

École polytechnique de Louvain

Determining the Optimal Location of Remote Renewable Energy Hubs for Importing Hydrogen to Belgium

Authors: **Adrien VAN DROOGENBROECK, Loïc VERWILGHEN**

Supervisor: **Francesco CONTINO**

Readers: **Diederik COPPITERS, Joris PROOST**

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Abstract

The transition to a low-carbon economy requires innovative approaches to the development and distribution of alternative fuels, such as green hydrogen. While the identification of the main regions for optimal hydrogen production on a country-scale is gaining interest, the allocation of exact locations within a country remains limited. Moreover, the location allocation is mainly driven by subjective weights and importances subject to bias of stakeholders. Therefore, this thesis explores a robust location allocation method for optimal remote renewable energy hubs aimed at producing green hydrogen and exporting it to Belgium. By using a robust Analytic Hierarchy Process (AHP) integrated with a Monte Carlo simulation, the inherent uncertainties and subjective biases in traditional decision-making processes are addressed.

Our case study focuses on Morocco, a country with substantial potential for solar and wind energy. We evaluate three scenarios: exporting hydrogen via seaports, via pipelines and non-export-focused production. Thanks to the insights of DEME Group, the research identifies critical criteria such as renewable energy potential, proximity to infrastructure, and exclusion zones, reclassifying these factors into standardized scores for comprehensive analysis.

The robust AHP methodology, facilitates a more reliable assessment by generating stochastic weight distributions for each criterion. While the southern regions are preferable for maximizing renewable energy production without export considerations, the best locations for other scenarios are located more in the north to be closer to seaports or pipeline connection. The analysis of cumulative distribution functions (CDF) ensure that selected locations maintain high suitability with minimal probability to score below the minimum acceptable performance. Moreover, the inclusion of uncertainty allows to make a trade-off between locations with high performance in specific conditions—but fragile when the importance on the inputs vary—and locations with stable performance regardless of the subjectivity in the weights.

This thesis contributes to global sustainability goals by proposing a scalable and robust framework for determining optimal locations for green hydrogen production sites. The adaptable nature of this framework allows it to be applied to diverse contexts, making it suitable for any country or region.

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Nomenclature

Acronyms

AHP	Analytic Hierarchy Process
CAPEX	Capital Expenditure
CDF	Cumulative Distribution Fonction
CF	Capacity Factor
CHP	Combined Heat and Power
CI	Consistency Index
CR	Consistency Ratio
DEM	Digital Elevation Model
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
LCOH	Levelized Cost of Hydrogen
OPEX	Operational Expenditure
OSM	OpenStreetMap
PCM	Pairwise Comparison Matrix
PEM	Proton Exchange Membrane
PV	Photovoltaic
RI	Random Consistency Index
SMR	Steam Methane Reforming

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1 Introduction

1.1 General context

As the significance of climate change has escalated in recent decades, the necessity for solutions to create industries with reduced carbon emissions and transition to a fossil free society has become increasingly apparent. This transition is crucial to limit future emissions of CO₂ and other greenhouse gases.

In fact, to keep global warming to no more than 1.5°C compared to the pre-industrial levels—as called for in the Paris Agreement—emissions need to be reduced by 45% by 2030 and reach net zero by 2050 [1].

Sustainable alternatives must then be developed to compensate for the wide use of fossil fuels, deep-rooted in our society and industries for decades. So far, solar and wind power stand out as some of the most promising and effective renewable energy sources available to achieve sustainability and the Paris Agreement goals.

Western Europe, and more specifically Belgium, is expected to consume much more energy than what can be provided locally with those renewable energies, and the net energy balance is expected to stay negative in the future (Figure 1.1) [2, 3]. In fact, the renewable energy sources potential is low compared to other regions of the world [4, 5], as illustrated on Figure 1.2 and Figure 1.3. The question is thus how to bring this energy to Western Europe and Belgium.

As an alternative to high-voltage lines which would need a higher transmission capacity and more efficiency, molecules, and especially hydrogen, can act as energy vectors, being imported through pipelines or in tanks on ships and trucks [2]. Also, hydrogen has a lot of applications in different industries, and is therefore seen as a solution to decarbonize them [6].

1 - Introduction

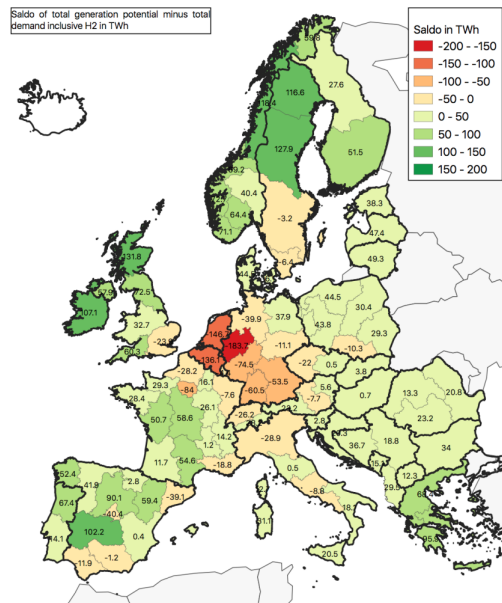


Figure 1.1: Balance of renewable generation potential and demand with electricity for hydrogen in Europe 2050 [3]. Belgium is the region with the third worst balance between potential and demand.

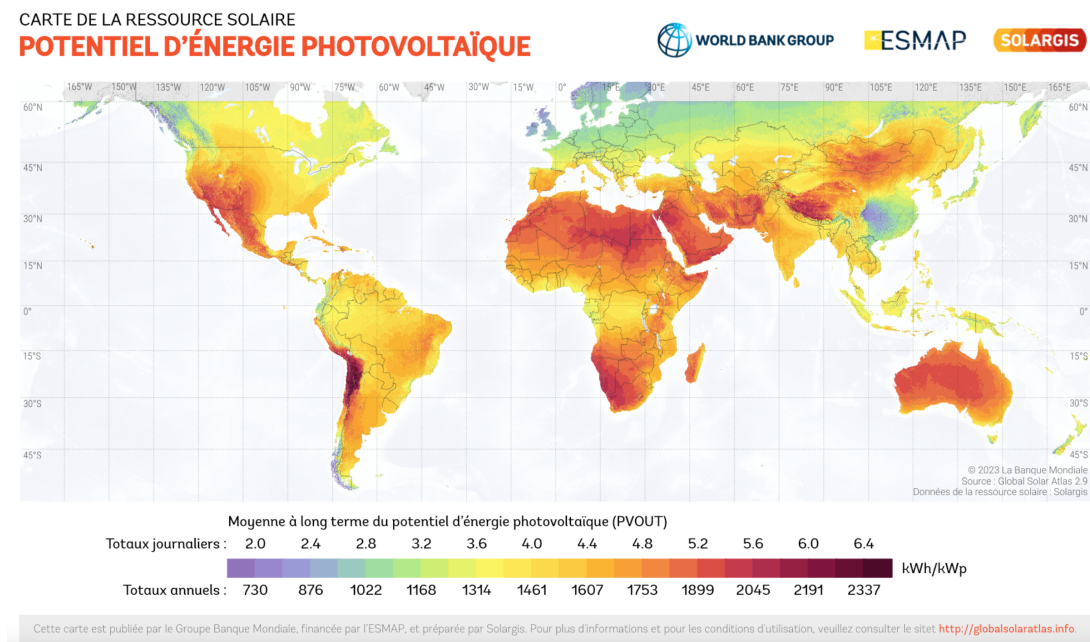


Figure 1.2: World's Photovoltaic Power Potential [4], illustrates that potential solar energy in Europe is low compared to Africa, Australia and South America.

ONSHORE & OFFSHORE WIND RESOURCE MAP

WIND POWER DENSITY POTENTIAL



WORLD BANK GROUP

DTU Wind Energy
Department of Wind Energy

ESMAP

VORTEX

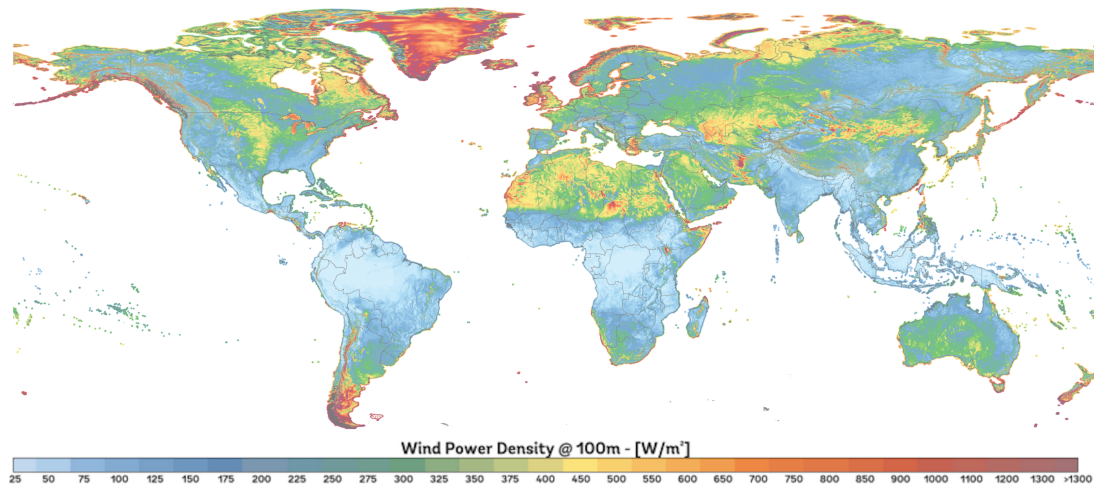


Figure 1.3: World's Wind Power Potential [5], illustrates that potential wind energy in Europe is low compared to northern Africa and South America.

1.2 The role of Hydrogen

Given that using more renewable energy is seen as a mean of achieving a low-carbon future, it is important to take into account the features of renewable energy sources and how it may affect national systems.

Compared to fossil fuels, wind and solar energy power generation is characterized by a high degree of intermittency. However, electricity systems have to be balanced at all times, which means that the produced electricity as input in the system must exactly match the electricity being consumed in real time. Otherwise, energy has to be stored. Batteries production requires scarce raw materials, and they are not fit for characteristics such as being an efficient storage medium for storing large amounts of energy for a longer period of time [2]. On the other hand, hydrogen can store MWh-GWh of energy [7] for up to 20 years [8]. Therefore, excesses of electricity can be used to produce green hydrogen, which molecules will store energy.

Green hydrogen is produced through a process of electrolysis powered by renewable energies such as solar and wind power.

During a water electrolysis process, water molecules are split into oxygen and hydrogen thanks to an electrical current [9]. The amount of hydrogen produced through electrolysis is thus directly proportional to the current intensity [10]. The different electrolysis processes are detailed in Appendix A.

It is then possible to retrieve electricity from green hydrogen through fuel cells. In fact, they are the exact opposite of electrolyzers, but instead, chemical energy is converted into electrical energy. This has applications in several sectors: maritime transportation, electric cars, aerospace sector and others [6].

However, when switching to a low carbon economy, electricity is not always the most appropriate energy vector. Industries may require heat at high temperature, which can not be provided efficiently with electricity [2]. A lot of industrial processes require molecules such as hydrogen for intermediate and final products. For example, fertilizer industries need hydrogen as a reactant to produce ammonia (NH_3) through the Haber-Bosch process [6]. Hydrogen also has the potential to become a key alternative as a gas turbine fuel for Combined Heat and Power (CHP) generation systems. It is thus possible to decarbonize such industries by providing green hydrogen. In fact, so far, Steam Methane Reforming (SMR) [11] is the most efficient, most developed and cheapest industrial process for hydrogen production. Nevertheless, this production process is responsible for significant amounts of CO_2 emissions as a byproduct and is therefore undesirable for a sustainable future [12]. Green hydrogen can therefore be a sustainable alternative to SMR. But as the demand and therefore the import of hydrogen to Belgium is expecting to grow significantly, large uncertainty remains regarding the expected quantity of imported hydrogen. Depending on studies, it is estimated to range from 100 TWh/year [13] to 350 TWh/year [2] in 2050.

In a country like Belgium, with low renewable energy potential and high population density, finding suitable renewable energy production sites and hence producing green hydrogen is a challenge. Meeting our energy needs from renewable sources is in fact challenging [3]. Therefore, a solution showing promise is to import green hydrogen from remote renewable energy hubs to Belgium [2]. However, despite hydrogen having a higher gravimetric energy density (143 MJ/kg) than most common fuels such as gasoline (46.4 MJ/kg), diesel (45.4 MJ/kg), kerosene (46.4 MJ/kg), natural gas (53.6 MJ/kg), its volumetric energy density is the lowest of them (at normal

conditions), due to its very low density (0.08375 kg/m^3) [14]. Luckily, more convenient solutions exist for an easier storage and transportation of hydrogen, such as compressing or liquefying it [14], but the resulting cost is higher. Yet, production of renewable electricity accounts for the majority of the overall costs through the value chain (Figure 1.4). It is therefore crucial to find optimal locations for renewable energy production sites, to ensure the cheapest production of electricity.

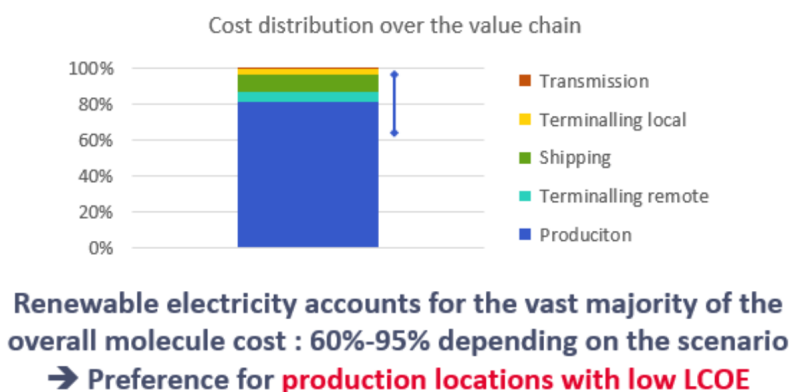


Figure 1.4: Cost distribution over the value chain, from [2].

1.3 Literature review

Several criteria must be considered when looking for suitable locations for green hydrogen production. For instance, one criteria could be the distance to waterbodies. Indeed, proximity to water plays a crucial role in minimizing expenses associated with hydrogen production, given the necessity of water for the electrolysis process, as discussed before.

Other criteria must be taken into account, such as high solar radiation and high wind exposure, to maximize power supply to the electrolyzers. Suitable topography, land use and proximity to existing infrastructure must also be considered. Geographic Information Systems (GIS) is a powerful tool which can be used to identify suitable areas to produce hydrogen from renewables. The analysis is conducted based on different criteria, displayed as maps (called layers) generated by datasets. GIS helps in mapping the potential for renewable energy resources and hydrogen production by merging the multiple layers of information (corresponding to each criterion), resulting in global suitability indices for each location of the map.

Several authors have already conducted this type of analysis. For example, Giamalaki et al. have conducted a GIS approach to determine the optimal location of solar power installations in the Mediterranean region [15]. Uyan et al. conducted a similar scientific research for GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey [16]. Al-Yahyai et al. did research about wind farm land suitability indexing using multi-criteria analysis in Oman [17].

But some criteria could have more importance than others. This is why each layer has a specific weight, and the overall suitability indices are computed as a weighted overlay of the different layers. For example, S.K Saraswat et al. [18] used GIS based modelling techniques for the assessment of solar and wind farm locations in India. In this study, a sensitivity analysis was conducted to understand the influence of each factor and assess the robustness of their approach. Their criteria were divided into three categories (technical, socio-environment and economic). After conducting a case study with weights based on expert analysis, they analyzed sensitivity by changing the weights for four different cases: equal weights (case 1), dominance of technical criteria (case 2), dominance of socio-environment criteria (case 3), dominance of economic criteria (case 4). They then compared it with the initial case study. In case 2, there was a significant increase of 'highly suitable land' area from 4.13% to 10.67% for solar farms and from 0.91% to 8.99% for the wind farms. In case 3, there was an increase of 4.13% to 27.45% for the solar farms while an increase from 0.91% to 26.28% for the wind farms. Thus, the results of the sensitivity analysis show that the output results are seriously sensitive to the weights of the criteria and that each criterion that is taken into consideration has an impact on how the study region is evaluated. Weight selection is therefore crucial in order to have reliable results.

A more robust approach of AHP has already been conducted in different fields. For example, MV. Almeida et al. have used a Monte Carlo method to assess the geological hazard for high rise buildings in Manila, Philippines [19]. Tsuen-Ho Hsu et al. used a Monte Carlo-aided AHP to assess the overall dental service quality of dentists [20]. Thus, robust AHP techniques have already been used in a variety of fields, but their application related to remote renewable energy hubs location-allocation for hydrogen production is still lacking.

1.4 Problem statement and thesis outline

The importance of each criteria is determined through a method called Analytic Hierarchy Process (AHP), which will be explained into more details in section 2.2. In this method, the relative importance of each criteria is determined by the author, or by experts, which by definition involves some degree of bias. This implies that subjectivity is at the roots of the whole process. Thus, at the end of the process, the weights associated to each criterion reflect the subjectivity of the authors. In the end, the optimal locations for remote renewable energy hubs are subject to a number of uncertainties related to the bias of every author and to the deterministic nature of a traditional AHP approach, as seen in the sensitivity analysis from [18] discussed in the previous section.

Also, as seen earlier, robust AHP techniques already have some applications [19, 20], but are still lacking in the field of GIS based location-allocation for remote renewable energy hubs for hydrogen production. Therefore, we will develop a robust location allocation method designed to address the specific uncertainties inherent in the allocation of renewable hydrogen production sites, thereby minimizing subjectivity in the decision-making process.

