamental parameters of the electrolyser identified, the SGM starts from the definition of a virtual hydrogen demand. Next, the amount of electricity needed at the stack input is computed using the net production rate of the electrolyser. When the electrolyser system's electric efficiency is considered, one gets the yearly energy needed to be generated by the coupled RES power plant. Finally, to find the size of the RES station, one needs to divide this quantity by the full load hours of the power plant. The annual solar and wind capacity factors are respectively collected from Global Solar Atlas and Global Wind Atlas. The size of the RES power plant is then tested against the upper–limits computed before to comply with the maximum physical allowance of installed capacity. The next step is the sizing of the electrolyser. In this work, an oversize factor is applied first: a ratio to apply between P_{RES} and P_{H_2} that best optimises the hydrogen output. The method to obtain this factor is described in the next section.

4.3. Optimised General Model

Some articles have been published before on this subject. The model developed in this thesis assimilates learnings from these (and other) works and builds on a traditional optimisation method. The objective of the optimised general model (OGM) is to find the cheapest LCOH in a given set of suitable locations, considering hourly changing values for P_{RES} and P_{H_2}. The algorithm presupposes the existence of a RES power plant and an electrolyser system in each location, with the possibility of having both solar PV and wind in a hybrid onshore configuration. The power plant's installed capacity and the electrolyser's nominal input power are the decision variables, where the latter is upper bound by the former.

The OGM is built with Pyomo. The first step consists of initialising the abstract mathematical model built on unconstructed components. Secondly, the three basic elements needed to construct a Pyomo model are declared in standard Python objects: sets, parameters and variables. Finally, when a solution is to be obtained, a concrete instance of the model is created with data values being applied via a 'DataPortal'. The following items lay out the definition of said objects: *Index Sets*—coding starts with the abstract declaration of sets $\mathbb{L}$ and $\mathbb{H}$, respectively, regarding the list of eligible location points and the number of hours in one year. These are followed by loading the concrete values from a prepared CSV file. *Parameters*—refer to a class of data values used to characterise the model. Most parameters are exogenous, with the exception of the real WACC, the capital and production spread factors, and the overall cost structures. As noted before, all these parameters are the same scalar for each location, apart from the capacity factors. Contrary to the yearly SGM analysis, the optimisation model requires an hourly time frame to operate correctly. *Variables*—represent the unknowns of a model. Ultimately, they are intended to store the values referred to as the 'solution' of the optimisation program. Variables are declared as indexed, bounded elements with a specific domain. This model envisions the existence of three decision variables and four support variables; while the former establish the actual solution, the latter exist to execute auxiliary computations.

Every optimisation problem requires the mathematical formalism that enables a rigorous description of the reality it is trying to model. The design of an efficient mathematical formulation rests on an understanding to derive innovative approaches to the architecture of the problem. In this thesis, the design aspects of the mathematical formulation undergo several iterations, culminating on the thorough descriptions of the constraints and the objective function. Constraints establish the functional relationships between variables, using equality or inequality expressions as rules of Python. These equations follow the reasoning to compute the optimised LCOH at each location; the solution then consists of the RES installed capacity values and the nominal input power of the electrolyser. Finally, the optimisation model concludes with the formulation of the objective function. Primarily, the objective is to minimise the levelised cost of hydrogen. Equation 2 displays these function.

$$\textbf{min}\ \mathtt{LCOH} = \textbf{min}\ \frac{\mathtt{K_{RES}} + \mathtt{K_{H_2}}}{\mathtt{Y_{H_2}}} \tag{2}$$

5. Results and Discussion

Following the methodologies examined in the previous sections, a set of results is presented and discussed.

The oversize factor is first determined to access the potential for extensive hydrogen production in a meaningful way. This ratio between the RES installed capacity and the electrolyser is computed to yield the lowest LCOH in each suitable location. Hence, the optimisation algorithm is run in three points per technology for each country, reflecting every set's minimum, average and maximum capacity factors. The next step is to plot this factor against the technologies to find a relation that can be used in the remaining points. Apparently, there is an inverse correlation between the oversize factor and the capacity factor; once plotted this way, the correlation is evident, although not entirely accurate. Nonetheless, this approach gives a first good estimation of a model that better resembles reality. Therefore, the centroid values are used to compute the LCOH for the remaining points associated with the respective technology.