Furthermore, we will propose a novel post-processing method, incorporating principles from robust design, to identify optimal locations based on both their expected suitability and the variability in their suitability due to varying weighting factors.

First, we will establish the different criteria that must be taken into account to select an optimal remote renewable energy hub for hydrogen production. Then, we will review the steps of a traditional Analytic Hierarchy Process. In section 2.3, our robust approach of AHP will be presented, and illustrated in section 3 with a case study in Morocco. Finally, the results of our analysis will be interpreted and discussed. It is important to mention that the method is general and can be extended to renewable energy hubs in others regions and countries.

The focus of the thesis will be to answer the following research question: "How can robust Analytic Hierarchy Process reduce subjective decision-making in location-allocation of remote renewable energy hubs for hydrogen production?"

2 Methodology

In this section, the methodology of our study will be elaborated. The selection of criteria will be first explained. Next, we will introduce the classical Analytical Hierarchy Process (AHP) and subsequently its robust version. Following this, the Monte Carlo simulation will be described and the process for selecting optimal locations will be outlined. Once the best location has been identified, metrics will be presented to analyze wind and solar profiles complementarity.

2.1 Criteria

When studying optimal locations for a specific type of application, we need to take into account various criteria that are likely to influence the suitability.

The relevant criteria for our case study will be further explained in section 3.1. In a GIS-based analysis, each criteria, displayed as a layer, has an importance determined by a weight assigned to each of them to perform the decision-making process. Those weights are calculated by a deterministic Analytic Hierarchy Process. Also, several areas will be excluded, since they are unsuitable for any infrastructure or installation.

Reclassing of the criteria

Once the weights are obtained, the output of a simulation can be computed from a weighted sum of all criteria. But the data values (displayed on maps), linked with each criterion, must first be standardized in terms of units.

Therefore, we use reclassing. It consists of assigning a score from 1 to 5 to the values of each criterion, regardless of its units and initial values [18]. In other words, for each criterion, the original values (with their original units) are reclassified into five ranges of values, each corresponding to an adimensional value between 1 (worst) and 5 (best), as shown on Figure 2.1. The scores are based on minimizing the costs of hydrogen production. For example, locations closest to water get a score of 5, and locations with the least wind exposure get a score of 1. The correspondance between values in their initial units, and adimensional reclass score will be established based on thresholds from literature.

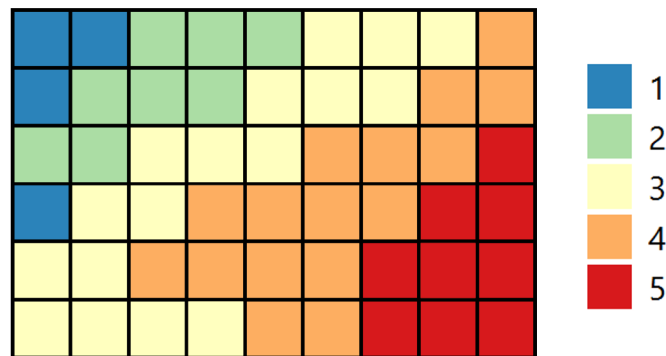


Figure 2.1: Reclassing of a layer. Pixels are assigned a score ranging from 1 to 5 depending on how good the pixel value is regarding the considered criterion.

2.2 Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is one of the most widely used multiple criteria decision-making tools. Its utility spans across various domains such as social contexts, manufacturing, politics, engineering, education, industry, and also fields like sports and management [21]. The process allows to assign weights to different criteria, by determining the relative importance between them at the start of the process [22].

2.2.1 Pairwise Comparison Matrix

The first step of a traditional deterministic AHP, is to determine the relative importance of a criterion relative to another following Saaty's fundamental scale of importance [22] as illustrated in Table 2.1.

Intensity of importance on an absolute scale	Definition
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between two adjacent judgements

Table 2.1: Saaty's fundamental scale of importance.

Thanks to this scale, experts are able to establish Pairwise Comparison Matrices (PCM), which reflect the relative importance of each criterion compared to the others. In fact, with n criteria, the matrix dimensions will be $n \times n$ and the elements a_{ij} of the matrix will be determined by the abovementioned scale, where a_{ij} is the relative importance of criterion i compared to criterion j with $i, j = 1, 2, \dots, n$. Since the relationship between criterion j and criterion i is logically inverse, this leads a property of reciprocity in the matrix, which means that

$$a_{ji} = 1/a_{ij}$$

Of course, the diagonal elements of the matrix are equal to 1, as $i = j$ (a criterion is compared to itself).

	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	1/2	3
Criterion 2	2	1	6
Criterion 3	1/3	1/6	1

Table 2.2: Example of Pairwise Comparison Matrix.

2.2.2 Determination of the weights and consistency ratio

Based on the established PCM, it is possible to determine the weights of each criterion by doing several operations on the matrix. Mu et al. [23] detailed the steps of this process, and they are summarized on a simple example in Appendix C. Then, the consistency of the judgements has to be checked. Consistency can be illustrated from the following example from [23]: in a PCM, if we provide a value of 2 (relative importance) to the first criterion over the second and assign a value of 3 to the second criterion with respect to the third one, the value of preference of the first criterion with respect to the third one should be $2 \times 3 = 6$.

But, it is unlikely that every assigned relationship is mathematically correct. Inconsistency in AHP is expected and allowed but must be limited. Therefore, a consistency ratio (CR) is computed comparing the consistency index (CI) of the matrix and a random consistency index (RI). In AHP, CR must stay below 0.1 and is given by

$$CR = \frac{CI}{RI}$$

where RI is given and depends on the number of criteria, and CI is computed from the weights. The detailed computation steps of CI are explained in [23], and summarized in Appendix C.

2.2.3 Problems arising from deterministic Analytic Hierarchy Process

As discussed in section 1.4, the PCM are often determined deterministically by an expert or a group of experts [15, 16, 17], which implies that their subjectivity is at the roots of all the analytic hierarchy process. Consequently, the weights associated to each criterion reflect the subjectivity of the authors. In the end, the optimal locations for remote renewable energy hubs depend on the bias of every author. For instance, two papers written by different authors based on the same case study, could lead to different results.

2.3 Robust Analytic Hierarchy Process

To take into account the uncertainties explained before and develop a robust location-allocation, one solution is to use stochastic distributions to reflect the relative importance between each criteria, instead of using one deterministic value, chosen by a rather subjective expert. This way, uncertainty is propagated through the AHP and stochastic results can be further analyzed.

2.3.1 Beta-PERT distributions

Instead of choosing a single value (based on Saaty's scale) for the relative importance between two criteria, a distribution can be used. In fact, since the exact intensity of importance of one criteria compared to another is uncertain, it can be determined with more confidence that it must be between a certain range of values, reflected by a distribution.

For our robust methodology, we use Beta-PERT distributions to represent uncertainty. Those distributions have already been used in several papers to model uncertainty [24, 25]. In fact, those types of distributions have the advantage of being intuitive to the estimator [26]. Only three parameters have to be determined to define the distribution : the minimum, most-likely and maximum values.

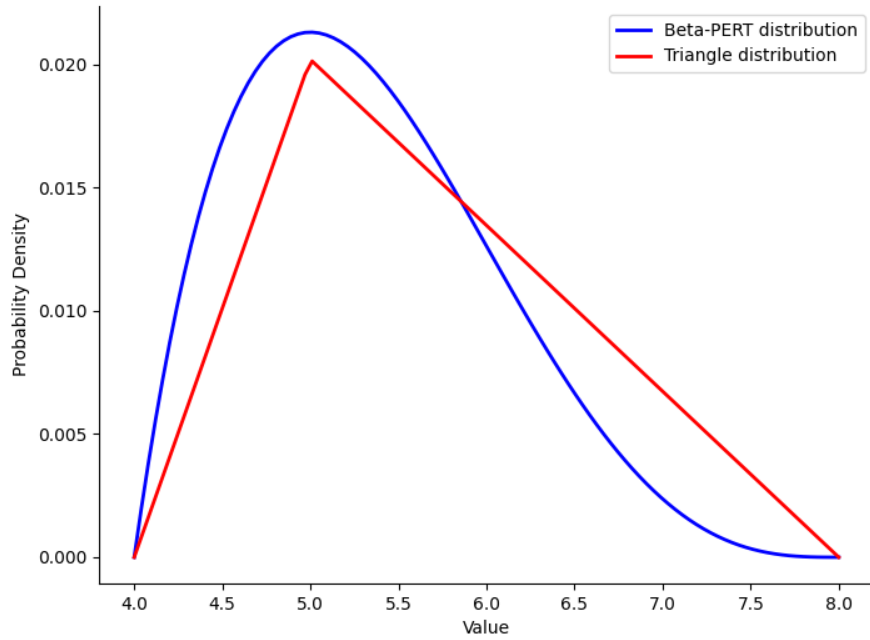


Figure 2.2: Example of distributions for relative importance values.

Figure 2.2 shows an example of a Beta-PERT distribution with a minimum value (a) of 4, most likely value (b) of 5 and maximum value (c) of 8. This figure also shows the comparison with a triangle distribution, often used in fuzzy-AHP methodologies [27]. In our case, the Beta-PERT distribution is preferable for several reasons. The triangular distribution has a mean equal to

$$\mu = \frac{a + b + c}{3}$$

which is the average of the three parameters. Unlike Beta-PERT, this approach gives equal importance to both extreme values, which are often less known than the most likely value. Consequently, it tends to be less reliable.

Beta-PERT curves are also smoother which better captures the nuanced knowledge and expectations of experts, providing a more refined estimate. In contrast, the triangular distribution's angular shape offers a simpler, less detailed approximation.

For the Beta-PERT distribution, the mean is a weighted average of the three parameters

$$\mu = \frac{a + 4b + c}{6}$$

with the weight applied to the most likely value being four times higher.

2.3.2 Robust Pairwise Comparison Matrix

To establish this robust PCM, we need to choose a minimum, a most likely and a maximum value to determine the relative importance distributions between each criterion. This is represented in Table 2.3 below. If a criterion i is more important than criterion j in all cases, we'll set the minimum value at 1 and the maximum value at 9 for element a_{ij} , according to Saaty's scale (Table 2.1). In the opposite case, where criterion i is less important than criterion j , the minimum and maximum values will be 1/9 and 1 respectively. However, if one criterion is sometimes more important and sometimes less important than another, then we allocate values of 1/9 and 9 to the minimum and maximum respectively. For the most likely value, in these three situations, this is determined according to the existing literature and the values most often used to compare the two criteria. Thanks to this approach, almost full uncertainty is allowed since only the relative importance between two criteria is decided, but the intensity of this relative importance is allowed in its full range (e.g from 1 to 9). In this matrix only the upper triangular part is filled, as shown in Table 2.3, because the only purpose of the robust PCM is to create normal PCMs that benefit from reciprocity property, as explained below.

	Criterion 1			Criterion 2			Criterion 3		
	min	most likely	max	min	most likely	max	min	most likely	max
Criterion 1	1	1	1	1/9	1/2	1	1	3	9
Criterion 2				1	1	1	1	6	9
Criterion 3							1	1	1

Table 2.3: Robust Pairwise Comparison Matrix.

Robust PCM to normal PCM

The aim of a robust Pairwise Comparison Matrix (PCM) is to establish standard PCMs by selecting random values from beta-PERT distributions for each criterion comparison. This process enables the creation of a standard PCM, based on which Analytic Hierarchy Process (AHP) can be conducted to derive weights for each criterion.

Given that comparisons between criteria are represented as distributions rather than single values, a random value is picked respecting the beta-PERT distribution to determine the relative importance between two criteria. This is how the upper part of the matrix is filled. The lower part being filled only using the reciprocity property explained in section 2.2.1.

Knowing that values in the normal PCMs are randomly taken from distributions of the robust PCM, the consistency must be verified to ensure the validity of the matrix. Therefore, we only take into account PCMs with a $CR \leq 0.1$. If a created PCM doesn't meet this condition, a new one is generated until it does.

2.4 Monte Carlo simulation

In order to propagate the uncertainty residing in the allocation of locations, we apply a Monte Carlo simulation of N iterations that allow us to generate N suitability indices overlays. QGIS overlays and the Monte Carlo loop we use in our simulation are explained below.

QGIS overlays

Once the weights and the reclassified layers of each criterion obtained from AHP, we are able to perform via QGIS a weighted sum of the different reclassified criteria, giving a final suitability index on a scale of 1 to 5 (because the weights range from 0 to 1 and their sum is 1), as shown on Figure 2.3.

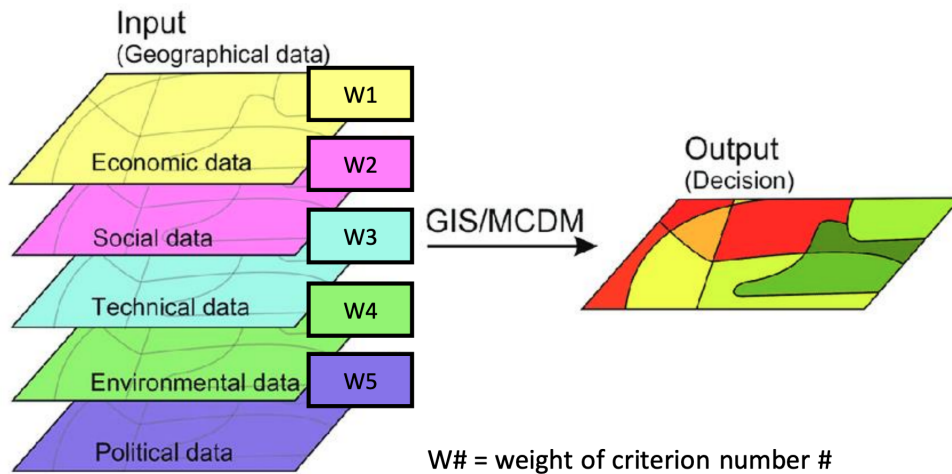


Figure 2.3: Weighted overlay of the different criteria, from [28].

Monte Carlo loop

Thanks to the robust PCM, we are able to run N iterations in our simulation, creating N normal PCMs with $CR \leq 0.1$, proceeding N AHP's, determining N sets of weights. Those weights and reclassified layers allow, thanks to weighted sums, to compute N suitability indices overlays, as explained on Figure 2.4.

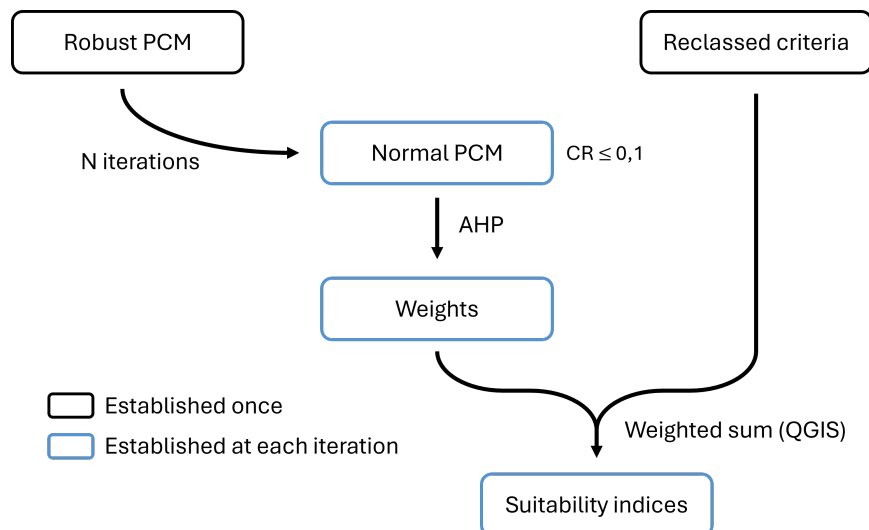


Figure 2.4: Monte Carlo loop. N normal PCMs are derived from the robust PCM. Each normal PCM leads to a set of weights through AHP. Combined with the reclassified criteria layers, the N sets of weights lead to N suitability indices overlays.

Stochastic weights

As a consequence, after the N iterations, the weight of each criterion is no longer a deterministic value but is shaped like a stochastic distribution.

In other terms, the distributions established at the beginning of AHP for the relative importance between two criteria based on Saaty's scale, are now propagated as distributions for each criterion's weight.

2.5 Selection of optimal locations

Selection based on mean suitability indices

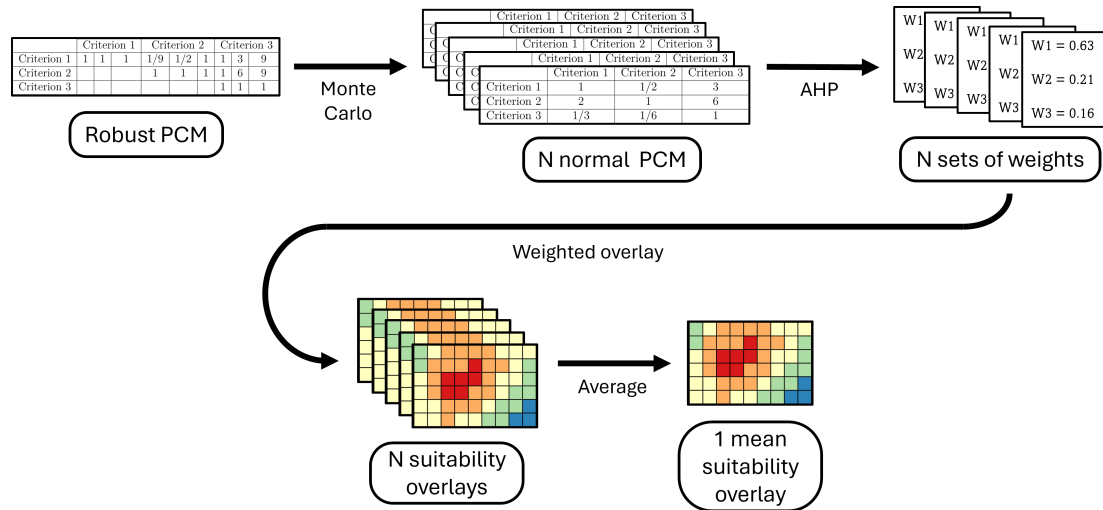


Figure 2.5: Robust PCM to mean suitability indices overlay. After running a simulation of N iterations, a mean suitability index can be computed for each pixel.

Then, depending on the size of the installation and therefore the surface area we wish to occupy, we can choose a surface area based on the surface area of a pixel and therefore a total number of pixels to take into account for an installation, for example a square of 2 x 2 pixels.

Once this has been determined, we look at the groups of pixels with the best average over the entire surface of the area under study. If we take 2 x 2 pixels area, we look at the groupings that obtain the best average over the 4 pixels within them.

Cumulative Distribution Functions analysis

To determine the optimal location, not only high suitability index is important. The optimal location must also have a low standard deviation for the suitability index after the N iterations have been performed. This way, the uncertainty regarding the suitability of this location is reduced. Therefore, a trade-off must be found between mean suitability index and standard deviation. Such trade-offs have already been discussed in the field of robust designs optimizations [29] and can be adapted to GIS analyses.

Knowing the best different groups of pixels, the cumulative distribution functions (CDF) of each group can be plotted based on the N suitability scores they got through the iterations. An analysis of the CDFs is performed on the selected locations, and a comparison between them is done to determine which location has the highest probability of having a high suitability score. By reducing the uncertainty, this analysis lowers the potential risks for the decision-makers and allows them to select a location depending on their risk aversion.

2.6 Capacity Factor analysis

One of the main challenges of coupling energy sources such as wind and solar power to electrolyzers is the fluctuation of input power. In fact, as those resources are intermittent, the power delivered to the electrolyzer is not constant. For a constant input power to the electrolyzer, it would be necessary to over-size the renewable production and store energy, which would incur additional costs. A varying power input may bring about two important issues related to the electrolyzer. Performance can significantly decrease (especially for Alkaline type electrolyzers, see Appendix A), and thermal management problems can also appear, which reduces the efficiency of the cell [9]. Therefore, it is preferable that the selected location has reasonable fluctuations of combined wind and solar energy yield. To analyze this, wind and solar capacity factors (CF) can be analyzed. They are defined to be the ratio between actual produced power output and installed power capacity. Wind and solar power can balance each other, since their profiles might not peak at the same times during the day. A metric called coefficient of stability can be computed based on their daily profiles, in order to quantify the daily synergy between wind and solar power. It is illustrated on Figure 2.6.

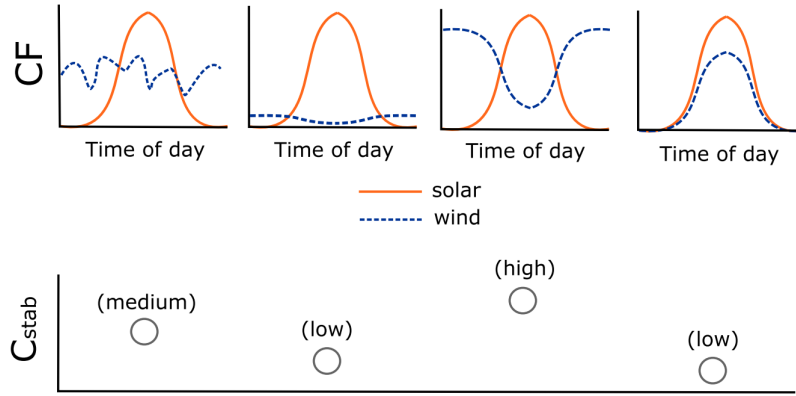


Figure 2.6: Schematic representation showing how the stability coefficient reflects the hybrid power output variability, from [30].

$C_{stab} = 0$ indicates no synergy between solar and wind sources and $C_{stab} = 1$ means that there is maximum synergy between both energy sources, meaning a flat daily output profile of solar-wind combination.

The stability coefficient can be computed mathematically as follows (from [30]):

$$C_{stab} = 1 - \frac{C_{v,mix}}{C_{v,sun}} \quad (1)$$

$C_{v,mix}$ and $C_{v,sun}$ are respectively the coefficient of variance of the hybrid wind and sun mix, and the one of the sun. $C_{v,mix}$ is based on a weighted average of solar and wind capacity factors. The coefficient of stability is thus a measure of the added value of wind power to balance daily photovoltaic (PV) electric power production.

To compute the proportion of solar and wind mixes in the hybrid site, an optimization is done in order to reduce the variability [31]. The variability of the following function, representing the total capacity factor, is minimized :

$$CF = a \times CF_{sun} + b \times CF_{wind}$$

a and b are the proportion of sun and wind respectively, and CF_{sun} and CF_{wind} are the capacity factors for every hour of the year 2019 for sun and wind respectively. This is minimized so that the total capacity factor has a minimum variability, under the constraint that $a + b = 1$.

3 Case study

The robust methodology is tested on the geographic area of Morocco. In fact, the belgian Hydrogen Import Coalition [2] showed that Morocco is a competitive location for hydrogen import to Belgium, mainly due to its proximity and to the abundant renewable energy sources on its territory. Also, Morocco plans on developing its green hydrogen production in the next years. In fact, 3000 km² will be made available by Morocco to investors [32], both domestic and foreign. Next phases will go up to 10 000 km² [32]. For our case study, three scenarios will be considered. First, the optimal location for a green hydrogen production plant will be studied in the case of export of hydrogen to Belgium via ships from existing seaports (scenario 1). Then, we will study possibility of export via pipelines to the north of Morocco (scenario 2). Finally, we will study the optimal location for a scenario in which there is no focus on the potential export (scenario 3). For the third scenario, once the best location determined, an economic analysis can be performed to determine the best export way.

3.1 Criteria

Previous literature has already discussed and established different criteria for solar and wind farms [18]. Some criteria must be added in order to find the best suitable locations for hydrogen production, such as proximity to waterbodies for example [33, 34]. The criteria we will take into account for our case study are explained in this section, and are referenced in Table B.1.

Several scenarios will then be studied, and for each scenario, a subset of all criteria will be used for the simulation. Discussions with the company DEME Group also helped us in establishing the most relevant criteria to be considered, and the threshold values for the exclusion of pixels.

Global Horizontal Irradiance: Since we want to generate electricity from renewable resources, solar power comes as an obvious solution. Morocco is a country with a high Global Horizontal Irradiance (GHI). In fact, with an annual GHI values between 1430 kWh/m²/year and 2265 kWh/m²/year [4], Morocco can be considered as a highly irradiated region [35].

Wind speed: The annual average wind speed also plays a crucial role in assessing the economic feasibility and technical viability of potential wind farm sites. Morocco has a significant wind energy potential due to its favorable climate proximity to the Atlantic Ocean, and temperature conditions [36]. Following the literature, the current research work considers a minimum average wind speed of 3 m/s at a height of 100 m [33, 37]. Below this value, wind turbines usually don't produce electricity. Therefore, locations with an average wind speed lower than 3 m/s are excluded, which represents 2.3% of the total area of Morocco (10 230 km²).

Slope: Slope is important to take into account, as locations with high slopes induce higher construction and maintenance costs [33]. Therefore, as discussed with DEME, locations with slopes higher than 5° must be excluded. That represents 28.9% of the total area of Morocco (126 720 km²).

Distance to roads: Being close to the road network has quite some importance since it implies more accessibility for transportation of equipment and materials to the site, reducing costs associated with maintenance and construction [33]. Also, as the produced hydrogen can be transported on trucks towards seaports, roads proximity is important. The distance to roads, as well as the other distances discussed hereafter are computed as the crow flies. Locations too far from the road network were excluded, as the construction of new roads would result in high capital expenditures. Therefore, according to DEME's thresholds, locations further than 100 km from existing roads are excluded.

Distance to seaports: The distance to seaports must also be considered. As the final goal is to export hydrogen to Belgium, it is important to reduce transportation costs from the production site to the closest seaport [38]. Only the commercial ports [39] were taken into consideration.

Distance to northern Morocco : As the goal is to export hydrogen to Belgium, locations far from the north of Morocco are penalized in case of export via pipelines because we assume a pipeline connection in the north of Morocco.

Distance to powerlines: Proximity to the powerlines has two purposes: to feed excess renewable generation into the grid and to feed power from the grid to the electrolyser when local renewable generation is insufficient, as those sources are intermittent [34]. Locations too far from the powerlines were excluded, as the construction

of long powerlines would result in high capital expenditures. Therefore, locations further than 100 km from existing powerlines are excluded (DEME).

Distance to coastline: The availability of water is also a major criterion to determine the optimal location for a green hydrogen production plant. In fact, electrolysis requires water to produce hydrogen. But DEME highlighted the fact that water is also needed in order to cool the electrolyzers, which makes the total consumption of water for electrolysis significant. Morocco is a water-scarce country, its water resources are limited and irregular in time and space [40]. Using water from rivers and other hydrographic networks would then just cause other problems, scarcity for local populations and difficult water management in some regions. Therefore, the only viable solution is to use seawater. This is not a concern since the desalination of water is relatively cheap (around 1 USD/m³) and adds about 0.01 USD/kg_{H₂} to the production cost of hydrogen [41, 42], which is expected to fall between 1.4 USD/kg_{H₂} and 2.3 USD/kg_{H₂} by 2030 [43].

The references for the gathered GIS data are available in Appendix B in Table B.1 and maps corresponding to criteria are illustrated on Figure 3.1 and Figure 3.2.

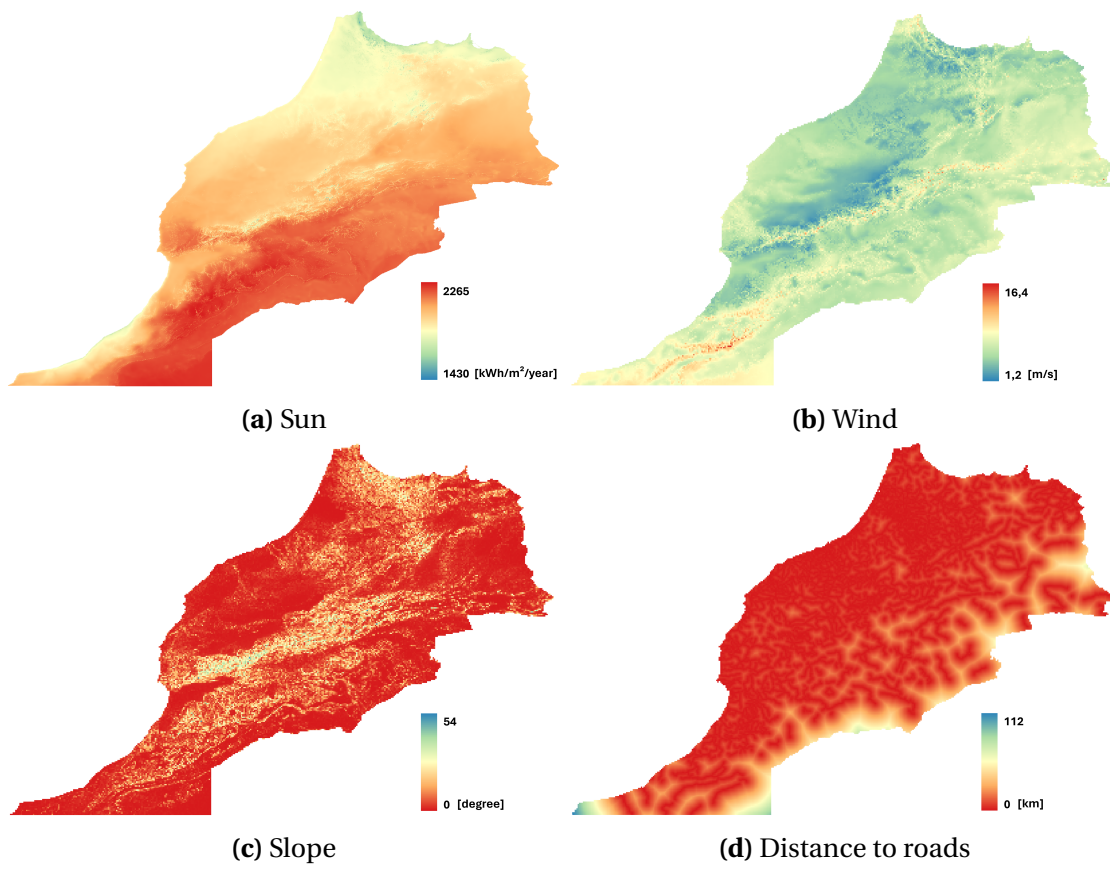


Figure 3.1: Criteria and scales.

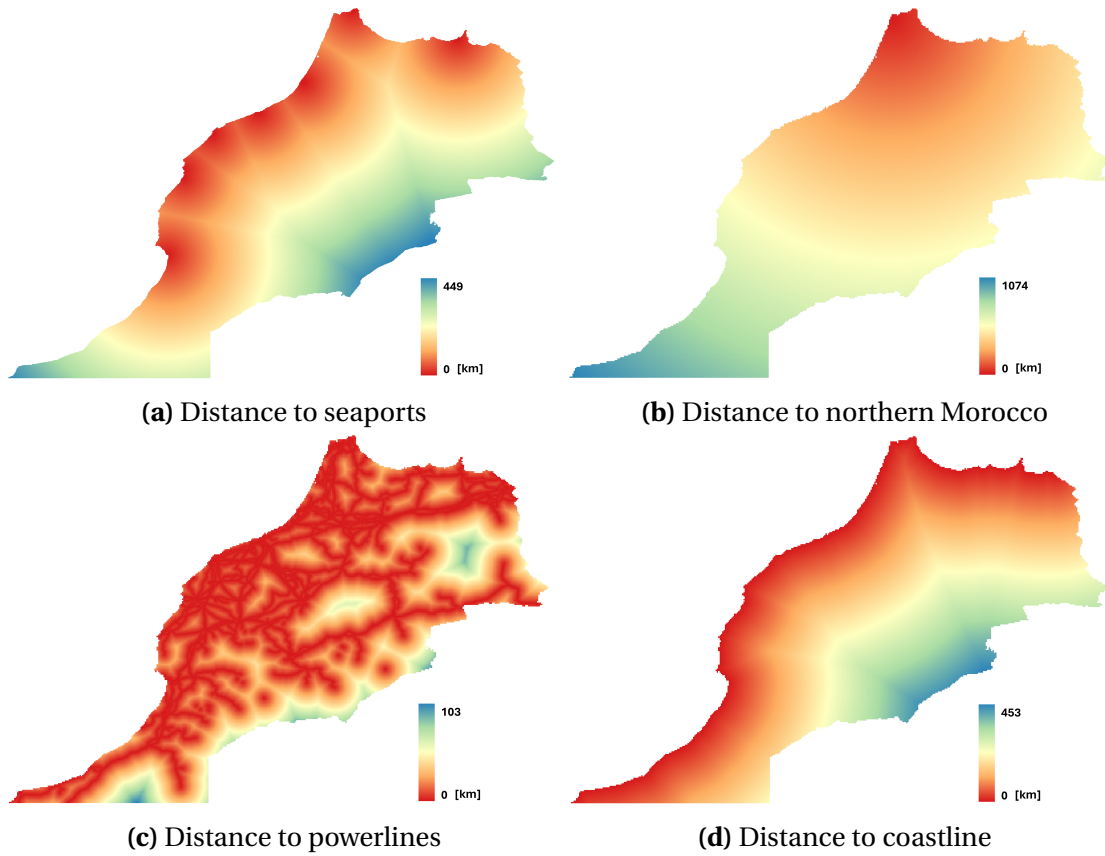


Figure 3.2: Criteria and scales (continued).

3.2 Exclusion areas

Apart from the exclusions for several criteria discussed in the previous section, some other areas must also be excluded, following the discussion with DEME.

Land use: General exclusion of urban areas, forests, farmlands, wetlands, water, snow and ice areas.

Military zones: Military zones of any purpose are excluded.

Protected areas: Protected areas are considered not suitable at all in order to protect wildlife and biodiversity [18]. Protected areas include national parks, wilderness, marine protection areas, heritage sites and other similar areas.

Airports: Solar panels and wind turbines can create interference with radar signals, distract pilots' vision, and lead to issues with air traffic monitoring [18, 44]. Therefore,

a general exclusion zone for locations closer than 5 km to airports was adopted.

Density of population: In order to avoid rejection of public opinion, delocalization of local inhabitants, and visual disturbance, locations with a density of population that is higher than 150 people/m² are excluded.

There are two types of exclusion in this work. The first one is a value exclusion, meaning a pixel is excluded if its value is below or above a critical value (e.g. wind speed below 3 m/s). The second one is a geographical exclusion if the pixel is located in an unsuitable area (e.g. protected area).

The references for the gathered GIS data are also available in Appendix B in Table B.1.

After taking into account the threshold values for some criteria and all the exclusion zones mentioned above, we get a map of Morocco depicting all suitable areas. This remaining area is about 240 000 km² which represents 54.8% of the total area of Morocco. The rest of the analysis will be about determining which are the optimal locations amongst the considered area.