Figure 1 maps out the current overall levelised cost of hydrogen in both Portugal and Italy. This illustrates the second expected deliverable of this thesis.

A direct comparison can be made between the

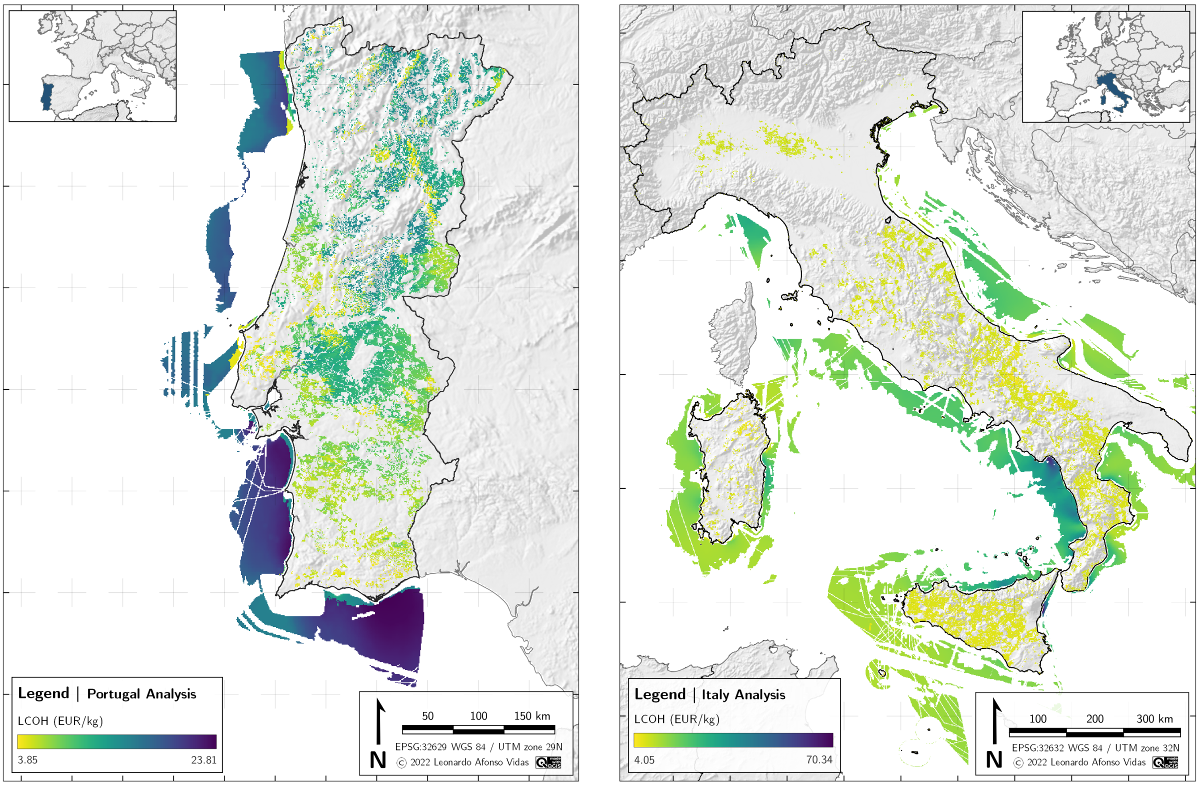

Figure 3: Current levelised cost of hydrogen in eligible locations of selected countries.

two countries, with the initial caveat that the colour–spectrum scale of the legend is not the same. Either way, the LCOH is generally lower onshore than offshore; in Portugal, onshore costs averages at 6.85 EUR/kg, while in Italy, the average is 7.25 EUR/kg (as opposed to 10.48 EUR/kg and 15.81 EUR/kg, respectively, offshore). While the main reason for the disparity between on/offshore costs is the cost structure of each technology, the primary cause for the discrepancy in values between the two countries is related to solar and wind exposure.