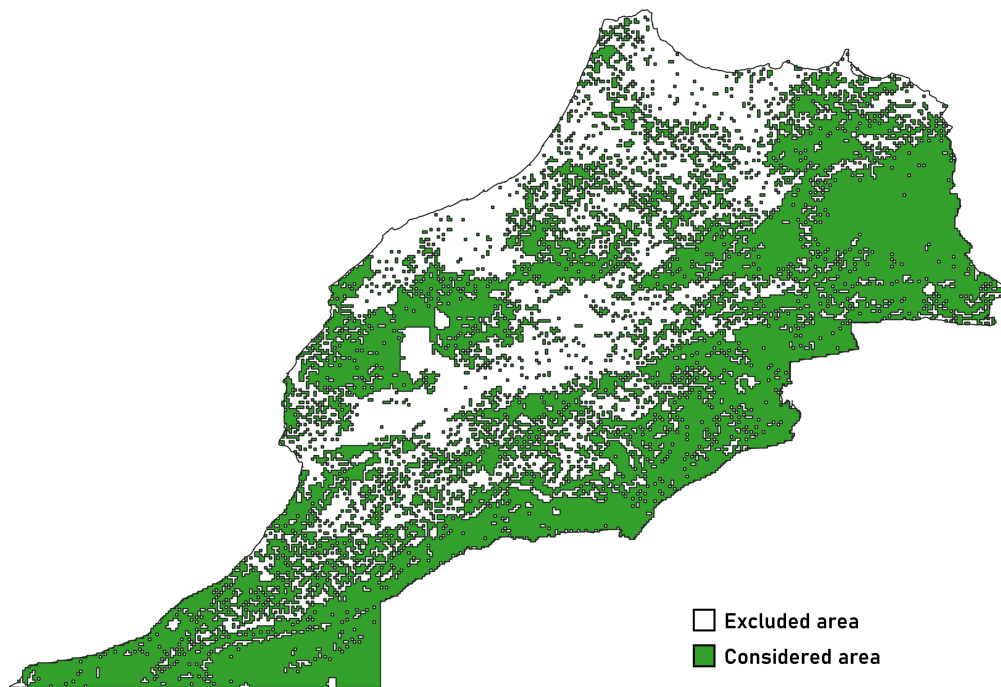


Figure 3.3: Map of Morocco after applying the exclusion criteria.

3.3 Reclassing

As explained earlier, values for each criterion have to be reclassified into an adimensional score from 1 to 5, in order to be able to do a weighted sum of all criteria.

The different criteria value ranges are reclassified following the literature. When the reference is missing, it means we divided the total range into 5 equal ranges. For example for slope, slopes above 5 degrees are excluded, but it is still preferable to have a flat location than a location of 4 or 5 degrees inclination. We therefore reclass this criteria linearly from 1 to 5.

For seaports proximity, no such reclass exists in the literature, because it is specific to the export of hydrogen through seaports. We therefore simply divided the total range into 5 equal ranges, meaning locations further from seaports have gradually smaller scores for this criterion. The same is applied for proximity to coastline. Once this reclassing has been done for all the different criteria, the weighted overlay can be performed for each simulation and we can get the maps showing the overall global suitability indices corresponding to each simulation. The exact reclassing of all criteria is given in Table 3.1.

Criteria	1	2	3	4	5	Reference
Global Horizontal Irradiance [kWh/m ² /year]	<1816	1816-1925	1925 - 2050	2050 - 2175	>2175	[35]
Wind Speed [m/s]	3-4	4-5	5-6	6-7	>7	[37]
Slope [deg]	4-5	3-4	2-3	1-2	0-1	
Distance to roads [km]	>20	15-20	10-15	5-10	<5	[37]
Distance to seaports [km]	>380	285-380	190-285	95-190	<95	
Distance to powerlines [km]	> 20	15-20	10-15	5-10	<5	[37]
Distance to northern Morocco [km]	> 860	645-860	430-645	215-430	< 215	
Distance to coastline [km]	>400	300-400	200-300	100-200	<100	

Table 3.1: Reclassing of the criteria.

It is noticeable that the values for GHI are objectively high, even for a score of 1. But as DEME highlighted, the renewable resources should be the main driver to select an optimal location. Therefore, GHI should still be ranked from 1 to 5 to make sure to distinguish good from excellent locations regarding this criterion. Here, it is assumed that wind speed and GHI have the same importance, which results in a global renewable potential reclass (Figure 3.4c) being the mean of reclassified scores of wind speed and GHI. This is a rough approximation, because for instance a location with very good wind and bad solar irradiance would have a bad renewable potential score (since it is the average of both), but could potentially produce a good amount

of electricity from wind energy only. This approximation is appropriate for a first analysis, but deeper analysis must be further investigated to assess more accurately the potential energy yield of different locations. This will be developed in section 4.5. The reclassified criteria are displayed as maps and illustrated on Figure 3.4 and 3.5. The colors scale is given on Figure 3.5d. The worst score is 1 and the best is 5.

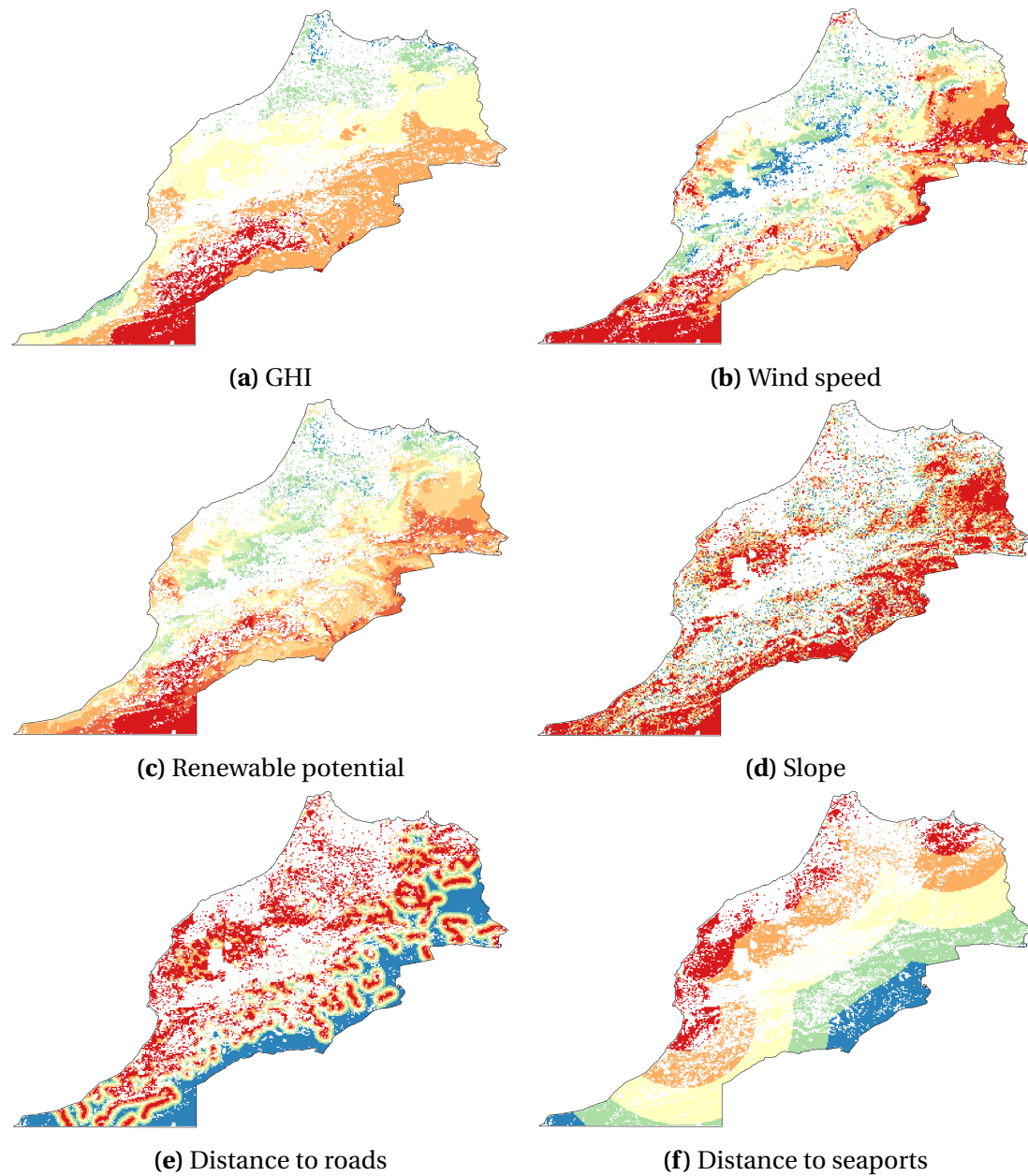


Figure 3.4: Reclassed criteria.

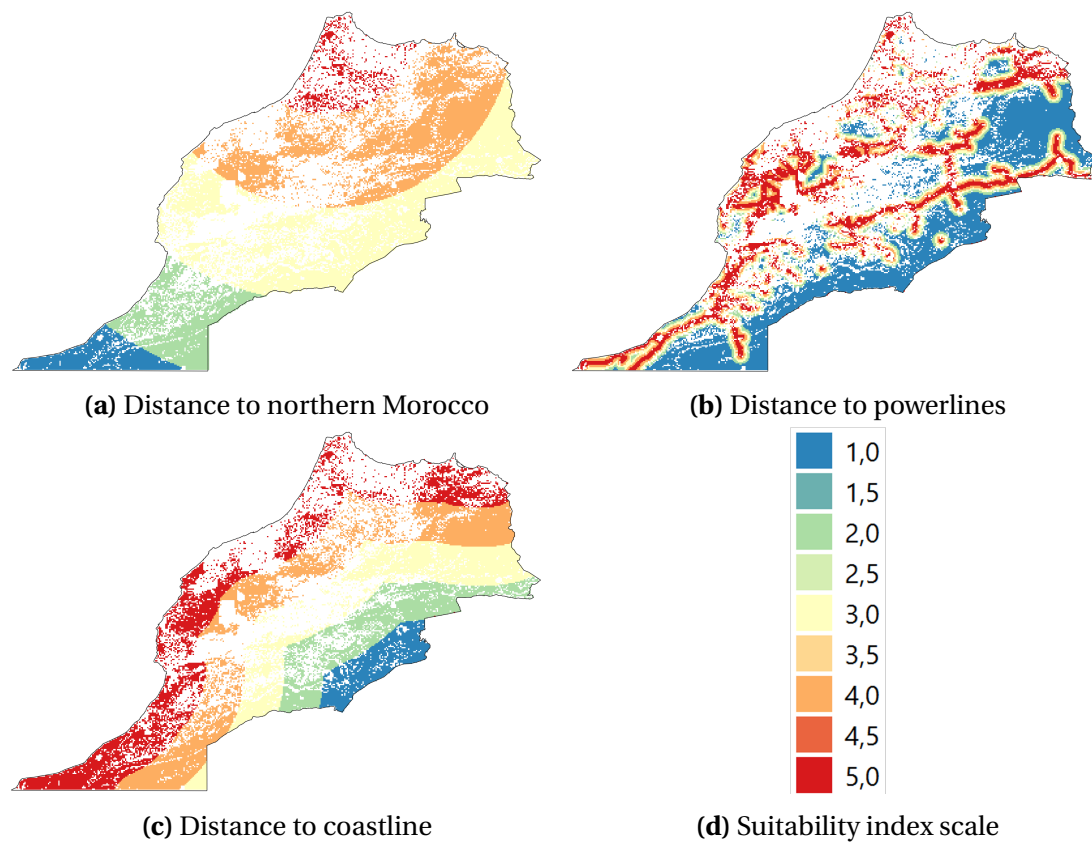


Figure 3.5: Reclassed criteria (continued).

3.4 Scenarios

For scenario 1, which is to export hydrogen from Morocco to Belgium via ships, we consider the criteria shown in Table 3.2.

	Scenario 1 : export via seaports	Scenario 2 : export via pipelines	Scenario 3 : non export focus
Renewable potential	×	×	×
Slope	×	×	×
Dist. to roads	×	×	×
Dist. to seaports	×		
Dist. to northern Morocco		×	
Dist. to powerlines	×	×	×
Dist. to coastline	×	×	×

Table 3.2: Criteria taken into account for each scenario.

For scenario 2, which is to export hydrogen from Morocco to Belgium via pipelines, the proximity to seaports is discarded and the focus is set on pipelines solutions. The only criteria changing is the proximity to seaports.

It is important to mention no hydrogen pipeline exists at the moment in Morocco. Hydrogen can be transported in a mix with natural gas (with a 15% blend [45]) and therefore using already existing natural gas pipelines infrastructure. But the existing infrastructure linking Algeria to Spain the "Maghreb-Europe" pipeline, is only passing through the North-Eastern region of Morocco [35].

However, for the transportation of 100% hydrogen (pure hydrogen), retrofitting of natural gas infrastructure is necessary to prevent the risk of leakage [46]. So far, there is no proper hydrogen pipeline infrastructure in Morocco. New infrastructure must be financed and we therefore also consider the distance to northern Morocco, since the cost of pipeline infrastructure can be considered linear with the length of pipeline, and locations in the south of Morocco should therefore be penalized. The criteria taken into account for this scenario are also displayed in Table 3.2. But as the cost of a new dedicated hydrogen pipeline is considerably higher than the cost of transport towards seaports, the relative importance of the distance to the north of Morocco has more significance in the PCM for scenario 2, than the importance distance to seaports had in scenario 1. In fact, the cost of repurposing existing pipelines is estimated to

0.5M€/km CAPEX. For a new dedicated hydrogen pipeline, those amounts can go up to 2.8M€/km CAPEX [45].

Scenario 3 is about finding the optimal location, without considering a particular way of exporting hydrogen. Consequently, this scenario mirrors the two first scenarios, except for the exclusion of the criterion regarding export.

Pairwise Comparison Matrices

In section 2.2.1, the need to establish the minimum, most likely, and maximum values in order to set the distribution reflecting the relative importance between two criteria was discussed. While exact values may be uncertain, it can still be decided if one criterion is generally more important than another.

This approach gives us a clear method to gauge the importance of criteria, even when exact values might be uncertain. Regarding the most-likely values, they are established from literature [33, 34, 47, 48, 49] in which they were set as deterministic values for relative importance between criteria.

Tables 3.3, 3.4 and 3.5 are the robust PCMs we established in order to create to create normal PCMs for scenario 1, 2 and 3 respectively.

The three values for each comparison are the minimum, most-likely and maximum values respectively.

	Renewable potential			Slope			Distance roads			Distance seaports			Distance powerlines			Distance coastline		
Renewable potential	1	1	1	1	7	9	1	6	9	1	5	9	1	7	9	1	6	9
Slope				1	1	1	1/9	1/5	1	1/9	1/3	1	1/9	1/5	1	1/9	1/7	1
Distance roads							1	1	1	1/9	1/3	9	1	5	9	1/9	1/4	9
Distance seaports										1	1	1	1	7	9	1/9	1/5	9
Distance powerlines													1	1	1	1/9	1/5	9
Distance coastline																1	1	1

Table 3.3: Robust PCM for scenario 1.

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	Renewable potential			Slope			Distance roads			Distance northern Morocco			Distance powerlines			Distance coastline		
Renewable potential	1	1	1	1	7	9	1	6	9	1	3	9	1	7	9	1	6	9
Slope				1	1	1	1/9	1/5	1	1/9	1/5	1	1/9	1/5	1	1/9	1/7	1
Distance roads							1	1	1	1/9	1/5	1	1	5	9	1/9	1/4	9
Distance northern Morocco										1	1	1	1	7	9	1	7	9
Distance powerlines													1	1	1	1/9	1/5	9
Distance coastline																1	1	1

Table 3.4: Robust PCM for scenario 2.

	Renewable potential			Slope			Distance roads			Distance powerlines			Distance coastline		
Renewable potential	1	1	1	1	7	9	1	6	9	1	7	9	1	6	9
Slope				1	1	1	1/9	1/5	1	1/9	1/5	1	1/9	1/7	1
Distance roads							1	1	1	1	5	9	1/9	1/4	9
Distance powerlines										1	1	1	1/9	1/5	9
Distance coastline													1	1	1

Table 3.5: Robust PCM for scenario 3.

4 Results and discussions

In this section, the stochastic weights for the three scenarios will be shown and discussed. Then, the averaged suitability indices overlays are presented and analyzed. A general screening of the total surface area of Morocco will be performed to identify the high suitability index clusters. Then, a selection of the optimal locations having a specific area is made based on the best mean suitability indices, and then the CDFs are generated to include the analysis of standard deviations. Finally, for the selected location for scenario 1, the wind and solar capacity factor profiles are analyzed to assess the complementarity of a combined hybrid wind and solar farm at this location.

4.1 Weights

On Figure 4.1, the different criteria weights are distributed as probability density functions for the three scenarios. The renewable potential consistently holds the highest importance among the criteria, as anticipated. In fact, this criterion dominates all other criteria in the PCMs since it is a prerequisite to have good renewable potential for an optimal location. Additionally, we observe that the stochastic weight assigned to the slope criterion is almost consistently the smallest. This is because slope is a less important criterion in the different PCMs since slopes above 5 degrees are already excluded.

Other criteria reflect well uncertainty as their distributions are overlapping. This means some of them are sometimes less important than others, but have some probability of being more important.

The fact that transporting hydrogen via pipelines to the North of the country (meaning building new pipelines) is way more costly [45] than to transport it to Moroccan seaports is well reflected on the weights distributions. In fact, we observe a clear shift of importance for the distance to seaports on Figure 4.1a for scenario 1, to the distance to northern Morocco on Figure 4.1b for scenario 2.

For scenario 3 (Figure 4.1c), there is no clear change in weights importances compared to the other scenarios, except for the fact that renewable potential carries even more importance. This reflects indeed the fact that for the third scenario, no attention

is paid to the export of hydrogen, but only for the optimal location to maximize cost-efficiency of hydrogen production only.

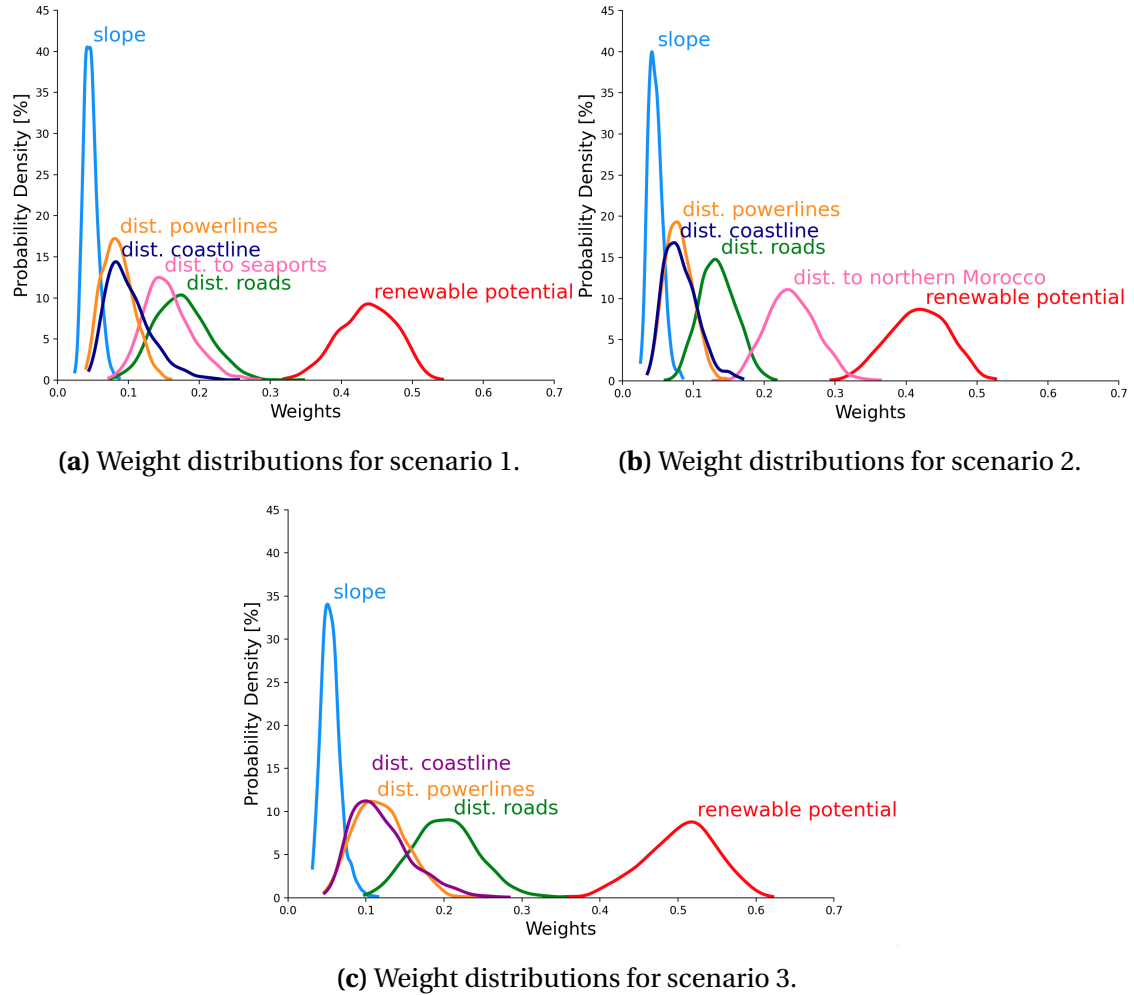


Figure 4.1: Weights probability density functions for the three scenarios. Renewable potential has always the highest mean weight, and slope the lowest. Distance to northern Morocco (Figure 4.1b) gets more importance than distance to seaports (Figure 4.1a).

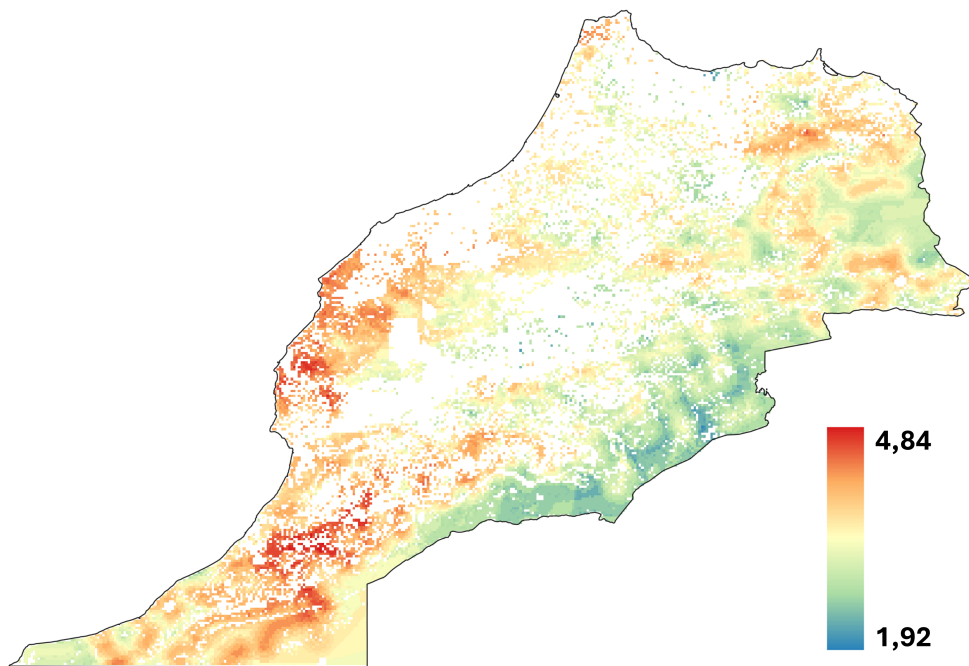
Those stochastic weights distributions are used to compute the weighted overlays.

4.2 Mean suitability indices overlays

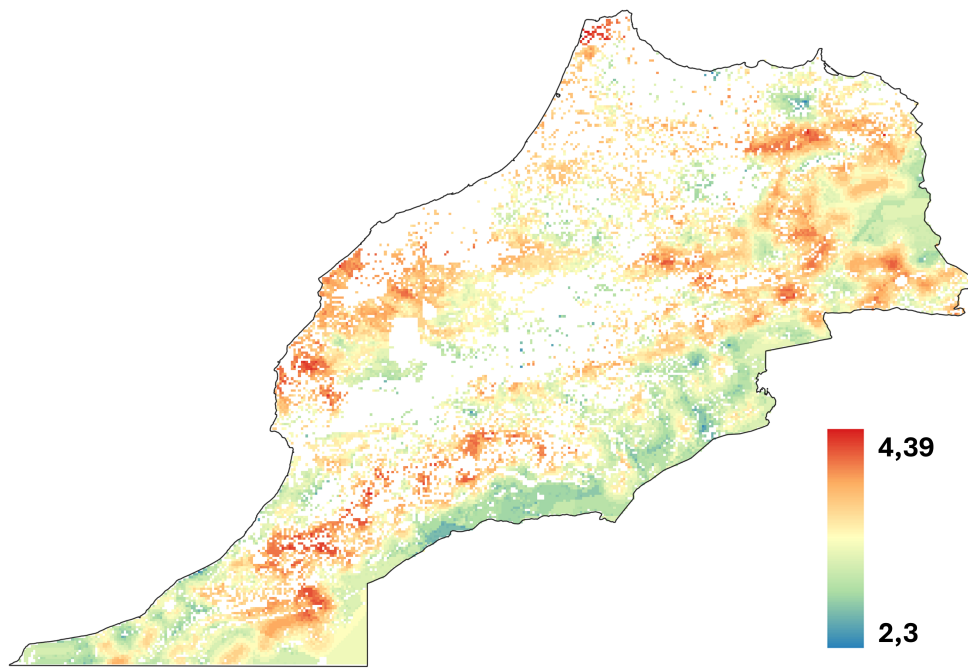
The three resulting overlays are displayed on Figure 4.2. On those overlays, the value of each pixel is the average of the suitability indices it has achieved through the 1000 iterations of the Monte Carlo simulation.

The Monte Carlo simulation has indeed converged after 1000 iterations, as shown in Appendix D. When comparing scenario 2 (Figure 4.2b) to scenario 1 (Figure 4.2a), we see that the locations in the North tend to be part of the best locations in scenario 2. This is explained by the importance of being close to north of Morocco, as explained before. The best locations in scenario 1, located more in the south, are strongly penalized in scenario 2 by this criterion and achieve lower suitability indices.

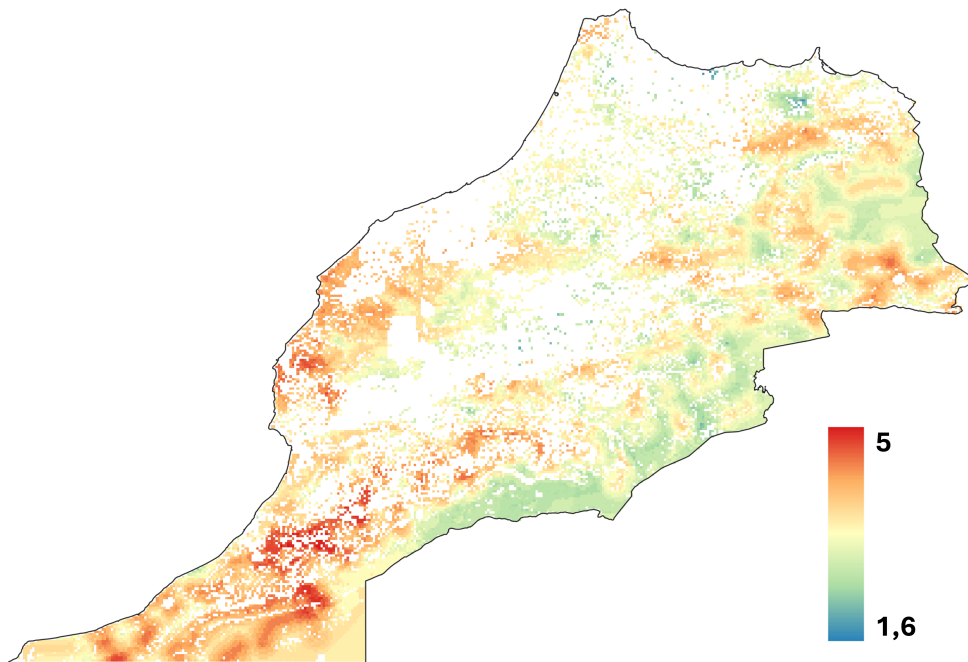
Also, when comparing scenario 3 (Figure 4.2c) to scenario 1, we notice that the locations in the far South are the best and achieve better suitability indices than in scenario 1. This is explained by the fact that there is a good renewable potential in this region and they are no longer penalized for being far from seaports or northern Morocco, because those last criteria are not taken into account for scenario 3.



(a) Scenario 1 : export via seaports.



(b) Scenario 2 : export via pipelines.

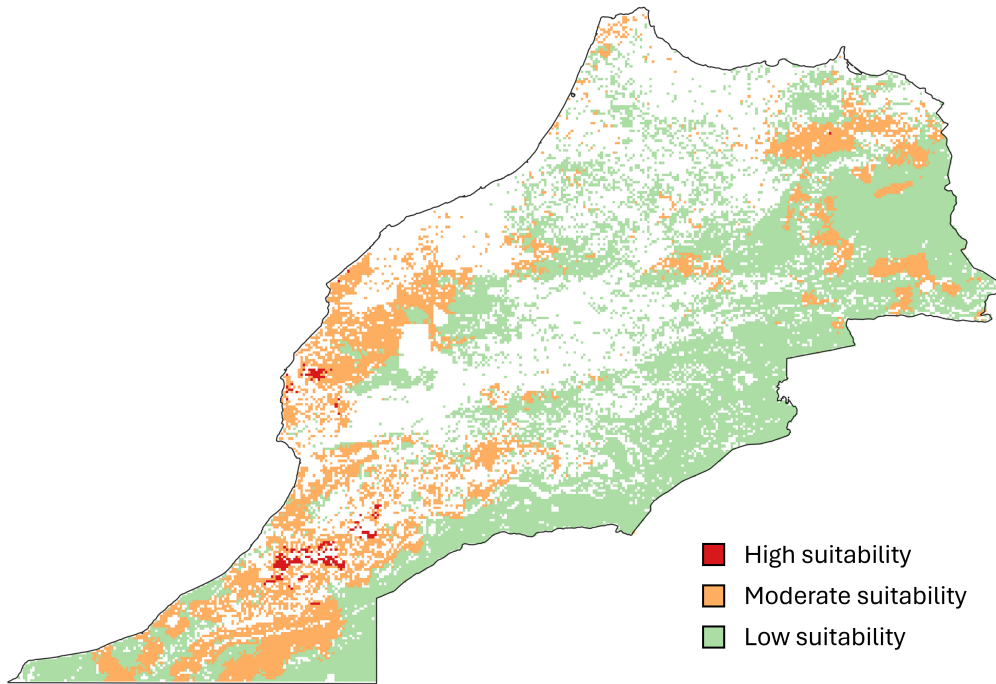


(c) Scenario 3 : non-export focus.

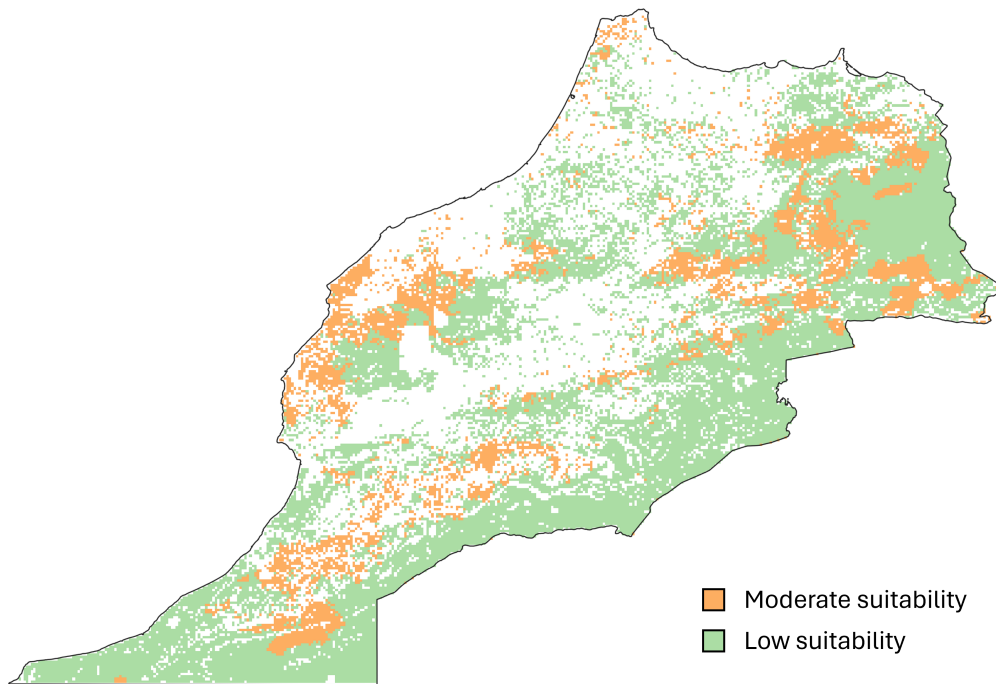
Figure 4.2: Average suitability indices maps for the three scenarios. Locations in the North have a better average suitability index in scenario 2 (Figure 4.2b) than in scenario 1 (Figure 4.2a). Locations in the far south have a better average suitability index in scenario 3 (Figure 4.2c) than in scenario 1 (Figure 4.2a).

4.3 General map screening

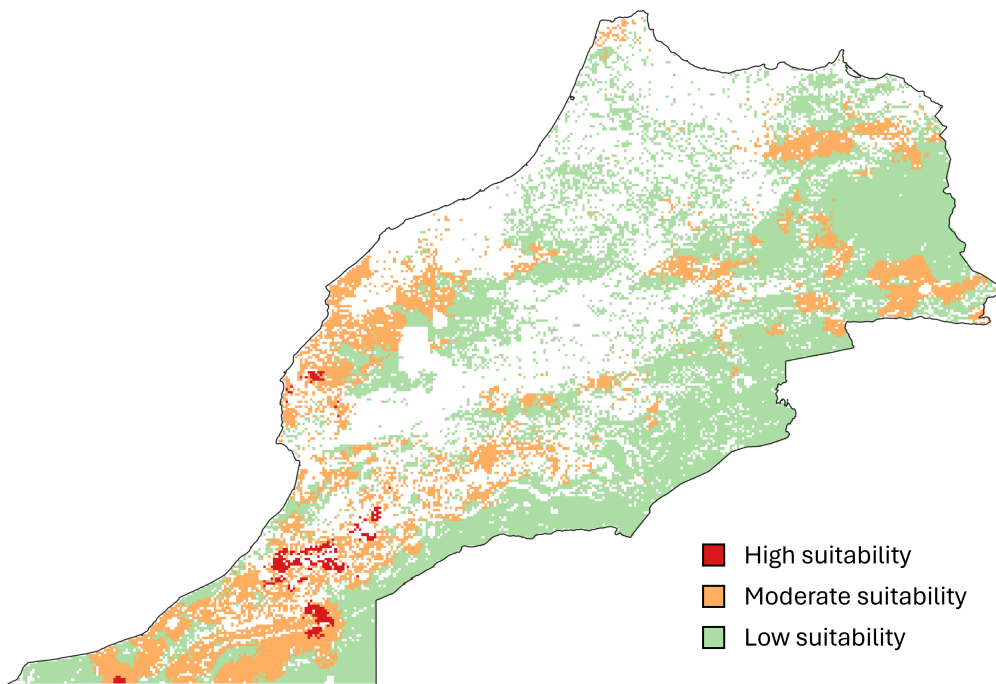
Analysis of suitability indices can be performed to find optimal regions in Morocco. The objective in this section is to identify areas with a high probability (95%) of having suitability scores above 4.5. The suitability indices percentile maps (Figure 4.3) classify areas into high (red), moderate (orange), and low (green) suitability.