5.1. Onshore Hybrid Optimisation

In addition to the results obtained from the traditional optimisation process, the model is further used to perform a specialised hybrid optimisation in selected onshore locations of both countries. Together with the algorithm procedure mentioned above, this operation constitutes the third and last objective expected to be delivered from this thesis, as stated in Section 1.

This procedure aims to join both onshore technologies in the same location and compute each installed capacity to minimise the levelised cost of hydrogen; a generalised use of this method was not possible due to insufficient computational resources. The algorithm as thus run and, to better understand the scale of improvement provided by this optimisation model, Figure 4 illustrates the results as a bar chart.

The yellow and blue bars respectively depict the LCOH from solar and wind systems alone, while the green bars represent the optimised hybridisation of both technologies. The true power of the algorithm is evident in the relative reductions displayed; in the specific case of these locations, it can be as high as 70%. It could be even higher for other locations, not addressed in this analysis. These reductions may lead to savings to the project owner in the order of €2 million for a 100–ton annual demand. With an annual demand of just 500 tons, the savings can reach close to €10 million.

6. Conclusions

This section concludes the investigation described so far. Section 6.1 summarises the key findings related to the research questions, discussing the value and contributions thereof.

6.1. Achievements

This study aimed to identify eligible regions to install green–hydrogen production facilities. Moreover, this study intended to find the configurations of renewable energy sources and electrolysers that return the lowest lifetime production cost in specific locations while also obtaining a preliminary oversize factor to apply in extensive geographical analysis.

The land availability of both countries is accomplished through a comprehensive 3–part methodology, based on state–of–the–art literature.

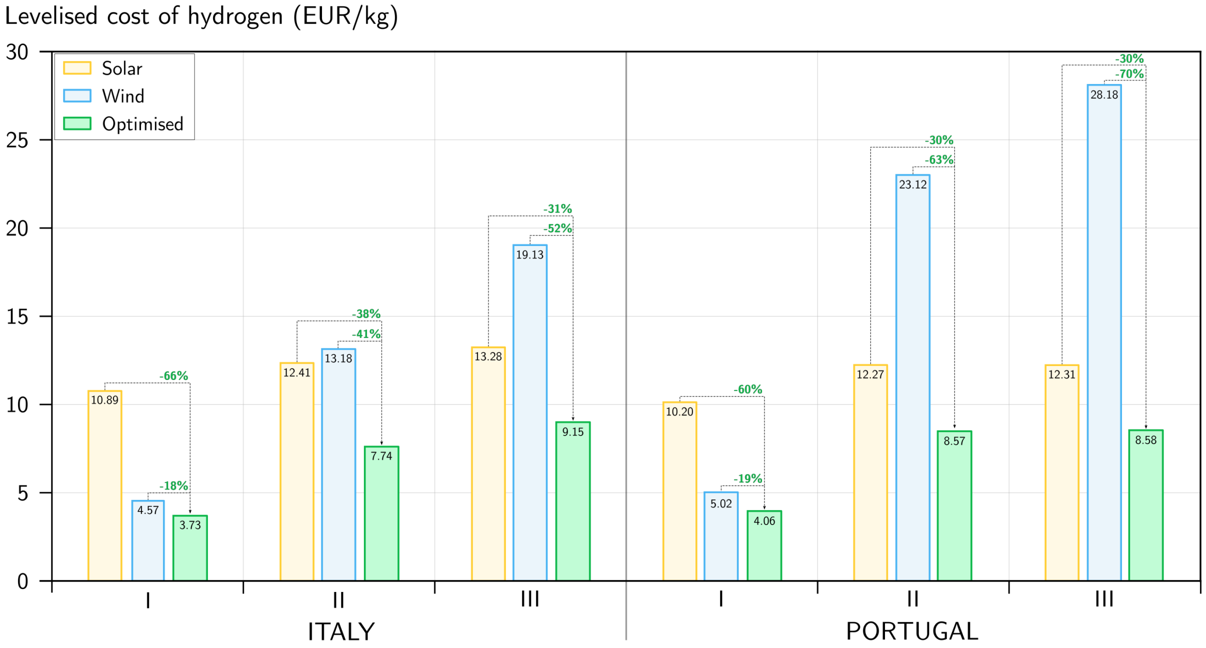

Figure 4: Onshore hybrid optimisation.