(a) Scenario 1 : export via seaports.



(b) Scenario 2 : export via pipelines.



(c) Scenario 3 : non-export focus.

Figure 4.3: General screening of Morocco. The locations have been reclassified in three categories based on their average suitability index percentile of 95%: high suitability (> 4.5), moderate suitability (3.5-4.5) and low suitability (< 3.5).

For scenario 1 (Figure 4.3a) a cluster is found in west-central Morocco. This location is in fact favorable for criteria such as closeness to seaports, roads and powerlines (see Figure 3.4 and Figure 3.5). There is another cluster more south, which is favorable due to its high renewable potential. The highly suitable regions represent 2100 km² which corresponds to 0.47% of the total area of Morocco.

For scenario 2 (Figure 4.3b), there are no high suitability locations. Locations in the south, which have the best renewable potential, are penalized for being far from pipeline connection of northern Morocco. This is also reflected on Figure 4.2b: the best mean suitability index was only 4.39.

For scenario 3 (Figure 4.3c), there is a similar cluster as in scenario 1 in west-central Morocco. Another compact cluster of highly suitable locations is located even more further south than in scenario 1. This is because the renewable potential is even better and there is no more penalization for being far from a seaport. The high suitable regions represent 3200 km² which corresponds to 0.72% of the total area of Morocco.

This cluster analysis allows to highlight the regions of Morocco where the installation of a green hydrogen production plant would be optimal, regardless of the size of the plant.

4.4 Site-specific location allocation

An additional analysis can determine the optimal location for a project with a specific installation area. To perform the selection of the most suitable locations, we must first define the required area of the installation. In this case study we will work on a base of 90 km². This is an arbitrary value, but based on the order of magnitude of DEME's recent project in Oman [50], and in the order of magnitude of the lots awarded by the Moroccan government in their green hydrogen plan [51]. It is important to note that this area is a parameter that can be changed if looking for an optimal location with another specific area.

With a square pixel area of 10 km², this corresponds to 9 pixels and we decided to look for a 3 pixels square area for our installation. The reason for taking pixels of 10 km² (and not directly 90 km²) is to have more flexibility in the shape of the optimal location, and also to be more precise for the exclusion areas. As the study is being carried out over the whole of the Moroccan territory, the total surface area is quite large, and so the use of 10 km² pixels is a good compromise between flexibility, precision and the

scale of the study. The area of Morocco is then divided into about 24,000 pixels of 10 km².

4.4.1 Selection based on mean suitability indices

Then based on the mean suitability indices overlays of section 4.2, we look for the five best groups of pixels by computing their mean suitability index among the 9 pixels.

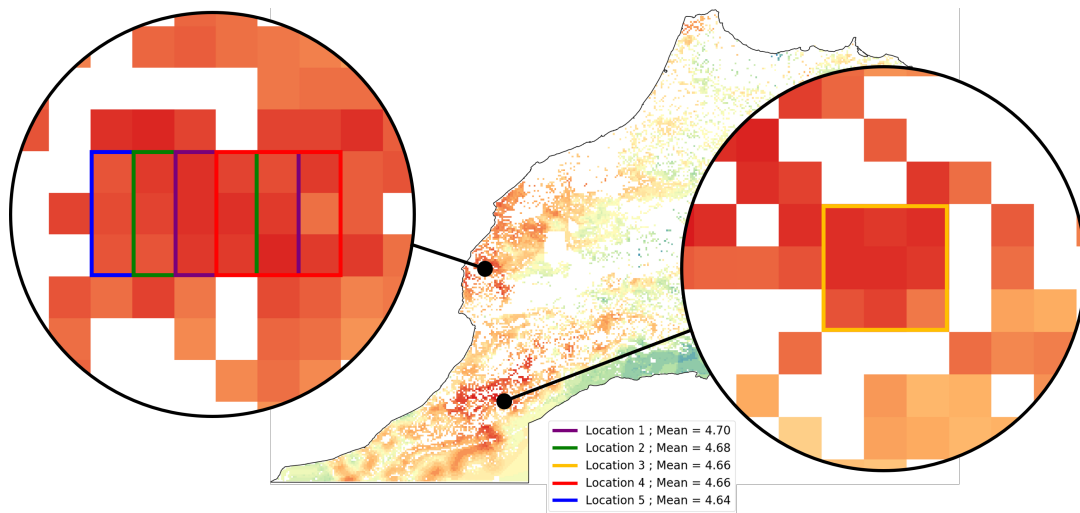


Figure 4.4: Five best locations in Scenario 1.

For scenario 1 (Figure 4.4), four of the five locations are located next to each other. The relevance of this zone can be explained by the fact that it is located in an area with strong renewable potential, and also close to a seaport leading to locations with suitability indices of 4.70, 4.68, 4.66 and 4.64. Location 3 is located in an area further away from the seaports but with a better renewable potential, more in the south of Morocco, with a suitability score of 4.66. The best locations are situated in the highly suitable clusters identified in section 4.3.

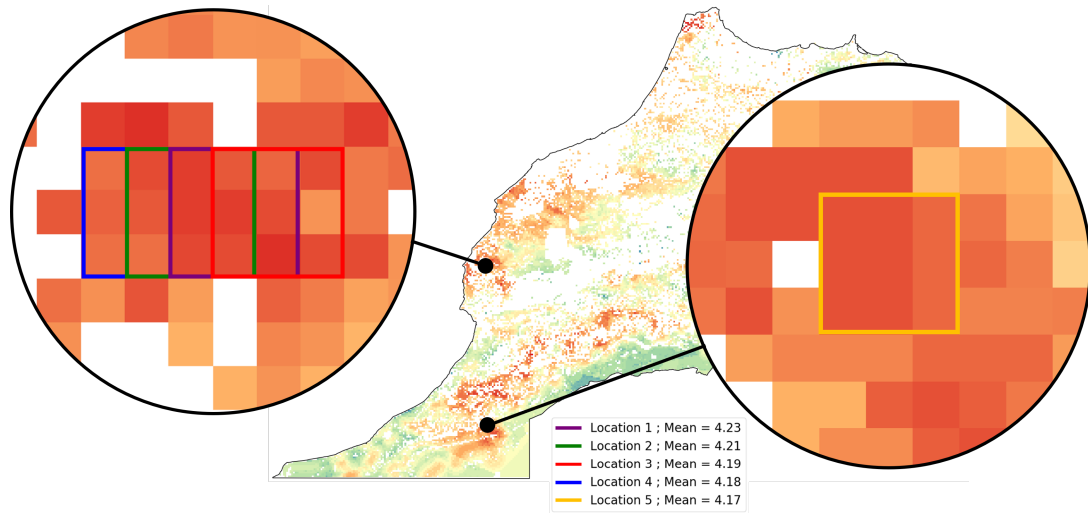


Figure 4.5: Five best locations in Scenario 2.

For Scenario 2 (Figure 4.5), the same four locations as in Scenario 1 come again but with suitability scores of 4.23, 4.21, 4.19 and 4.18. This may come as a surprise, given that we aim to focus on export via pipelines to northern Morocco. This should lead us to more northerly locations. As we specified in section 4.4, the best scores for this scenario are achieved in the north of Morocco, because it has good renewable potential and also a minimum distance to northern Morocco. However, the various exclusions we have made lead to many excluded pixels in this area, which means that we cannot bring together a group of 9 pixels in this region, as illustrated on Figure 4.6. If smaller areas for optimal locations were chosen, perhaps an optimal location would have been allocated in this region.

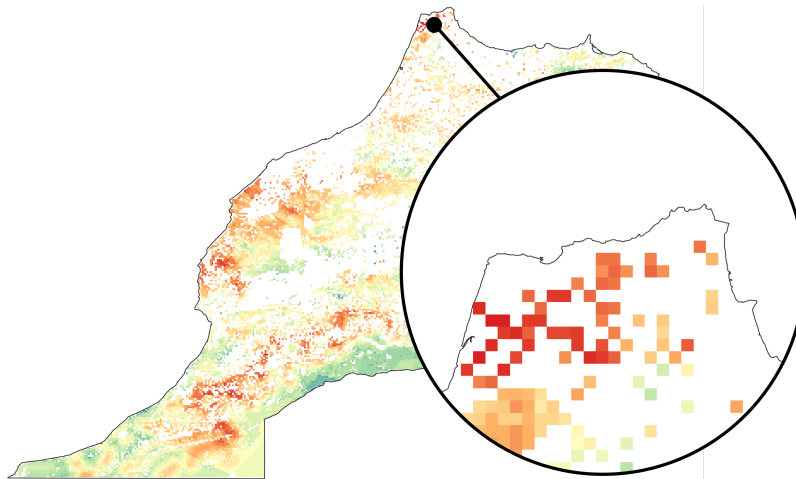


Figure 4.6: North of Morocco in Scenario 2.

Since there are no groups of pixels with a better suitability score more in the north, four locations of scenario 1 (locations 1, 2, 4 and 5) come back as being considered among the five best locations for scenario 2. Should these locations ultimately be selected for our installation, it would be preferable to opt for export via seaport rather than via pipeline, given the cost of installing hydrogen pipelines from there to northern Morocco. And this is reflected in the suitability scores for these locations in those 2 scenarios where higher mean suitability indices are achieved for scenario 1 than for scenario 2.

Location 5 is a little further south than location 3 in Scenario 1 and has a suitability index of 4.17. It seems even more surprising considering locations far from the north are penalized in this scenario. This may in fact be explained by the fact that this group of pixel has the same score for distance from northern Morocco as the location in scenario 1, but with a lower reclass score in terms of distance to seaports. As a result, it was penalized for this in scenario 1, but no longer in scenario 2, making it a potential best location for scenario 2.

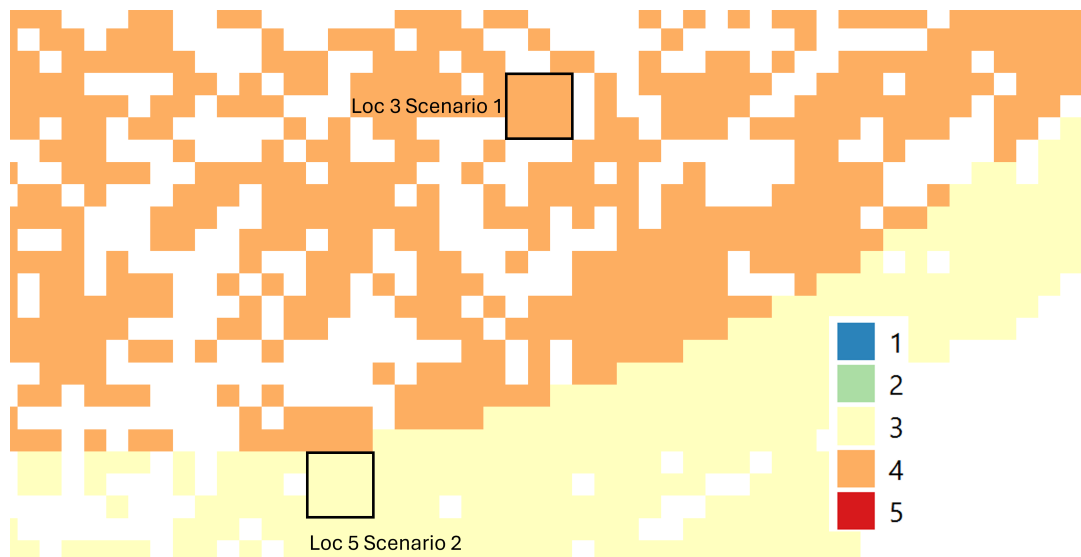


Figure 4.7: Distance to seaport reclass overlay.

As there were no highly suitable clusters identified in section 4.3, the best locations for scenario 2 are situated in the moderately suitable area.

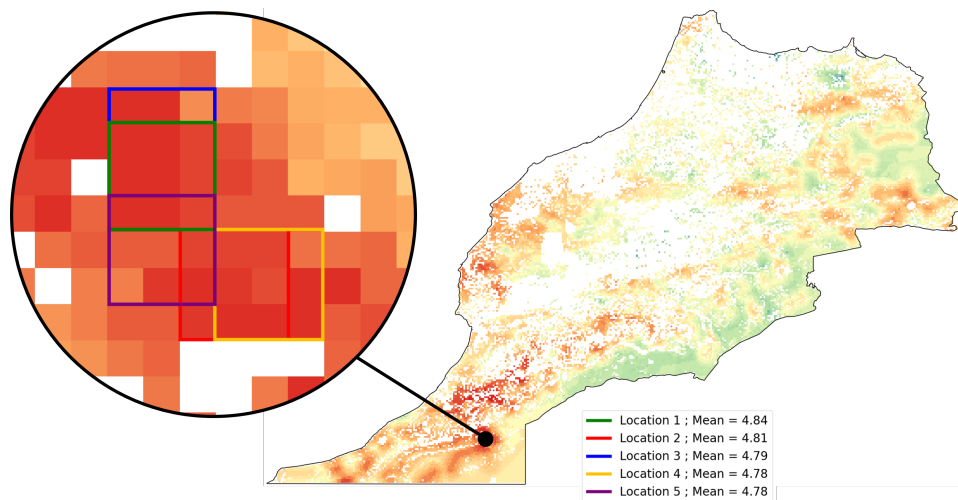


Figure 4.8: Five best locations in Scenario 3.

Looking at this last scenario (Figure 4.8), which focuses simply on production and not on export, all the best locations are in the same area. This area is obviously targeted for its optimal renewable potential in the Moroccan territory and presents

then an ideal place to produce green hydrogen. This leads to good suitability indices of 4.84, 4.81, 4.79 and 4.78.

Again, the 5 best locations are situated in the compact southern cluster of highly suitable locations identified in section 4.3.

4.4.2 Cumulative Distribution Functions analysis

The CDFs of the five best locations for each scenario are analyzed. They provide visual representation of the trade-offs between the mean suitability index and the variability for each location, allowing decision-makers to select a location that aligns with their risk preferences.

Scenario 1 : Export via seaports

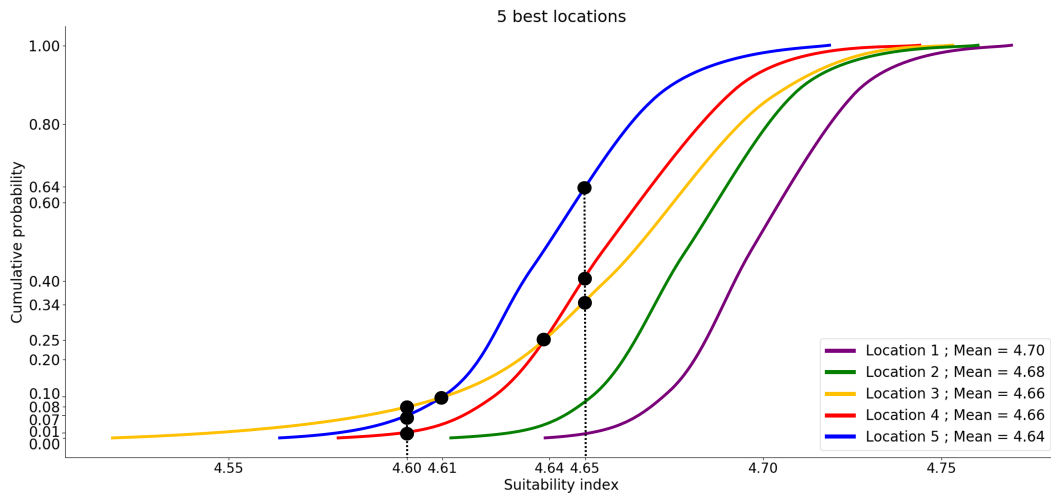


Figure 4.9: CDFs of the five best locations in scenario 1.

As illustrated on Figure 4.9, locations 1 and 2 are obviously the first and second best respectively, with location 1 having 100% probability of being better than the others, as it is never crossed by any other curve and always lies to the right of the other curves.

But it is also interesting to look at the near-optimum solutions. In fact, it can happen that locations 1 and 2 are not suitable afterall, for example if there are small villages,

no public acceptance, land use ownership, terrain instability, and other unforeseen elements that datasets could not take into account. The other three locations should then also be analyzed.

If we decide to consider acceptable locations with a minimum suitability index of 4.6, locations 3, 4 and 5 will have a probability of 92%, 99% and 93% respectively of achieving a score higher than 4.6. Therefore, if a minimum score of 4.6 is required, location 4 should be selected.

Then if we change to a minimum suitability index of 4.65, locations 3, 4 and 5 will have a probability of 66%, 60% and 36% respectively of achieving a higher score, and location 3 should therefore be selected.

We can also see that location 4 is always better than location 5. Only location 3 is likely to become better than locations 4 and 5, depending on the acceptability of the suitability indices.

Locations 3 and 5 both have a probability of 90% that their suitability index will be higher than 4.61. If a even higher suitability index is required, location 3 results in a higher probability to have a better score. In fact even if location 3 can in some cases come with a lower suitability index than location 5, the probability of this happening is still small (10%). The risk of selecting location 3 is then manageable since we could reach even higher suitability indices in most cases.

Knowing that location 3 and 4 have the same mean suitability index, and that location 4 has a lower standard deviation since the curve is steeper, an initial choice would be to select location 4, to minimize risk. If the minimum required suitability index is higher than 4.64, location 3 has more probability of scoring higher. But, overall, this location is fragile as the score can significantly decrease down to 4.5 (higher standard deviation). Location 3 is therefore less robust than location 4 and more risky to select.

Scenario 2 : Export via pipelines

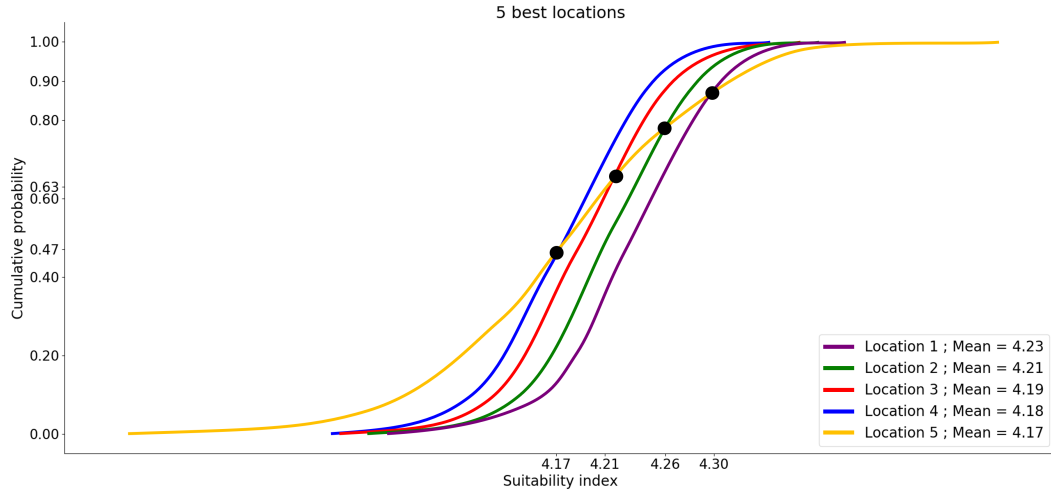


Figure 4.10: CDFs of the five best locations in scenario 2.

For this pipelines export scenario, as we can see on Figure 4.10, locations 1, 2, 3 and 4 are easily comparable, as they don't cross at any point, have different mean suitability indices and fairly similar standard deviations. However, location 5, which has the lowest mean suitability index but the highest standard deviation, intersects each of the other locations.

If we compare location 5 with locations 4, 3, 2 and 1 successively, they both have a probability of 53%, 27%, 20% and 10% respectively that their suitability index will be higher than 4.17, 4.21, 4.26 and 4.30 respectively. If a higher suitability index is required, location 5 results in a higher probability to have a better score than each location. In other words, depending on the minimum acceptable suitability index, location 5 might become a better choice than the other locations, even though it has the lowest mean suitability index.

Overall, location 5 is more sensitive to the variation of weights, meaning its score has more variability than other locations. Choosing this location is therefore more risky (larger standard deviation) than the other locations which have a more robust performance.

Scenario 3 : Non-export focus

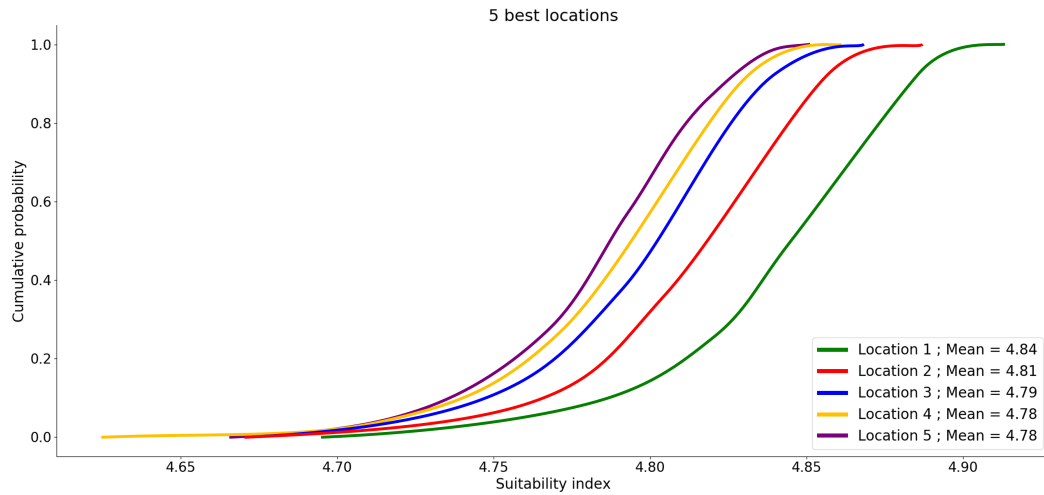


Figure 4.11: CDFs of the five best locations in scenario 3.

For the latter scenario (Figure 4.11), the curves hardly cross at any point, so the comparison of one location with another is straightforward. From right to left, locations with a greater probability of having a better suitability index.

4.5 Capacity Factor analysis

For a given location, hourly capacity factors can be computed on Renewables.ninja for the year 2019 [52]. The capacity factors are computed from methods described in [53, 54].

For the location 1 of scenario 1, which appears to be the best location for this scenario, daily average cycles by months can be computed for the year 2019 (Figure 4.12).

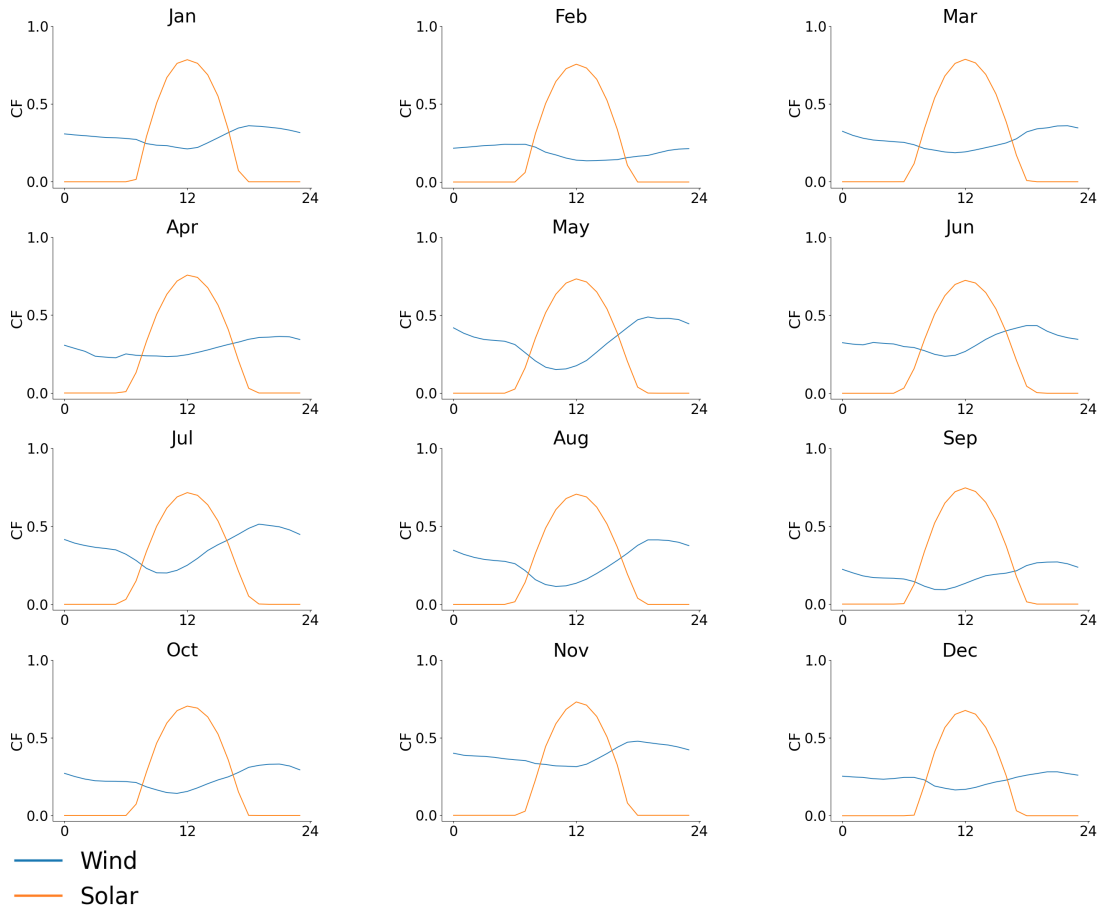


Figure 4.12: Daily average cycles for each month.

The optimal mix is found to be 56% wind and 44% solar power generation, and is computed following the method described in 2.6 . Then, the coefficient of stability can be computed for every month, by taking the average coefficient of stability of each day of the month (Figure 4.13).

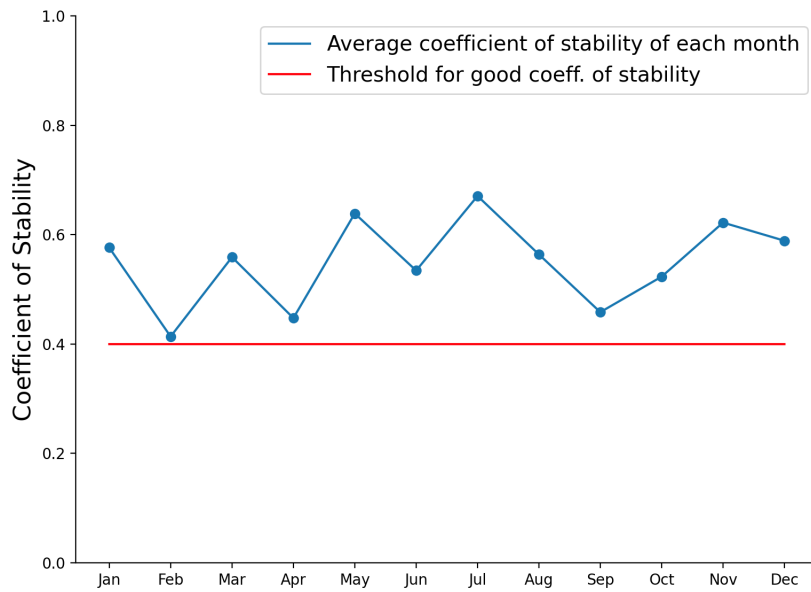


Figure 4.13: Coefficients of stability for each month.

Nyenah et al. [55] define a threshold for a good coefficient of stability when it is higher than 0.4. For our selected location for scenario 1 (location 1), we see that this coefficient is always good for year 2019 and even excellent for several months (Figure 4.13).

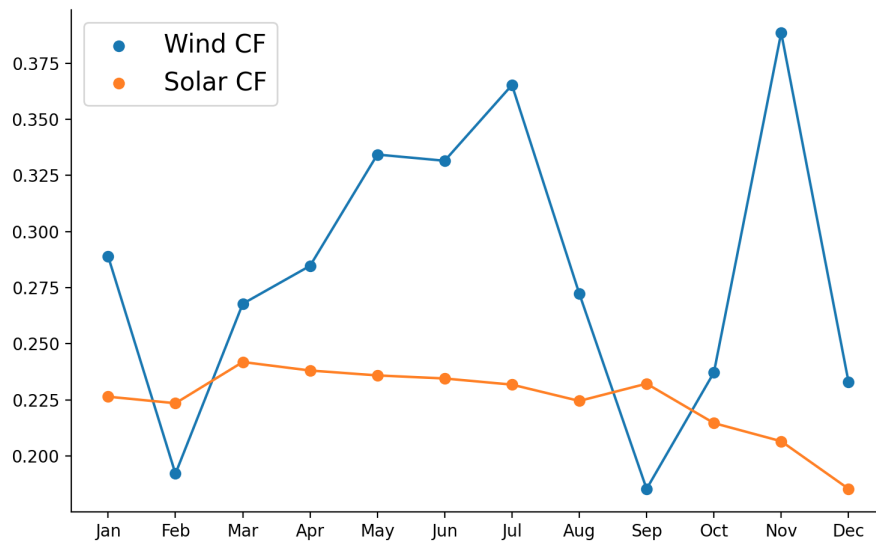


Figure 4.14: Mean Capacity Factors for each month of year 2019.

What is also noticeable on Figure 4.14 and Figure 4.13, is that wind capacity factors and coefficients of stability are quite strongly correlated. This correlation can also be observed on Figure 4.15, when plotting the mean wind capacity factors for each month and the coefficients of stability for the corresponding months. Each dot thus represents values for one month.

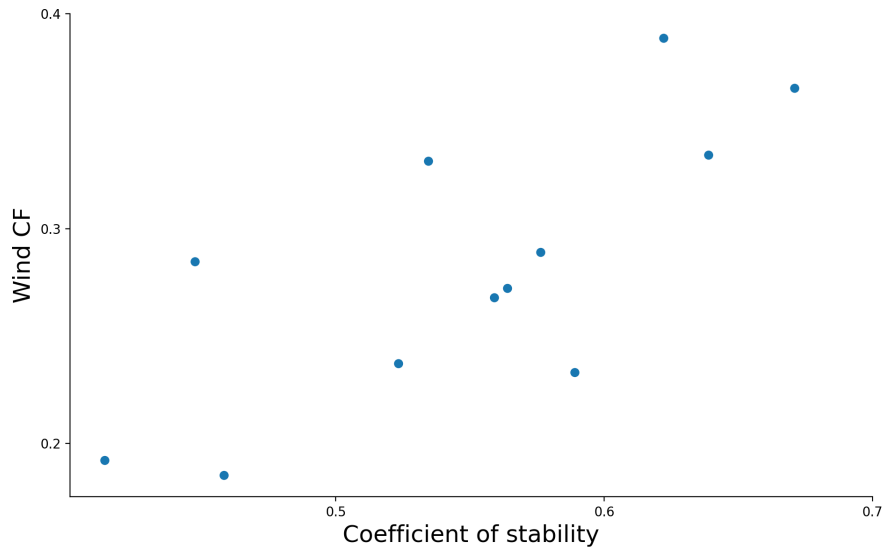


Figure 4.15: Correlation between wind capacity factor and coefficient of stability.

Wind capacity factor and coefficient of stability have a correlation coefficient of 0.74. This correlation has already been discussed in [30] and is explained by the following : the wind capacity factor varies much more depending on the months than the solar capacity factor, and therefore the wind capacity factor influences the stability coefficient much more. Also, when wind production is low (low capacity factor), knowing only wind is produced during nighttime, the variation with the solar energy produced during the day is considerable, which leads to a low coefficient of stability. But while there is a tendency of higher stability when higher wind capacity factors, some months achieve a similar coefficient of stability with a varying monthly wind capacity factors.

To conclude, the selected location for scenario 1 has a good daily synergy for all months of the year, allowing to avoid too much daily fluctuations in power input for the electrolyzer. This confirms the optimality of the chosen location for scenario 1. Similar analysis can be conducted for other locations.

5 Limitations and further analyses

In this section, we discuss the limitations of our study. Recognizing these limitations is crucial for understanding the scope and applicability of our findings. By identifying the constraints and challenges faced, we aim to provide a clearer context for our results and suggest areas for future research that could address these issues.

5.1 Limitations of the study

Exclusion areas

For the geographic exclusions, some pixels are excluded, even though they are not fully covered by an exclusion zone and some are not excluded even if they include a minor exclusion zone. In fact, pixels are excluded when the majority of it is categorized as unsuitable area.

More accuracy would require a better resolution (smaller pixels) for the analysis of optimal locations. But as this study covers the total area of Morocco, finer resolution would significantly increase computing time and resource requirements, as explained in Appendix E.

Selection of the optimal locations

For now, the selection of optimal location for a specific area is done by selecting squares of 3 by 3 pixels. This is done to guarantee compactness of the green hydrogen production site, but the layout could be in fact modified and the chosen area (number of pixels) also. Depending on the number of pixels and the layout of the grouping of pixels, the solution can be influenced.

Analysis of Capacity Factor profiles

In this study, a rough approximation was done at first to combine the wind and solar potential (see section 3.3). Then, the capacity factor's profiles were analyzed for the best selected location, to confirm the renewable potential was high at this location. Another possible way to analyze the renewable potential would have been to take into account the coefficient of stability directly as criteria in the simulation to select locations with the best energy profiles. Unfortunately, the data required

for those analyses was only available when selecting specific locations, thus in the "post-processing" part. It was therefore not possible to map coefficients of stability, such as in [56], to then take into account such a criteria in the Monte Carlo simulation. Also, the analysis was made based on hourly data for the year 2019, because it was the only open-source data available for this location. To be more accurate, it is preferable to do the analyses based on a one year average calculated based on real measurement of data over e.g. 25 years. This is more representative of the true meteorological trends.

Aknowledging bias

While the objective of this study is to reduce subjectivity in a decision-making process, it is impossible to reduce all subjectivity. In fact, there is still a bias in choosing the criteria, and the importance they have (most-likely value) in the decision-making process. The criteria we have chosen describe a techno-economic analysis for export of hydrogen to Belgium. In fact, it doesn't take into account the local hydrogen demand, unlike studies which are not export focused [34]. Also, it doesn't take into account proximity to cities, or rates of employment to assess the feasibility of employment of local people. Unlike other studies [18], socio-environment criteria such as urban areas or protected areas were taken into account as exclusion zones but the distance to those areas were not taken into account in the simulation, meaning an optimal location could be located just outside such areas, without being penalized for the closeness of it.