The three phases comprise the different stages of any standard geographical information system analysis, from data collection and handling to data exclusion and further evaluation. The main findings are: **1)** Italy has 37 637 km^2 and 104 338 km^2 of onshore and offshore area available, respectively, corresponding to 12.50% and 19.44% of the total area; **2)** Portugal has 24 734 km^2 and 22 495 km^2 of onshore and offshore area available, respectively, corresponding to 27.79% and 7.13% of the total area; **3)** Despite the eligible locations being small percentages of the countries' surface, their thorough use would be enough to produce millions of tons of hydrogen annually.
These findings represent an unprecedented achievement for both Italy and Portugal in the sense that they close a critical research gap related to these two countries. Such material data may be a valuable asset to any economic analysis conducted by municipalities and even the central government.

The study then examines the hydrogen economic fairways in the locations mentioned earlier, computing the levelised cost of hydrogen through an extensive sequence of formulations. A simplified general model is created per present–day international literature, based on the maximum allowed capacity of the renewable power plants. Still, this model improves on the existing ones by using an oversize factor determined via an optimisation algorithm.
Regarding this finding, the main conclusions are: **1)** There is an apparent inverse correlation between the oversize factor and the full load hours of the renewable energy system contemplated. This means that for RES technologies with higher capacity factors, the coupled electrolyser should approximate the size of the renewable power plant; **2)** Making use of this factor, the LCOH generally yields lower values onshore than offshore. The averages for Italy and Portugal are respectively 7.25 EUR/kg and 6.85 EUR/kg (onshore), and 15.81 EUR/kg and 10.48 EUR/kg (offshore); **3)** The fundamental cause of disparity between onshore and offshore values is the cost structure of each technology; the leading explanation for the value discrepancy between both countries is the solar/wind exposure. The capacity factor is one of the most predominant aspects affecting the levelised cost of hydrogen.
The introduction of this oversize factor significantly improved the study's credibility, producing results ever closer to reality. This procedure constructively challenges the standard way of assessing large–scale green–hydrogen projects and thus may be replicated in subsequent analysis as a means to make estimations better resemble the real world.

Lastly, the algorithm developed to obtain the oversize factor, as part of the optimised general model, is in itself one of the major outcomes of this thesis. Its foundation is grounded on a comprehensive problem setting and mathematical formulation, comprising the detailed definition of index sets, parameters, support and decision variables, as well as an objective function constrained by ten equations. When used on a country–specific set of points, the following was concluded: **1)** Single configurations, where only one renewable energy source is coupled to the electrolyser, obtained LCOH reductions in Italy and Portugal of up to 7% and 11% (offshore), and 29% and 27%

(onshore), respectively. Such cutbacks could translate to hundreds of thousands of euros in savings for the project investors, if not more, depending on the established hydrogen demand. **2)** Hybrid onshore configurations, where both solar and wind power plants are connected to the electrolyser, generated the highest reductions in the cost of producing hydrogen. In the cluster of three selected locations, the LCOH decreased as far as 52% in Italy and 70% in Portugal. Reductions such as these could lead to €10 million in savings to the owner, for a 500–ton annual demand. These results validate the initial premise of the algorithm in providing the optimal computation of the levelised cost of hydrogen with notable success. A model with such attributes was yet to be found in the literature, evidencing its important contribution towards addressing this gap.

As a concluding remark, one has to acknowledge that the evidence base is fast–moving and so there can be expected gaps in the knowledge. Nonetheless, this work improves on the body of research published so far and contributes to the development of this field.

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