5.2 Further analyses

Once the optimal location has been determined, further analyses can be conducted regarding the optimization of a design for the layout of wind turbines and solar panels coupled to electrolyzers. In fact, the goal is to minimize the LCOH (levelised cost of hydrogen), by maximizing hydrogen production while minimizing expenses related to it. The expenses are divided into CAPEX (funds used to acquire physical assets such as PV panels, wind turbines, electrolyzers, property, among others) and OPEX (funds that covers day-to-day operations). Electrolysers operate with a minimum load, or base load, necessitating continuous operation at this level. To meet this requirement, the capacity of both the wind and solar farms must be expanded until they generate

sufficient power every hour of the day to satisfy the base load. For example, PEM electrolyzers require a smaller base load than Alkaline electrolyzers (see Appendix A) but have a higher CAPEX. Adding more wind turbines or solar panels increases the CAPEX, but also increases the annual production. By running multiple scenarios of wind turbines, solar PV's, batteries and electrolyzers (types and amount), an optimum can be found (lowest LCOH). Many studies have already described methodologies in order to optimize such designs [57, 58, 59] and can be used as starting points to continue this work. Also, scenarios for importing hydrogen to Belgium from Morocco have already been described in [2], and can be further analyzed.

6 Conclusion

This study has successfully developed and applied a robust Analytic Hierarchy Process (AHP) methodology to reduce subjectivity in the decision-making process for the location-allocation of remote renewable energy hubs for hydrogen production. By integrating stochastic importances of criteria through Beta-PERT distributions and a Monte Carlo simulation, the research provides a more reliable and less subjective framework for evaluating optimal locations.

The case study focused on Morocco, a country with significant renewable energy potential, for solar and wind power. Three scenarios were analyzed: export via seaports, export via pipelines, and non-export-focused production. The robust AHP approach demonstrated clear advantages by considering a range of possible weights for each criterion, therefore accounting for uncertainties and reducing the impact of subjective judgments typically arising in traditional AHP methods.

For the export via seaports scenario, the mean weights are 0.43, 0.21, 0.17, 0.14, 0.09 and 0.05 for respectively renewable potential, distance to roads, distance to seaports, distance to coastline, distance to powerlines and slope.

For the export via seaports scenario, two clusters of high suitability indices were identified, which represent 2100 km², or 0.47% of Moroccan territory. For the non export focus scenario, the total area of highly suitable locations represents 3200 km², or 0.72% of Morocco's surface area. Key findings indicate that optimal locations for export via pipelines are located further in the south of Morocco than optimal locations in the scenario for export via seaports, despite having better pixels in the north. Conversely, regions in the far south, characterized by high renewable potential, are optimal when the focus shifts solely to cost-effective hydrogen production without considering export logistics. The locations with the best mean suitability index for scenario 1, scenario 2 and scenario 3 have a mean suitability index of 4.70, 4.23 and 4.84 respectively.

The results highlight the importance of incorporating variability in criteria weighting, which significantly affects the selection of optimal sites. The methodology's

robustness is further validated through the CDF analysis, which ensures that selected locations not only have high suitability indices but also low variability. By setting a minimum required suitability index, CDFs analysis allows to select locations based on their probability of having such suitability indices. Moreover, the inclusion of uncertainty allows to make a trade-off between locations with high performance in specific conditions—but fragile when the importance on the inputs vary—and locations with stable performance through the iterations.

The complementarity of wind and solar capacity factors was also analyzed in this study. For the selected location of scenario 1, the daily synergy of wind and solar capacity factors is evaluated through the coefficient of stability. With a mean coefficient of stability of 0.55, the daily synergy is considered as good.

Further research could focus on a detailed analysis of the design and dimensioning of green hydrogen production plants, to optimize hydrogen production while minimizing costs.

In conclusion, this thesis provides a significant contribution to the field of renewable energy site selection, offering a practical and robust framework that can be adapted to various geographic and economic contexts.

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Note: ChatGPT was used as a tool to translate and facilitate english expression. However, it was not used to create any content or reference information. All content is our own production or systematically referenced.

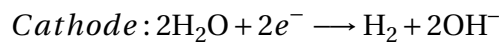
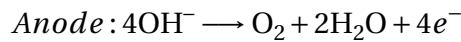
Appendix A

Production of Hydrogen

There are two main types of electrolyzers:

Alkaline electrolyzer

Alkaline electrolyzers are the most common electrolyzer types and the most mature technology. It has also the lowest capital cost between different types of electrolyzers. In this type of electrolyzer, the electrolyte is in the aqueous form and typically contains potassium or sodium hydroxide (KOH or NaOH). Water is fed into the cathode. Receiving the electrons from the external circuit, water is split into hydrogen and OH^- ions. The OH^- ions travel through the electrolyte to the anode where oxygen and water is formed. The reactions at the anode and the cathode are the following [9]:

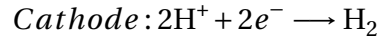
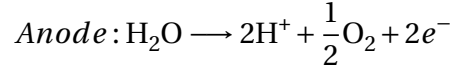


But, alkaline electrolyzers have problems related to the aqueous characteristics of its electrolyte. In fact, this type of electrolyte can lead to leaking and corrosion. Also, the high ohmic losses, which leads to lower current densities. Moreover, its performance is decreased when used at part-load conditions [9], which often happens if coupled with intermittent energy sources.

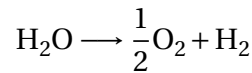
Proton Exchange Membrane (PEM) electrolyzers

In this other type of electrolyzer, water is fed to the anode where it is split into hydrogen

and oxygen. Then, the produced proton is transferred through the membrane to the cathode where it receives electron and forms hydrogen. The reactions at the anode and the cathode can be written as [9]:



The full reaction is thus given by the following equation:



This type of electrolyzer has many advantages compared to others. First of all, the electrolyte is solid and thus resolves the leaking problems. This also allows a reduction of its thickness which results in lower ohmic losses and higher current densities.

PEM electrolyzers also have a fast response time (<1s) and can operate at partial loads (from 0 to 100% of the nominal load). The operating temperature is relatively low (50°C-80°C) [60], which implies there is no need for a thermal energy supply [9]. Those are crucial characteristics, as the goal here is to couple electrolyzers to renewable energy sources, which are intermittent and generate only electricity. This type of electrolyzer thus benefits from a lot of flexibility, with an operating life time going from 60,000–10,000 hours [60].

Other promising types of electrolyzers exist, such as Solid Oxide electrolyzers, but still need further research and development before considering their large scale use and commercialization [9].

According to Faraday's law the molar flow rate of hydrogen at the cathode side is [10]

$$\dot{n}_{\text{H}_2} = \frac{I}{2F}$$

Where I is the current intensity [A] and F the Faraday constant (96485 [$\frac{\text{As}}{\text{mol}}$])

Appendix B

References for the gathered GIS data

References for gathered data

Criteria	File format	Source	Key [61]	Value [61]
Sun (GHI)	Raster	Global Solar Atlas [4]		
Wind (speed)	Raster	Global Wind Atlas [5]		
Slope	Raster	SRTM DEM and GDAL [62]		
Roads network	Shapefile	OpenStreetMap [63]	Highway	Motorway
			Highway	Trunk
			Highway	Primary
			Highway	Secondary
			Highway	Tertiary
Seaports	Shapefile	OpenStreetMap [63]	Industrial	Port
Powerlines network	Shapefile	OpenStreetMap [63]	Power	Line
Coastline	Shapefile	OpenStreetMap [63]	Natural	Coastline
Land use	Shapefile	OpenStreetMap [63]	Landuse	Forest
			Landuse	Farmland
			Natural	Wetland
			Natural	Water
			Natural	Glacier
Urban areas	Shapefile	OpenStreetMap [63]	Place	City
			Place	Town
			Place	Village
			Place	Hamlet
Military zone	Shapefile	OpenStreetMap [63]	Landuse	Military
Protected areas	Shapefile	OpenStreetMap [63]	Boundary	Protected Areas
Airports	Shapefile	OpenStreetMap [63]	Aeroway	Aerodrome
Population density	Raster	Humanitarian Data Exchange [64]		

Table B.1: References for the gathered GIS data.

Appendix C

Analytic Hierarchy Process & Consistency Ratio

Analytic Hierarchy Process

First step of the AHP is to determine the PCM.

	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	1/2	3
Criterion 2	2	1	6
Criterion 3	1/3	1/6	1

Since the PCM is defined, the sums for each criterion must be computed vertically.

	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	0.5	3
Criterion 2	2	1	6
Criterion 3	0.33	0.16	1
Sum	3.33	1.66	10

Then each column is divided by the sum to be normalized.

	Criterion 1	Criterion 2	Criterion 3
Criterion 1	$1/3.33 = 0.3$	$0.5/1.66 = 0.3$	$3/10 = 0.3$
Criterion 2	$2/3.33 = 0.6$	$1/1.66 = 0.6$	$6/10 = 0.6$
Criterion 3	$0.33/3.33 = 0.1$	$0.16/1.66 = 0.1$	$1/10 = 0.1$
Sum	3.33	1.66	10

The last step is to take the mean for each line to determine the final weight of each criterion.

	Criterion 1	Criterion 2	Criterion 3	Criteria weights
Criterion 1	0.3	0.3	0.3	$(0.3+0.3+0.3)/3 = 0.3$
Criterion 2	0.6	0.6	0.6	$(0.6+0.6+0.6)/3 = 0.6$
Criterion 3	0.1	0.1	0.1	$(0.1+0.1+0.1)/3 = 0.1$

Consistency Ratio

Once the weights are known, the CR must be checked to be sure it is well below 0.1 and that the PCM was well acceptable to perform the AHP.

Criteria weights	0.3	0.6	0.1
	Criterion 1	Criterion 2	Criterion 3
Criterion 1	1	0.5	3
Criterion 2	2	1	6
Criterion 3	0.33	0.16	1

The weight of each criterion is multiplied to its column

Criteria weights	0.3	0.6	0.1
	Criterion 1	Criterion 2	Criterion 3
Criterion 1	$0.3 * 1 = 0.3$	$0.6 * 0.5 = 0.3$	$0.1 * 3 = 0.3$
Criterion 2	$0.3 * 2 = 0.6$	$0.6 * 1 = 0.6$	$0.1 * 1 = 0.1$
Criterion 3	$0.3 * 0.33 = 0.1$	$0.6 * 0.16 = 0.1$	$0.1 * 1 = 0.1$

The weighted sum value of each criterion is then computed horizontally.

	Criterion 1	Criterion 2	Criterion 3	Weighted sum value
Criterion 1	0.3	0.3	0.3	$0.3 + 0.3 + 0.3 = 0.9$
Criterion 2	0.6	0.6	0.6	$0.6 + 0.6 + 0.6 = 1.8$
Criterion 3	0.1	0.1	0.1	$0.1 + 0.1 + 0.1 = 0.3$

The weighted sum divided by the weight is then computed for each criterion.

	Weighted sum value	Criteria weights	Weighted sum/weight
Criterion 1	0.9	0.3	$0.9/0.3 = 3$
Criterion 2	1.8	0.6	$1.8/0.6 = 3$
Criterion 3	0.3	0.1	$0.3/0.1 = 3$

The principal eigenvalue of the matrix λ_{max} is then computed by taking the mean of all the ratios between the weighted sums and the criteria weights.

$$\lambda_{max} = \frac{3+3+3}{3} = 3 \quad (C.1)$$

The consistency index can now be calculated by this formula :

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{3 - 3}{2} = 0 \quad (C.2)$$

where n is the number of criteria, in this case $n = 3$.

Consistency ratio is finally computed by dividing the CI by the Random Index RI which is determined with the number of criteria n (Table C.1).

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table C.1: Random Index for the number of criteria n .

$$CR = \frac{CI}{RI} = \frac{0}{0.58} = 0 \quad (C.3)$$

It shows that the PCM is acceptable to perform the AHP since the CR is below 0.1 and even perfect because it is null.

Appendix D

Convergence of Monte Carlo method

For the selected location (location 1) of scenario 1, the convergence of the Monte Carlo method can be analyzed.

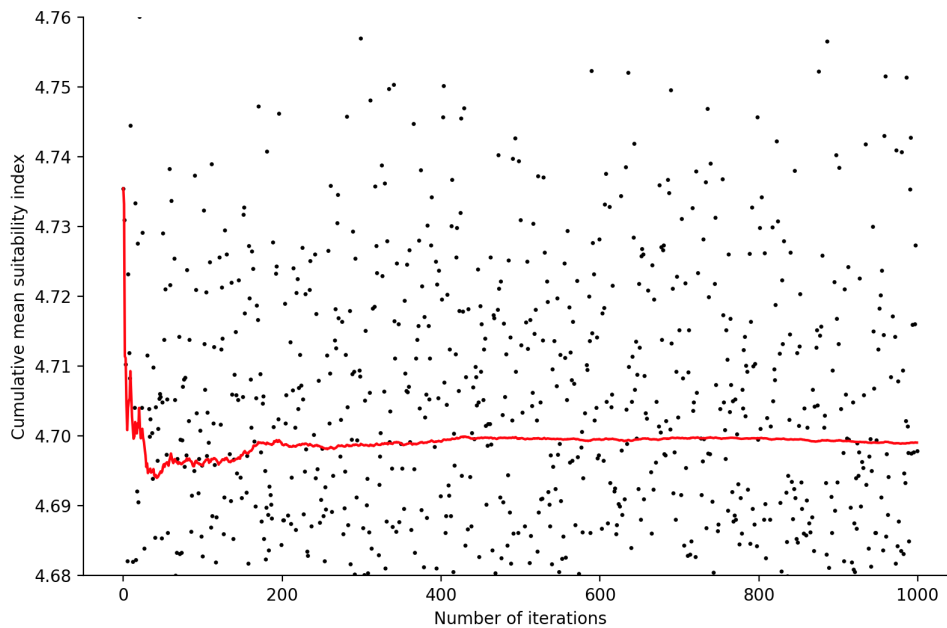


Figure D.1: Convergence of mean for Monte Carlo method for location 1 of scenario 1.

The convergence of the Monte Carlo method is observed on Figure D.2. The red line represents the cumulative average score and the black dots are the scores computed

for each iteration. As seen on Figure D.2, at the beginning of the simulation, with fewer simulations completed, the cumulative average is fluctuating quite significantly. This is because the average is calculated based on a smaller number of samples, making it more sensitive to individual values. Then, as more simulations are run, the cumulative average tends to stabilize. This means that the average value becomes less sensitive to individual random samples, and it converges towards a more stable value. By observing the plot on Figure D.2, we can assess whether the cumulative average appears to converge to a certain value. The plot indeed shows a clear trend towards stabilization as the number of iterations increases, it suggests that the Monte Carlo simulation is converging quickly, as it is almost completely stabilized after 1000 iterations.

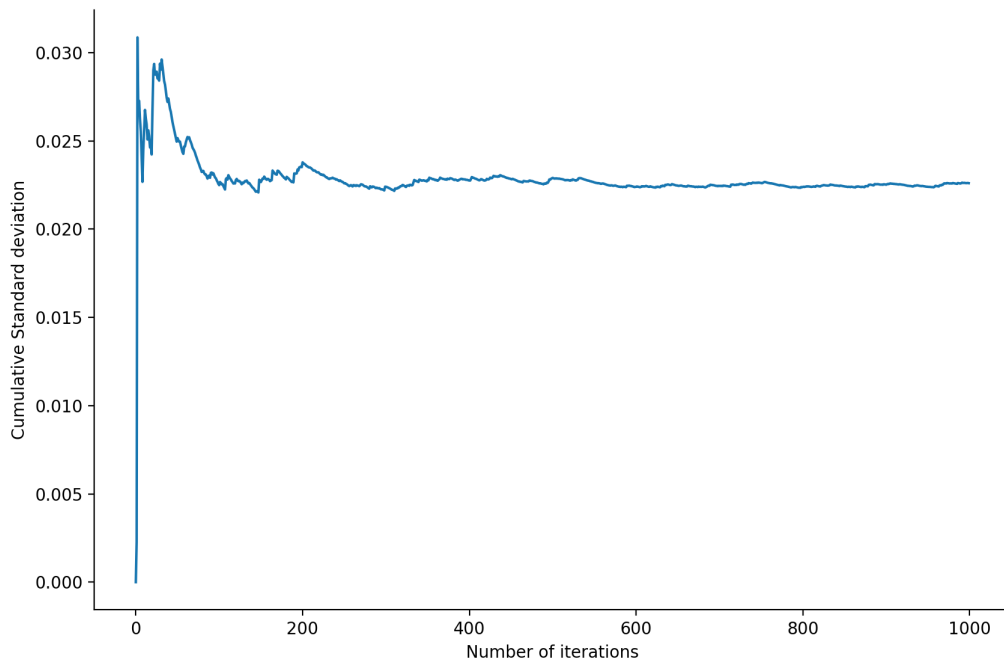


Figure D.2: Convergence of standard deviation for Monte Carlo method for location 1 of scenario 1.

For the selected location, the standard deviation is relatively small and also converges rapidly, as the average score does.

Appendix E

Simulations data

In the code that applies Monte Carlo to our case study, compilation times are separated into simulation and saving times. Simulation time is the time taken to perform N iterations on all pixels. This simulation time is linear with respect to these 2 parameters: numbers of iterations and number of pixels. However, saving time, the time taken to save data in the Excel file is superlinear. It increases significantly with higher number of pixels as Excel has some difficulties to manage very big datasets. More efficient data structures should be considered for further works.

Number of iterations	Pixel area [km ²]	Number of pixels	Simulation time [min]	Saving time [min]	Total time [min]
1000	40	6000	10	2	12
1000	20	12000	19	6	25
1000	10	24000	42	23	65
500	10	24000	21	7	28
250	10	24000	9	2	11

Table E.1: Data of proceeded simulations with different pixel resolutions and different number of iterations.

Since the code is linear, but saving the data to Excel is superlinear, the time complexity based on this data is rather approximately $O(n^{1.5})$.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN

École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl