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Opportunities and challenges of green hydrogen in the energy transition framework: analysis of potential cross-border cooperations through a multi-dimensional approach

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Summary

To tackle climate change issues and to achieve the decarbonization targets, effective pathways enabling the energy transition process must be developed, exploiting renewable energy sources, electrification, new clean technologies, storage solutions, and strategic interconnections. Even if energy-based, the transition represents a changeover involving the broader social, techno-economic, environmental, and geopolitical aspects; it is an intrinsically multi-disciplinary process that evolves over time and space and will reshape countries' identities. In this context, policymakers' decisions and actions could slow down or speed up the process; supporting informed interventions in the decision-making process becomes crucial.

For the purposes of the research, different instruments are exploited; geomatics, scenario analyses and modelling, qualitative and quantitative indicators, and multi-criteria decision methods are integrated to elaborate powerful science-stakeholder-policy tools, able to tackle the multi-disciplinarity of the problems. The methodological approach is developed on the concepts of (i) predisposition, (ii) multi-dimensional suitability, (iii) multi-level competitiveness. Using specific indicators for a multi-criteria analysis, the first step allows for a preliminary assessment of the availability of resources and infrastructure, the social acceptance, the environmental issues, and the geopolitical conditions, concerning the development of new technologies or strategies. Secondly, the combination of spatial analyses with multi-criteria assessment is exploited to spatially define the multi-dimensional suitability of alternatives enabling strategic energy planning. As last step, scenario analyses unlock the possibility to study different long-term perspectives involving the whole energy system, to better investigate the concept of competitiveness.

The research and its main applications focus on green hydrogen, produced through water electrolysis supplied by renewable energy and which represents a key player in the transition. The main goal is to study hydrogen not only on a technical perspective, but including social benefits and barriers, environmental issues, and economic and geopolitical standpoints, if green hydrogen is produced in North Africa and imported by Europe. In a world that will be completely reshaped by the transition, developing a structured science-based decision-making process can represent a win-win option for all the dimensions affected by the transition and all

the countries involved in strategic interconnections. In this regard, it is needed to investigate the role that specific countries can have in the ongoing process, especially in case of new or renewed alliances when new clean solutions like hydrogen are adopted. The preliminary assessment for predisposition exploits the PROMETHEE II multi-criteria method; Algeria, Egypt, Libya, Morocco, and Tunisia are assessed through the elaboration of twelve different criteria belonging to Society, Technology, Atmosphere and land, Geopolitics, Economy (i.e., the so-called "STAGE" view), collected from literature or self-elaborated. By weighting these criteria according to specific experts' preferences, Morocco, Tunisia, and Algeria are ranked as the most predisposed to green hydrogen production. Secondly, the methodological approach deepens the multi-dimensional suitability of these three countries; different drivers and barriers are spatially analyzed, to assess the land suitability in terms of solar hydrogen production (i.e., water electrolysis enabled by solar electricity) and wind hydrogen production (i.e., water electrolysis enabled by wind power plants). In this way, a detailed mapping is developed, making use of spatially defined data, through the combination of the Analytic Hierarchy Process method and GIS techniques; it allows to obtain a classification of different ranges of suitability. By exploiting this Multi-criteria Spatial Decision Support System, ten different spatially defined criteria are elaborated; the majority of the available land under analysis is classified as moderately or highly suitable, even if the most favorable areas in terms of availability of resources are often negatively influenced by the geopolitical or economic assessment. Finally, to adequately investigate the concept of multi-level competitiveness, the energy system modelling through TIMES is exploited; under specific assumptions, the Levelized Cost of Hydrogen for the countries of interest is estimated, in parallel with the alternative transport modes and costs, to collect valuable techno-economic inputs for scenarios working on uncertainty of parameters. Analyzing to what extent Europe will rely on green hydrogen import to achieve carbon-neutrality by 2050, the role of trade is estimated as crucial, even if sensitive to uncertain factors.

This structured science-based decision-making approach could be appropriate for policymakers, investigating the complexity of the energy transition towards carbon-neutrality, allowing to prioritize energy security and affordability, and geographically address the multi-level impacts of green hydrogen adoption, stressing if and how it can be techno-economic, social, geopolitical, and environmental competitive.

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"Mi raccomando, devi sprintare!"

A mamma e papà per tutto il possibile e l'impossibile,
a Valeria per l'infinita pazienza e il sano ottimismo,
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a Sofia e Patrícia per aver fatto molto di più del dovuto,
alle tante altre persone che mi hanno permesso di arrivare fin qui.

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Chapter 0

A brief instruction manual for reading

This first section aims to briefly introduce the structure of the PhD thesis to the reader, through the support of graphical information. With the title *"Opportunities and challenges of green hydrogen in the energy transition framework: analysis of potential cross-border cooperations through a multi-dimensional approach"*, the study is developed around the main framework of the energy transition, requiring a structured overview on its main challenges, and focusing on the role that hydrogen – and specifically the renewable one – can play to achieve carbon-neutrality by 2050. This general overview is developed by the first chapter, which investigates the multi-disciplinarity of the transition as a complex multi-interest process, affected and affecting different actors and sectors. Within this context, clean hydrogen can drive the transition from fossil fuels, redefining ad-hoc pathways for trade; the emerging role of North Africa as potential export leader for Europe will be investigated as main application of the thesis. Before detailing the case studies, the second chapter is devoted to the definition of a more general methodological approach supporting policymakers towards informed decisions and actions by strategic energy planning. Specifically, it is required a method (i) to assess strategic pathways for carbon-neutral solution, (ii) to quantify and qualify the related multi-dimensional drivers and barriers involved, (iii) to obtain clear and usable outcomes for policymakers. To this end, specific instruments and tools are introduced and analyzed to finally elaborate a structured science-based decision-making process, assessing (i) predisposition, (ii) suitability, and (iii) competitiveness of specific low-carbon solutions. Multi-criteria analyses, Geographic Information System environment, qualitative and quantitative indicators, and energy scenarios modelling are introduced as main instruments and tools to target the research questions. This methodological approach is applied in the third chapter to the green hydrogen production in North Africa and its potential export to Europe, representing the core section addressing the case studies of interest and for which the whole approach is detailed and analyzed step-by-step.

Figure 1 summarizes the thesis structure, from the first chapter to the third one.

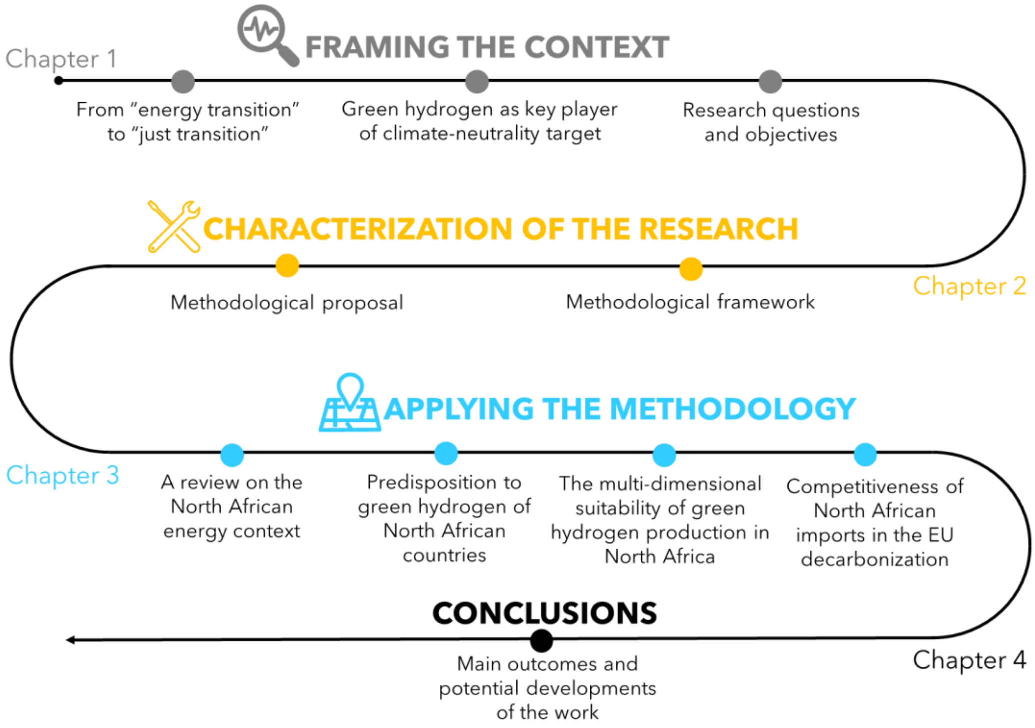


Figure 1: An overview on the structure of the thesis.

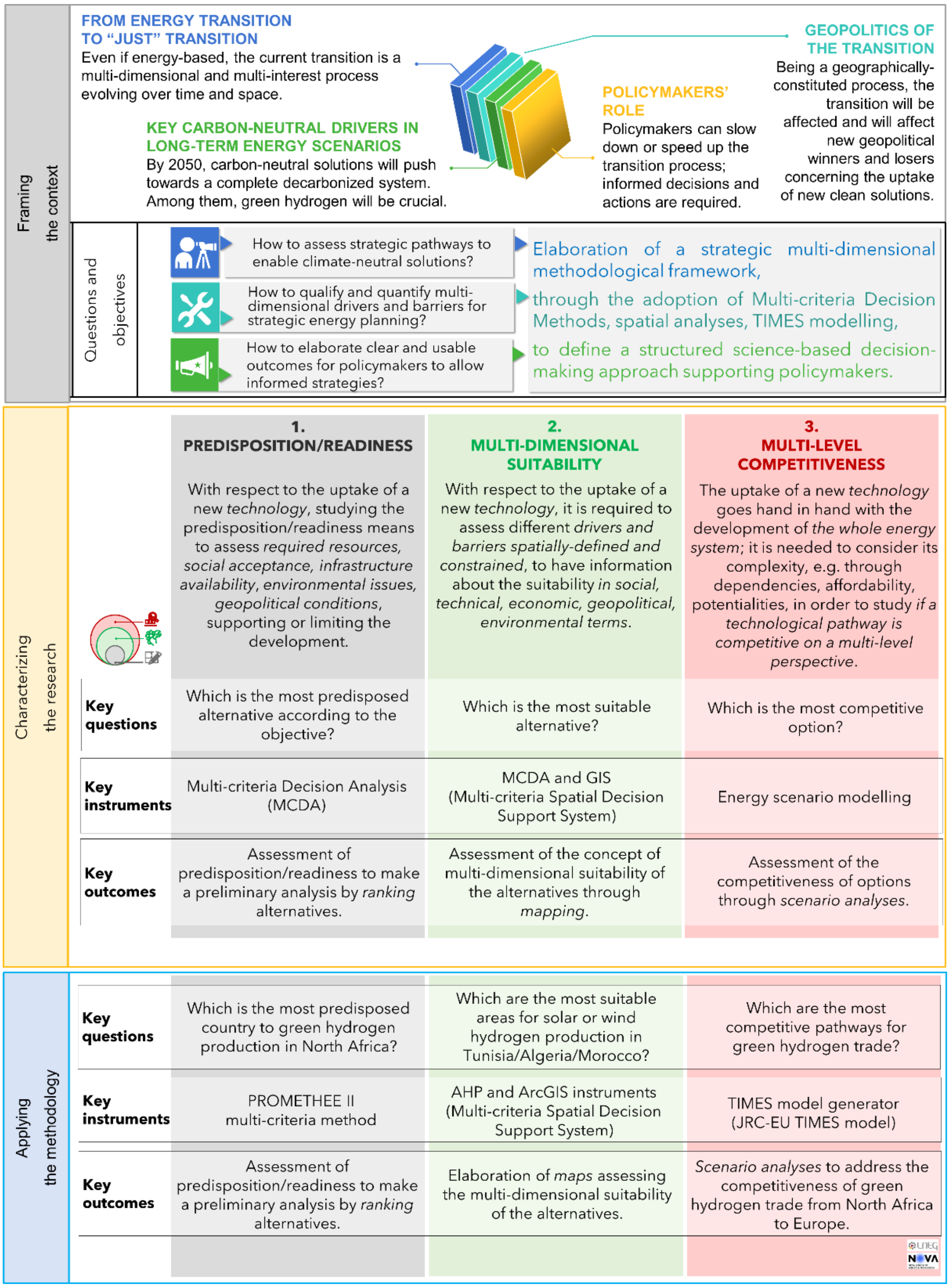
The first chapter is subdivided into three sub-sections, with the first one focusing on the transition process and the role of geopolitics and policymakers within this multi-actors and multi-interest process, while the second one addresses the potentialities and criticalities of clean hydrogen and its influence on cooperations and alliances. The last section of this chapter aims to point out the main research questions and targets of the PhD thesis.

The second chapter allows to understand how the methodology towards the development of a science-based decision-making approach is developed; there are specific sub-sections focusing on scenario analyses, multi-criteria decision methods and indicators, paving the way to their exploitation in the methodological setting.

In the third chapter, the methodological proposal is applied to support policymakers in strategic energy planning related to North African hydrogen production and trade with Europe. The first section reviews datasets and procedures for strategic energy planning involving North Africa, to have an overview on the countries to be analyzed and the studies already developed concerning these areas. Secondly, the PROMETHEE II method is introduced as multi-criteria analysis to rank North African countries with respect to their predisposition to green hydrogen production. Having studied the predisposition, it is introduced the concept of suitability. To do this, a preliminary study of local strategies and targets for Morocco, Tunisia, and Algeria – assessed as the most predisposed – is conducted, followed by a spatial preliminary analysis to elaborate their theoretical maximum potential for solar hydrogen production. After this, the combination of the Analytic Hierarchy Process and GIS environment allows to map the suitability in terms of solar and wind hydrogen production for these three countries. The last sub-section of the third chapter focuses on the concept of competitiveness, to understand to what extent green hydrogen from North Africa can support the European decarbonization by 2050. In this regard, it is firstly required to analyze the uncertainty in parameters affecting costs of production and transport; after this, different scenarios are elaborated exploiting the TIMES model generator and specifically the JET-EU-TIMES model. This final specific work on model was made possible thanks to Maria Gaeta and the collaboration made real with Sofia Simões (National Laboratory of Energy and Geology) and Patrícia Fortes (FCT NOVA University) in Lisbon.

Finally, the last chapter reports the conclusions of the work, summarizing the main outcomes and potential future developments of the study.

Figure 2 allows to have an overview on which are the research questions, how the methodological proposal tries to answer to these questions and how the research framework is applied and detailed through the application of interest.



FROM ENERGY TRANSITION TO "JUST" TRANSITION
Even if energy-based, the current transition is a multi-dimensional and multi-interest process evolving over time and space.

KEY CARBON-NEUTRAL DRIVERS IN LONG-TERM ENERGY SCENARIOS
By 2050, carbon-neutral solutions will push towards a complete decarbonized system. Among them, green hydrogen will be crucial.

POLICYMAKERS' ROLE
Policymakers can slow down or speed up the transition process; informed decisions and actions are required.

GEOPOLITICS OF THE TRANSITION
Being a geographically-constituted process, the transition will be affected and will affect new geopolitical winners and losers concerning the uptake of new clean solutions.

How to assess strategic pathways to enable climate-neutral solutions?	Elaboration of a strategic multi-dimensional methodological framework,
How to qualify and quantify multi-dimensional drivers and barriers for strategic energy planning?	through the adoption of Multi-criteria Decision Methods, spatial analyses, TIMES modelling,
How to elaborate clear and usable outcomes for policymakers to allow informed strategies?	to define a structured science-based decision-making approach supporting policymakers.

	1. PREDISPOSITION/READINESS	**2. MULTI-DIMENSIONAL SUITABILITY**	**3. MULTI-LEVEL COMPETITIVENESS**
	With respect to the uptake of a new *technology*, studying the predisposition/readiness means to assess *required resources, social acceptance, infrastructure availability, environmental issues, geopolitical conditions*, supporting or limiting the development.	With respect to the uptake of a new *technology*, it is required to assess different *drivers and barriers spatially-defined and constrained*, to have information about the suitability *in social, technical, economic, geopolitical, environmental terms*.	The uptake of a new *technology* goes hand in hand with the development of *the whole energy system*; it is needed to consider its complexity, e.g. through dependencies, affordability, potentialities, in order to study *if a technological pathway is competitive on a multi-level perspective*.
Key questions	Which is the most predisposed alternative according to the objective?	Which is the most suitable alternative?	Which is the most competitive option?
Key instruments	Multi-criteria Decision Analysis (MCDA)	MCDA and GIS (Multi-criteria Spatial Decision Support System)	Energy scenario modelling
Key outcomes	Assessment of predisposition/readiness to make a preliminary analysis by *ranking* alternatives.	Assessment of the concept of multi-dimensional suitability of the alternatives through *mapping*.	Assessment of the competitiveness of options through *scenario analyses*.

Key questions	Which is the most predisposed country to green hydrogen production in North Africa?	Which are the most suitable areas for solar or wind hydrogen production in Tunisia/Algeria/Morocco?	Which are the most competitive pathways for green hydrogen trade?
Key instruments	PROMETHEE II multi-criteria method	AHP and ArcGIS instruments (Multi-criteria Spatial Decision Support System)	TIMES model generator (JRC-EU TIMES model)
Key outcomes	Assessment of predisposition/readiness to make a preliminary analysis by *ranking* alternatives.	Elaboration of *maps* assessing the multi-dimensional suitability of the alternatives.	*Scenario analyses* to address the competitiveness of green hydrogen trade from North Africa to Europe.

Figure 2: Graphical overview on the PhD thesis, from the introduction to the application.

Chapter 1

Framing the context

Achieving the decarbonization target following the appropriate energy transition pathways is a challenge not only in terms of energy. Even if energy-based, the current energy transition is a transition at all, intrinsically multi-dimensional, evolving over time and space, geopolitically constrained, and strictly affected by policymakers' decisions and actions. To deepen the main features of the transition towards carbon-neutrality, a comprehensive review is conducted analysing:

- the multi-disciplinarity of the transition, focusing on the geopolitical implications of the process, to study how decarbonization could reshape countries' identity and cooperation, through the strategic role of policymakers;
- the key technological avenues towards decarbonization, introducing the potentialities of clean hydrogen, which is among the enablers of carbon-neutrality in the long-term perspective, and focusing on the role played by critical raw materials.

Keywords*: energy transition, climate-neutrality, geopolitics, multi-disciplinarity, green hydrogen.*

1.1 From “energy transition” to “just” transition

Due to its unprecedented pace and relevance, in the last decades climate change issues have required more incisive decisions and more urgent actions, to fight against the increase of temperatures and the extreme climatic events impacting the whole ecosystem. A transition away from fossil fuels to low-carbon solutions will play a crucial role, set that two-thirds of all greenhouse gases (GHG) consists of energy-related carbon dioxide (CO_2) emissions [1]. However, the transition is not happening fast enough [2]-[4]. After the historical breakthrough represented by the Paris Agreement adopted in 2015 by the COP21 [5], an important signal was also given by the COP26 at the end of 2021, when the world leaders signed the Glasgow Climate Pact [6]. Stressing the importance of mitigation and adaptation measures, together with appropriate financial actions and collaborations, this Pact finally agreed on the Paris Agreement, also including commitments to end subsidies for fossil fuels and enable the phase-out from coal [6]. Specifically, if the obligations signed at Glasgow will be fully implemented, global warming will be kept below 2°C; moreover, with further incisive actions over the next decade, we have kept 1.5°C in reach [1]. The year after, the COP27 in Egypt ended up with an agreement on a compensation fund for specific countries most affected by climate change [7], an aspect also highlighted by the last COP28 in Dubai (December 2023), where an alignment on emissions reductions consistent with 1.5 °C and net zero emissions by 2050 was made explicit in the text [8]. To manage these objectives, pursuing the 1.5°C goal, a series of key actions is required, summarised in **Figure 3** through a guiding framework proposed by the International Renewable Energy Agency (IRENA) [9].

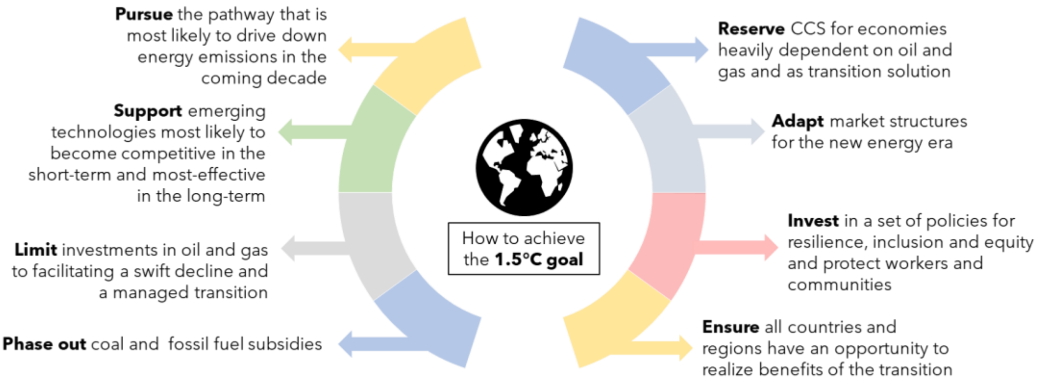


Figure 3: Guiding framework for 1.5°C pathway, adapted from [9].

As reported in **Figure 3**, it is clear that the transition, to be effectively implemented, requires the involvement of several sectors and different actors, through a structural changeover of the energy system that, involving technology, society, and economy, must positively impact the environment.

York et al. [10] stress how energy transition typically implies that both energy addition and energy substitution are taking place, with the term "addition" consisting of developing infrastructure for new energy sources and expanding the related production, while "substitution" refers to a transition away from more established resources [10]. In line with this, at this moment two major developments at the energy system level are ongoing: (i) electrification of end-use and (ii) decarbonization of energy system [11]. Moreover, while the past transitions have followed the trend of an increase of energy use, now the technological improvements for energy efficiency are instead prioritized, also revealing the increasing complexity of energy systems and spatial organization of societies [12]. The term "transition" readily captures changes over time for a given geographical unit, but often overlooks changes in the spatially-defined structure of the energy system and economic activities; these geographical shifts are both internal – within a particular region or country – and external, involving relationships between one country or region and others [13]. A key aspect of the current transition is that it is more than a series of improvements in the technological and political frameworks [14]; it is not limited to the changes of energy infrastructure but involves transformations of "the broader social and economic assemblages that are built around energy production and consumption" [15]. In fact, the transition agenda is facing a series of uncertainties, including scale, complexity and interdependencies across systems, the pressure of economic growth on emission reductions, energy justice, global versus local interests, the attractiveness of investments, structural issues, regulatory environment [16]; this comes with the continuous increase of energy consumption in emerging countries [17]. Looking at the different countries' roles worldwide, there are also potential risks for economies that are going to shift the production from fossils to renewables, concerning the possible job displacements in fossil-based sectors, the economic impact on societies relying mostly on fossils in the past, the transitioning workforce to be ensured, the society welfare to be always preserved [14]. A study conducted by Defeuilley [18] on the impact of transition on the future of the electricity sector underlines how up to now attention has devoted mostly to the technical, economic and regulatory aspects of changes, while social, political and institutional factors have been less investigated [18]; "trajectories of change (their pace, magnitude and orientation) are not only the outcomes of the physical and technical characteristics of the electricity system" [18]. By explaining the concept of an ongoing "socio-technical transition”, Ulli-Beer [19] underlines that, as a transition, it refers to “reconfiguration processes between technological change and evolution of science, industry structure, markets, policy instruments, governance, coalitions of actors, cultures, that enable new, more desirable, trajectories towards sustainability” [19]. Having set this, it is a matter of fact that to tackle the urgent climate change issues, all the dimensions of energy, society, economy, geopolitics, and environment must be involved and analysed, to deliver the urgent actions required for a sustainable future development.

1.1.1 Geopolitics of the transition and policymakers’ role

Set that geopolitics is a concept which seems harder to define, enclosing different interpretations and implications, a valuable definition refers to it as “great power competition over access to strategic location and natural resources” [20]. In this sense, it can be envisioned a strong and durable link between geopolitics and renewables, and all the resources involved to support the emerging technologies. Specifically, each country has a specific relationship with its own resources, being them fossil fuels or renewables; the energy transition must not exacerbate the regional discrepancies, paying attention also to water scarcity, depletion of critical resources and materials, land degradation [14]. According to the analysis of Research & Development investments in energy technology of the International Energy Agency (IEA) member countries, Lee and Yang [21] identify four different transition categories under the common slogan of “transition toward clean energy”: (i) from fossil to non-fossil; (ii) from carbon to de-carbon; (iii) from non-renewable to renewable; (iv) from plant construction to efficiency enhancement [21]. In the attempt to map the role of countries in the energy transition, also Svobodova et al. [16] make a classification through the analysis of: (i) the economic health, through the Growth Domestic Product (GDP), the growth of GDP and the Human Development Index (HDI); (ii) the dependency on coal, based on coal rents, imports of coal, and the coal share in energy mix; (iii) the carbon contribution to climate change, evaluating the CO_2 production and its increase [16]. According to this categorization, eight main groups are identified, playing six different roles in the global transition landscape; in particular, the recalcitrant nations, the late-stage transition leaders and the late-state transition followers belonging to the countries highly dependent on coal, while the early-stage transition followers, the early-stage transition leaders and the late-stage transition followers referred to the less dependent on coal [16]. Considering that the world will be effectively reshaped by the ongoing transition, the implications of Renewable Energy Sources (RES) in geopolitics are envisioned according to the concept of “renewed conflicts” and “reduced conflict” [20]. Specifically, in the first case the energy-related conflicts will be not reduced by the transition, while according to the second perspective the greater self-sufficiency will reduce them. **Figure 4** summarises the implications of these two positions, grouped the big oil exporters and the resource-poor developing countries as losers, while identifying as winners all the countries able to achieve an industrial leadership in clean technologies [20]. Specifically, the MENA region should benefit from large-scale renewable energy adoption and could no longer need to invest in fossil fuels [20].

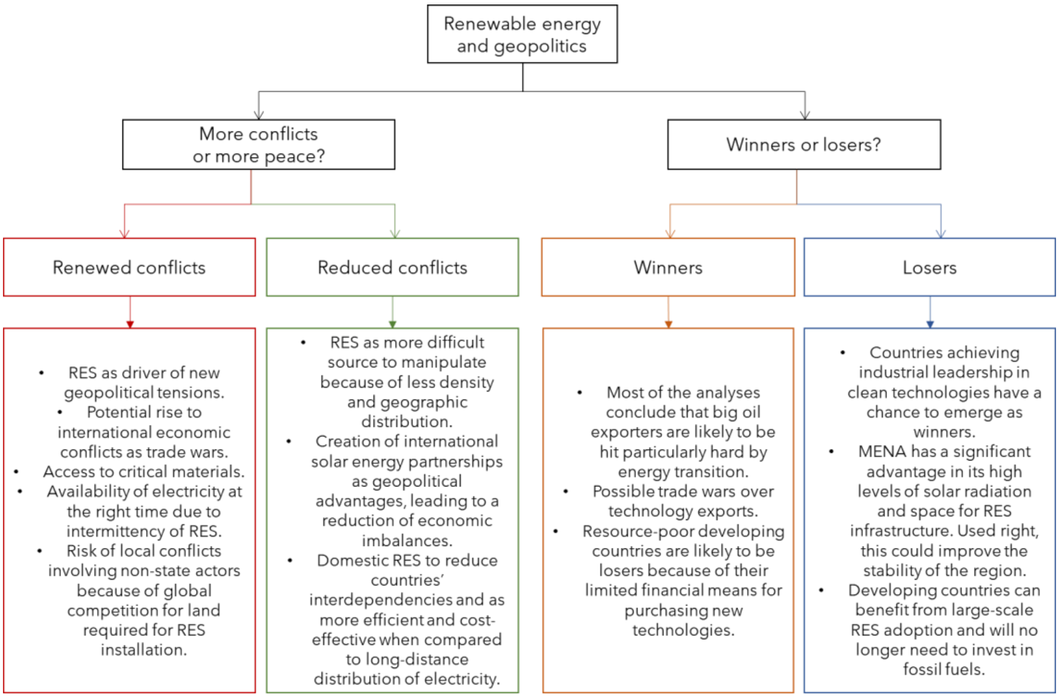


Figure 4: Potential implications of energy transition, adapted from [20].

Focusing on Europe, Mata Perez et al. [22] work on a multi-speed energy transition for the different countries of the European Union (EU); two main clusters are identified, grouping from one side those countries envisioning opportunities for industry and for lowering import dependence (Italy among them), and on the other, those aiming to prioritize reliable supply, with renewables as too volatile and expensive to substitute fossil fuels [22]. In particular, the West cluster, for which renewable energy is perceived as a win-win option, could become an interconnected region with a high degree of cooperation and interdependence. This EU side would reap the geopolitical and socio-economic benefits of RES, being also able to minimize the negative aspects of fossil fuel dependence, while the East cluster would still be bound to fossil fuels, which provides with short-term security of supply, but obstruct the political and socio-economic benefits of RES [22]. These countries would be more likely to have bilateral than multilateral connections with each other and to be less connected, in general, to the more prosperous green Europe [22]. A detailed study of Gielen et al. [23], based on the findings of the IRENA's Remap (Renewable Energy Roadmaps), analyses the specific role of RES in the transition, stressing the significance of renewables and efficiency for a global transition. "Although a successful transformation is found to be technically possible, it will require the rapid introduction of polices and fundamental political changes towards concerted and coordinated efforts to integrate global concerns, into local and national policy priorities" [23]. In parallel, it is needed to investigate specific lock-ins which could affect the renewable energy landscape and slow down the shift from fossils to cleaner solutions, as argued by Eitan et al. [24] which study the effects of (i) neglecting alternative technologies, (ii) impeding decentralized facilities, (iii) limiting innovation, (iv) impairing energy justice, (v) endangering the environment, and (vi) distorting the economic settings [24]. Halttunen et al. [25] work on diversified strategies option for companies earning from fossil fuels; it is found the need to address technical skills, project management, infrastructure and trading while working with new low-carbon solutions [25]. Within this framework, it becomes clear the need to work on diversification and resilience of the energy systems; also the Covid-19 Pandemic has revealed the effective vulnerabilities of social and economic systems, asking for a new comprehensive view on the transition and its implications [26]. It is required a holistic approach to address all the complex challenges related to extreme events, recognizing that multi-faceted and collaborative solutions for long-term resilience are a prerogative of the post-pandemic world. To this regard, key aspects concern the adoption of innovative strategies, the enhancement of global collaboration, a clear commitment to sustainability [26]. Beside the Covid-19 crisis, the invasion of Ukraine by Russia has pointed out the relevance of concepts like energy security, energy dependence and diversification. But together with the energy-related issues, this conflict and also the Israeli-Palestinian one both represent two "extreme" events world is facing; society, energy, food, health, economy, politics, geopolitics, everything is now questioned. The events of these years lead to think about how dealing with energy has so many multi-level implications, and conversely, what is apparently not energy-related has also implications in the energy system. In this sense, the thesis aims to strongly investigate the link between energy and all the other dimensions involved, while targeting the transition towards a carbon-neutral world.

Focusing on the pace and effectiveness of this transition, the role of policy is crucial; policymakers with their decisions and actions allow to speed up or slow down the process. In particular, the politics of accelerating low-carbon transition is analysed by Roberts et al. [27], studying three themes strictly interconnected: the roles of (i) coalitions, (ii) of feedbacks, (iii) of broader contexts (political economies, institutions, cultural norms, and technical systems), in creating more or less favourable conditions towards this acceleration [27]. Moreover, Lee and Yang [21] analyse how, while from the foraging period to the oil age energy has been a factor in determining political systems, with the expansion of energy trade among countries and the uptake of new technologies the situation has been reversed; now political systems have become a determinant of energy transitions [21]. In the IEA Roadmap "Net Zero by 2050" [28], focusing on policymakers' crucial role, specific priority actions are identified, as summarised in **Figure 5**.

1 To make *the 2020s* the decade of *massive clean energy expansion*
2 To prepare for the next phase of the transition by *boosting innovation*
3 To increase *clean energy jobs* strongly but also making them spread widely
4 To set *near-term milestones* to get on track for long-term targets
5 To drive a *historic surge* in clean energy *investment*
6 To address *emerging energy security risks* since now
7 To take *international co-operation* to new heights

Figure 5: Priority actions for policymakers to support transition from the near- to the long-term, adapted from [28].

Another key challenge of the current transition process concerns the cross-sectoral actors involved and their influence on decision-making in a renewable energy system [20]; it is argued how players like environmental Non-Governmental Organizations (NGOs) and individual consumers are expected to increase in a renewable energy system, considering the higher degree of decentralisation and a more equal distribution of power among them [20]. **Figure 6** summarises the heterogeneity of roles played by different citizens in the transition, according to a detailed study conducted on the heterogeneity of human behaviour when dealing with the transition [29]. The effectiveness of policy framework through informed strategies and interventions relies on recognizing this heterogeneity; new policies approaches and analyses are required to integrate human and behavioral dimensions for an inclusive and just transition [29].

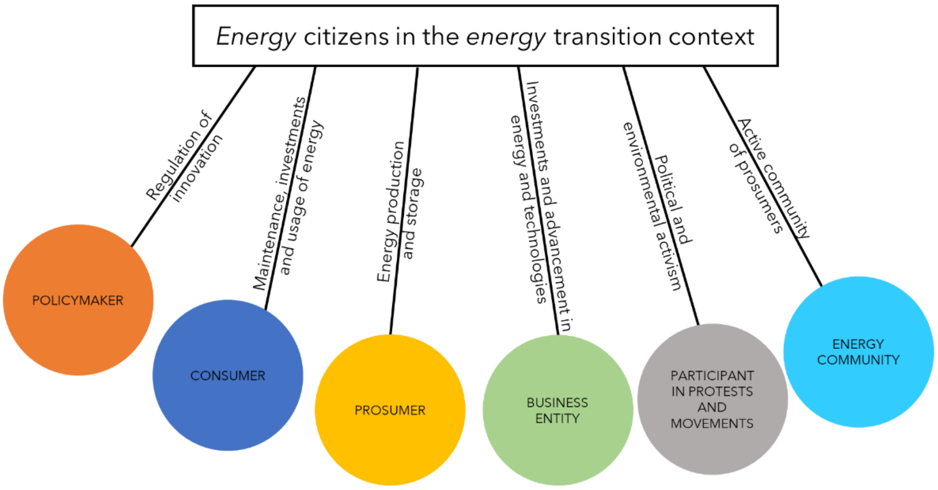


Figure 6: Heterogeneity of human behavior in the transition context, adapted from [29].

1.2 Green hydrogen as key player of climate-neutrality target

The starting point of the research is based on the study of different pathways towards decarbonization, to focus on the key pillars for climate-neutrality and to analyse the projections in the long-run worldwide. As references for the decarbonization scenarios, among the others, the analyses of the World Energy Council (WEC), IEA and IRENA are deepened. WEC has developed its analysis through the definition of the "Jazz Scenario" and the "Symphony Scenario", both examined in detail to study the significance of key drivers enabling global trends [30]. Moreover, in the World Energy Issues Monitor released by WEC [31] it is stressed how "the energy leaders everywhere are grappling with the certainty of much greater economic uncertainty and there is a re-alignment in energy leaders' ambitions to decarbonise energy, secure climate-neutrality and avoid climate change catastrophe" [31]. About IRENA, it is of interest the focus on the key pillars of the long-term scenarios [9], collected in **Figure 7**, recognizing, among the others, the crucial role played by green hydrogen adoption.

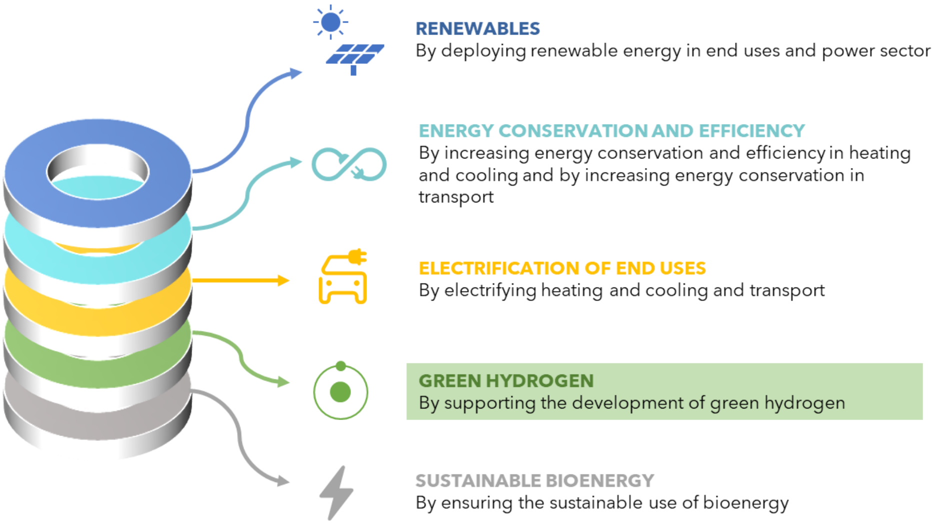


Figure 7: Key pillars for the 1.5°C Pathway, adapted from [9].

In addition to this, the IEA analyses highlight the need to perform a huge jump for the development of new technologies, considering among them electrolysers, advanced batteries and direct air capture and storage; “in 2050 almost half of the CO_2 emissions reductions will come from technologies that are currently at the demonstration or prototype phase” [28]. It is also addressed the need to strategically develop the required infrastructure, also taken into account hydrogen pipelines for its transport [28].

Although different studies and analyses are spreading worldwide on hydrogen uptake, the majority of decarbonization pathways identifies it as “the fundamental pillar of the energy transition critically needed to fight global warming and other issues related to traditional energy systems” [32]. Moreover, “being an historically valuable commodity gas and chemical feedstock, it can become an important fuel and energy storage vector for the energy transition” [33]. Hydrogen, specifically the clean one, is selected among the chosen actors to achieve the decarbonization target; studying the challenges and opportunities of its adoption fits with the aim of this PhD work; in the following, some of the information collected and elaborated for an already published contribution [34] are detailed.

Dawood et al. [35] identify the so-called “hydrogen square”, made of four main steps, connected and interdependent, i.e., production, storage, safety, utilization [35]. When analysing the possible ways of production, several colours (i.e., grey, brown, black, green, blue, pink) are used in literature, in the attempt to create a common language. About 95% of hydrogen produced worldwide is fossil-fuel based, generally of grey type [35]. Mostly using the steam methane reforming process, grey hydrogen production increases CO_2 emissions; similar considerations are valid for the so-called brown (or black) hydrogen, obtained by coal, and corresponding to the 19% of the total hydrogen production [36]. A climate-friendly solution for its production is represented by the green colour, which is used to address the exploitation of water electrolysis enabled by renewable energy, and now representing less than 1% of the global hydrogen production [9]. Moreover, there is also an increasing interest in the blue hydrogen, produced from natural gas but exploiting the possibility of compression, liquefaction, transportation and storage for the CO_2 emitted by the production process (Carbon Capture and Storage, CCS), or also the potential of supplying it to a process, reusing CO_2 in new products (Carbon Capture and Use, CCU) [37]. According to the IEA Net Zero pathway, while in the Global Hydrogen Review (GHR) released in 2022 the blue hydrogen production should covered a share of 40% on the total production by 2050, and the remaining one would be green [28], in the more recent GHR 2023 the estimates for the blue decrease up to 25% [38],[39]. However, it is worth mentioning that, at present, the required CCS and CCU technologies for the blue hydrogen exploitation are still not technologically ready and economically competitive [36]-[40]. For the sake of completeness, also pink hydrogen is discussed in literature, which consists of the exploitation of nuclear energy for the water electrolysis process. In **Figure 8** the main options for hydrogen production are listed, following the review of [41]:

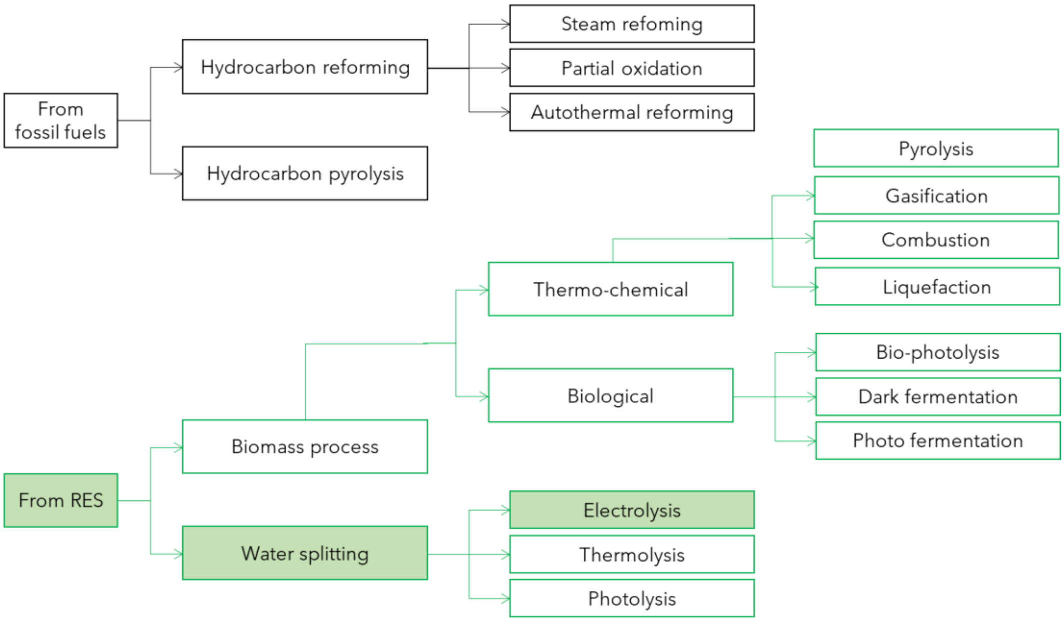


Figure 8: Hydrogen production options from fossil fuels or RES, adapted from [41].

"Despite the existence of multiple production methods (e.g., steam reforming, biological production etc.), water electrolysis has been the focus of many studies for energy applications, especially in connection with renewable energy technology"

[42]. In its 2020 guide to policymakers [43], IRENA identifies the main drivers and barriers to support policymakers' actions towards green hydrogen implementation, ranging from the readiness of technologies to scale up to the lack of infrastructure (**Figure 9**).

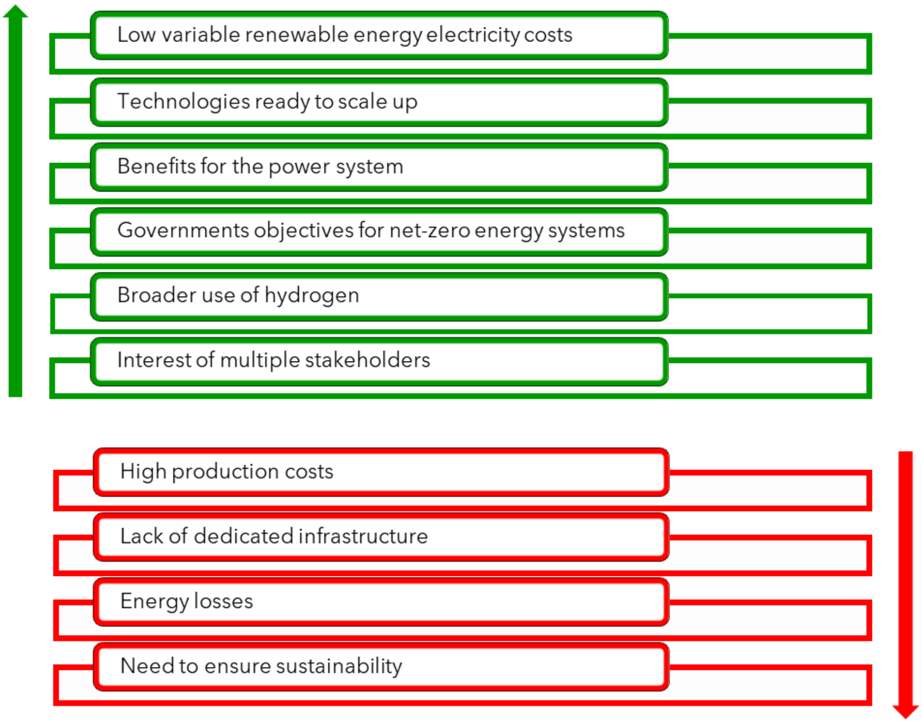
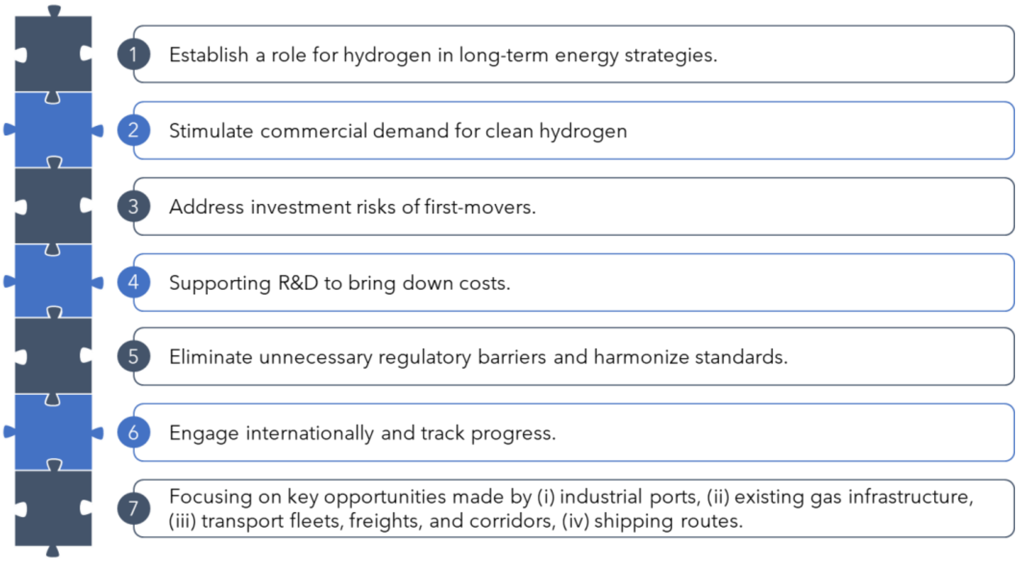


Figure 9: Drivers and barriers for green hydrogen adoption, adapted from [43].

Moreover, through the update of 2021 of this policymakers' guide [44], it is highlighted how the policy options to overcome the hydrogen barriers can be grouped into three main stages: (i) technology readiness, (ii) market penetration and (iii) market growth [44]. According to the IEA, to scale up hydrogen production and adoption, seven key recommendations must be followed [45]:



1. Establish a role for hydrogen in long-term energy strategies.
2. Stimulate commercial demand for clean hydrogen
3. Address investment risks of first-movers.
4. Supporting R&D to bring down costs.
5. Eliminate unnecessary regulatory barriers and harmonize standards.
6. Engage internationally and track progress.
7. Focusing on key opportunities made by (i) industrial ports, (ii) existing gas infrastructure, (iii) transport fleets, freights, and corridors, (iv) shipping routes.

Figure 10: The key recommendations for scaling up hydrogen, adapted by [45].

Concerning the long-term energy strategies, when the report "The future of hydrogen" was published (2019), only Japan and Korea had developed national hydrogen strategies and France had announced an ad-hoc hydrogen plan [45]. After that, 13 countries (Australia, Canada, Chile, the Czech Republic, France, Germany, Hungary, the Netherlands, Norway, Portugal, Russia, Spain, the United Kingdom), together with the European Commission, had published their own strategies referred to the hydrogen technology [46]. Moreover, in 2021 Italy and Poland had released their strategy for public consultation and 20 other countries are developing its own plan referred to hydrogen, while also more than 20 others are actively planned the same [46]. Looking at the IEA update in September 2023 [38], a total of 41 governments have currently in adoption specific hydrogen strategy or plans. The establishment of targets and long-term policy signals is the first policy trend listed (**Figure 10**), followed by the support to demand creation, the mitigation of the investment risks, the promotion of Research & Development, innovation, strategic demonstration projects and knowledge-sharing, the harmonization of standards and remotion of barriers [46]. While governments continue to promote hydrogen by integrating it more in the energy sector strategies, there is still not enough effort for creating hydrogen demand, and this could have a huge impact on final investment decisions and the increasing export-oriented project plans [47]. Looking at the export potential, it is now clear that there will be geoeconomic and geopolitical consequences, considering that countries with the highest amount of renewable power will play the biggest role in hydrogen production and trade. Hydrogen will influence the geography of energy trade in the next decades, with a less competitive and lucrative market than the oil and gas one [48]. It is assessed that the green hydrogen potential worldwide is almost 20 times the global energy demand estimated for 2050, but on the other side this potential relies on renewable constraints, specifically based on a continuous relationship between cost and renewable capacity [49].

1.2.1 The European context: opportunities and challenges

Having set that the more ambitious the target, the higher the hydrogen penetration in the energy system, **Figure 11** highlights the impacts that different strategies and constraints have on hydrogen development, and vice versa. Reviewing hydrogen demands among alternative scenarios, it is found that its penetration by 2050 can increase from 150 Mt to more than 600 Mt worldwide [50].

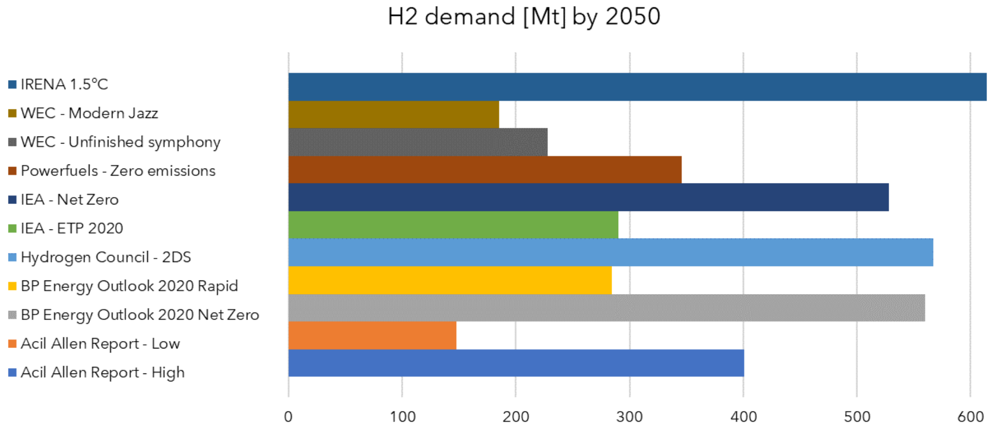


Figure 11: Global 2050 hydrogen demand according to energy scenarios, adapted from [50].

While IRENA estimates a hydrogen demand increase up to 600 Mt to make effective the pathway towards the achievement of the 1.5°C threshold [9], WEC evaluates a demand of 200 Mt by 2050 to achieve the less ambitious target of 2°C as limiting rising temperature [50]. Despite variations in climate targets and strategies, there is a widespread acknowledgment of the imperative to address the key challenges involving to investment costs and reliable infrastructure, to effectively unlock the hydrogen market by 2040, a crucial period to influence a carbon-constrained world [51]. In its update of the Net Zero on September 2023 [39], IEA estimates an average annual growth rate of 80% in the demand for low-carbon hydrogen and hydrogen-based fuels until 2030 and 90% up to 2050 [39]. To meet this demand, it will be necessary to satisfy the hydrogen needs of industry and transport, which will cover the 80% of the overall demand by 2050 [39]. As the global demand for hydrogen changes over time, following specific evolutionary trends, the EU is actively promoting hydrogen development, being expected a demand increase by 2050 that is 9 times higher than the level observed in 2020 [52]. **Figure 12** illustrates the timeline encompassing significant EU decisions within the hydrogen context, starting from the formulation of the European Hydrogen Strategy released in December 2020 [53], up to the key findings regarding hydrogen from the REPowerEU initiative presented in May [54].

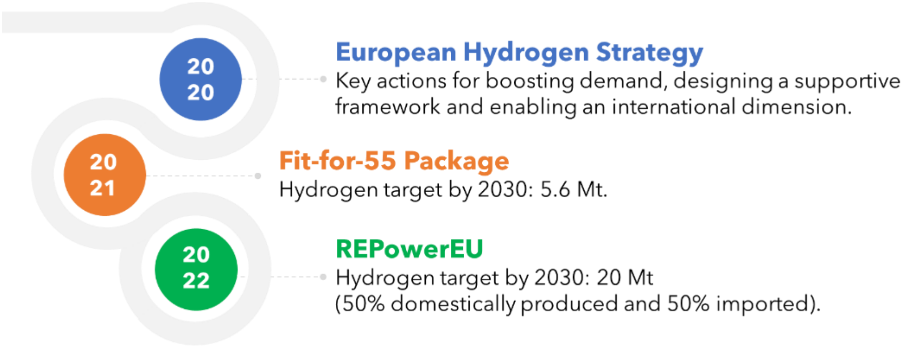
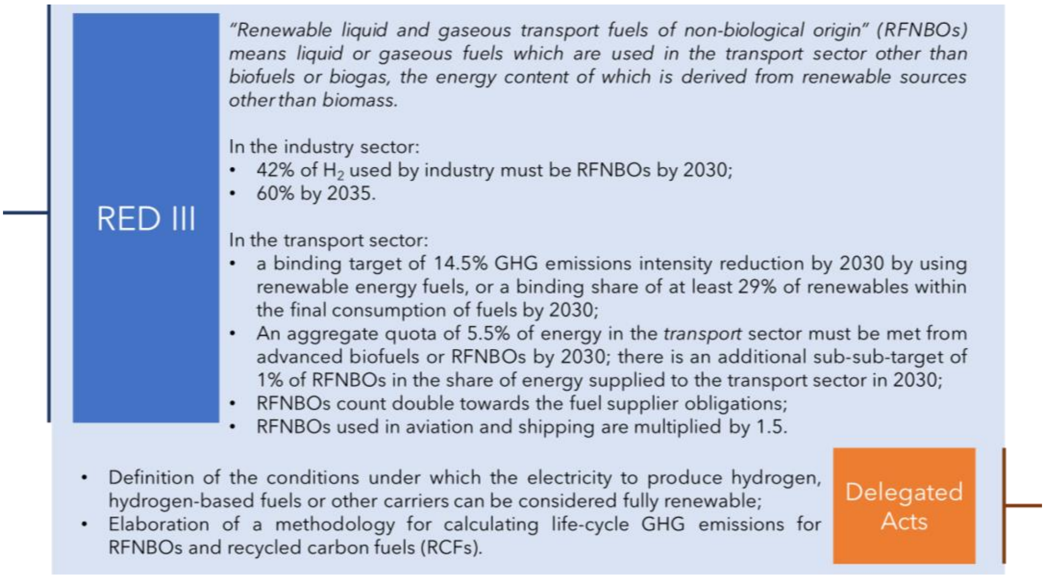


Figure 12: From the EU Hydrogen Strategy to the REPowerEU hydrogen targets.

Advocating for a 55% reduction in GHG emissions by 2030, the Fit-for-55 (F55) Package announced in July 2021 is followed by the REPowerEU, designed as a response to the Russia's invasion of Ukraine. If from one side the former addresses various policy areas within the energy transition process [55], the latter is more narrowly focused on promoting hydrogen use within the EU [54]. Examining the specific targets for renewable hydrogen, the value of 5.6 Mt [55] has been replaced by the revised target of 20 Mt outlined in [54]. This represents a substantial increase compared to the primary objectives of the European Union Strategy released in December 2020, which initially emphasized the effective involvement of only the hard-to-abate sectors in hydrogen usage [53]. Examining recent updates and advancements, the Renewable Energy Directive (RED) III [56], released in late October 2023, establishes obligations for hydrogen consumption in both transport and industry sectors by 2030. This is achieved through the definition of Renewable Fuels of Non-Biological Origin (RFNBOs), as elaborated in **Figure 13**.



RED III

"Renewable liquid and gaseous transport fuels of non-biological origin" (RFNBOs) means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass.

In the industry sector:

- 42% of H_2 used by industry must be RFNBOs by 2030;
- 60% by 2035.

In the transport sector:

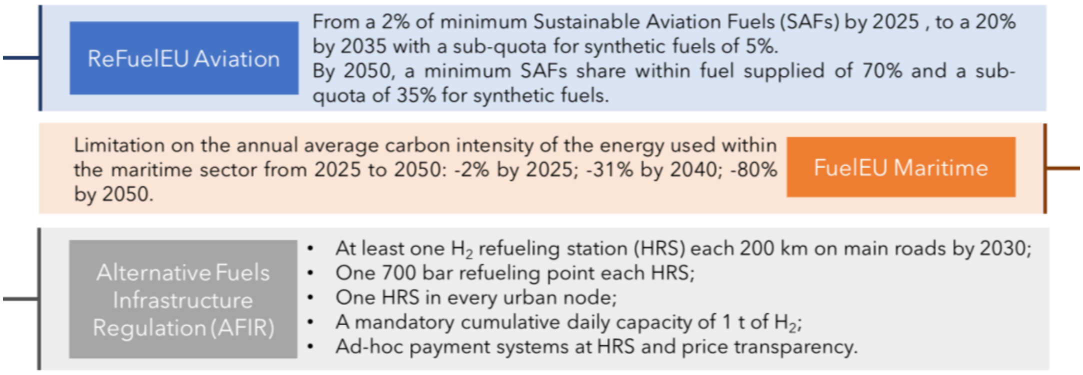
- a binding target of 14.5% GHG emissions intensity reduction by 2030 by using renewable energy fuels, or a binding share of at least 29% of renewables within the final consumption of fuels by 2030;
- An aggregate quota of 5.5% of energy in the *transport* sector must be met from advanced biofuels or RFNBOs by 2030; there is an additional sub-sub-target of 1% of RFNBOs in the share of energy supplied to the transport sector in 2030;
- RFNBOs count double towards the fuel supplier obligations;
- RFNBOs used in aviation and shipping are multiplied by 1.5.

Delegated Acts

- Definition of the conditions under which the electricity to produce hydrogen, hydrogen-based fuels or other carriers can be considered fully renewable;
- Elaboration of a methodology for calculating life-cycle GHG emissions for RFNBOs and recycled carbon fuels (RCFs).

Figure 13: Focus on RED III about RFNBOs and related Delegated Acts [56],[57].

Considering the pivotal role of hydrogen in decarbonizing the aviation and maritime sectors, ReFuelEU Aviation [58] and FuelEU Maritime [59] offer actions and strategies to facilitate this transition, as outlined in **Figure 14**. Complementing these initiatives, the Alternative Fuels Infrastructure Regulation (AFIR) is set to guarantee the utilization of hydrogen refuelling stations, thereby to effectively unlock the potential of zero-emission vehicles [60] (**Figure 14**).



ReFuelEU Aviation

From a 2% of minimum Sustainable Aviation Fuels (SAFs) by 2025 , to a 20% by 2035 with a sub-quota for synthetic fuels of 5%.
By 2050, a minimum SAFs share within fuel supplied of 70% and a sub-quota of 35% for synthetic fuels.

Limitation on the annual average carbon intensity of the energy used within the maritime sector from 2025 to 2050: -2% by 2025; -31% by 2040; -80% by 2050.

FuelEU Maritime

Alternative Fuels Infrastructure Regulation (AFIR)

- At least one H_2 refueling station (HRS) each 200 km on main roads by 2030;
- One 700 bar refueling point each HRS;
- One HRS in every urban node;
- A mandatory cumulative daily capacity of 1 t of H_2;
- Ad-hoc payment systems at HRS and price transparency.

Figure 14: Details on EU regulations and strategies for hydrogen end-use sectors, adapted from [57].

In addition to the technological emphasis on end-uses, two key pillars in the context of decarbonization are the Emission Trading System (ETS) [61] and the Carbon Border Adjustment Mechanism (CBAM) [62],[63]. The CBAM covers sectors such as cement, iron and steel, aluminium, fertilizers, electricity, and hydrogen. In its initial phase (2024-2026), this mechanism is applied to the import of products considered carbon-intensive and at significant risk of carbon leakage. Starting from 2026, its implementation will instead result in the gradual elimination of free allowances under the ETS, with the complete phase-out targeted by 2034 [57]. Regarding the ETS, the ETS II has been also introduced to address additional sectors such as buildings and road transport, through a separate emission trading system [64]. The goal is to achieve a 42% reduction in emissions compared to 2005 levels by 2030 [64]. Through a detail analysis of decarbonization scenarios outlined by [52], it is observed that hydrogen usage in end-use sectors within the EU will be still minimal in the next decade. However, by 2050, it is projected to constitute more than 10% of the final energy demand. Long-term analyses consistently affirm the crucial role of transport and industry as the two primary sectors where hydrogen will expand, alongside electrification. Specifically, transport is anticipated to account for an average of hydrogen share of 27%, while industry is expected to satisfy over 20% of its energy demand through hydrogen supply [52]. In the context of how hydrogen can contribute to the decarbonization of the European energy system [65], it is estimated that the increasing prominence of renewable hydrogen will significantly accelerate RES integration. In fact, if the share of renewables in gross final energy consumption reaches 80% by 2050, it implies that approximately 95% of electrolysers will be powered by a direct connection to wind and solar plants [65].

1.2.2 Positioning hydrogen in international trade strategies and projects

To effectively pave the way to hydrogen development, key actions must be undertaken by policymakers worldwide to scale up hydrogen and facilitate its trade, boosting its uptake. Starting from the promotion of trade and services related to renewable energy production, it is required to implement subsidies to support an increasing capacity of electrolysers and green hydrogen production, also developing national measures based on international hydrogen standards and intensifying dialogues among countries [66]. As declared by IEA, the production of low-emission hydrogen was less than 1 Mt in 2021 [47]; this low amount, considering an hydrogen demand of 94 Mt reached in 2021 [47], clarifies the need to take urgent actions towards the development of ad-hoc strategies to produce and trade green hydrogen and its derivatives like ammonia or methanol. Currently, there is a huge increase of projects concerning production of green hydrogen, pushing for its trade and adoption, characterized by an impressive speed [47]. Through the realization of all the planned projects, by 2030 it is envisioned to have from 16 to 24 Mt of low-emission hydrogen, with more than 50% produced by electrolysis and the remaining part exploiting fossils but also CCUS [47]. The critical aspect is related to the real pace of implementation of these projects; only 4% of them is under construction or has reached a final investment decision (FID), with the main influencing factors related to demand uncertainties, lack of regulatory frameworks and infrastructure which are not ready yet [47]. On the other side, an acceleration could be influenced by the increase of fossil fuels energy prices, in contraposition to the high availability of renewable sources in several countries of the world and the huge amount of export-oriented hydrogen project plans [4]. Specifically, while currently about 85% of hydrogen is produced and consumed on-site [6], the spread of green hydrogen adoption will imply a significant production in locations having optimal combination of renewable sources, availability of land, of water and of transport infrastructure [67]. According to IRENA, because of the local vision and specific market strategy, there are some countries identified as front-runners countries, which could play a crucial role in the development of the green hydrogen market to implement effective decarbonized solutions by 2050; among them, EU, China, India, Japan, Republic of Korea, the United States of America [67]. **Figure 15** shows the main projects and investments for clean hydrogen, collected up to the end of November 2021 by IRENA, while **Figure 16** and **Figure 17** highlight the main import markets for hydrogen, ammonia and methanol up to 2021, as reviewed by IRENA on a report released in December 2023 [66].

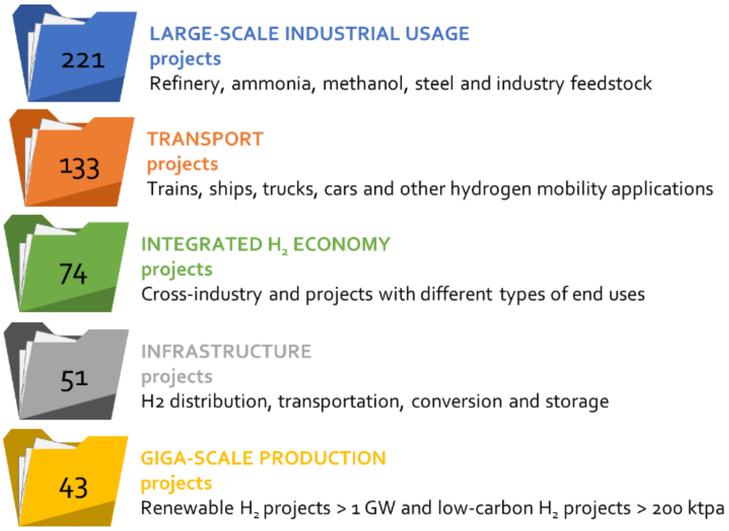


Figure 15: Clean hydrogen projects and investment (2021), adapted from IRENA [67].

Focusing on **Figure 16**, among the main importers there are Canada – which is responsible of the 99% of the US hydrogen trade –, Belgium as main supplier of the Netherlands, and Chinese Taipei taking hydrogen from Singapore [66]. Concerning ammonia and methanol (**Figure 17**), the amounts and investments are much higher if compared to the hydrogen ones in 2021; India has currently the highest import share, trading with Saudi Arabia, Qatar and Ukraine, while the highest volume of methanol is imported by China which trades with United Arab Emirates, Oman and Saudi Arabia [66].

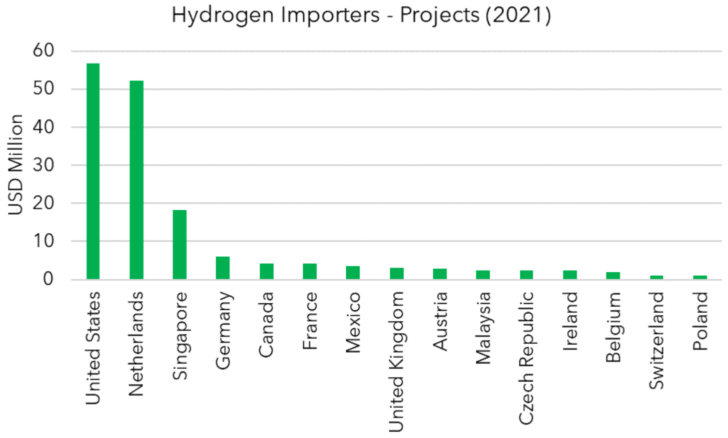


Figure 16: Main importers of hydrogen in 2021, adapted from [66].

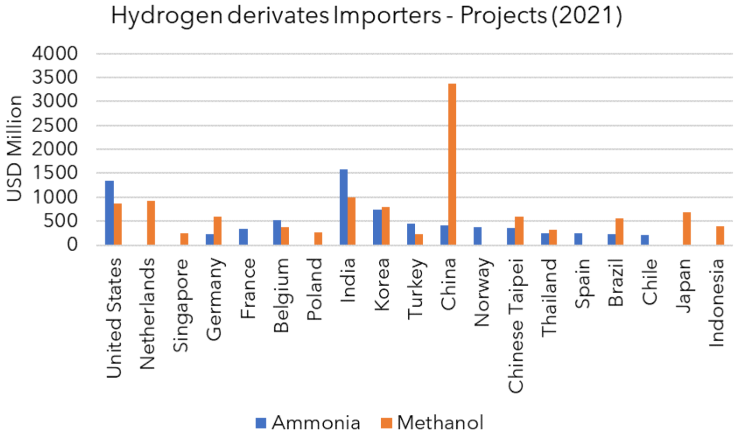


Figure 17: Main importers of hydrogen derivates in 2021, adapted from [66].

Focusing on Africa and its renewable potential, there are international investors announcing various projects on green hydrogen; among the others, Egypt and Zimbabwe have already installed over 100 MW of electrolysers, in Mauritania a 16

GW electrolysis project was announced in May 2021, while at COP26 the government of Namibia announced the collaboration with HYPHEN Hydrogen Energy to develop strategic green hydrogen project [67]. However, the renewable potential is not the unique factor to be addressed; there are much more drivers and barriers that can speed up or slow down the adoption of green hydrogen, from “hard” to “soft” factors (**Figure 18** and **Figure 19**).

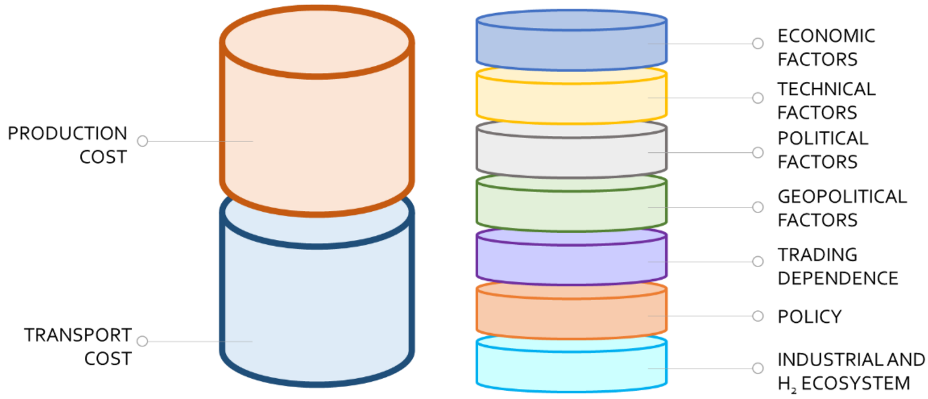


Figure 18: Hard and soft factors impacting on green H_2 production, trade, use; adapted from IRENA [67].

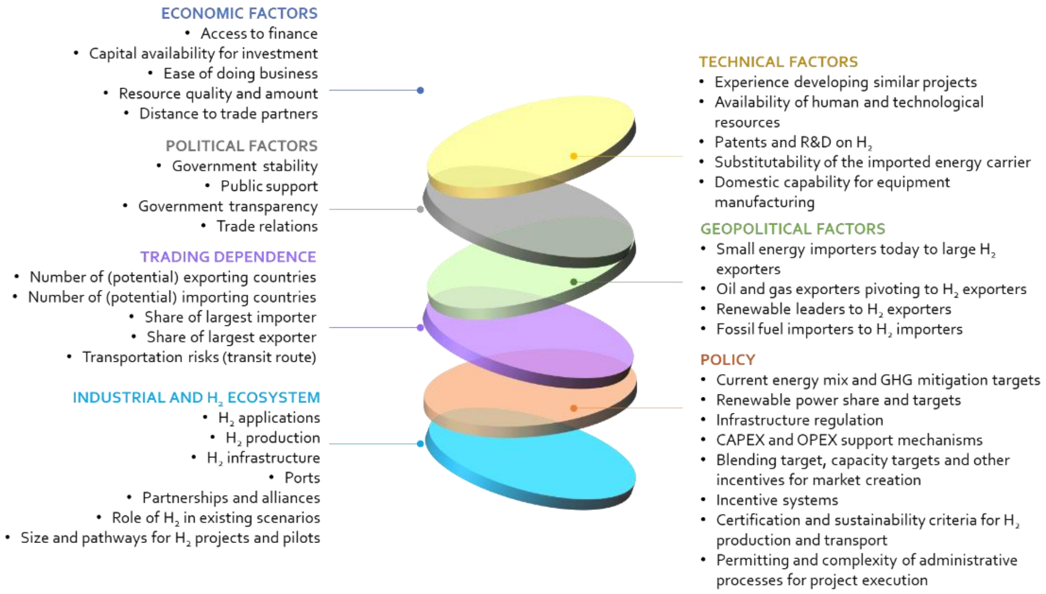


Figure 19: Focus on soft factors impacting the value chain of green H_2, adapted from IRENA [67].

Looking at **Figure 19**, it is evident that a huge amount of factors contributes for a successful development of the green hydrogen value chain; specifically, the majority of them can be not energy-related but can involve the social and political dimensions, relying on the stability and transparency of the government, or geopolitical relations. Concerning the more techno-economic aspects, it is evident how a change of paradigm is needed to adequately implement strategic pathways for green hydrogen development. A specific analysis is required for the potential trade and new alliances as consequences of green hydrogen deployment; according to IEA, the international trade will emerge as component of the green hydrogen value chain [47]. If by 2030 it is expected to cover 3% of the hydrogen demand through international trade, by 2050 the share of traded hydrogen will increase up to 12% in the Announced Pledges Scenario (APS) of IEA [4]. In this regard, IEA identifies Middle East, Australia, North Africa, North America, and Latin America as exporters [47]. On IRENA side, the same countries are identified as the areas with the major potential; specifically, three different groups are defined, as detailed by **Table 1**:

Table 1: From exporters to importers of green H_2 globally, adapted from [67].

Role	*Country*	*Detailed role*
Net H_2 exporters	Australia, Chile, Morocco, Spain	Low cost for green H_2 production; exploitation of renewable market to attract investments
Self-sufficient	China, United States	Sufficient potential to satisfy the domestic H_2 demand
Importers	Japan, republic of Korea, parts of Europe, Latin America	Need of imports to satisfy the domestic H_2 demand

According to the 1.5°C Scenario of IRENA [9], about the 25% of the global hydrogen demand by 2050 is expected to be satisfied by trade; of this, around 55% is estimated to be delivered through pipelines, mostly in Europe and Central America, and the remaining part to be shipped [67]. Concerning the exploitation of pipelines in Europe, North Africa is identified as one of the key partners for trade, with Italy and Spain playing the relevant role of hub for the rest of Europe [67]. Specifically, the strategic role that the Mediterranean area can play in this regard is widely recognised, considering the perfect physical conditions in terms of resources and the increasing hydrogen demand, which must push for huge investments in clean infrastructure [68]. In this sense, consisting of a group of thirty-one energy infrastructure operators, the European Hydrogen Backbone (EHB) initiative has been built up to make the infrastructure ready for hydrogen trade, connecting supply and demand across Europe [69]. The EHB study assessed 12 Mt as domestic supply by 2030, so it exceeds the REPowerEU domestic target by 20%, but in this way supporting the need of enhancing energy independence and security of supply. In **Figure 20** the main features related to the five corridors elaborated by the EHB initiative are summarised; it is evident how the potentialities of renewable resources play a crucial role, together with the infrastructure already available, the estimated demand and ongoing projects.

Corridor A: North Africa & Southern Europe	Corridor B: Southwest Europe & North Africa	Corridor C: North Sea	Corridor D: Nordic and Baltic regions	Corridor E: East & South-East Europe
- Major driver: to decarbonize industry, power and transport in Italy, Central Europe and Germany. - Major opportunity: to repurpose a large share of existing gas pipeline across Italy, Austria, Slovakia and Czechia and the Trans-Mediterranean pipeline. - In the near-term, the corridor offers access to aboundant and low-cost RES from Italy and Tunisia; in the long-term: Algeria (via Tunisia) and additional supply from Central and South-Central Europe. - It is estimated a cost ranging from 2.1 to 3.8 €/kg of H_2 by 2030.	- Major driver: to decarbonize industry, power and transport in Iberian Peninsula, France and Germany. - Major opportunity: new interconnection between France and Spain through the East Pyrenees. - In the near-term, the corridor offers access to low-cost RES from Spain and Portugal; in the long-term: from Morocco and potentially Algeria. - It is estimated a cost ranging from 2 to 3.8 €/kg of H_2 by 2030.	- Major driver: to decarbonize industry, power and transport in the UK and northwestern Europe. - Major opportunity: large portfolio of ongoing and planned H_2 infrastructure projects, and a list of planned import terminals for H_2 and derivatives, in the Netherlands, Belgium, Germany and France. - In the near-term, the corridor offers access to abundant and low-cost blue H_2 supply from the North Sea; in the long-term: access to strong onshore and offshore resources in the North Sea. - It is estimated a cost ranging from 1.6 to 3.5 €/kg of H_2 by 2030.	- Major driver: to decarbonize industry, power and transport in the Nordics, the Baltics, Poland and Germany. - Major opportunity: development of new H_2 infrastructure in the Bothnian Bay, one of the earliest, greenfield H_2 projects in Europe. - In the near-term, the corridor offers access to aboundant and low-cost onshore wind and grid-based hydrogen supply from the Nordics; in the long-term: access to H_2 supply from offshore wind in the Nordics and the Baltics. - It is estimated a cost ranging from 2.1 to 3.8 €/kg of green H_2 by 2030.	- Major driver: to decarbonize industry, power and transport across Eastern and South-Eastern Europe, particularly along the corridor through Greece, Romania, Hungary, Austria, Germany. - Major opportunity: to leverage the abundant renewables potential in Eastern Europe. - In the near-term, the corridor offers access to abundant and low-cost RES from Eastern and South-Eastern Europe; in the long-term: further access to H_2 supply across the entire region. - It is estimated a cost ranging from 2.5 to 4.5 €/kg of H_2 by 2030.

Figure 20: Summary of the key features of the analysis of supply corridors elaborated by EHB, adapted from [69].

If from one side the EHB initiative allows to support a strategy for hydrogen development in terms of production, transport and trade, there are also interesting analyses focusing on the possibility to choose different pathways, while studying a trade-off among energy security and energy independence. Having clear that green hydrogen requires the availability of both renewable energy and water as primary sources, it is of interest to deepen the hydrogen mapping proposed by De Blasio and Pflugmann [70], who, taking care of (i) RES endowment, (ii) renewable freshwater resource endowment, and (iii) infrastructure potential, classify countries distinguish among (i) export champions, (ii) renewable-rich but water constrained with high infrastructure potential, (iii) renewable-constrained with a high infrastructure potential, (iv) resource-rich with high infrastructure potential, (v) resource-rich with low infrastructure potential [70]. Similar results of IRENA (**Table 1**) are found; Australia, United States, Morocco and Norway are definitely identified as export champions, while parts of EU, Japan and Korea are assessed as renewable-constrained nations with high infrastructure potential and most parts of South America are included in the group of research-rich countries with low infrastructure potential [70]. When talking about resource endowment, renewable freshwater resources must be addressed in parallel with renewable energy. According to a recent study focusing on land and water availability, Africa, South America, Canada and Australia are identified as potentially hydrogen leaders [71]; nevertheless, hydrogen production could exacerbate water scarcity in North Africa – although water withdrawal for hydrogen is negligible compared to its use in other sectors [72]. In March 2022, Nunez-Jimenez and De Blasio published a work to study an independent, a regional dependent and long-distance dependent scenario on hydrogen production and trade [73]. Assuming an EU hydrogen demand by 2050 equivalent to 15% of the current primary energy consumption – about 75 Mt yearly – three different scenarios were modelled to satisfy this demand (**Figure 21**).


HYDROGEN INDEPENDENCE

PRIORITY:
energy independence.
DESCRIPTION:
demand met with EU international production only.
COUNTRIES:
EU Member States.

REGIONAL IMPORTS

PRIORITY:
cost optimization.
DESCRIPTION:
EU internal lowest-cost production complemented with imports from regional neighbors.
COUNTRIES:
Regional neighbors and EU Member States.

LONG-DISTANCE IMPORTS

PRIORITY:
energy security.
DESCRIPTION:
Long-distance imports complement EU and regional supplies.
COUNTRIES:
Long-distance export champions, regional neighbors and EU Member States.

Figure 21: Optional scenarios developed by Nunez-Jimenez and De Blasio for hydrogen production and trade in EU [73].

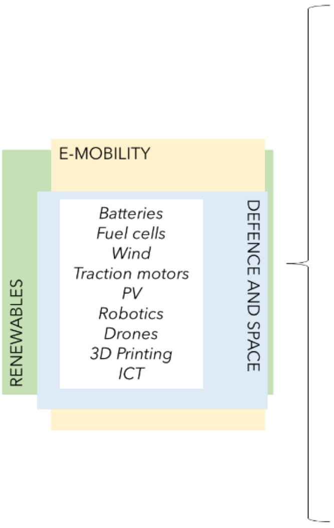
Being a very interesting study, for the assumptions made, the methodological approach applied, and the obtained results, some outputs need to be highlighted. It is found that all the European Member States have moderate or low renewable potential, while, for the opposite reason, neighbouring countries like Morocco or Norway and long-distance partners like Australia and United States could emerge as global export champions [73]. To this regard, cross-border cooperation and infrastructure planning play a key role for the implementation of an adequate hydrogen market in all the scenarios. With respect to the costs, it is found that investments in renewables and electrolysis account for more than 80% of the overall CAPEX, while the cost of capital is the variable having the highest impact on overall supply costs, across all the scenarios [73]. Finally, the economic trends highlight the potential effectiveness of policy measures at reducing the cost of capital, increasing competitiveness and adoption, even if a cheaper hydrogen supply could mean a higher price in terms of new energy dependence patterns and risks of security of supply [73]. Other numerous studies have examined the hydrogen domestic potential of Europe and explored alternative import routes – specifically from North Africa. These investigations, such as those referenced as [65],[74]-[78], model various scenarios combining local production and trade. Within the possibility to use existing pipelines, North Africa could strengthen its cooperation with Europe, specifically through pivotal hubs in Italy and Spain [67]. The work of Timmemberg and Kaltschmitt [78] assesses the future feasibility of blending hydrogen into existing pipelines from North Africa to Europe, while the one of Van der Zwaan et al. [77] investigates the potential export of electricity and hydrogen along existing routes through scenario analyses. This last study stresses that North Africa has the potential to become a hydrogen export-oriented region, emphasizing the importance of cost-effectiveness when trade amounts are less restricted [77]. It exploits the Integrated Assessment Model TIAM-ECN to assess the competitiveness of trade, estimating that North Africa could benefit of significant trade revenues, becoming a major player in the hydrogen game [77]. To this regard, multiple studies concur that, by 2050, alternative routes for trade could include repurposed gas pipelines and ammonia shipping, considering the former more cost-effective than new pipelines [9],[79]-[81]. Seck et al. [65], through the modelling of pipelines and ammonia or liquefied hydrogen ships, underline the critical advantage of existing cross-border pipeline infrastructure over maritime transport; infrastructure requirements and availability are stressed as crucial factors to boost hydrogen projects [65]. Combining three models, namely MIRET-EU, Integrate Europe, and HyPE, this study evaluates different scenarios working on different shares of renewables [65]. Additionally, off-grid solutions are identified as sources that can potentially cover up to 95% of total hydrogen production via electrolysis, highlighting how it becomes crucial to unlock off-grid solutions to supply electrolysers. Regarding the import options modelled by [65], which include routes from North Africa, Russia, Middle East, and Ukraine, it is estimated that the imported volume could reach 10 to 15 Mt by 2050. Focusing on the geopolitical implication of hydrogen, Van de Graaf et al. [82] identified the following ones: (i) the creation of new dependencies between countries along the path of large-scale imports; (ii) a change in the interest and actors of transition if hydrogen throws a lifeline to fossil fuel producers and incumbents; (iii) a potential intensification of technological and geo-economic rivalry between countries [82]. However, “the geopolitical angle is just one of a broader set of social science research questions that the hydrogen transition is opening up” [83]. Moreover, Acar and Dincer [84] stress how “there is a lack of studies focusing on social, technical, financial, and environmental aspects of sources and systems required for sustainable hydrogen production” [84].

All these aspects become crucial when dealing with Italy and North African countries; from the other side of the Mediterranean Sea there are countries already undergoing “an unprecedented set of demographic, social, political, and economic changes that are likely to significantly modify the energy landscapes in the region” [85]. In order to better stress the importance of an assessment going beyond the techno-economic aspects of the energy transition, an interesting point of view is the one related to the megaprojects not concretized yet in North Africa; in fact, “the non-technical risks in North Africa are very real and likely to create an indefinite delay in the realization of electricity market megaprojects” [86]. In particular, Van De Graaf et al. in [87] investigate the Desertec idea (2009), to identify the factors that slowed down the initiative, which aims to both supply Europe with electricity produced by solar power plants in North Africa and Arabic peninsula and contribute to self-supply of MENA region [87]. Among these influencing factors there are (i) corruption and authoritarianism, (ii) technical problems and cost overruns, (iii) inflated expectations, (iv) ecological and social externalities, (v) stakeholder fragmentation [87]. Schmitt names this specific project as “failure” [88], underlining how “technical feasibility is not social feasibility” and moreover, how the Desertec idea has emphasized the relevance of hard economic and institutional factors for the selection of innovative paths, and also bought a number of critics into the arena, “including, surprisingly, actors from the ecology and environmental movements” [88].

Trying to put in contact the completely different realities sharing the Mediterranean is a very challenging task, but beyond these challenges there are a lot of opportunities coming from this kind of heterogeneous cross-border cooperation. The PhD research aims to encourage the rising of opportunities, taking care of the potential risks. All these aspects are detailed and investigated in section 3.

1.2.3 The role of critical raw materials

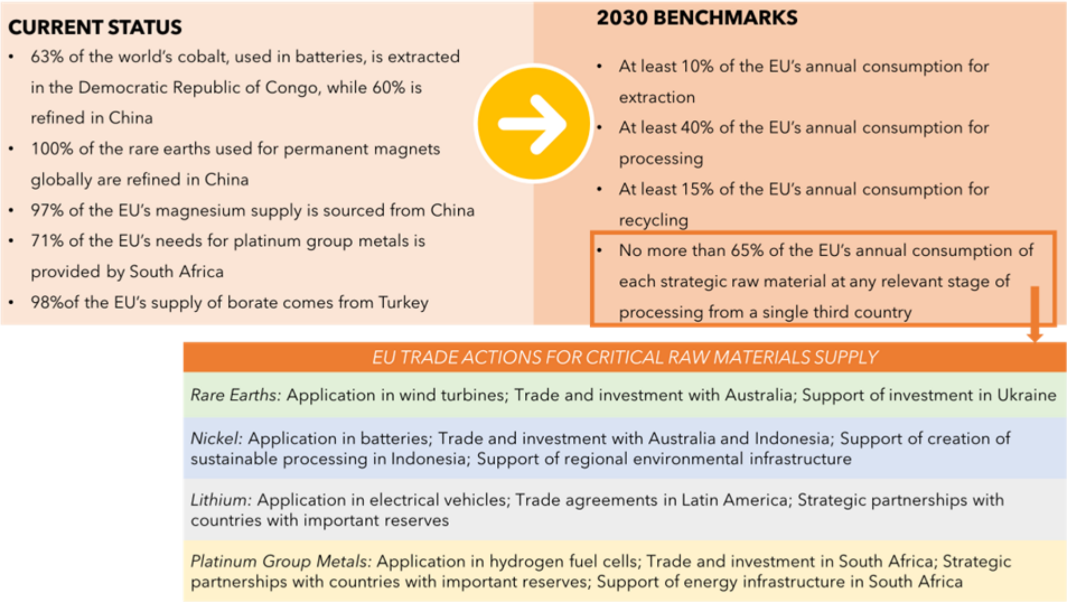
While dealing with the dynamics of the energy transition and how it will reshape countries' identities and alliances, it is also essential to address the role of critical raw materials and their increase in demand for the next decades. Defined mineral- and metal-intensive, the transition appears to be exposed to a challenging mismatch of supply and demand for several minerals, especially concerning lithium [89],[90]. It is important to notice how each raw material has its own market worldwide, generating a specific geography of trade. Also the definition of "critical material" is strongly subjective and location-specific, having as core criteria typically the economic importance and the level of supply risk, based on factors like scarcity and proximity of supply, complexity of extraction and refining processes, lack of viable substitutes [9]. But focusing on the technological sectors working for carbon-neutral solutions, the list can include – but it is not limited to – cobalt, copper, graphite, iridium, lithium, manganese, nickel, platinum, and selected rare earth elements. **Figure 22** summarises the main sectors and related technologies affected by flows of critical raw materials, considering a renewable-based energy transition [89],[90].



	Main energy-related applications	Other energy-related applications
COBALT	EV batteries	Battery storage; Bioenergy; Electrolysers
COPPER	Electricity grid; EV batteries; Solar PV	Battery storage; Bioenergy; CSP; Electrolysers; Geothermal; Hydro
DYSPROSIUM	EV motors; Wind	
GRAPHITE	EV batteries	Battery storage
IRIDIUM	PEM electrolysers	
LITHIUM	EV batteries	Battery storage
MANGANESE	EV batteries	Battery storage; CSP; Electrolysers; Geothermal; Hydro; Wind
NEODYMIUM	EV motors; wind	
NICKEL	Electrolysers; EV batteries	Battery storage; Bioenergy; CSP; Geothermal; Hydro; Solar PV
PLATINUM	PEM electrolysers	

Figure 22: Selected sectors and technologies most affected by critical raw materials, adapted from [89],[90].

Concerning clean hydrogen production and consumption, iridium and platinum are envisioned to be the most required minerals, followed by zinc, nickel, aluminium, titanium and copper; specifically, it is estimated an average annual primary demand by 2050 of iridium ranging from 30% to 95% of the primary production in 2021, while for platinum the range is 10% to 30% [91]. There are key mining countries for specific minerals, making the topic geographically constrained; among them, Australia and Chile play a crucial role for lithium, China for graphite and rare earths, South Africa for platinum and iridium [89]. Specifically, there are different supply risks associated to each raw material; Europe needs to invest significantly in R&D to match the pace of the other countries and to develop manufacturing opportunities [90]. In fact, the President of the EU Commission von der Leyen has recently argued how “raw materials are vital for manufacturing technologies for our twin transition – like wind power generation, hydrogen storage and batteries”; it is urgent to reduce the dependency on a few countries, pushing for diversification and an increase in domestic production [92]. Specifically, this position is related to the announcement of a proposal of a comprehensive set of actions to support the access of Europe to a supply of critical raw materials that is secure, diversified, affordable and sustainable (**Figure 23**) [92],[93].



CURRENT STATUS

- 63% of the world’s cobalt, used in batteries, is extracted in the Democratic Republic of Congo, while 60% is refined in China
- 100% of the rare earths used for permanent magnets globally are refined in China
- 97% of the EU’s magnesium supply is sourced from China
- 71% of the EU’s needs for platinum group metals is provided by South Africa
- 98%of the EU’s supply of borate comes from Turkey

2030 BENCHMARKS

- At least 10% of the EU’s annual consumption for extraction
- At least 40% of the EU’s annual consumption for processing
- At least 15% of the EU’s annual consumption for recycling
- No more than 65% of the EU’s annual consumption of each strategic raw material at any relevant stage of processing from a single third country

EU TRADE ACTIONS FOR CRITICAL RAW MATERIALS SUPPLY

Rare Earths: Application in wind turbines; Trade and investment with Australia; Support of investment in Ukraine

Nickel: Application in batteries; Trade and investment with Australia and Indonesia; Support of creation of sustainable processing in Indonesia; Support of regional environmental infrastructure

Lithium: Application in electrical vehicles; Trade agreements in Latin America; Strategic partnerships with countries with important reserves

Platinum Group Metals: Application in hydrogen fuel cells; Trade and investment in South Africa; Strategic partnerships with countries with important reserves; Support of energy infrastructure in South Africa

Figure 23: Summary of the EU Critical Raw Materials Act [92],[93].

As clearly shown (**Figure 22** and **Figure 23**), hydrogen production and consumption, through the use of electrolysers and fuel cells, rely on supply of critical raw materials; their availability and costs will have strong impact on the uptake of hydrogen technologies and costs reduction. The goal of domestically producing 10 Mt of hydrogen by 2030 will increase the European demand of platinum group metals (e.g. platinum, iridium) and other base metals like nickel and copper, which are possibly subjected to shortages and price spikes because of other clean technological sectors in competition [94]. Nevertheless, even if it cannot be ignored the influence that critical raw materials can have on hydrogen market, it is also estimated that the overall material footprint of the hydrogen sector is unlikely to address significant stress to the majority of the materials market, according to a joined recent report by the Hydrogen Council and the World Bank [95]. It is in the whole material-stressed energy transition that the large quantities of cobalt, copper, nickel required for wind, solar and batteries can generate problems also for hydrogen production and consumption [95]. Sustainable practices and policies are required to effectively support the critical raw materials supply, including the exploitation of recycled materials, the improvement of water efficiency, and promotion of innovations in design to reduce material intensities [95].

1.3 Research questions and objectives

By setting the framework, through its complexity and research gaps, specific research questions can be addressed (**Figure 24**):

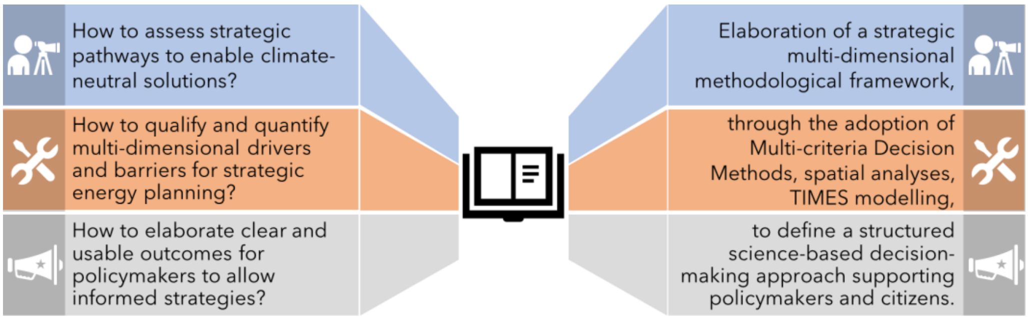


Figure 24: The main research questions to be addressed and potential outcomes.

In the context of the energy transition, the research aims to develop a science-based approach for decision-making, allowing to analyse to what extent different energy transition pathways and potential interconnections can be explored to balance sustainability, energy security and affordability. There is the need to build a strong “shield” made by people, institutions, and innovation, to model, simulate and manage climate change issues, resource availability, quality of life, strategic infrastructures, health crisis, and social efforts. The main target of the research deals with the elaboration of a multi-dimensional framework for strategic energy planning, to help this shield to be put in force, act, and react with respect to the transition challenges, through powerful science-stakeholder-policy interfaces and tools supporting energy planning processes. As already introduced, the transition is a multi-interest process, involving a series of different actors with specific roles; in line with this, the target subjects of the research can be summarised as in **Figure 25**, introducing (i) policy, (ii) mindset, and (iii) Research&Development, as key targets interplaying within the complexity of the transition.

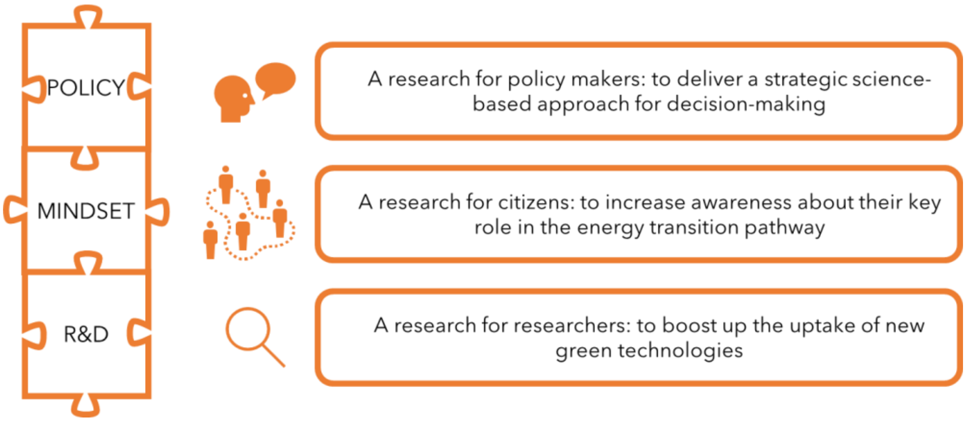


Figure 25: Potential target subjects of the research.

Tackling the multi-dimensionality of the goals and the need to have a sustainable view for the future, the main objective of the research is to develop a structured science-based decision-making approach to push towards strategic planning involving energy interconnections affecting society, economy, environment, geopolitics, and technology in the long-term perspectives towards the achievement of the decarbonization targets.

Chapter 2

Characterizing the research

The characterization of the research aims to define a methodological procedure able to tackle the multi-dimensionality of the problem, through the adoption of different steps involving the use of qualitative and quantitative sets of data, to deliver a reproducible and scalable methodology and to guarantee its applicability at different scales.

After introducing (i) long-term scenario analyses, (ii) multi-criteria decision methods combined with spatial analyses, and (iii) multi-dimensional indicators as key players within the context of strategic energy planning and informed decision-making processes, a methodological framework is developed, based on three-step procedure. With respect to the uptake of a new technology, strategy, or a sustainable plan towards carbon-neutrality, it is decided to explore firstly the concept of predisposition/readiness – through a multi-criteria assessment; as second step, multi-criteria and spatial analyses are combined to study the concept of multi-dimensional suitability; as last step, competitiveness is assessed, involving long-term scenario analyses as valuable tool.

Keywords*: Multi-criteria Analysis (MCA), Multi-criteria Spatial Decision Support System (MC-SDSS), Scenario Analysis, Geographic Information System (GIS), indicators.*

2.1 Methodological framework

Both at the national and international level, the definition of strategies and plans aiming to identify an adequate pathway for the energy transition targets is a key priority. However, energy planning – as instrument to set the centrality of RES deployment, taking care of the uptake of new technologies and the ambition of climate-neutrality for 2050 – is not sufficient. The driving role of low-carbon or carbon-neutral solutions within the next decades, often spatial-constrained for definition, pushes for a multi-level change of paradigm. It is needed to shift from energy planning to strategic planning, so that the influencing factors become more and different, as the potential issues and conflicting solutions. In line with this, dealing with strategic planning and guaranteeing effective and stable solutions become a very challenging task. To this end, the integration of different instruments is needed; spatial analyses, qualitative and quantitative indicators, scenario analyses, and multi-criteria assessment methods are the specific tools selected to define the proper methodological framework. As reviewed and summarised by [96],[97], there are several energy policy evaluation approaches which can support the implementation of ad-hoc strategies to enable renewable energy and achieve climate targets; nevertheless, there are advantages and drawbacks related to the adoption of one methodological framework with respect to another, in the attempt to address the linkages with other sectors and dimensions than the merely energetic one. **Figure 26** details the different levels of application for strategic energy planning, involving specific tools and evaluation tools for policy implementation [96]-[98].

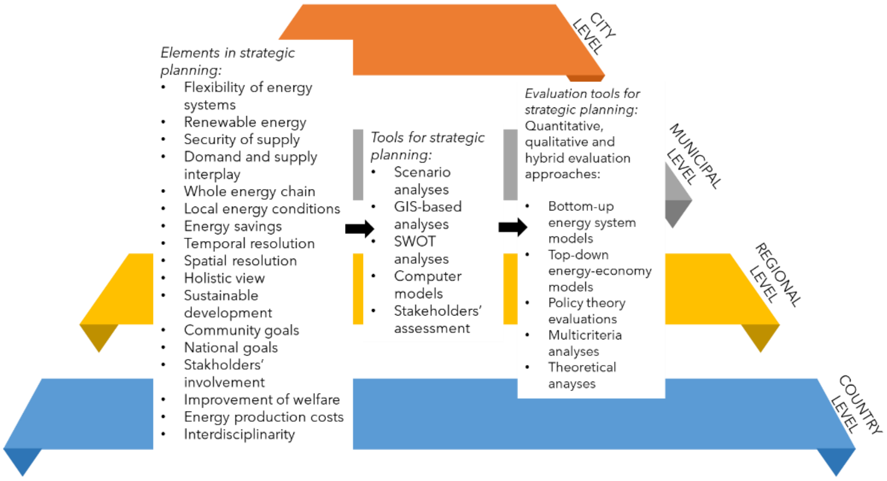


Figure 26: Strategic energy planning at different level of applications: elements, tools and evaluation approaches for the analyses, adapted from [96]-[98].

In the following sub-sections, the main tools and approaches of interest to structure a multi-dimensional framework for strategic energy planning are detailed. Starting from the role of scenario analyses in the long-term (section 2.1.1), secondly, the setting of Multi-criteria Decision Methods, with a focus on the added value of spatial analyses, is deepened (section 2.1.2). Lastly, insights on the exploitation of indicators to deal with the complexity of the transition (section 2.1.3) are collected. In line with this, it is finally proposed a methodological approach integrating all these elements within potential applications (section 2.2).

2.1.1 The role of energy scenarios in decision-making processes

Providing plausible alternative pathways for the evolution of energy systems, energy scenario modelling represents a well-known and effective way to support economic and political decisions; stakeholders are facilitated in anticipating and planning uncertainties, facing risks, and elaborating informed decisions. In other words, "scenarios improve the quality of executive decision-making", through a collection of different futures based on specific boundaries of uncertainties [99]. Being widely recognized as valuable tool to explore a series of narratives for the evolution of energy systems, scenario analyses address sets of influencing factors such as technological developments, economic conditions, geopolitical aspects, and environmental policies. An energy scenario is not a forecast but a realistic alternative trajectory according to which the whole system can evolve in the future, being conditioned by specific targets, objectives, policies, trends, technologies (**Figure 27**).

Figure 27: The definition of a scenario as alternative trajectory.

In other words, an energy scenario aims «to support conscious decisions about the future», it is not giving «a specific image of the system in the future». Different classifications can be elaborated; according to the questions to be answered, e.g. “What will happen?”, “What can happen?”, “How to reach a specific target?”, three main categories of scenario studies can be addressed: (i) predictive scenarios, to make it possible to adapt to situations expecting to occur; (ii) explorative scenarios, answering to what can happen and making a distinction between external and strategic scenarios; (iii) normative scenarios, which looks for understanding which conditions must be verified in order to get a specific target [100]. Specifically, a predictive scenario can be of «what-if» type, meaning that it allows to test what happens to the system if certain consistent hypothesises are verified.

Another classification concerns the nature of the datasets, distinguishing among (i) qualitative scenarios, usually based on participatory methods and stakeholders’ interview or workshops, and (ii) quantitative analyses, generating numerical figures [101],[102]. The majority of energy scenarios adopted the two series of datasets separately, so that through quantitative analyses it is often neglected the interaction between social and economic dimensions. The integration of socio-economic storylines with energy modelling can instead provide comprehensive and realistic long-term energy scenarios [103]. In fact, the final trajectory generated by a scenario is based on the great number of assumptions required by each specific model, accounting for a huge increase in the level of uncertainty when dealing with long-term assessments, specifically in social terms. To this regard, there is also the possibility to explore the combination of scenarios and participatory Multi-criteria Analyses (MCA), to capture from one side the context of technological opportunities and challenges, and on the other side to create a basis on a robust and democratic process [104]-[106].

2.1.2 The role of Multi-criteria Decision-Making in the transition framework

To tackle all the involved multi-disciplinary aspects of a problem, the framework of Multi-criteria Decision-Making (MCDM, or MCDA, Multi-criteria Decision Analysis, or MCA, Multi-criteria Analysis) is identified as the appropriate approach, to test different alternatives, taking care of the criteria to be assessed to support policymakers. For the case studies of interest involving the green hydrogen uptake, the application of a multi-methodological approach would allow accounting for, from one side, the multiplicity of options for the value chain of hydrogen and, from the other side, for the variety of benefits and barriers coming from the adoption of different geopolitical alternatives.

Looking at the available instruments to develop the PhD work, an example of a valuable approach is proposed by Serdeczny et al. [107], who define a framework to categorize different features of Non-Economic Loss and Damage (NELD), exploiting a series of methods as economic evaluation, multi-criteria decision analysis, composite risk indices, and qualitative and semi-qualitative approaches [107].

A focus concerning the different and possible approaches to the MCA framework is required, having defined it as one of the most appropriate methodological frameworks to be exploited within the PhD research activities. "MCDA is an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi-interests and perspectives, and accounting for complex and evolving biophysical and socio-economic systems" [108]. Or also, "MCDM is an evaluation structure to solve environmental, socio-economic, technical, and institutional barriers involved in energy planning" [109],[110]. Moreover, an approach like this perfectly fits with contemporary issues, that represents "weak" or unstructured problems, being characterized by multiple actors, with a lot of values and views, often conflicting, and a wealth of possible outcomes and high uncertainty [111],[112]. There are different classifications for MCA methods; one considers the form of the final results for the alternatives (ranking, choice, description, classification), another regards the nature of information (cardinal, ordinal and mixed scales) – with the possibility to distinguish among quantitative (or hard) methods and qualitative and mixed (or soft) methods –, a third one refers to the level of compensation allowed by the different methods (compensatory, partially-compensatory, non-compensatory). Among the most common approaches, there are the Analytic Hierarchy Process (AHP), the Analytic Network Process (ANP), the Multi-Attribute Value Theory (MAVT), Outranking methods like ELECTRE and PROMETHEE, the approach of the Multi-criteria Spatial Decision Support Systems (MC-SDSS). Regardless of the different classifications and methods, a common step-by-step MCDA procedure can be identified [110], as shown in **Figure 28**.

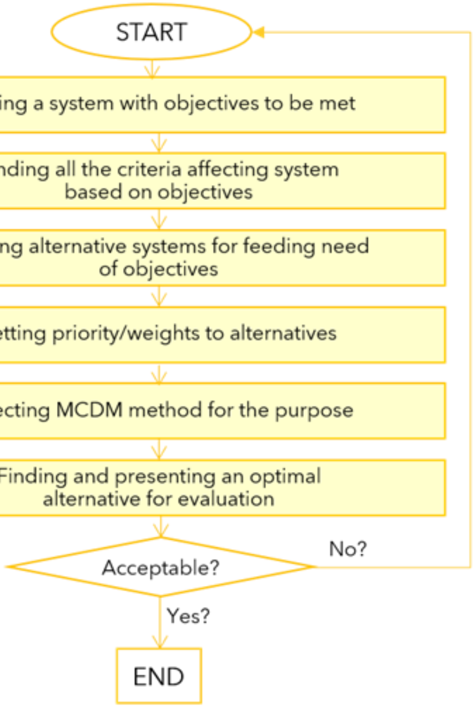
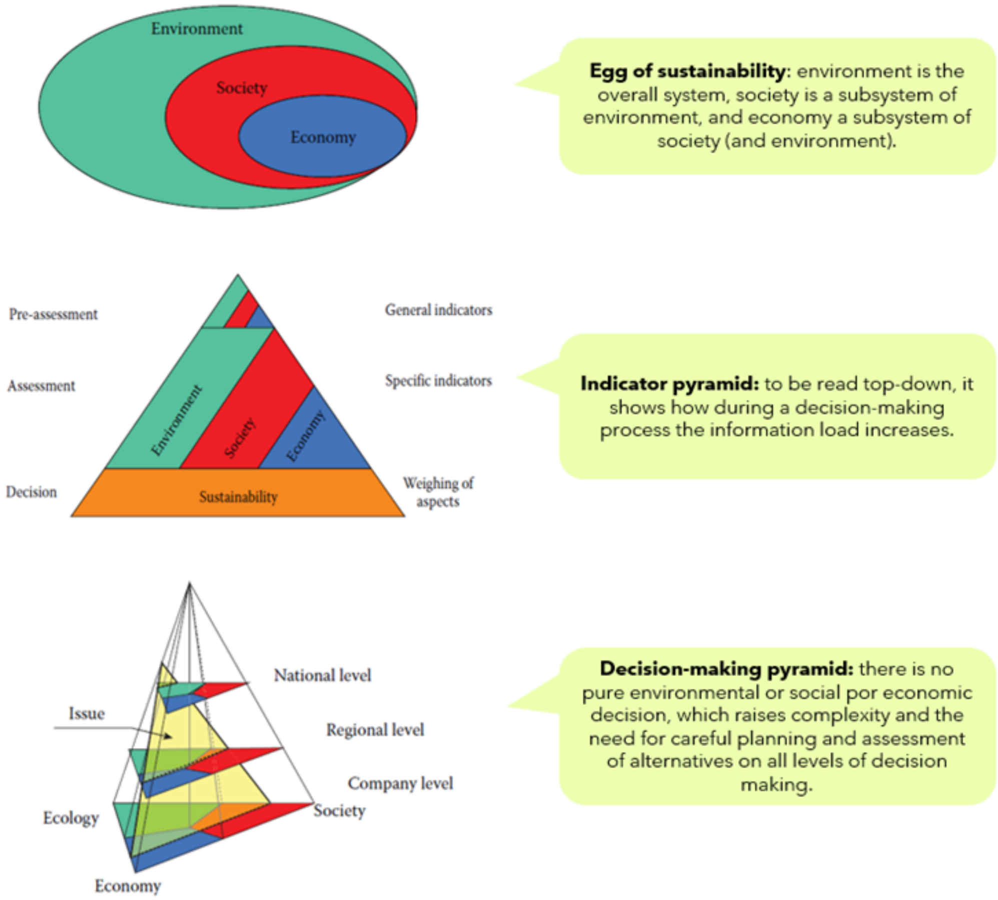


Figure 28: A common procedure for facing MCDA framework, adapted from [110].

According to the objective of the analysis, so the problem to be addressed, a method would be more appropriate than another; the first step is the crucial one, concerning the establishment of the decision context and the setting of target and key players of the assessment. The point is that "every method has its own strength and weakness depending upon its application in all the consequences and objectives of planning" [110].

The multi-disciplinarity of the research activities can be found in the multi-disciplinarity and heterogeneity of instruments useful for the analysis; multi-criteria integrated with spatial analyses through Geographic Information System (GIS) tools, aggregated indicators, are some of them. Dealing with strategic planning and assessment methods means to build up a structure that: (i) is strategic, (ii) is integrated, (iii) support social learning, (iv) support national-communicative planning, (v) provide consistent guidance [113]. In line with this, **Figure 29** details a significant multi-layered approach explored by Stoegleher et al. [113]:



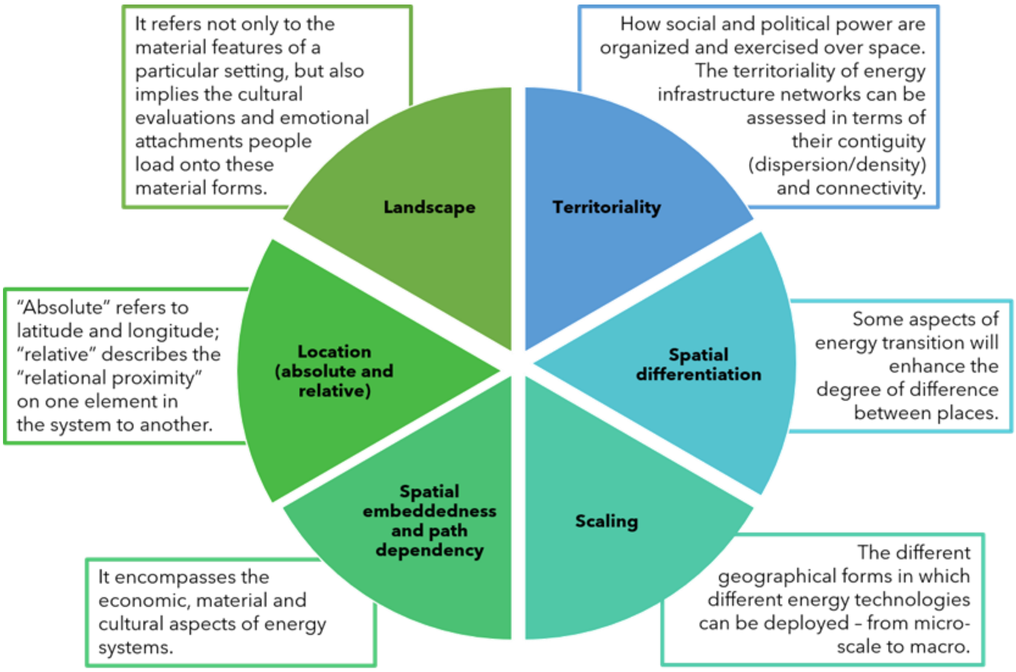
Egg of sustainability: environment is the overall system, society is a subsystem of environment, and economy a subsystem of society (and environment).

Indicator pyramid: to be read top-down, it shows how during a decision-making process the information load increases.

Decision-making pyramid: there is no pure environmental or social por economic decision, which raises complexity and the need for careful planning and assessment of alternatives on all levels of decision making.

Figure 29: Multi-layered energy planning assessment, adapted from [113].

Another fundamental concept refers to the geographic nature of the transition; "different places can do things differently" [13] and what is most important is that "understanding transition as a geographically-constituted process – rather than as a process that affects places – has a number of significant implications for policy" [13]. Specifically, the geographic components of the transition are synthetized in **Figure 30**, increasing the awareness about the relevance of the topic and its methodological implications:



It refers not only to the material features of a particular setting, but also implies the cultural evaluations and emotional attachments people load onto these material forms.

How social and political power are organized and exercised over space. The territoriality of energy infrastructure networks can be assessed in terms of their contiguity (dispersion/density) and connectivity.

Some aspects of energy transition will enhance the degree of difference between places.

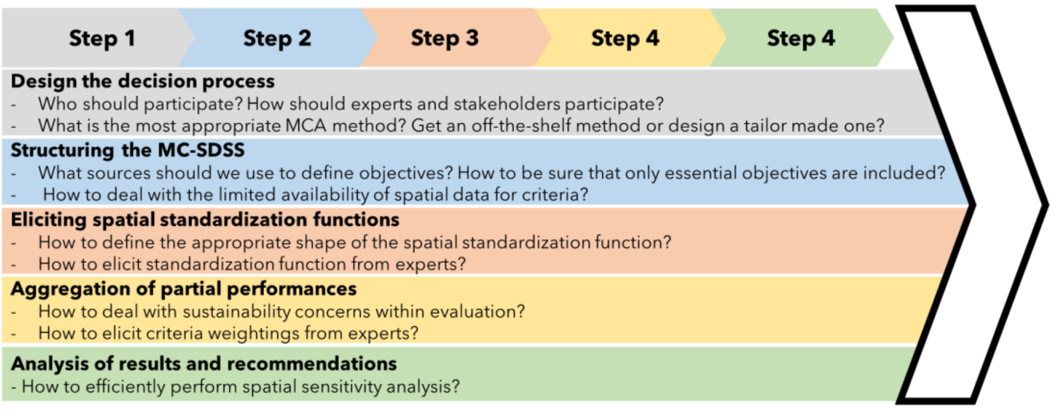
The different geographical forms in which different energy technologies can be deployed - from micro-scale to macro.

It encompasses the economic, material and cultural aspects of energy systems.

“Absolute” refers to latitude and longitude; “relative” describes the “relational proximity” on one element in the system to another.

Figure 30: The six geographical components of the energy transition, based on [13].

Within this framework, having clear that the energy transition is a geographic problem more than a merely energetic one, the combination of GIS – to cover the “geographic” aspect – and MCA – to cover the strategic planning needed – can be the key enabler of effective decision-making, considering that “there are several complexities in spatial planning and decision-making that may explain the need for MC-SDSS, from both technical and social perspectives” [114]. In this last work mentioned, an interesting focus on the key challenges in the design and application of MC-SDSS is conducted [114]; it is summarised by **Figure 31**.



Design the decision process
- Who should participate? How should experts and stakeholders participate?
- What is the most appropriate MCA method? Get an off-the-shelf method or design a tailor made one?

Structuring the MC-SDSS
- What sources should we use to define objectives? How to be sure that only essential objectives are included?
- How to deal with the limited availability of spatial data for criteria?

Eliciting spatial standardization functions
- How to define the appropriate shape of the spatial standardization function?
- How to elicit standardization function from experts?

Aggregation of partial performances
- How to deal with sustainability concerns within evaluation?
- How to elicit criteria weightings from experts?

Analysis of results and recommendations
- How to efficiently perform spatial sensitivity analysis?

Figure 31: Key challenges in MC-SDSS design and application, adapted from [114].

Focusing on **Figure 31**, an interesting focus is required with respect to the second step, by considering the involving guiding questions for the adequate selection of the MCA: (i) What kind of results are needed? (ii) How to gather input from stakeholders? (iii) How to share the output of the analysis? (iv) What are the main characteristics of the problem in terms of compensability, uncertainty and interaction? [114]. As far as concern this methodology, the literature review made by Ferretti [115] can help to amplify the knowledge of the research about applications of MC-SDSS, mostly referred to land suitability analysis in the context of urban and regional planning [115]. In particular, the interest in studies and applications of GIS integrated with MCA is spreading exponentially in a lot of different fields [116]; in the last three decades, "MC-SDSS has become an increasingly relevant topic both from a theoretical and a practical point of view in the context of spatial complex problems" [117]. This work of Caprioli and Bottero [117], through the application of an integrated approach to urban planning, highlights the role of spatial MCA in supporting policymakers, also stressing how an approach like this can increase the awareness of stakeholders and their involvement, according to a clear and transparent visualization of data and results [117]. In the attempt to define this multi-methodological framework, a work of interest is the one of Witt et al. [118], in which Scenario Planning (SP), Energy System Analysis (ESA) and MCA are combined, exploiting their benefits to investigate the transition of the electricity sector to renewable energy for a German state [118]. Specifically, SP enables the development of energy scenarios with transparency, ensuring internal consistency in assumptions for various options and external scenarios, ESA qualitatively models alternatives in diverse scenarios, while MCA aids in problems structuring by identifying pertinent alternatives, scenarios and evaluation criteria [118]. MCA also facilitates a balanced and impartial assessment of alternative energy systems based on multiple criteria, enhancing informed discussions among stakeholders and potentially boosting acceptance [118].

2.1.3 The role of multi-dimensional indicators

To adequately assess the framework already introduced by scenarios and multi-criteria analyses, it is needed to study how and if indicators, quantitative and/or qualitative, can help to manage information and study different outcomes. Indicators can be useful as key inputs to better assess problems or can represent a powerful instrument to report and discuss outputs, enhancing evaluation processes and allowing comparability analyses.

Energy indicators, addressing critical issues within the energy systems, are required to measure the current state and the vision for the future [119]. In line with this requirement, there is the need to structurally change the quantification of the energy system now that the energy system is structurally changed [11]. It is of interest the approach proposed by Krikstolitis et al. [120], when dealing with the evolving concept of energy security; in the attempt to elaborate the Energy Security Level, the trend of this indicator is analysed, to show measures that positively or negatively impact the energy security [120]. Moreover, it is of interest to deepen how for different countries (i.e., industrialized net importers, major hydrocarbon-exporting countries, emerging countries, mid-to-low-income energy importers), several concept of energy security can be introduced [121]. Concerning its complexity, an expanded analysis of the significance of this concept focuses on the perspectives of sovereignty, robustness, and resilience; a simple energy indicator is compared to a composite one, exploiting in the latter case, as environmental factors, the availability of resources and GHG emissions [122]. In a detailed review conducted by Arias et al. [14], specific indicators belonging to environment, society, economy, and governance are collected, in order to effectively assess the adequacy of energy transition towards the promotion of a more sustainable and circular energy system [14]. Dealing with not only energy indicators is more complex, but there is the need to use and define indicators able to face and measure multi-level strategies towards decarbonization. To this regard, a review in terms of existing indicators is conducted, with the idea to exploit them within the methodological framework. Among the analysed works, one of interest concerns the study of Gunnarsdottir et al. [123], which assess established sets of indicators having sustainable development as overarching goal, and considering sustainable energy supply, energy security, access to affordable modern energy services, and sustainable energy consumption as interrelated themes concurring for sustainability [123]. The assessment is conducted according to the following set of criteria: (i) transparency of indicator selection, (ii) transparency of indicator application, (iii) conceptual framework, (iv) linkages, (v) stakeholder engagement; it is then underlined how the lack of transparency is a common issue; moreover, the effective communication of indicators can influence interpretability and aid with understanding [123]. Finally, another interesting review on indicators, regarding the competition for energy projects, is conducted by Colla et al. [124], by performing a classification of projects according to the Key Performance Indicators (KPIs) belonging to four main categories, i.e. the physical, environmental, economic and social ones [114].

As clearly understandable by different references analysed, indicators can be of different types, can come from different assumptions, and can lead to different outcomes according to the objectives, but always representing a powerful instrument to collect and spread valuable information.

2.2 Methodological proposal

Before detailing the methodological outline, it is needed to assess all the dimensions involved in the transition process, trying to integrate all of them within the research pathway and ad-hoc strategic energy planning procedures. To do this, the "STAGE" of the energy transition is developed, or, in other words, it is considered that "the transition happens on STAGE"; Society, Technology, Atmosphere and land, Geopolitics, and Economy represent all the different factors and actors involved and playing their role (**Figure 32**).

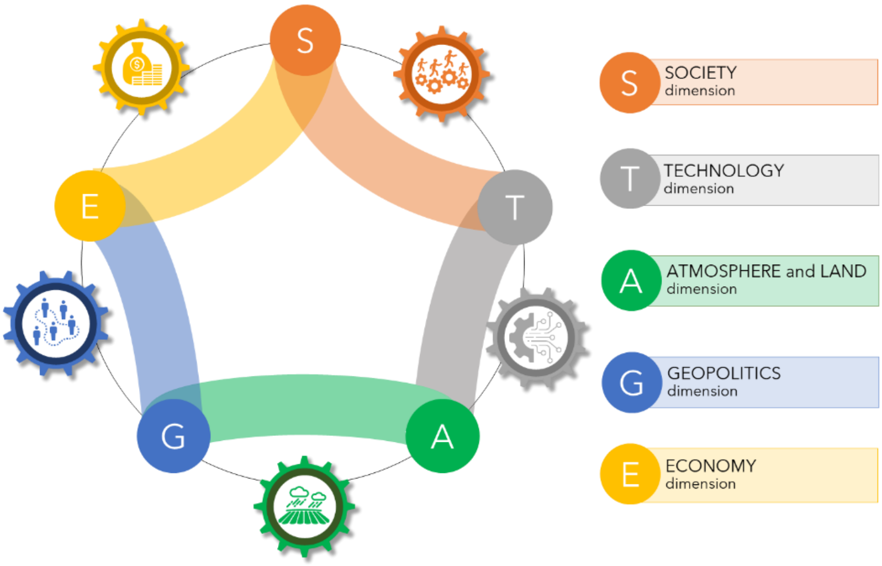


Figure 32: The STAGE on which the methodological approach must be developed.

Working with all these dimensions means (i) to identify and elaborate both qualitative and quantitative information, (ii) to deepen the current framework of the applications of interest, (iii) to develop multi-criteria assessments towards the implementation of strategic analyses supporting policymakers. The PhD activities are developed according to the idea that whatever is the goal or the type of analysis, the assessment can occur if only all the dimensions are considered; the STAGE approach is the added value of the methodological procedure in each case. **Figure 33** focuses on the MCA framework and how it fits with the "STAGE view"; according to the exploitation of qualitative and quantitative information and the "added value" of geo-referenced data in case of MC-SDSS application, the five dimensions are investigated to effectively study opportunities and assess strategic pathways towards decarbonization. Strictly connected with the STAGE definition, there is the choice of using a multi-methodological approach concerning the scenario analyses about the energy transition pathways, trying to merge the long-term perspectives with the drivers and barriers of the proposed dimensions.

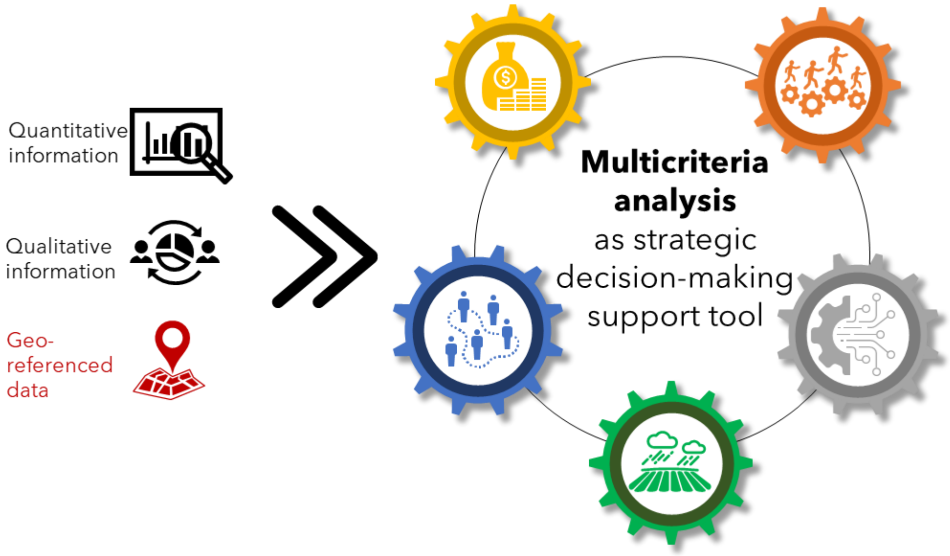


Figure 33: MCA as strategic instrument fitting with the research objectives.

Figure 34 details the proposal of this methodological approach aiming to develop a structured and strategic research around the topics of interest, able to tackle the multi-dimensional aspects related to the case studies of interest. Firstly it is needed to elaborate a preliminary overview on the objective through the concept of predisposition, secondly the conflicting drivers and barriers must be assessed to deepen the concept of suitability, to finally analyse the competitiveness of specific alternatives when the interactions with the whole energy system are considered.

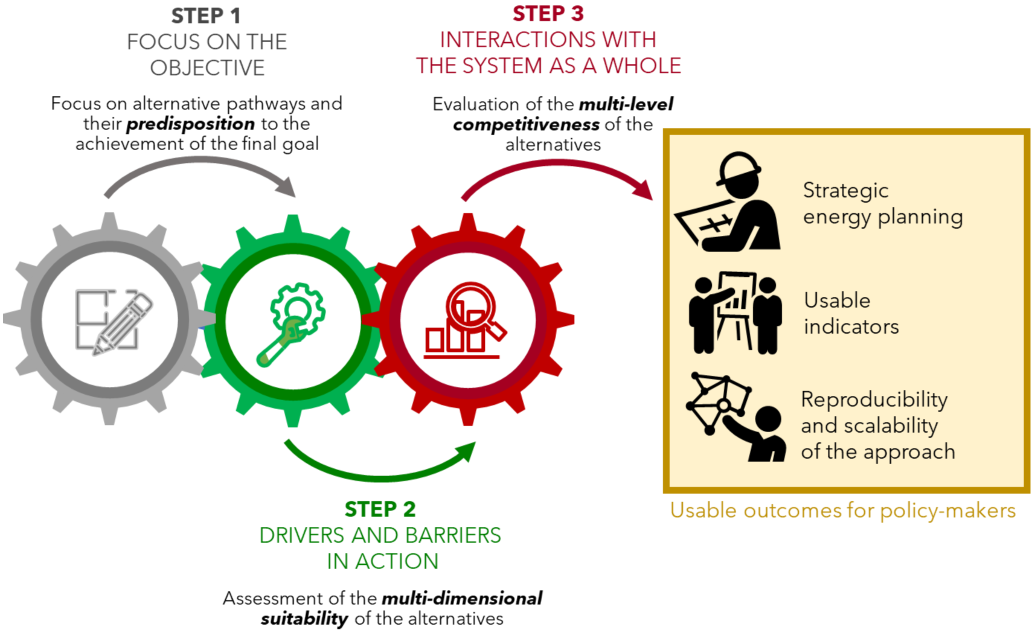


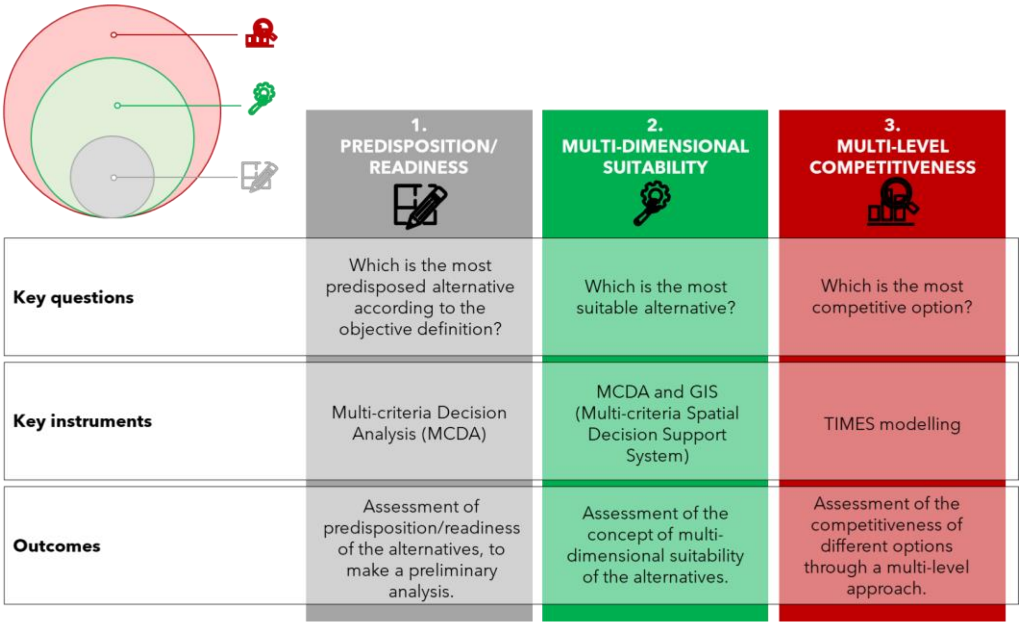
Figure 34: Step-by-step procedure of the methodological approach towards the achievement of final goal.

To this regard, **Figure 35** focuses on the definitions of how these concepts of (i) predisposition/readiness, (ii) multi-dimensional suitability, and (iii) competitiveness are intended and used in the methodological approach.

READINESS/ PREDISPOSITION	With respect to the development of a new technology, being ready or predisposed means making reference to the resources needed, the social acceptance, the infrastructure availability, the environmental issues and the geopolitical conditions; all these factor could support or not the development of a new technology.
MULTI-DIMENSIONAL SUITABILITY	With respect to the development of a new technology, it means to assess different drivers and barriers in order to have spatial information about the suitability in social, techno-economic, geopolitical, environmental terms.
MULTI-LEVEL COMPETITIVENESS	The development of a new technology goes hand in hand with the development of the system as a whole; it is needed to involve the concepts of security, independence, affordability, suitability and readiness in order to understand if a technology is competitive.

Figure 35: The concept of predisposition – suitability – competitiveness.

Figure 36 reports a summary on the proposed possible multi-methodological and multi-step approach. Specifically, the steps are developed consequentially; the first one is useful to better work on the second step, and both of them are needed to generate ad-hoc inputs for the third one, related to the analysis of the system as a whole through scenarios.



	1. PREDISPOSITION/ READINESS	2. MULTI-DIMENSIONAL SUITABILITY	3. MULTI-LEVEL COMPETITIVENESS
Key questions	Which is the most predisposed alternative according to the objective definition?	Which is the most suitable alternative?	Which is the most competitive option?
Key instruments	Multi-criteria Decision Analysis (MCDA)	MCDA and GIS (Multi-criteria Spatial Decision Support System)	TIMES modelling
Outcomes	Assessment of predisposition/readiness of the alternatives, to make a preliminary analysis.	Assessment of the concept of multi-dimensional suitability of the alternatives.	Assessment of the competitiveness of different options through a multi-level approach.

Figure 36: Multi-step procedure proposal for the methodological approach.

The first concept to be analysed consists of a preliminary elaboration of the predisposition of a country with respect to the deployment of a new technology; it could rely on the availability of resources and infrastructure, the political stability, the local welfare, and some other influencing factors, even if not directly related to the objective of interest. To make this first focus on the problem, a multi-criteria method is a valuable methodological choice, giving the possibility of preliminarily ranking alternatives and collecting different evaluation criteria, and stakeholders' or experts' preferences. Secondly, to investigate the concept of multi-dimensionality, the combination of a multi-criteria assessment and geographical datasets is a strategic solution, so that a MC-SDSS is exploited, allowing the elaboration of spatially-defined information which strongly impact a strategic energy planning process. Finally, focusing on the multi-level competitiveness means to consider the whole system, in the attempt to better investigate the hydrogen security, affordability, independence. To this end, the modelling of energy scenarios is required, with the aim to study how the system interact with some specific inputs – which are based on the outputs from the predisposition and suitability assessments, together with specific techno-economic analyses – and how the elaborated scenarios work in terms of energy indicators related to hydrogen deployment.

Having set the methodological framework, the activities must be referred to specific case studies, considering different local contexts and real possible alternatives, looking at the future perspectives but paying attention to the current status of countries; in this sense, the analysis of the case studies is essential in providing specific targets. In particular, the interest in the hydrogen uptake and the different challenges in terms of possible cross-border cooperation (sub-section 1.2) represent a milestone of the research, contributing to better design also the methodological steps and helping to find out useful results and outputs, to be communicated in a transparent manner to policymakers, as reported in section 3, fully dedicated to the applications.

2.2.1 Expected results

As introduced by **Figure 34**, **Figure 35**, and **Figure 36**, the methodological approach is built to be suitable at different scales and for different applications of interest. Considering the target of the research and its framework, the main results can be focused on the application of strategic assessments, allowing to identify the best options leading to the achievement of the ambitious decarbonization targets in the long-term. Before working directly on spatial analyses, a preliminary assessment is required to have a general overview on the main challenges and opportunities involving different alternatives with respect to the adoption of a specific solution (i.e., green hydrogen adoption). The suitability deals with the strategic assessment in terms of economic, social, environmental, geopolitical, and technological aspects, in order to range from "excluded areas" or "very low suitable" areas, to "very highly suitable" areas. From the other side, combining the information from the suitability assessment and the techno-economic analyses through the modelling of energy scenarios means to assess the multi-level competitiveness of hydrogen and to offer a critical overview of the alternative pathways analysed. The expected outcomes must consist of clear and transparent results, trying to fulfil the gap between science and stakeholders; in other words, a science-based approach in support of decision-makers must be able to extract – from the complexity of the occurring problems – understandable and usable outcomes useful for policymakers and to adopt real solutions for future.

Chapter 3

Applying the methodology on case studies

The PhD activities are in line with the interests of RSE S.p.A, as funder of the PhD research. Concerning the main topic of "*local and global energy interconnections in the energy transition framework*" which is the one assigned within the PhD framework, there is the interest to study the future uptake of renewable electricity and green hydrogen production, exploiting cross-border cooperations among Italy and North African countries. To this end, the methodological approach elaborated is applied step by step, conducting:

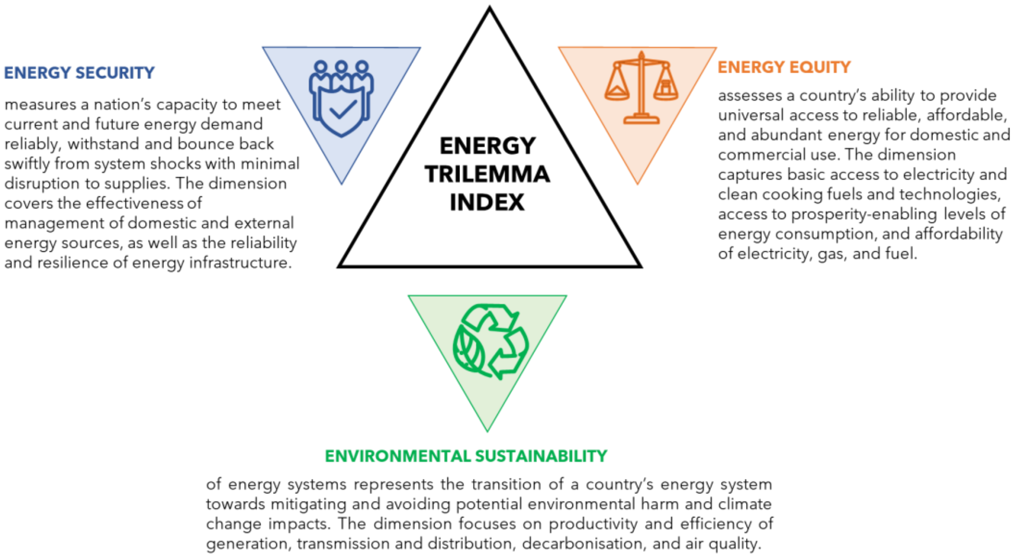
- a review on data and methods concerning strategic energy planning in North Africa and its trade links within Europe;
- the evaluation of the predisposition of North African countries with respect to the development of a hydrogen market;
- the assessment of the multi-dimensional suitability for green hydrogen production by solar and wind energy of Algeria, Morocco and Tunisia – preceded by a preliminary analysis on solar hydrogen potential;
- scenario analyses exploiting TIMES modelling to address the competitiveness of green hydrogen trade from North Africa to Europe.

Keywords: *Green Hydrogen, Cross-border Cooperation, North Africa, Hydrogen Trade, PROMETHEE, MC-SDSS, Scenario Analyses, TIMES.*

3.1 Strategic energy planning in North Africa and Italy: a review on data and methods

Energy and non-energy indicators are definitely key instruments to identify and support valuable decision processes and evaluations (sub-section 2.1.3); to this regard, in this section Italy, Morocco, Tunisia, Libya, Egypt, and Algeria are assessed through several multi-dimensional indicators from different sources, in the attempt to characterize the current situation and future perspectives of these countries with respect to the energy transition framework.

Firstly, the world Energy Trilemma Index developed by WEC is introduced (**Figure 37**) and reported for Italy and North African countries (**Figure 38**); it is “an annual measurement of national energy system performances across each of the three trilemma dimensions: energy security, energy equity, energy sustainability” [125].



ENERGY SECURITY

measures a nation’s capacity to meet current and future energy demand reliably, withstand and bounce back swiftly from system shocks with minimal disruption to supplies. The dimension covers the effectiveness of management of domestic and external energy sources, as well as the reliability and resilience of energy infrastructure.

ENERGY EQUITY

assesses a country’s ability to provide universal access to reliable, affordable, and abundant energy for domestic and commercial use. The dimension captures basic access to electricity and clean cooking fuels and technologies, access to prosperity-enabling levels of energy consumption, and affordability of electricity, gas, and fuel.

ENVIRONMENTAL SUSTAINABILITY

of energy systems represents the transition of a country’s energy system towards mitigating and avoiding potential environmental harm and climate change impacts. The dimension focuses on productivity and efficiency of generation, transmission and distribution, decarbonisation, and air quality.

Figure 37: The concept of the WEC Energy Trilemma Index, adapted from [125].

As shown by **Figure 38**, for Libya no information are available and for this reason it is not included in the graph. The highest values for the 2022 update are reached by energy equity, which ranges from 68% (Morocco) to 88.8% (Italy) [125]. The lowest percentage is associated to Morocco for what concerns the energy security (49.1%). The overall Energy Trilemma Index by WEC ranges from 59.1% assigned to Morocco to 74.8% for Italy (**Figure 38**).

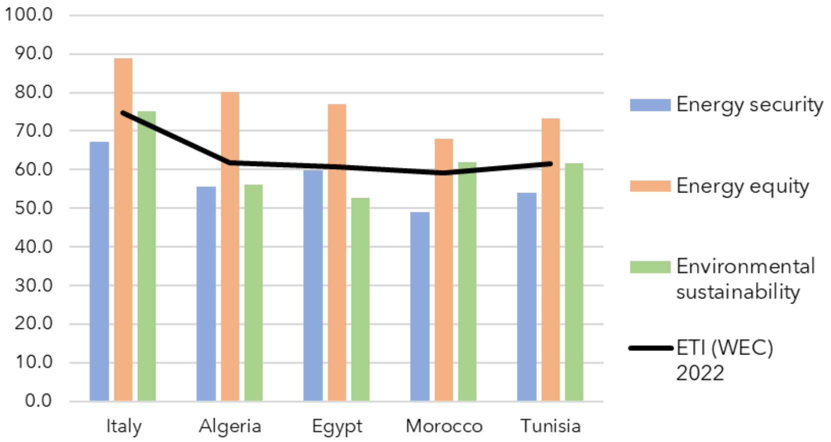


Figure 38: Energy Trilemma Index for Italy, Algeria, Egypt, Morocco and Tunisia, adapted from [125].

There is another indicator but with the same acronym which represents the Energy Transition Index; it consists of a composite index of 40 variables developed by the World Economic Forum [126], covering the energy triangle of (i) security and access, (ii) environmental sustainability, (iii) economic development and growth [126],[127]. As a tool to enable informed energy decision-making processes, it tracks the country-specific energy performance, integrating macroeconomic, institutional, social, and geopolitical considerations [127]. **Figure 39** reports the outputs from the 2022 update related to the Energy Transition Index built on the System Performance and Transition Readiness Indexes [126].

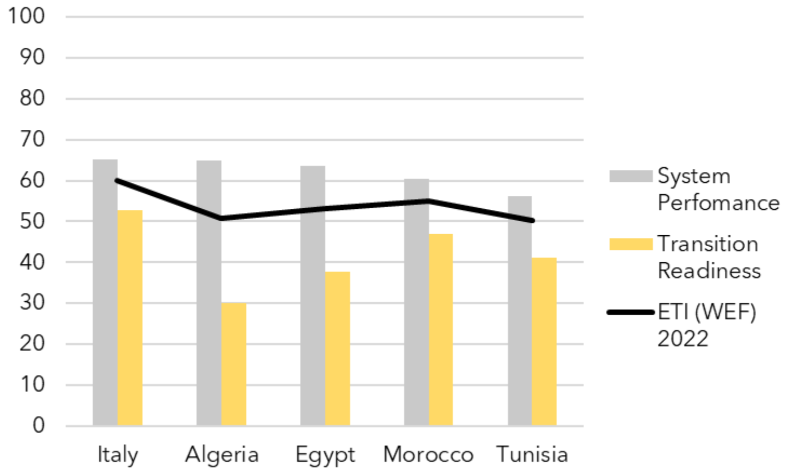


Figure 39: Energy Transition Index for Italy, Algeria, Egypt, Morocco and Tunisia, adapted from [126].

In addition to these first two indicators, the evolution of the Environmental Performance Index (EPI) is also of interest; elaborated by the Yale and Columbia Universities and commissioned by the World Economic Forum, it aims to assess the state of sustainability, using 32 performance indicators across 11 issue categories and three policy objectives, i.e. ecosystem vitality, environmental health, and climate change [128]. Looking at the EPI update of 2022 (**Figure 40**), the Italian performance is better than the North African one, whose values range between 28.4% (Morocco) and 40.7% (Tunisia), against the Italian EPI of 57.7%. There are no data collected and elaborated for Libya; Italy and Algeria obtain good results with respect to the environmental health, Egypt in ecosystem vitality, while Tunisia and Morocco in climate change policy objective (**Figure 40**).

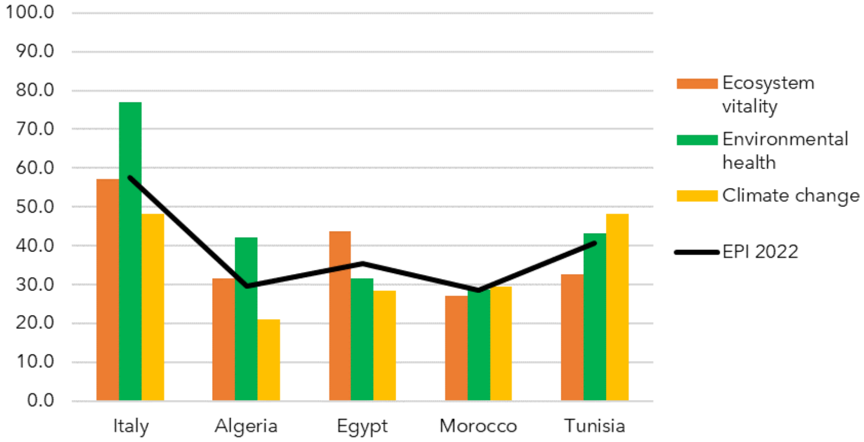


Figure 40: Environmental Performance Index for Italy, Algeria, Egypt, Morocco and Tunisia, adapted from [128].

With respect to the research objectives, it is of interest to analyze also the Renewable Energy Country Attractiveness Index (RECAI), developed by Ernst & Young [129]; "it reflects an assessment of the factors driving market attractiveness in a world where renewable energy has gone beyond decarbonization and reliance on subsidies" [129]. The methodology is based on key pillars focusing on energy imperative, policy stability, project delivery and diversity of natural resources, with a correction parameter accounting also for Covid, to temporarily catch its effects [129]. As detailed by **Figure 41**, Italy, Morocco and Egypt are reported in the top 40 ranking updated to October 2021; also the specific performances on wind energy (onshore and offshore), solar (photovoltaic, PV and Concentrated Solar Power, CSP), biomass, geothermal, hydro sub-scores are reported.

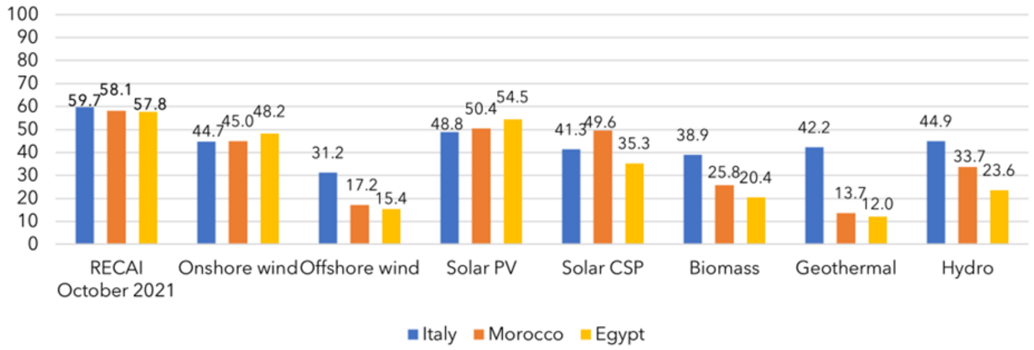


Figure 41: Renewable Energy Country Attractiveness Index 2021 for Italy, Egypt, Morocco, adapted from [129].

Other information can be extracted from the Economic Freedom Index (EFI) by the Heritage Foundation [130]; it covers 12 types of freedoms in 184 countries, in order "to help readers track over two decades of the advancement in economic freedom, prosperity, and opportunity and promote these ideas in their homes, schools, and communities" [130]. **Table 2** highlights the weakness of the analysed countries in terms of economic freedom, ranging from the definition of "moderately free" assigned to Italy to "repressed" obtained by Algeria and Egypt (which means having an EFI ranging from 49.9 to 0).

Table 2: Economic Freedom Index 2022 for Italy, Algeria, Egypt, Morocco, Tunisia and Libya [130].

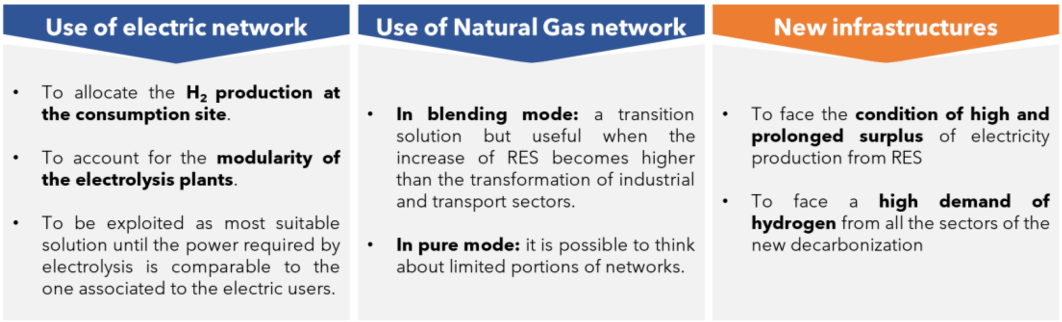
country	*EFI 2022*	
Italy	65.4	*moderately free*
Algeria	45.8	*repressed*
Egypt	49.1	*repressed*
Morocco	59.2	*mostly unfree*
Tunisia	54.2	*mostly unfree*

Having set the added value of aggregated indicators in giving information and present results, this review is also focused on the methodological approaches and tools adopted for strategic energy planning concerning these specific areas. Moreover, it is needed to better investigate specific projects and assessments addressing potentialities to be enhanced and criticalities to be overcome.

According to the classification with respect to the countries' hydrogen readiness proposed by De Blasio and Pfluggman and previously introduced [70], Morocco is identified as export champion, Egypt belongs to the group of "renewable-rich but water constrained with high infrastructure potential", while Italy is defined as "renewable-constrained with a high infrastructure potential"; Algeria, Tunisia, and Libya are instead classified as "resource-rich with low infrastructure potential" [70]. The results of this study clearly show the heterogeneity of the countries under assessment, also stressing how working on resource potential and infrastructure development is of primary importance.

Concerning Italy, having reviewed its regulatory framework and strategies for the long-term – in line with the climate-neutrality target set by the EU (section 1.2.1) – a focus on hydrogen projects and opportunities is required. To this regard, the work of Kaoukulaki et al. [75] is developed on a three-step procedure to analyse to what extent the current European production of hydrogen together with the power demand can be covered by RES, country by country. It is estimated (i) the current national and regional level of hydrogen production and electricity demand, (ii) the technical potential of renewable, (iii) a balance between the results of the previous steps for mapping sub-national availability [75].

About the hydrogen penetration scenarios for the long-term, RSE in a recent report focuses on the efforts needed for the climate-neutrality target by 2050; it is suggested a change of the energy paradigm on the national level, made by energy efficiency, RES technologies and negative emissions, significant electrification, radical change in the energy mix [131]. In particular, the highest penetration of hydrogen will involve the industrial sector, the transport one and the production of renewable fuels [131]. **Figure 42** summarises the potential pathways identified for hydrogen transport:



Use of electric network

- To allocate the H_2 **production at the consumption site**.
- To account for the **modularity of the electrolysis plants**.
- To be exploited as most suitable solution until the power required by electrolysis is comparable to the one associated to the electric users.

Use of Natural Gas network

- **In blending mode:** a transition solution but useful when the increase of RES becomes higher than the transformation of industrial and transport sectors.
- **In pure mode:** it is possible to think about limited portions of networks.

New infrastructures

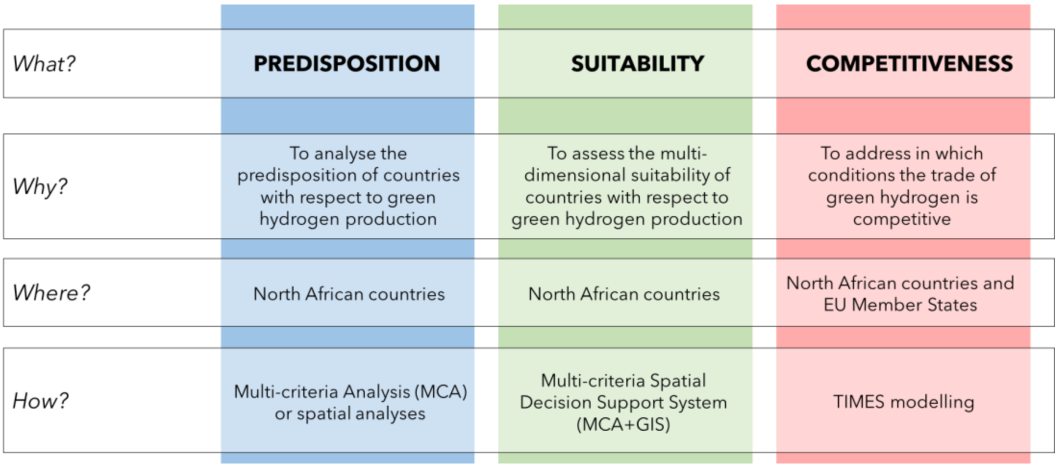
- To face the **condition of high and prolonged surplus** of electricity production from RES
- To face a **high demand of hydrogen** from all the sectors of the new decarbonization

Figure 42: Transport alternatives for hydrogen penetration up to 2050, adapted from [131].

To exploit the possibility to use the existing Natural Gas (NG) pipelines – connecting Italy with Algeria and Libya – the research of Timmemberg and Kaltschmitt [78] details costs and potentials for hydrogen production by electrolysis from RES in North Africa and its transport as a blend in Transmed (connecting Algeria and Italy via Tunisia) and Greenstream (connecting directly Libya and Italy) [78]. Mainly focused on techno-economic aspects, this work is useful to understand which are the feasible alternatives and to fulfil the technical and economic criteria which are part of the strategic assessment to be done. In fact, it allows (i) to increase of knowledge for existing infrastructure and data available, (ii) to collect useful criteria for a lower and upper-cost scenario within the economic analysis, (iii) to consider the technical limit of the hydrogen share in NG existing pipelines, (v) to study the optimization model for costs minimization [78]. The limits of the study can be found in the reference year fixed in 2020, without considerations about the national future perspectives, for instance in terms of increasing energy demand or population for the exporting countries; moreover, there are no reference to social, environmental, or political aspects involved in these kinds of cross-border megaprojects.

On the other side of the Mediterranean Sea, there are several studies based on mapping for strategic energy planning for specific North African areas, restricted on a country scale or also referred to possible cross-border alliances. At the country level, Haddad et al. [132] propose a hybrid approach combining MCDA and GIS to assess the suitability of CSP in Algeria; the work consists of a first step leading to the exclusion of unsuitable areas and a second step allowing to rank the suitable ones [132]. According to this work, it is possible to collect some exclusion criteria, spatially measurable, e.g. annual direct solar radiation, slope, roads and railways, water availability, based on specific sources, such as the Global Solar Atlas by the World Bank, the Digital Elevation Model (DEM) from Shuttle Radar Topography Mission (SRTM), the International Steering Committee for Global Mapping. These exclusion criteria for renewable spatial planning are reviewed also through other studies [133]-[135]. The work of Haddad et al. [132] is also interesting for the fact that other non-technical criteria like visual impact or social acceptance are not investigated; moreover, the involvement of only PhD students belonging to different fields as stakeholders can be considered a limit. It could be crucial to involve industry or other proper sectors expertise in assessments like this [132]. Another interesting study, conducted at a country-level and considering long-term electricity scenarios as alternative pathways to be assessed, is the one of Zelt et al. [136]. After using Renewable Energy Pathway Simulation System GIS (renpassG!S) to develop the alternative scenarios for Jordan, Morocco, and Tunisia, the AHP as multi-criteria analysis is exploited to capture stakeholders' preferences [136]. Having fixed as target year the 2050, the study exploits on-site workshops in the countries of interest, with about 25 participants each, among which academia members, people from private sector and policymakers, creating a heterogeneous group to make choices about criteria and how weighting them. These criteria are heterogeneous too, aiming to assess the techno-economic dimension, the social and the environmental one, according to qualitative and quantitative information [136]. Although the general methodological approach of this study is very interesting, it does not consider exports/cross-border cooperations, focusing only on the future development of the electricity sectors. In order to face how the alliances among countries for can be exploited and assessed for trade, a work of relevance is the one of Papapostolou et al. [137], who propose a methodology to adopt the most appropriate strategic plan for successful cross-border cooperation, considering Europe and Morocco and Europe and Egypt as case studies [137]. In particular, the AHP, Strength Weakness Opportunities and Threats (SWOT) analysis and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are exploited, in a multi-step procedure [137]. As pros of the approach, there is the involvement of a committee of experts and the exploitation of bilateral meetings, together with the adoption of different methodologies to make the assessment more consolidated. The limits of the work are found in the target year – which is 2030 – and with respect to the elaboration of the criteria, considering that the investment field counts 7 criteria over the total of 12, while for the socio-environmental side (society and environment are put together), only two criteria are assessed. To better stress the importance of an assessment going beyond the techno-economic aspects of the energy transition, an interesting point of view is the one related to the megaprojects not concretized yet in North Africa; "the non-technical risks in North Africa are very real and likely to create an indefinite delay in the realization of electricity market megaprojects" [86]. This aspect is already introduced in the sub-section 1.2.2.

Figure 43 reports the application of the methodological approach introduced in section 2 and now tailored on the case studies of interest, making reference to the concepts of predisposition, suitability and competitiveness (**Figure 35**) with respect to production and trade of green hydrogen in the Mediterranean areas.



What?	PREDISPOSITION	SUITABILITY	COMPETITIVENESS
Why?	To analyse the predisposition of countries with respect to green hydrogen production	To assess the multi-dimensional suitability of countries with respect to green hydrogen production	To address in which conditions the trade of green hydrogen is competitive
Where?	North African countries	North African countries	North African countries and EU Member States
How?	Multi-criteria Analysis (MCA) or spatial analyses	Multi-criteria Spatial Decision Support System (MCA+GIS)	TIMES modelling

Figure 43: The concepts of predisposition-suitability-competitiveness for the application to green hydrogen.

3.2 Predisposition to green hydrogen of North African countries

In the framework of the ENEMED Report 2021, a contribution assessing the green hydrogen predisposition of twenty countries of the Mediterranean area was developed by the author [138]. In line with this methodological approach, consisting of the exploitation of a multi-criteria method, here it is presented a more specific application, related only to Algeria, Egypt, Libya, Morocco, and Tunisia, as elaborated for the RSE deliverable in 2021 [139]. Through the use of the criteria identified in the decision process developed for the ENEMED Report it is explored the predisposition of the North African countries with respect to the green hydrogen production; here the indicators are updated to the most recent values until December 2021 when possible.

3.2.1 The PROMETHEE II method

The Preference Ranking Organisation METhod for Enrichment of Evaluations (PROMETHEE) is exploited to conduct the analysis on predisposition and readiness for green hydrogen production in North Africa, exploiting the Visual PROMETHEE software [140]. PROMETHEE is an outranking method which allows to rank the alternatives by pairwise comparison and with respect to a set of criteria [141]-[144]; this is the reason why it is chosen as valuable MCA to assess the predisposition to North African countries for green hydrogen production. Being widely used in several fields, energy management is one of the application areas of interest, within environment and water management, logistic and transportation, social topics, business and financial management [145],[146]. The main steps of this outranking method exploited are shown in **Figure 44**:

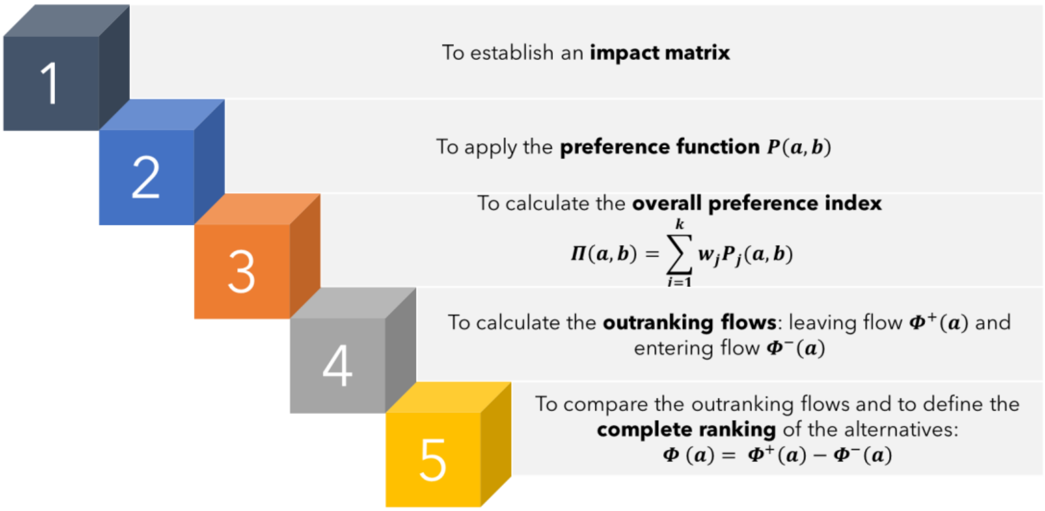


Figure 44: The main steps of the PROMETHEE II method [143].

Having identified the objective of the problem to be assessed, the impact matrix is elaborated as a double-entry table linking the alternatives that represent the rows to the evaluation criteria, on the columns. Then, it is needed to identify the preference functions to be assigned to each criterion; a preference function $P_j(a,b)$, allows to quantify how much preferred is an alternative with respect to another one, ranging from 0 (no difference among the two alternatives under analysis) to 1 (strict preference of one alternative over the other). Six different preference functions can be exploited: usual criterion, quasi-criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion [143]. Then, the overall preference index $\Pi(a,b)$ integrates all the criteria while comparing the alternative a to b, with w_j the weighting of sub-criterium j-th (equation 3.1).

$$\Pi(\mathrm{a},\mathrm{b}) = \sum_{j=1}^{k} w_j \cdot P_j(a,b) \tag{3.1}$$

The weighting procedure is based on the preferences of the experts involved in the assessment; this makes possible to identify different scenarios of analysis, each representative of their own preferences. The preference matrix is built up with all the elaborated preference indexes, calculating the entering flow Φ^{+}(i) and the leaving flow Φ^{-}(i) for the each i-th alternative. The higher Φ^{+}(a) and the lower Φ^{-}(a), the better the alternative a is. The net flow Φ of each alternative generates the complete ranking, allowing to identify the best and the worst options, or the best compromise solution. These last steps consist of the following equations:

$$\Phi^{+}(\mathrm{a}) = \frac{1}{(n-1)} \sum_{b} \Pi(a,b) \tag{3.2}$$

$$\Phi^{-}(\mathrm{a}) = \frac{1}{(n-1)} \sum_{b} \Pi(b,a) \tag{3.3}$$

$$\Phi(\mathrm{a}) = \Phi^{+}(a) - \Phi^{-}(a) \tag{3.4}$$

According to the net flow Φ computed, the complete set of alternatives is defined, based on the experts' judgements. The higher the net flow Φ, the better the alternative is.

3.2.2 The application on North African countries to assess predisposition

The methodological framework introduced in the previous section is exploited to analyse the predisposition of Algeria, Egypt, Libya, Morocco, and Tunisia with respect to the production of green hydrogen. The next sections are related to the identification and calculation the different criteria able to multi-dimensionally assess the problem and rank criteria. To do this, it is required the involvement of multi-interest experts that can investigate the criteria and adequately rank them according to their specific preferences. Specifically, here the Simos-Roy-Figueira method (SRF) is exploited [147] to obtain the experts' weightings, through the use of the online software DecSpace [148], while the Visual PROMETHEE software [140] is used to apply the PROMETHEE method and to analyse the results.

3.2.2.1 From the identification of criteria to the calculation of the outranking flows

As first main step, to adequately apply a multi-criteria assessment, the decision problem must be defined; the objective is to rank the North African countries according to their predisposition to the production of green hydrogen. Then, it is needed to identify and calculate the criteria involved together with the multi-interest experts involved the assessment, in the attempt to consider the five domains previously introduced (so considering that the energy transition happens on STAGE, so involving Society, Technology, Atmosphere and Land, Geopolitics and Economy). **Figure 45** shows the assessment of criteria according to the STAGE approach, while **Table 3** focuses on the sources exploited for the involved indicators and the relative units of measure.

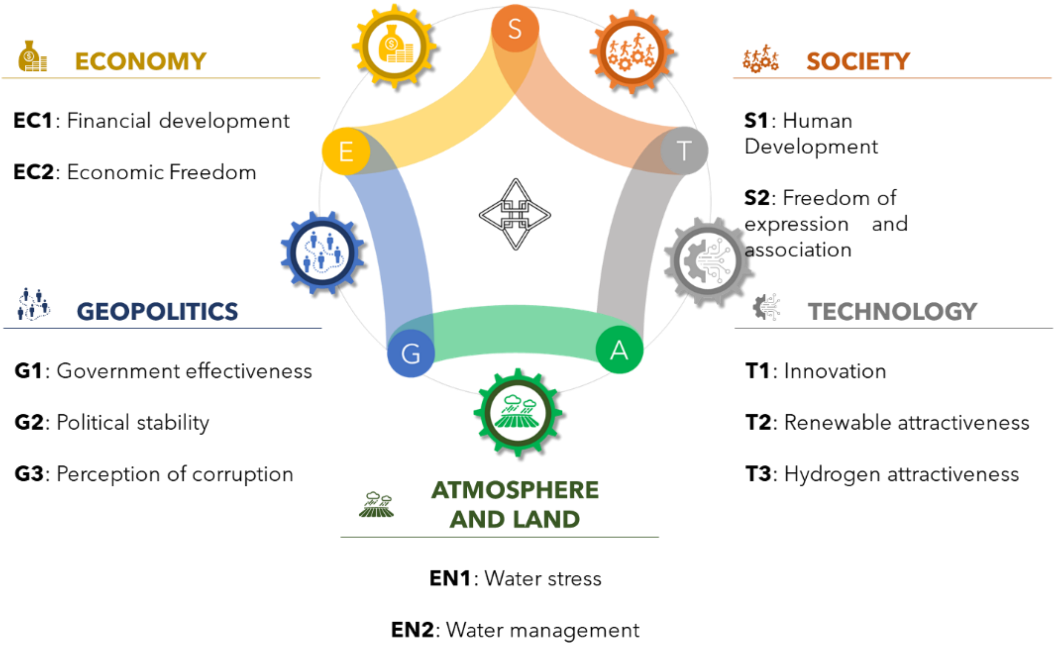


Figure 45: The STAGE approach to evaluate the green hydrogen predisposition among North African countries.

Table 3: Assessment of criteria for the application of PROMETHEE.

Domain	*Criterion*	*Range/unit*	*Source*
Society (S)	Human development (S1)	0-1	UNDP [149]
	Freedom of expression and association (S2)	0-5	World Bank [150]
Technology (T)	Innovation (T1)	0-100	WIPO [151]
	Renewable energy attractiveness (T2)	0-100	Self-elaboration base on material from ESMAP, World Bank, IEA, Ernst & Young [129],[152],[153]
	Hydrogen attractiveness (T3)	0-5	Self-elaboration based on IEA [154],[155]
Atmosphere and land (A)	Water stress (A1)	%	FAO, UN [156]
	Water management (A2)	0-100	IWRM, UNEP [157]
Geopolitics (G)	Government effectiveness (G1)	0-5	World Bank [150]
	Political stability (G2)	0-5	World Bank [150]
	Perception of corruption (G3)	0-100	Transparency International [158]
Economy (E)	Financial development (E1)	0-1	IMF [159]
	Economic freedom (E2)	0-100	Heritage Foundation [130]

The first social criterion, named S1, corresponds to the Human Development Index (HDI), published by the United Nations Development Programme (UNDP) [149]. It measures, in a range from 0 to 1, three basic dimensions of human development: long and healthy life, access to knowledge and decent standard of living. The values shown in **Figure 46** are referred to the 2019 update [149].

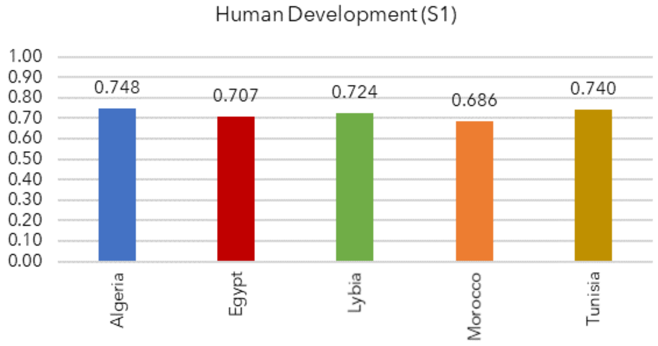


Figure 46: The Human Development Index [149], as social criterion S1.

The second social criterion is identified under the name of "Freedom of expression and association" (S2), and it is related to the "Voice and accountability" index as one of the Worldwide Governance Indicators (WGI), elaborated by a research program of the World Bank [150]. Ranging from -2.5 to 2.5, in this assessment it is reported on a 0-to-5 scale (**Figure 47**). This index aims to quantify the perceptions of the extent to which citizens participation is allowed for the selection of their government, in terms of freedom of expression, freedom of association and free media (values refer to 2020).

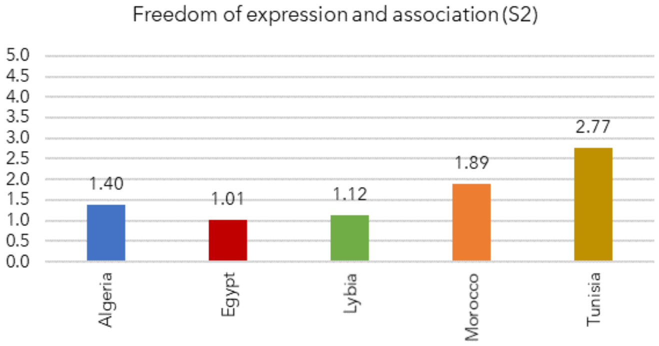


Figure 47: Freedom of expression/association, adapted from [150], as social criterion S2.

As technological criterion T1, the Global Innovation Index (GII), elaborated by the World Intellectual Property Organization (WIPO), is exploited [151]. The values shown in **Figure 48** – and exploited for this application – refer to the report of 2021 [151], with the sole exception of Libya, whose value refers to 2016 [152].

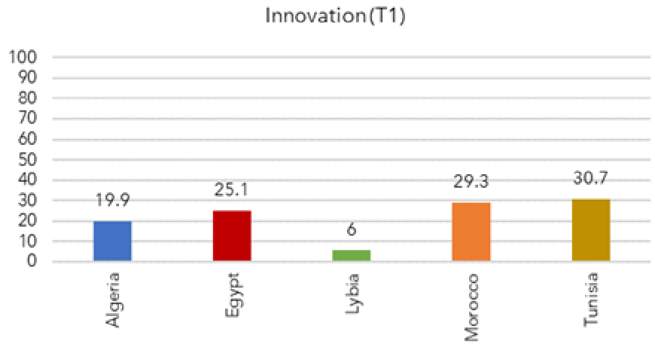


Figure 48: The Innovation criterion T1, adapted from the Global Innovation Index [151].

The Renewable Attractiveness indicator – identified as T2 – takes into account the need of renewable electricity for water electrolysis (**Figure 49**). Specifically, different information and data are aggregated, collecting (i) the national regulatory frameworks about RES and the related planning expansion, (ii) the information from the Renewable energy pillar of the Regulatory Indicators for Sustainable Energy (RISE) released by World Bank Group and Energy Sector Management Assistance Program (ESMAP), (iii) the IEA databases and elaborations, (iv) the ranking released by Ernst & Young concerning the RECAI (introduced in sub-section 3.1) [129],[152],[153].

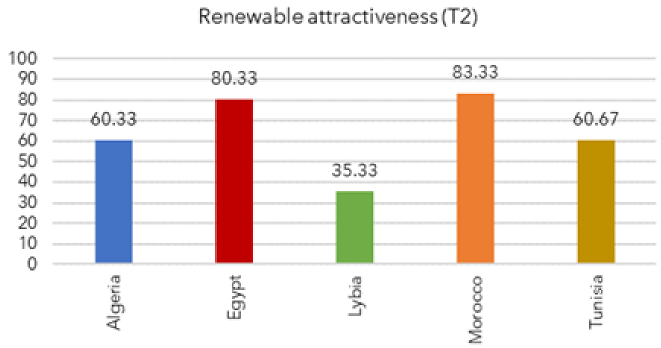


Figure 49: The renewable attractiveness criterion, self-elaborated on [129],[152],[153].

The Hydrogen Attractiveness is the name chosen for the third criterion (T3) belonging to the technological domain. It is self-elaborated based on the qualitative assessment of the different countries' policies and strategies related to hydrogen adoption [154] and of the current hydrogen-based projects, according to a dataset elaborated by IEA [155].

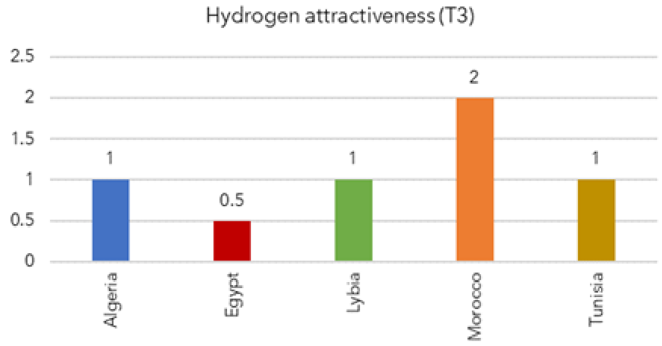


Figure 50: The hydrogen attractiveness criterion, self-elaborated on [154],[155].

Concerning the environmental dimension, the Level of water stress, elaborated by the Food and Agriculture Organization of United Nations (FAO), is exploited [156], considering the required water for the electrolysis process. As Sustainable Development Goal (SDG) index, it tracks how much freshwater is being withdrawn by all economic activities, compared to the total renewable freshwater resources available, taking into account environmental flow requirements (**Figure 51**, values updated to 2018). Countries withdrawing 25% or more of their own renewable freshwater resources are identified as “water-stressed” [157].

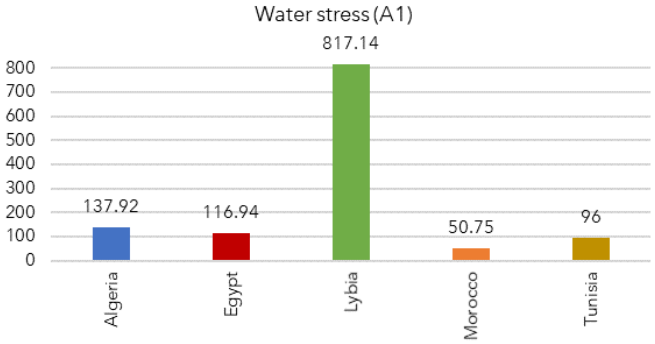


Figure 51: The water stress level, elaborated on [156], as environmental criterion A1.

The second environmental criterion (A2) introduces the Degree of integrated water resource management implementation [157] as valuable information for the analysis. Its computation assesses the four main dimensions of Integrated Water Resources Management (IWRM): enabling environment, institutions and participation, management instruments and financing. The degree of implementation is measured on a 0 to 100 scale, based on a self-assessed country questionnaire (**Figure 52**, values updated to 2020).

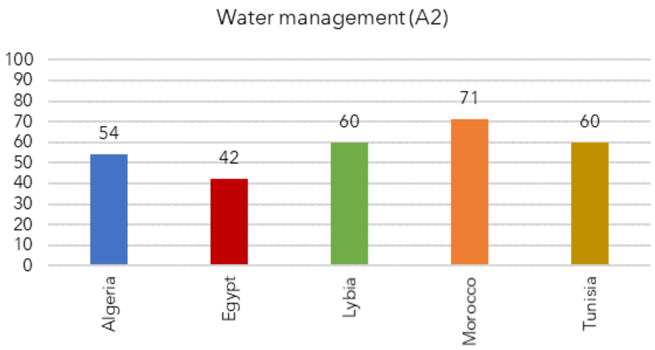


Figure 52: The degree of water management as criterion A2, elaborated on [157].

Looking at the geopolitical dimension, it is selected the Government effectiveness index as G1 [150]. It measures the perceptions of the quality of public and civil services and the degree of their independence from political pressures, the quality of policy formulation and implementation and the credibility of the government's commitment to such policies [150]. **Figure 53** shows the values of G1 for the alternatives, updated to 2020.

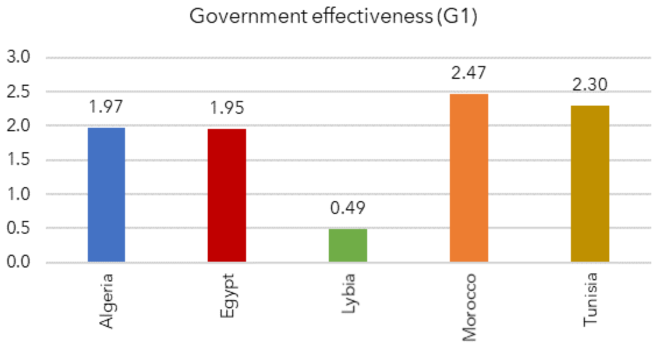


Figure 53: The Government effectiveness index [150], as geopolitical criterion G1.

Also the political stability criterion (G2) is elaborated in the framework of the WGI dataset (**Figure 54** shows the exploited values, updated to 2020); the Political Stability and absence of Violence/Terrorism reflects the perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism [150].

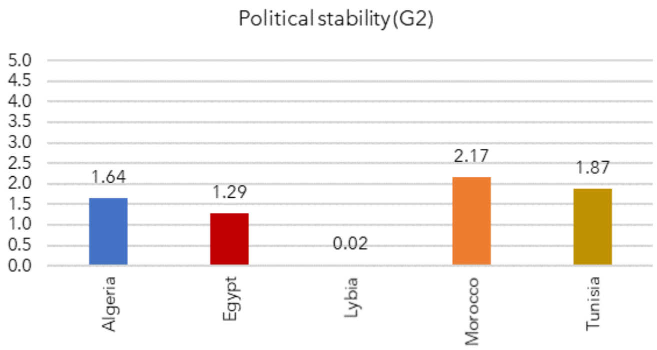


Figure 54: The Political stability [150], as geopolitical criterion G2.

The third geopolitical criterion assesses the perception of corruption, evaluated as the Corruption Perceptions Index by Transparency International, to elaborate the perceptions of public sector corruption, i.e. administrative and political corruption (the exploited values, shown in **Figure 55**, are updated to 2021) [158]. The higher the index, the lower the presence of corruption, so the higher the potential predisposition under assessment, with transparency supporting and enabling technological advancements.

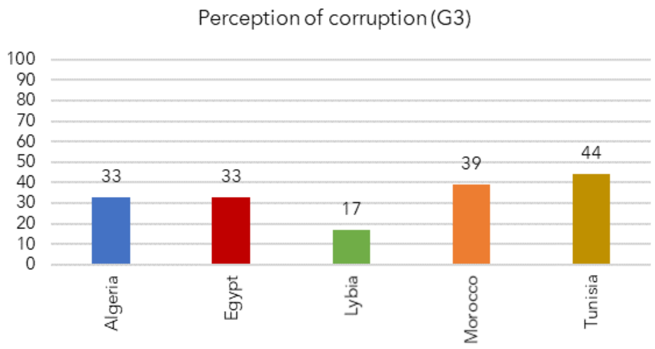


Figure 55: The Perception of Corruption [158], as geopolitical criterion G3.

Concerning the economic domain, the Financial Development Index (FDI) developed by the International Monetary Fund (IMF) is considered as E1 [159]. **Figure 56** shows the values of E1 for the alternatives (updated to 2019). Ranging from 0 to 1, it provides an indication of the depth, access (accessibility of individuals and companies to financial services) and efficiency (ability of institutions to provide financial services at low cost and with sustainable revenues and the level of activities and capital markets) of developed financial institutions and markets [159].

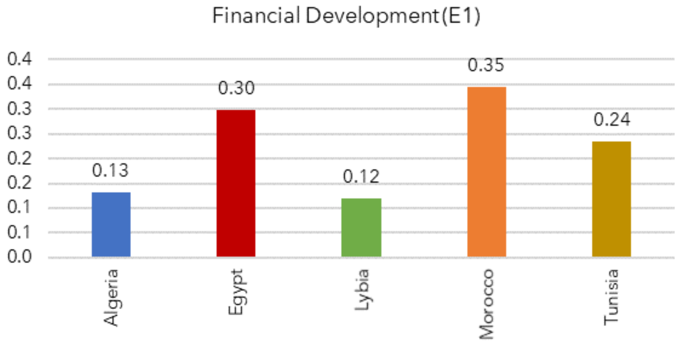


Figure 56: The Financial Development Index [159], as economic criterion E1.

The second economic criterion is elaborated averaging 3 of the 12 sub-indexes making the Economic Freedom Index (EFI), developed by the Heritage Foundation [130]; in particular, the three sub-indices of the Regulatory Efficiency category are taken into account: Business Freedom index, Labor Freedom index and Monetary Freedom index. Specifically, the values used in the assessment and reported in **Figure 57** refers to the 2021 report [130].

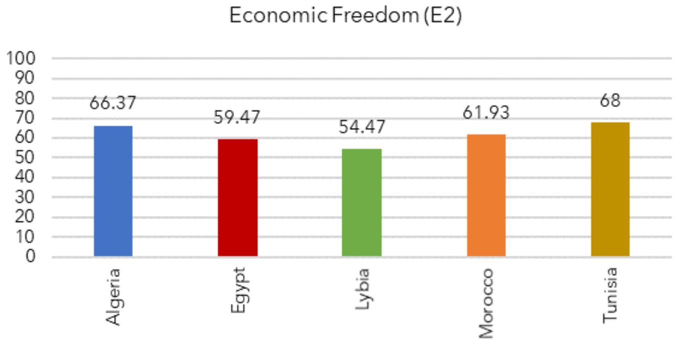


Figure 57: The Economic freedom criterion as E2, elaborated through [130].

According to the objective of the MCDA, all the presented criteria should be maximized (when comparing the different alternatives, those with higher values are preferred), except the environmental criterion A1 (water stress), which should be minimized (the lower, the better). As preference functions, the linear or V-shape functions is used, tailored on the criteria involved. On the weightings side, three energy experts are interviewed; **Figure 58** shows the weightings obtained according to the experts' judgement. Specifically, to elaborate this assessment an electric engineer, an energy engineer and a professor of energy economics have been involved.

Figure 58: Weightings of analysed scenarios referred to experts' preferences.

3.2.2.2 Results on the analysis of predisposition

In the three assessed scenarios Morocco appears as the most predisposed to green hydrogen among the North African countries, while Libya is always ranked as the worst performing. Tunisia is classified as the second one, followed by Algeria and Egypt, which show a very similar trend (**Figure 59**).

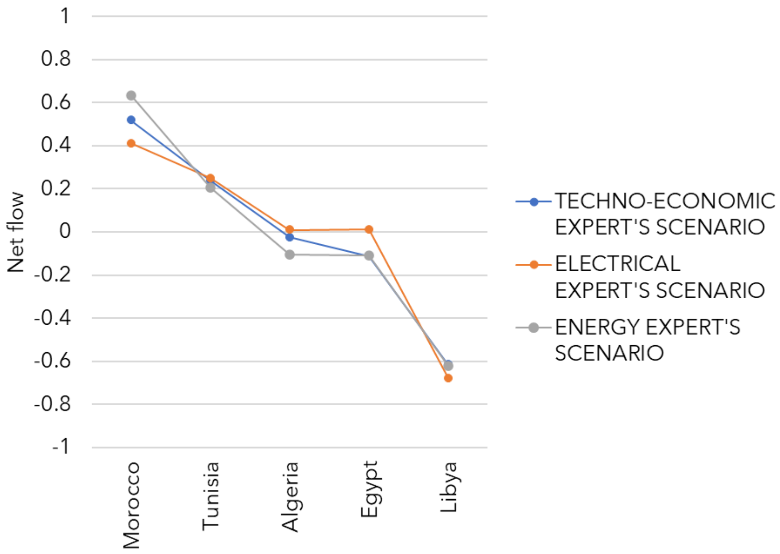


Figure 59: Net flows and final rankings according to the experts' preferences.

To better investigate the influence of weightings and experts' preferences, a sensitivity analysis is conducted, through the study of the "equal case", "extreme geopolitical case", and the "extreme social case". Specifically, the equal case exploits the same weight for each criterion; while for the two extremization cases, it is applied a 25% weight to each criterion belonging respectively to the geopolitical and the social domains, with the remaining percentage (the sum of all weights should be equal to 100%) subdivided in equal terms among the remaining criteria. **Figure 60** shows the net flows obtained according to the sensitivity analysis proposed.

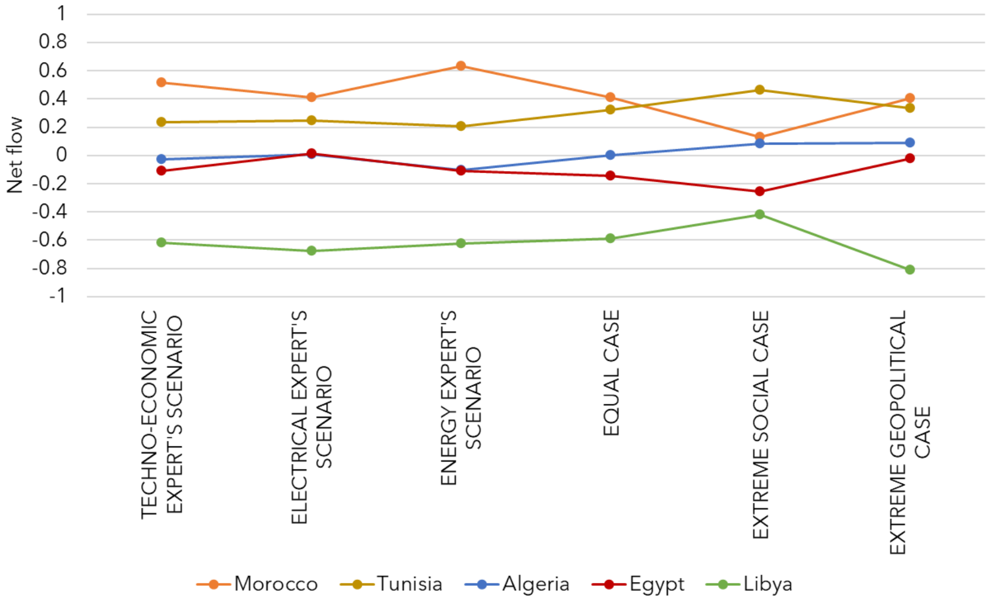


Figure 60: Net flows evolution for the alternatives according to the analysed scenarios.

Through the lens of the extreme social scenario, Tunisia performs better than Morocco, which obtains a score very close to the one of Algeria. For the extreme geopolitical case, it is of interest to notice how Libya's score is much lower than the one obtained as net flow in the other scenarios, increasing the gap with the other countries, which in this case appear closer in terms of final results. The use of Visual PROMETHEE software allows to study also different outputs, exploiting several data visualization, thanks to the GAIA Visual Analysis on a multi-dimensional plane [140]. **Figure 61** reports the rainbow output according to the energy expert's view; it consists of a disaggregated view of the complete ranking of a scenario, showing the alternatives from the most to the least preferred, from left to right, presenting their performances through the flow value times the weighting coefficient associated to the specific criterion by the expert involved. In this case, it is evident that, according to the energy scenario, the performances of Morocco are strongly positive with respect to all the criteria except for EC2 and S1, while Libya collects minimum positive contributions only for EN2, S1, T3 (**Figure 61**).

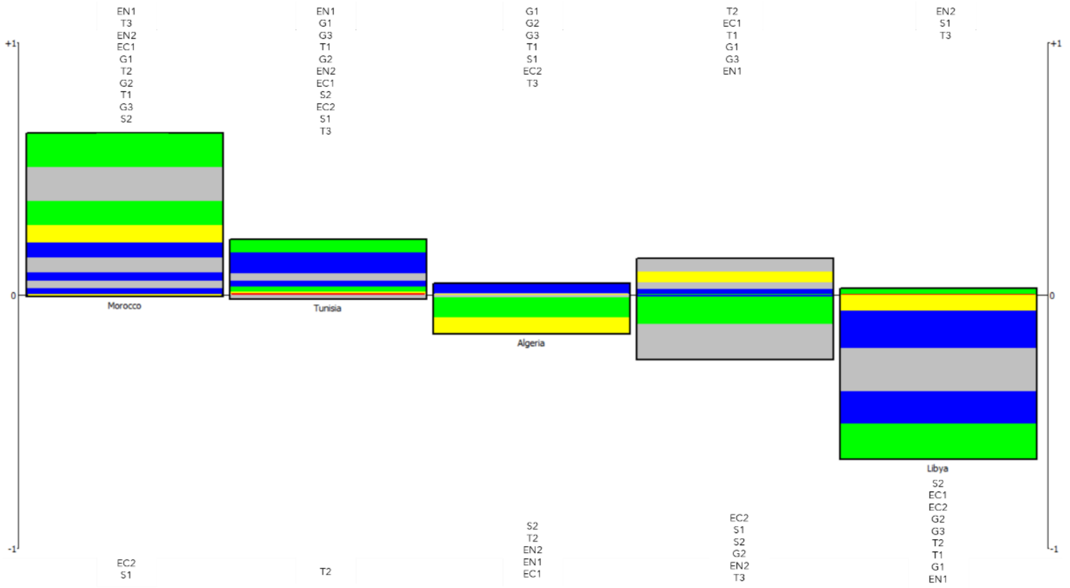


Figure 61: The Rainbow output from [140], according to the energy expert's preferences.

This first analysis gave the possibility to obtain a preliminary assessment of the North African countries with respect to their predisposition to the potential production of green hydrogen. Specifically, this qualitative assessment allows to better introduce and define the countries of interest, each of them potentially involved in the development of a hydrogen market, focusing on the Italian case in terms of import/export availability.

3.4.2.6 Limitations and possible development of the work

The application of PROMETHEE II to analyse the predisposition of North Africa countries for green hydrogen production highlights the relevance of multi-dimensional indicators and the influence of experts while addressing problems like the one of interest. Specifically, this analysis makes possible to preliminarily rank the countries involved, but also to understand how different topics – which are translated into indicators to be elaborated and evaluated – can be involved to target an energy-based issue.

To this regard, it is important to stress how the analysis is strongly affected by the reference year for the calculation of the indicators; it can be noticed how indicators like the used ones, e.g. economic freedom, human development, political stability, are dynamic and strongly affected by time. A useful development of the work could involve a time series analysis on these specific indicators, to address if and how their potential changes over time can impact the final results, i.e. the final ranking. Moreover, it can be useful to introduce the judgments and preferences of other experts, to better investigate the impact of weightings and different expertise. If from one side the PROMETHEE II method is a powerful instrument for this application, making possible to rank countries and identify the main potentialities and criticalities associated, on the other it requires a careful analysis with respect to the identification of experts involved and related criteria to be analysed.

3.3 The multi-dimensional suitability for green hydrogen production in North Africa

Being the most predisposed to green hydrogen production (according to the analysis conducted in sub-section 3.2), Morocco, Tunisia and Algeria are briefly discussed and introduced in 3.3.1 with respect to their energy strategies and pathways, while 3.3.2 is devoted to preliminarily assessed their theoretical potential for solar hydrogen production.

After this, the MC-SDSS application for land suitability is detailed for the three counties in sub-sections 3.3.3 and 3.3.4, respectively for solar and wind hydrogen production.

3.3.1 Country-specific targets and strategies towards 2050

In order to study the North African countries, deepening their strategies and roles in the transition context, it is important to consider that “each country has its own priorities, economic interests, policy strategy, RES program, distinct legislation and a distinct approach to the concept of RES export” [85].

3.3.1.1 The Tunisian case

Listed as a developing country of North Africa, basically net-oil importer and labour abundant – the same of Morocco and Egypt [86] –, Tunisia has signed an agreement with Germany in December 2020 supporting the creation of an alliance for green hydrogen and aiming to develop a competitive export-oriented hydrogen industry

[160]. Specifically, this country has shown an increasing interest for energy issues in the last years, looking for the development of ad-hoc policies and strategies towards the decarbonization target. In fact, according to its Nationally Determined Contribution (NDC) updated in October 2021, there is the target of reducing its carbon intensity by 45% by 2030 [161], to finally reach carbon-neutrality in 2050, as stated in the 2050 low-carbon strategy [162]. **Figure 62** summarises the main targets of the strategy [162], focusing on the technological instruments and economic tools required to achieve the ambitious goals:

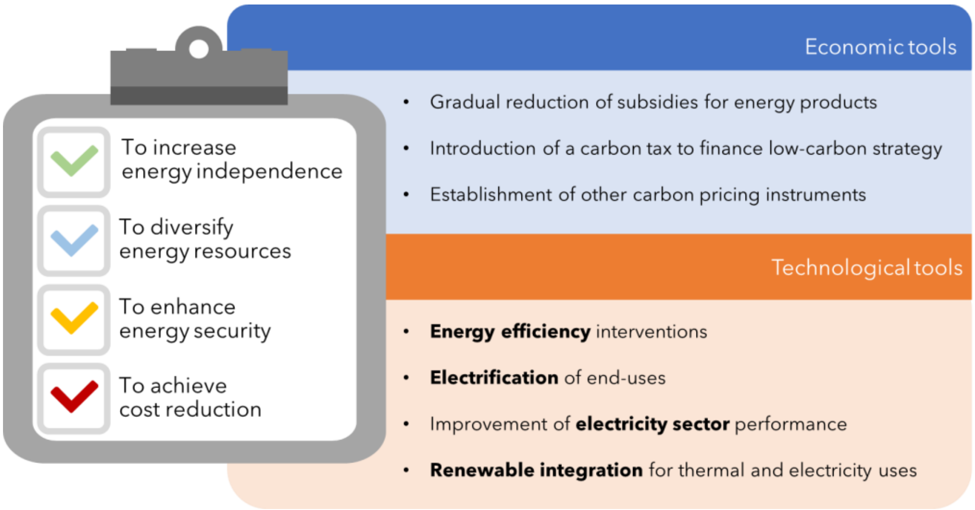


Figure 62: Technological and economic tools supporting the Tunisian energy transition towards 2050 carbon-neutrality, adapted from [162],[163].

Considering the strong increase of energy imports in the past years and the current limited renewable energy production, a full changeover for Tunisia is expected; its energy transition will be notably based on (i) diversification of the energy mix and integration of RES; (ii) strengthening energy efficiency; (iii) rationalization of subsidies in energy sector; (iv) strengthening of grid and interconnections [164]. Analysing the Tunisian energy system, it is undoubted the importance given to ad-hoc national energy efficiency strategies and action plans, regulatory, fiscal, and financial instruments covering electricity, impactful energy subsidy reform measures, strong institutional support [86]. Considered as one of the Mediterranean countries most exposed to climate change, with also a high degree of risk to natural hazards, the significant environmental and socio-economic vulnerability with respect to its climate future must be considered [165]. Specifically, primary risks like temperature increases, reduced precipitations, rising sea levels, and extreme events, like floods and droughts, are impacting and will impact human and animal health, agriculture, water resources, ecosystems; adaptation measures are required and must be concretized [166], as summarised in **Figure 63**:

Adaptation options *for agriculture*

- Increased meteorological and climatic monitoring
- Adoption of the National Program of Water Savings (since 1995)
- Adaptation strategies planned by each governorate, tailored on the type of agricultural development

Adaptation options *for water resources*

- Desalination plants
- Reuse of wastewater
- Transference of surplus water
- Inclusion of water and soil conservation in the new strategy integrating the impact of climate change
- Reduction of water demand from key sectors

Adaptation options *for energy*

- Diversification of energy supply, specifically through the increase of RES deployment
- Implementation of customer energy savings programs
- Increased support for research and technological development
- Development and implementation of innovative new regulatory and finance models to increase efficiency
- Development of new approaches to the delivery of electricity, especially the renewable one

Figure 63: Adaptation options supporting Tunisian energy transition, adapted from [166].

Even if some challenges must be overcome with respect to water availability, the exploitation of green hydrogen starting from the solar energy can represent an important step for Tunisia, in line with its targets for 2050, and its need to increase the production of renewable energy, so its energy independence and security. Although Tunisia has planned to push for renewable energy production up to 30% by 2030, infrastructure and investments have yet to keep pace within these goals [166].

3.3.1.2 The Algerian case

Algeria is defined as net-oil exporters and labor abundant; it is well-known to be oil- and gas-rich, and for this reason still highly dependent on fossil fuels [86]. Considering that the Algerian energy demand is undergoing an unprecedent increase because of (i) demographic changes, (ii) industrial development and (iii) urbanization, it is urgently needed a changeover in energy production. In fact, in 2018 the energy mix was still dominated by fossil fuels, with natural gas accounting for 63.8%, oil for 35.4%, and coal for 0.6%, while renewable energies had in total a negligible share of 0.1% [167]. Despite its slow expansion of renewables, the solar potential of Algeria is among the highest worldwide, considering that the 86% of its land is covered by the Sahara Desert. To tackle the huge increase in energy consumption, the country is planning to integrate a substantial amount of renewables into its power network, even if the process promises to be very slow, as reported in **Table 4**, which highlights how the RES targets set for 2020 were absolutely not achieved [168].

Table 4: National RE program target installation and achievements, from [168].

Source	*Target in 2020 [MW]*	*Installed in 2020 [MW]*
PV	3000	400
Wind	1010	50
Bio-power	360	0
Geothermal	5	0
CSP	-	25
total	*4375*	*475*

Although the ratification of the Paris Agreement, the specific setting of RES targets, the regulation policies for RES implementation, and the energy efficiency strategy, the pace of transition towards the development of RES is still too slow. **Figure 64** extracts from the last two decades the most important laws and decisions encouraging the uptake of renewables, as reported in [168],[169].

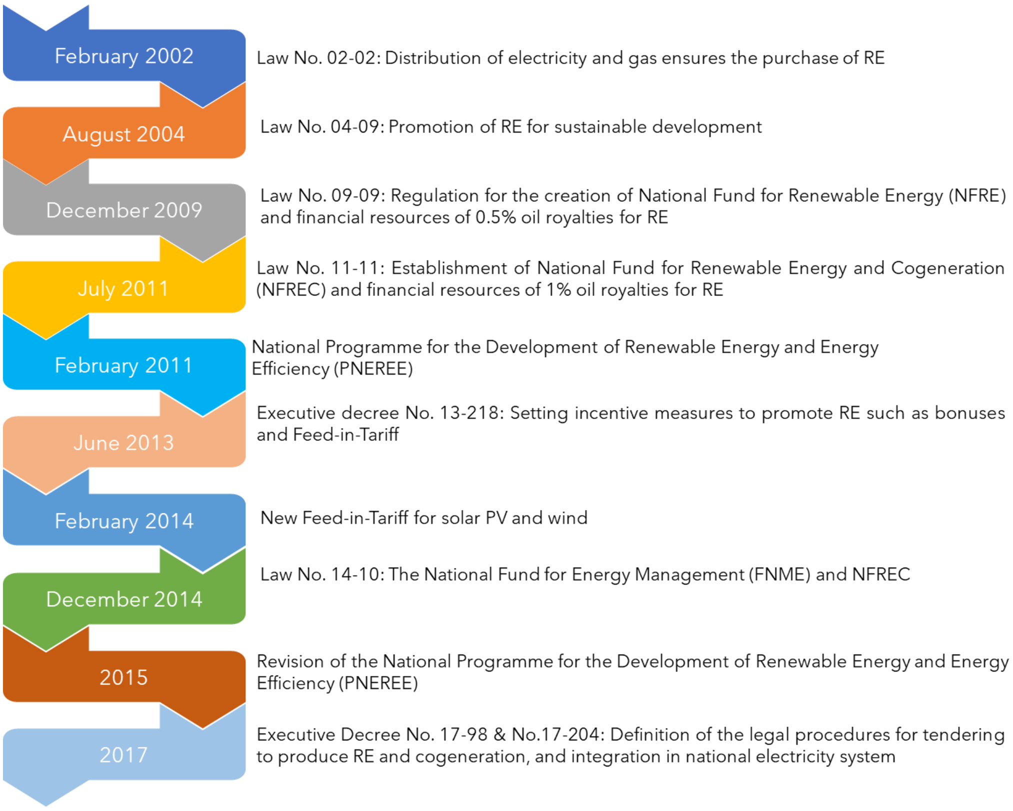


Figure 64: Main regulations and laws referred to RE in Algeria, adapted from [168],[169].

The reasons behind the slow implementation of effective clean strategies can be found in a series of barriers to be addressed; among them, cost effectiveness, energy policies, lack of skills and information, subsidies for conventional forms of energy, poor market acceptance, infrastructure requirements, integration of water security, food security and agriculture [169]. As long as the government continues to subsidize energy prices and the well-developed energy infrastructure near coastal demand centers remains in place, there will be not a fast large-scale change as it is required by the transition process [170]. If from one side the legal framework is mature, on the other the financial and regulatory mechanisms seems to be insufficient to an adequate development. There is a still high level of fragmentation and lack of coordination in renewable energy initiatives [170],[171]. **Figure 65** reports the main challenges slowing down the development of a robust renewable energy market in Algeria, as analyzed in [169]-[171].

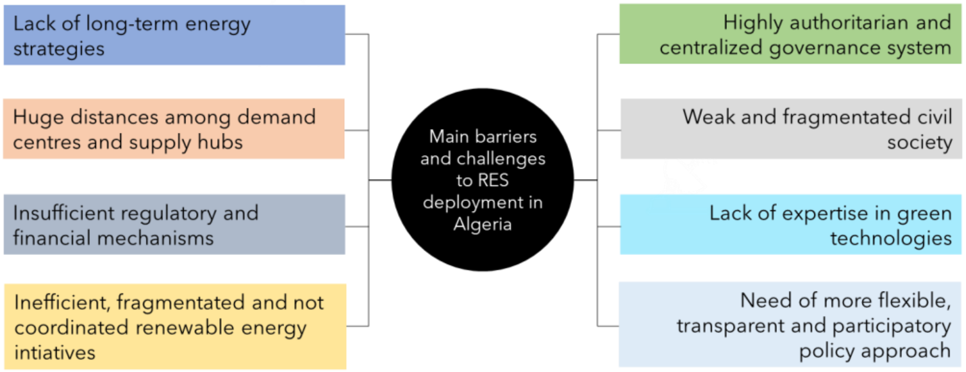


Figure 65: Main barriers and challenges to RE deployment in Algeria, based [169]-[171].

In addition to this, Algeria is facing an increase of social, cultural, environmental organisations, also with a rise of environmental awareness; nevertheless, the social acceptance of renewable projects should not be taken for granted [170].

3.3.1.3 The Moroccan case

Listed as a developing country of North Africa, basically net-oil importer and labour abundant [86], Morocco is identified as potential global leader in producing green hydrogen, due to its massive economically viable solar and wind resources [73],[172]. The Moroccan fast economic growth has lead to an increase in energy consumption in the last years, requiring a better diversification of the sources for electricity production and to decrease the energy imports. Specifically, the adoption of the National Energy Strategy (NES) in 2009 pushed for RES deployment, energy efficiency and diversification, strengthening the integration with regional and international markets and encouraging the development of indigenous resources [173]. In 2015, this NES has been renewed, in line with the Paris Agreement, fixing the targets for 2030. **Figure 66** shows the main priorities for the current decade [174]:

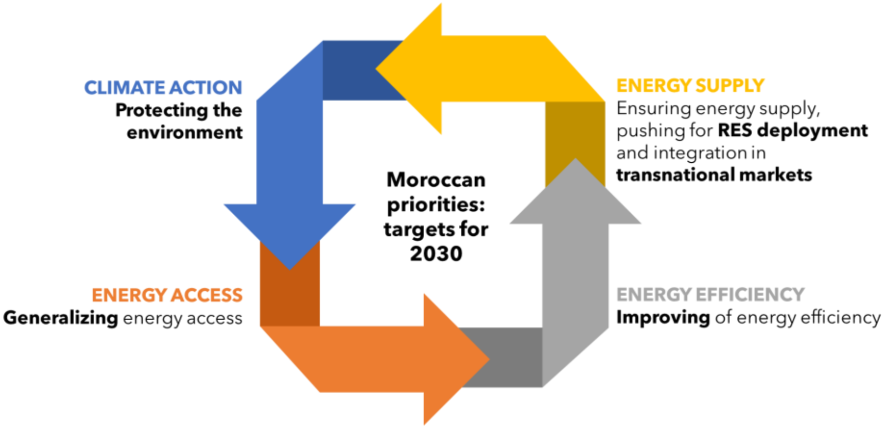


Figure 66: Moroccan targets for 2030 [174].

All the Moroccan initiatives in energy policies lead to visible improvements in terms of energy diversification, management, and optimization; the desired changeover is effectively ongoing. Specifically, looking at its 2019-2023 Investment Strategy, Morocco aims to expand its renewable production, which is also the objective of the Moroccan Rural Electrification Programme (PERG). Nevertheless, it is important to consider the strong vulnerability of this country with respect to climate variability and change, as shown by temperature rising, variable rainfall patterns and intensity of droughts; all these events are impacting and will influence the future of agriculture, water, tourism, and health [165].

Looking at the multiple possibilities in terms of potential bilateral and multilateral agreements, the role of this country in the international context could be crucial; Morocco and European Union had already announced the intention to establish a “Green partnership” on energy, climate and environment ahead of COP26, in order to support the implementation of climate-neutral solutions [175]. Despite this, there is an effective slowdown of projects and partnerships due to the growing tensions especially in the Western Sahara; in May 2021 two projects for green energy production belonging to the German-Moroccan energy partnership have been suspended because of tensions among Morocco and some European Member States, after the signature by Morocco of the Abraham accords [176].

Although there are several challenges to be faced, the role of Morocco in the green hydrogen market will be surely strategic, as shown along with the Moroccan low carbon strategy for 2050 and specifically through the publication of a green hydrogen roadmap and strategy definition by the government [177]-[179]. **Figure 67** synthetizes the key pillars according to which Morocco is going to develop its 2050 action plan for green hydrogen.

Figure 67: Key pillars of the 2050 action plan for green H_2 deployment [177]-[179].

3.3.2 A preliminary assessment on theoretical production potential of solar hydrogen

As first application, the photovoltaic plants on ground are investigated for producing the renewable electric energy required for green hydrogen production. This application is presented in the deliverable elaborated for RSE in December 2021 [139]. It is decided to deepen the solar availability and specifically the PV potentials since in literature there are a lot of different applications deals with the combination of GIS and AHP to assess the land suitability for the installation of PV plants [133]-[135],[180]-[183]. “Spatial multi-criteria analysis becomes at the same time a tool for identifying suitable areas for the location of a new infrastructure, an instrument to evaluate hypothetical alternatives already explored or, even, a means by which it is possible to legitimize policies and actions in an urban and territorial context or elaborate a consensus scenario among all parties” [117]. The integration of geographic datasets allows to identify criteria as constraints to be put in input for a multi-criteria analysis (**Table 5**), supporting policymakers’ sustainable informed actions.

Table 5: List of spatial-measurable criteria for PV site selection, according to [133]-[135],[180]-[183].

Criterion for PV site selection (main case study: Morocco)	
Global Horizontal Irradiation [kWh/m^2/y]	It is the source for solar PV panels productivity: the higher the GHI, the higher the productivity.
Temperature [°C]	It negatively influences the PV panels efficiency, whenever the 25°C are exceeded.
Elevation [m]	Lower elevations are recommended; areas below 200 m are the most suitable for PV installations.
Slope [°]	Flat places are the most favourable for solar PV panels, to guarantee productivity and a simpler maintenance.
Distance from built-up areas [km]	It is needed a trade-off to ensure urban expansion but also to facilitate job creations.
Distance from road and railway network [km] Distance from airports [km] Distance from electricity grid [km]	The more connected, the more suitable is the area; it means to have a simpler access to the installations, for the development of the plants and for their operation and maintenance.
Distance from water ways [km] Distance from dams [km] Distance from groundwater [km] Distance from flood-sensitive areas [km] Land use [-] Distance from protected areas [km]	For environmental reasons, solar farms should not be built up on land used for other purposes like agriculture, or should not replace protected areas or forests, waterways, dams. The choice of locations should account for critical areas like flood-sensitive ones.

The objective of the preliminary analysis developed for Morocco, Tunisia and Algeria is to map the ground-mounted solar PV potential to be exploited for green hydrogen production; this consists of the first main step of the multi-step suitability approach proposed, aiming to finally obtain a more specific and detailed green hydrogen potential, through the MC-SDSS (AHP and GIS) application. According to the review conducted on similar case studies, the exclusion criteria reported in **Table 6** are selected for the preliminary assessment of hydrogen potential exploiting PV energy for water electrolysis:

Table 6: Exclusion criteria adopted for the preliminary assessment.

Exclusion criterion	*Area excluded if*	*Source*	*Buffering area*
GHI (Global Horizontal Irradiation)	GHI < 4.5 $kWh/m^2/day$	Global Solar Atlas 2.0 [184]	
Slope	Slope > 5°	DEM - SRTM NASA [185]	
Water bodies	Water areas and water lines	Open Africa dataset [186]	Buffer of 500 m
Protected areas and Other Effective Conservation Measures areas	Biologic reserves, sites of ecologic and biologic interest, protected maritime areas, natural parks, hunting reserves, UNESCO sites	World Database on Protected Areas (WDPA) [187]	Buffer of 500 m
Populated areas	Populated places points and polygons	OpenStreetMap [188]	Buffer of 3 km
Other land uses	Not bare areas neither areas with scrubs	Esri 2020 LandCover [189]	

To conduct each spatial analysis reported in this thesis – from data collection to data processing and analysis of results – the software arcGIS Pro by Esri is exploited [190]. Specifically, after applying the exclusion criteria (**Table 6**), on the remaining available areas is firstly calculated the solar panel energy potential to obtain the final green hydrogen mapping [191],[192]. In particular, it is set E_{PV} as the annual energy produced by a polycrystalline PV panel, with GHI evaluated in [kWh/m^2/y], η_{PV} representing the module reference efficiency [%] and η_{PG} the power conditioning efficiency [%]. Then, by taking into account the area factor (AF), so the area to be effectively covered by PV panels, the annual electric solar energy generation potential per unit of surface is calculated [193]. An AF of 50% is adopted for this preliminary analysis.

$$E_{gp}\left[\frac{kWh}{m^2y}\right] = GHI * \eta_{PV} * \eta_{PG} * AF = E_{PV} * AF \tag{3.5}$$

For more specific calculations, the value of AF should consider the tilt angle, the solar altitude angle and the solar azimuth angle evaluated at 3 PM at winter solstice [194]. By multiplying the E_{gp} for the area of suitable land of interest, the annual EGP in [kWh/y] can be obtained [193],[195]-[198]. For the estimation of the renewable hydrogen production, it is assumed to use a Polymer Electrolyte Membrane (PEM) electrolyser:

$$M_{H2}\left[\frac{kg}{m^2y}\right] = \frac{E_{gp} * \eta_{ELE}}{HHV_{H2}} \tag{3.6}$$

M_{H2} is the annual green hydrogen produced, with E_{gp} evaluated in [kWh/m^2/y], η_{ELE} representing the PEM reference efficiency [%] and HHV_{H2} which is the hydrogen Higher Heating Value [kWh/kg].

Figure 68 shows the preliminary mapping of Tunisia elaborated with respect to the green hydrogen production by water electrolysis, exploiting the renewable energy of ground-mounted solar PV. The black areas stand for the excluded places, i.e. that cannot be exploited for solar hydrogen production.

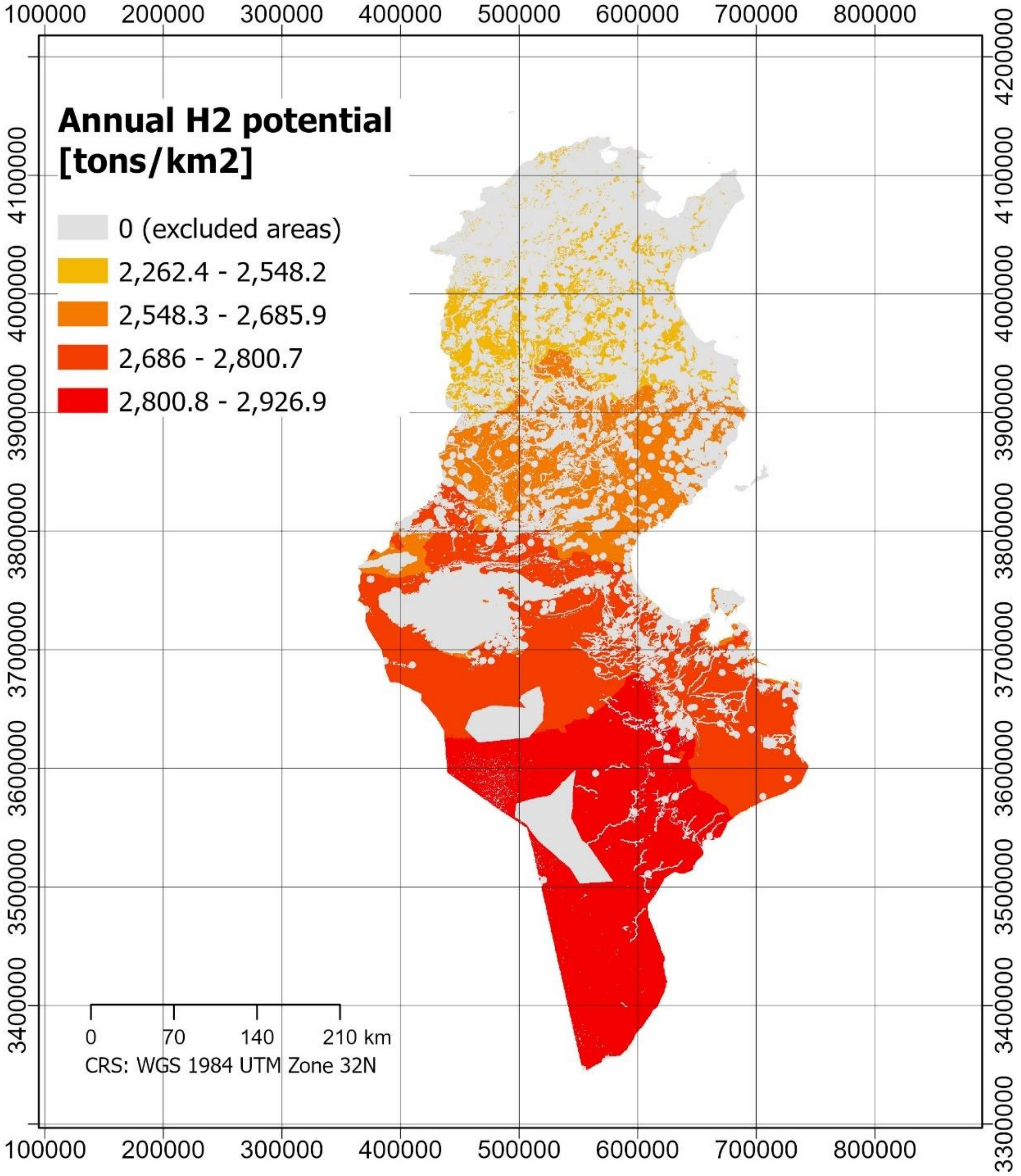


Figure 68: Tunisia, preliminary suitability analysis on solar hydrogen production potential.

The 55.7% of the country, according to the exclusion criteria introduced, is potentially suitable for green hydrogen production, making use of the renewable electricity generated by ground-mounted solar PV. With a module efficiency of 15.9%, a η_{PG} equals to 91% and an AF of 50%, the potential amount of produced hydrogen ranges from 2262.4 t/km^2/y to 2926.9 t/km^2/y, with an average of 2717.8 t/km^2/y. In **Figure 69** is presented the Algerian case; it is reported the preliminary mapping concerning the solar hydrogen potential, taking care of the exclusion criteria, according to which the 81.39% of the Algerian land is assessed as potentially available. It results that the potential amount of solar hydrogen reaches the maximum amount of 3300 t/km^2/y.

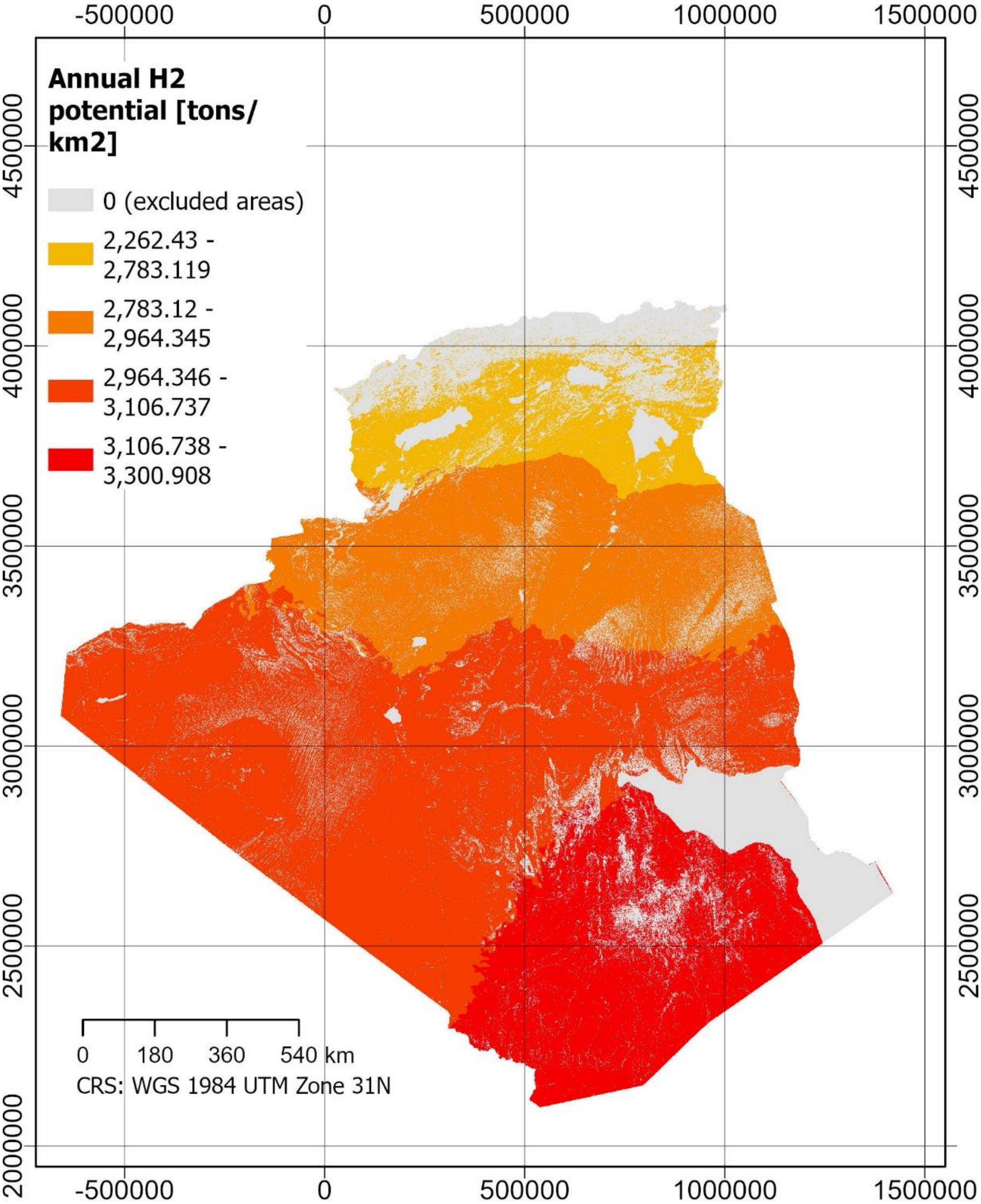


Figure 69: Algeria, preliminary suitability analysis on solar hydrogen production potential.

Concerning Morocco and Western Sahara, it is decided to separately assess the latter, resulting a conflicting area since 1970s, put in contrast the Saharawi population and the Kingdom of Morocco, and involving different international actors with several positions and ideas [199]. According to the assumptions, the 78.3% of the assessed areas must be excluded from the evaluation of the green hydrogen potential (all the grey areas in **Figure 70**).

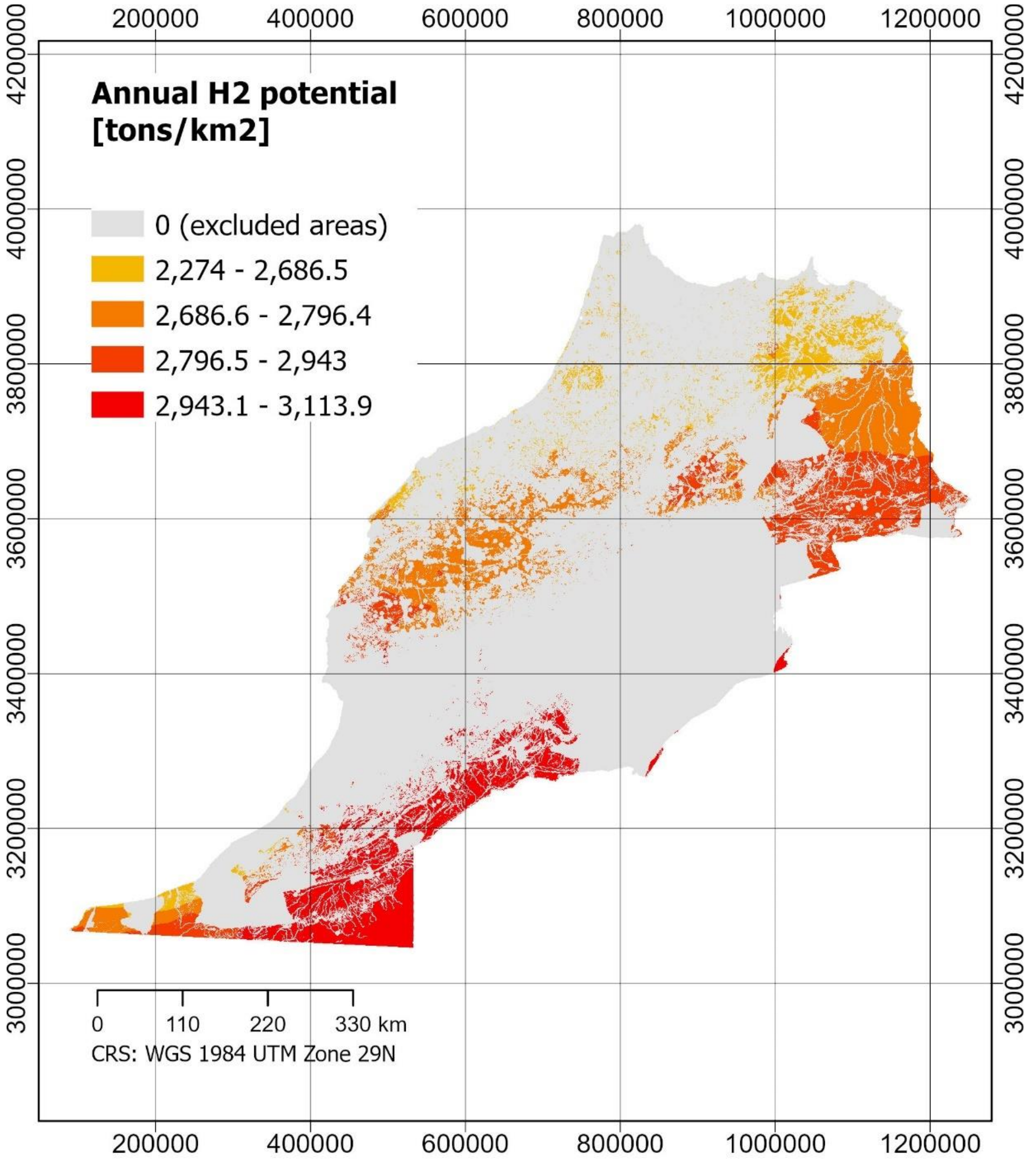


Figure 70: The preliminary suitability analysis for Morocco on solar hydrogen production potential.

The amount of solar electricity potential per unit of surface evaluated for PV installations ranges from 119.5 kWh/m^2/y to 163.6 kWh/m^2/y, with an average value of 147.3 kWh/m^2/y. Concerning the green hydrogen production, the calculated amount goes from 2274 t/km^2/y to 3113.9 t/km^2/y, with an average of 2803.8 t/km^2/y. As expected, this first mapping releases a mapping of solar hydrogen production directly proportional to the solar radiation, assessing the most productive sites in the South-Eastern part of the area, where the radiation reaches its peaks. Looking at the Western Sahara area, the same analysis is elaborated, through the assessment of the relative GHI, slope, populated areas, water bodies, protected areas and other land uses. The outputs of this analysis are reported in **Figure 71**:

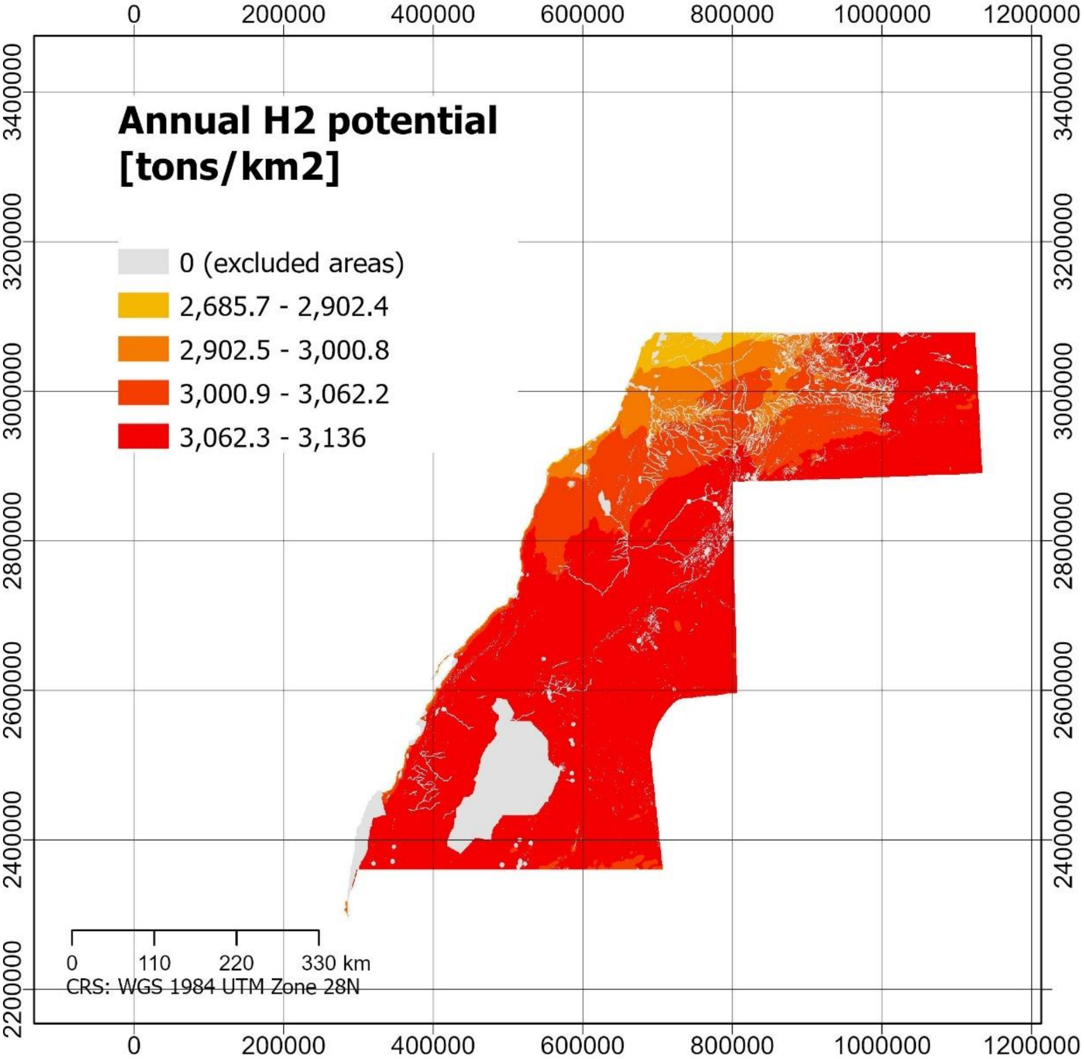


Figure 71: The preliminary suitability analysis for Western Sahara on solar hydrogen production potential.

As highlighted through the maps, the potentiality of Western Sahara is higher, due to more favourable conditions in terms of GHI and slope and to a lower presence of urban areas and agricultural land. In fact, the 87.9% of this surface is assessed as suitable, with an average solar electricity potential per unit area of 159 kWh/m^2/y and a potential hydrogen production that ranges from 2685.7 tons/km^2/y to 3136 tons/km^2/y and an average production of 3026.4 tons/km^2/y.

3.3.3 The combination of AHP and GIS for multi-dimensional suitability

The preliminary mapping shown from **Figure 68** to **Figure 71** refers to specific exclusion criteria (**Table 6**) to deliver preliminary information of land suitability for the areas of interest with respect to solar hydrogen production. It is needed to conduct a more detailed analysis allowing to explore the concept of land suitability in more specific terms, through the combination of GIS and AHP to deliver a structured MC-SDSS, introduced as tool in sub-section 2.1, to map the “multi-dimensional suitability”. Combining GIS and MCDA is a valuable option to deal with spatial complex problems; in the last decades, MC-SDSS has become more relevant as decision support systems, being most often used for tackling land suitability problems ranging among different applications [116]. In particular, AHP is a popular method in MC-SDSS application, allowing (i) to deal with very large number of alternatives, (ii) a simple implementation within the GIS environment, (iii) to easily involve non-technical participants, requiring qualitative statements of preferences [116]. According to these reasons, it is decided to exploit the AHP as multi-criteria for the assessment of green hydrogen suitability in North Africa through MC-SDSS. **Figure 72** outlines the five main steps required to apply the AHP [200], while **Figure 73** shows how it works if combined with GIS, specifying the four phases of the methodological framework, consisting of nine steps which exploit both AHP and GIS (intelligent phase, design phase, review phase) or only GIS (choice phase) [111],[112],[201]-[203].

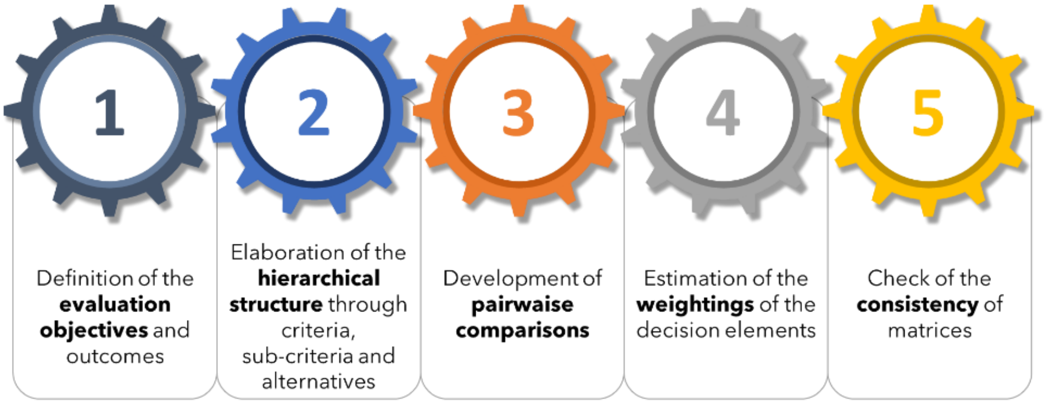
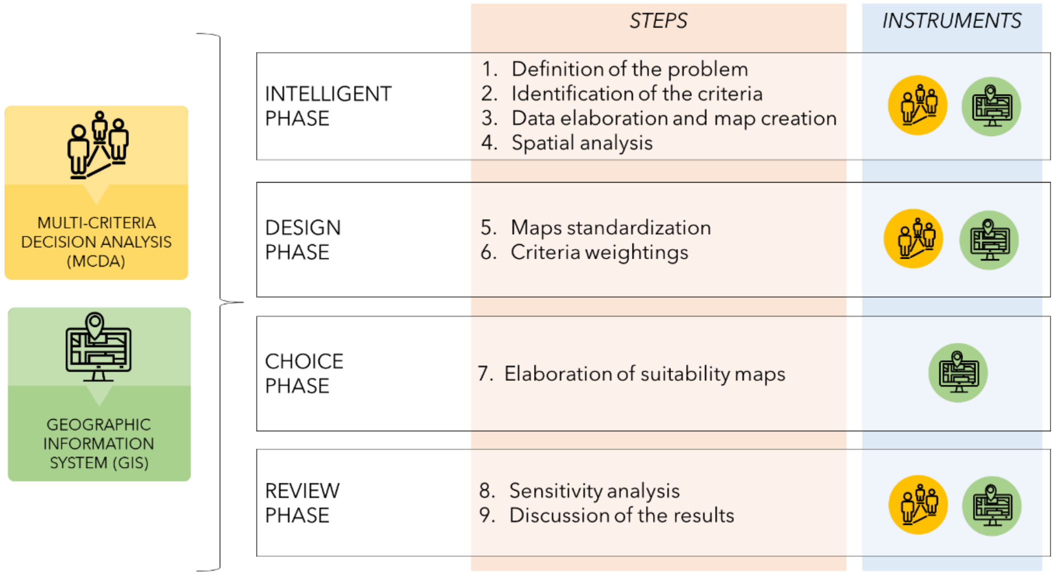


Figure 72: The AHP main steps, adapted from [200].



	STEPS	*INSTRUMENTS*
INTELLIGENT PHASE	1. Definition of the problem 2. Identification of the criteria 3. Data elaboration and map creation 4. Spatial analysis	🟡 🟢
DESIGN PHASE	5. Maps standardization 6. Criteria weightings	🟡 🟢
CHOICE PHASE	7. Elaboration of suitability maps	🟢
REVIEW PHASE	8. Sensitivity analysis 9. Discussion of the results	🟡 🟢

Figure 73: Conceptual framework for MC-SDSS integrating GIS and AHP, adapted from [111],[112],[201]-[203].

As outlined by **Figure 73**, the first step of the procedure consists of defining the problem and criteria, followed by the data elaboration and maps criterion to be analysed through ad-hoc spatial tools. Having set this, the design phase requires to standardize each map, in order to adequately applied the weightings on criteria. In this regard, the role of experts and stakeholders is essential to properly conduct pairwise comparisons on criteria and sub-criteria, so that specific weightings are assigned (**Figure 72**). In both the intelligent and design phases, it is required exploit both the multi-criteria method and spatial analyses, while for the choice phase GIS is the only environment addressing the elaboration of final maps. In the last phase, the review processes, which include both the discussion of results and sensitivity, both tools are required again.

Figure 74 addresses the case studies of interest to the methodological steps. In the following sub-section (3.3.3), the procedure of the MC-SDSS is tailored on the specific objective concerning the potential for solar hydrogen production in Tunisia, Algeria, Morocco; each phase and related steps are explained and detailed, to finally obtain the suitability maps of interest. The sub-section 3.3.4.1, with Tunisia as case study, is the first application introduced and for this reason is better detailed and commented, having that the others follow the same approach. There is also another sub-section (3.3.4) on MC-SDSS, related to the application on the second objective, concerning the specific mapping of wind hydrogen production potential.

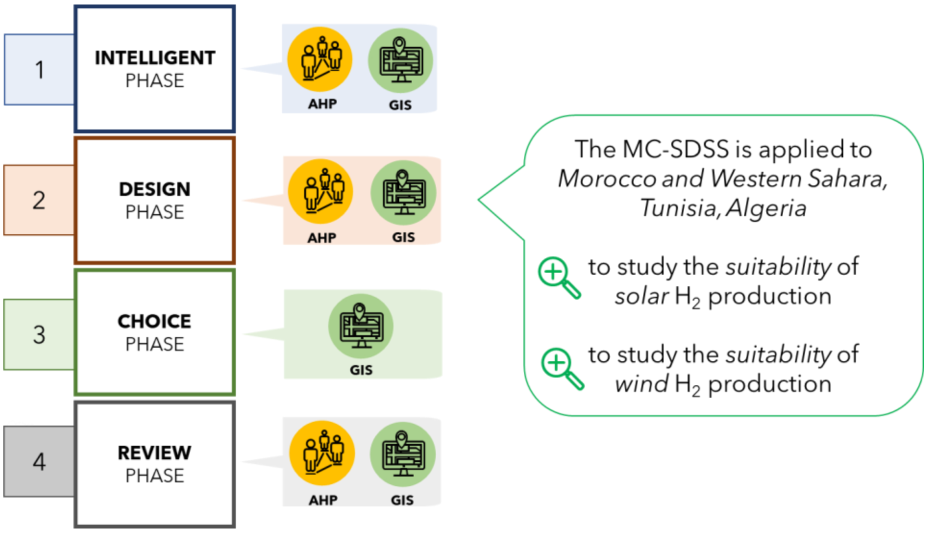


Figure 74: Applications and specific case studies for the MC-SDSS.

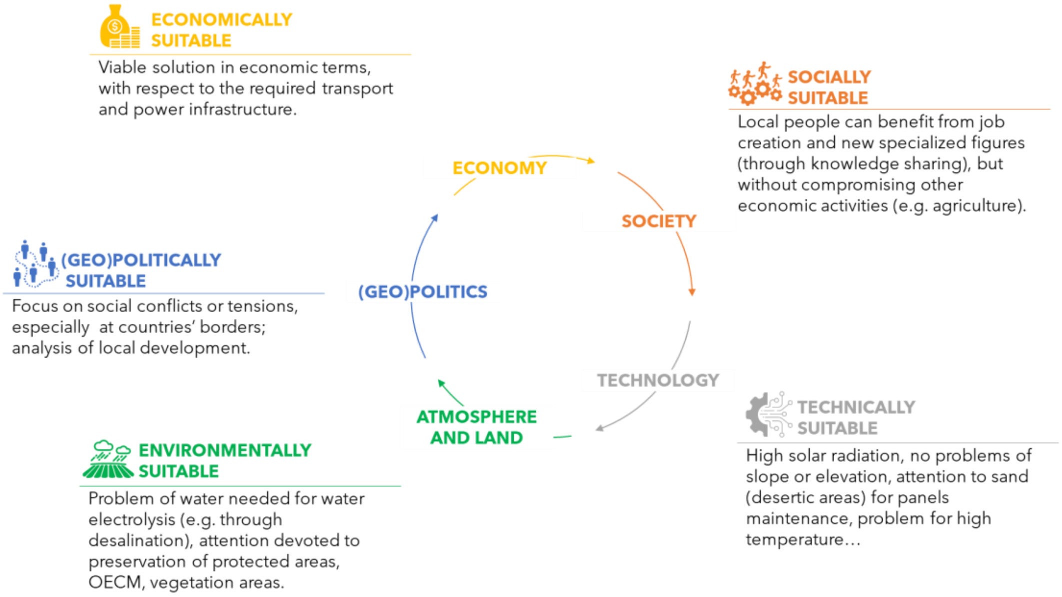
3.3.4 The solar hydrogen production

In this section the application of the methodological approach presented in **Figure 73** is applied to Tunisia, Algeria, Morocco, respectively, focusing on green hydrogen production by water electrolysis enabled by solar photovoltaic plants. This application is currently submitted to the journal "Energy, Sustainability, and Society" [204], as also reported in the appendix.

3.3.4.1 From the intelligent phase to the review phase

The problem definition – as first step of the procedure – clarifies the objective of this first application; in this case, “Which are the suitable areas for green hydrogen production if solar energy from photovoltaic panels is exploited to enable water electrolysis?” At this step, it is of interest to elaborate a detailed analysis with respect to the stakeholders involved in the decision-making process, so the relevant actors having a role in the assessment, allowing the inclusion of often conflicting interests and expectations.

Secondly, the identification of the criteria and sub-criteria is required; to adequately structure the problem, different stakeholders and experts are involved, so that several opinions and points of view are collected, to be integrated with the information reviewed from the literature. The expectations of each involved stakeholder must be considered to perform a valuable decision-making process; here some significant opinions and suggestions with respect to the objective of the assessment are reported. In particular, through an interview to an energy engineer, involved in specific activities in Tunisia and Algeria regarding mostly natural gas, the environmental aspects are addressed as crucial, considering also that green hydrogen is increasing its relevance because of the challenges of transition to tackle climate change. In other words, the key driver of green hydrogen adoption is the environment, so it must be prioritized. Another criterion to be considered and prioritized, especially if dealing with North African countries, is the political condition, to the extent that technological readiness is not enough, and it can be limited if there is a condition of political instability. In this sense, the geopolitical criterion must be prioritized with respect to the technological one, which loses its value if peace and prosperity are not guaranteed. According to the environmental engineer included in the study, water availability represents a crucial problem; it becomes a key factor for the assessment, both from technical and environmental points of view, also considering that North African countries are strongly experiencing water scarcity and imbalance in water availability. Moreover, dealing with desertic areas requires to focus on specific technical or environmental aspects, concerning sand, high temperature, and droughts. Finally, an energy policy expert has stressed the importance of ensuring economic affordability and stability; it is a key aspect to invest in areas where uncertainty in economic and financial terms is significant. In this sense, the economic criterion must be also a priority, taking care of the needs of local and foreign investors, without leaving behind the social opportunities and challenges for local people. Considering the different expectations and opinions, also taking care of the potential conflicting preferences among the involved stakeholders, it is possible to summarise the concept of multi-dimensional suitability for the areas under assessment through the “STAGE” view, as in **Figure 75**:



Viable solution in economic terms, with respect to the required transport and power infrastructure.

Local people can benefit from job creation and new specialized figures (through knowledge sharing), but without compromising other economic activities (e.g. agriculture).

Focus on social conflicts or tensions, especially at countries’ borders; analysis of local development.

High solar radiation, no problems of slope or elevation, attention to sand (desertic areas) for panels maintenance, problem for high temperature…

Problem of water needed for water electrolysis (e.g. through desalination), attention devoted to preservation of protected areas, OECM, vegetation areas.

Figure 75: The concept of the multi-dimensional suitability along the intelligent phase of the assessment.

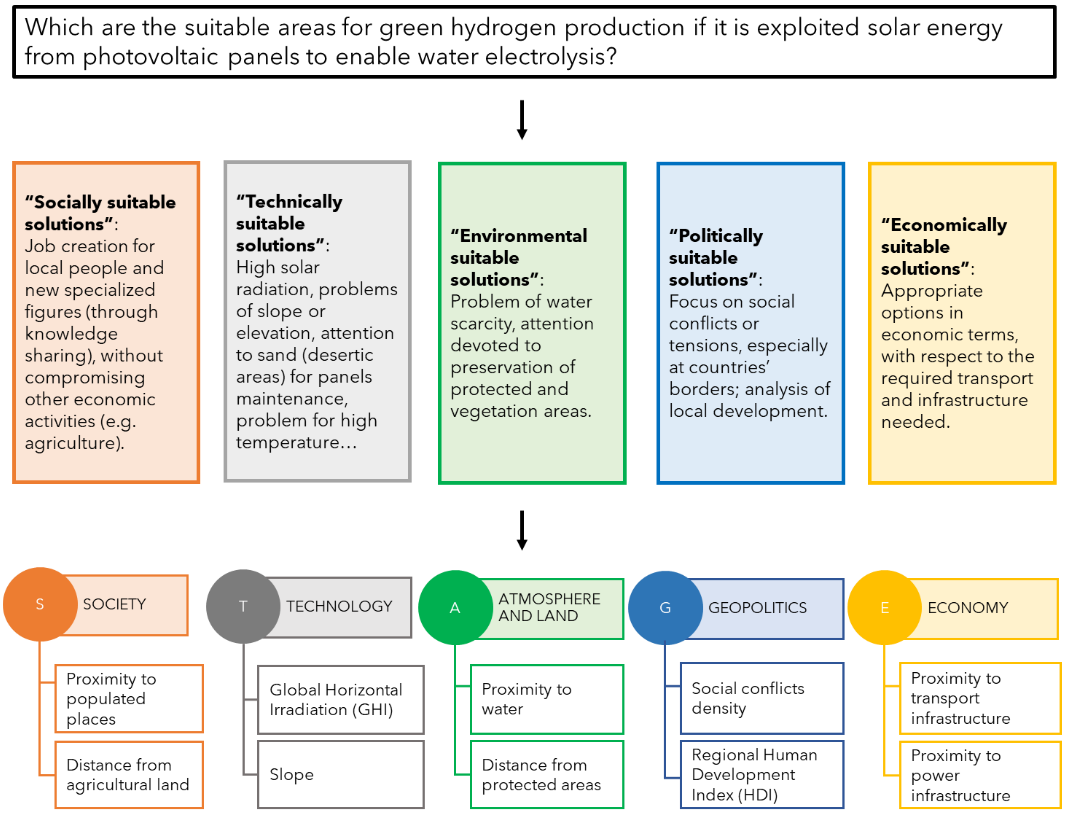
Following **Figure 75** and starting from the five criteria identified (i.e. society, technology, atmosphere and land, geopolitics and economy), two sub-criteria for each one are identified for the assessment, according to (i) experts’ opinions, (ii) availability of spatially measurable data, (iii) specific literature review (**Table 7**).

Table 7: The criteria and sub-criteria identified for the assessment.

Criterion	*Sub-criterion*	*Unit of measure*	*Direction of preference*
Society	Proximity to populated places	[km]	minimization
	Distance from agricultural land	[km]	maximization
Technology	Global Horizontal Irradiation (GHI)	[kWh/m^2/day]	maximization
	Slope	[°]	minimization
Atmosphere and land	Proximity to coastline	[km]	minimization
	Distance to protected areas	[km]	maximization

Geopolitics	Social Conflicts Density	[%]	minimization
	Human Development Index	[0-1]	maximization
Economy	Proximity to transport infrastructure	[km]	minimization
	Proximity to existing infrastructure	[km]	minimization

The social criterion takes into account from one side the proximity to cities, towns, and villages of the potential areas where new jobs opportunities will be developed because of new renewable projects; the second sub-criterion allows to preserve the agricultural areas, considering that it is actually a key sector for the economy in North Africa. On the technical side, it is considered the GHI as a key factor to be maximized to enhance PV productivity, together with the slope, which must be minimized to guarantee significant performances. Concerning the environment, it is decided to consider water availability, specifically assessing the proximity to coastline as a positive aspect (aiming to exploit the desalination option as valid solution). Moreover, the protected areas and the Other Effective Conservation Measure areas (OECM) must be excluded as suitable land and so preserved, considering that the higher the distance from these areas, the higher the suitability. The geopolitical sub-criteria are the most critical to be identified and spatially assessed; this dimension aims to investigate the stability (or instability) of the country under assessment – especially at the borders –, in parallel with considerations on internal politics and foreign affairs. It is decided to define a sub-criterion accounting for the stability and a second one related to the local welfare, respectively calculated at the governorate and macro-region level. The (geo)political sub-criterion "Social conflicts density" is self-elaborated through the collection of social conflicts registered in 2021 on ACLED portal [205] and involving battles, protests (peaceful, with interventions, with excessive force practiced against protesters), riots, violence against civilians, strategic development, explosion/remote violence. Specifically, it is calculated as a percentage resulting from the total number of the social conflicts' events registered in the specific governorate in 2021 divided by the population of the governorate. In this way, a social conflicts density is elaborated, as the percentage of the number of events over people; the lower the percentage, the better the performance of the governorate under assessment. Regarding the second geopolitical sub-criterion, the HDI is available for each macro-region of each country according to the UN Programme (it is already discussed in section 3.3, at national level) [149]. Finally, looking at the economic criterion, it is decided to firstly consider the available transport infrastructure, addressing railway lines, main roads and seaports infrastructure, while in order to take care of the possibility to exploiting the existing electric power infrastructure or the natural gas pipeline already used, the other sub-criterion refers to this infrastructure mapping. **Figure** 76 summarizes the workflow from the problem definition to the elaboration of the criteria, while **Table 8** collects the main information exploited to spatially identified the involved sub-criteria, with the related sources and data format.



Which are the suitable areas for green hydrogen production if it is exploited solar energy from photovoltaic panels to enable water electrolysis?

"Socially suitable solutions": Job creation for local people and new specialized figures (through knowledge sharing), without compromising other economic activities (e.g. agriculture).

"Technically suitable solutions": High solar radiation, problems of slope or elevation, attention to sand (desertic areas) for panels maintenance, problem for high temperature…

"Environmental suitable solutions": Problem of water scarcity, attention devoted to preservation of protected and vegetation areas.

"Politically suitable solutions": Focus on social conflicts or tensions, especially at countries' borders; analysis of local development.

"Economically suitable solutions": Appropriate options in economic terms, with respect to the required transport and infrastructure needed.

Figure 76: Mapping solar hydrogen suitability in North Africa, from the problem statement to the definition of sub-criteria.

Table 8: Elaboration of spatial sub-criteria.

Sub-criterion	*Dataset (map/table)*	*Source*	*Data type*
Proximity to populated areas	Populated places	Humanitarian Open Street Map [188]	shp file – Points; shp file - Polygons
Distance from agricultural areas	Land cover 32R, 32S	ESRI [189]	TIFF file
GHI	Average_daily	Global Solar Atlas [184]	TIFF file
Slope	SRTM 38_05, 38_06, 39_05, 39_06	SRTM 90m DEM Digital Elevation Database [206]	TIFF file
Proximity to coastline	Coastline	GADM (Database of Global Administrative Areas) [207]	shp file - Lines
Distance from protected areas	Protected areas	World Database of Protected Areas (WDPA) [187]	shp file – Points; shp file - Polygons
Social conflicts density	Administrative borders	Database of Global Administrative Areas (GADM) [207]	shp file - Polygons
	2021 conflicts	Armed Conflict Location & Event Data Project (ACLED) [205]	excel file
Human Development index	HDI	UNDP 2019 [149]	excel file
Proximity to transport infrastructure	Railways	Humanitarian Open Street Map [208]	shp file – Lines; shp file - Polygons
	Main roads	WFP Geonode (OSM) [209]	shp file - Lines
	Seaports	Humanitarian Open Street Map [208]	shp file – Points; shp file - Polygons
Proximity to existing power infrastructure	Electricity transmission network	energydata.info (from Arab Union of Electricity and country utility) [210]	GeoJSON
	Natural Gas pipelines	self-elaboration	shp file - Lines

Starting from the georeferenced maps available or elaborated through the open sources listed in **Table 8** (specific citations in the text refer to the Tunisian case), different spatial analyses are conducted, to obtain a first map for each sub-criterion.

Specifically, the following spatial elaborations available on ArcGIS Pro are mainly exploited [190]: merge of feature classes, mosaic to raster, conversion from vector to raster format, resample, buffer, raster calculator, Euclidean distance. This last tool allows to map the required distances, calculating the distance between two points, i.e. measuring the segment having as extremes two points. Each map obtained through this data processing is a raster file in the WGS 84 UTM projection CRS suitable for each country, with a spatial resolution of 90 m x 90 m. Concerning the adopted resolution, it is chosen to make it reasonable the exploitation of buffering areas associated to 100 m or 250 m. Looking at the scale, for the majority of the maps the appropriate one would be 1:180’000, which allows to visually appreciate the details. For the layouts shown along the following mapping processes, to have the overview on the suitability at a country level, the scale ranges from 1:5’000’000 (Tunisia) to 1:15’000’000 (Algeria). The standardization occurs on a 0-to-1 scale, according to a linear function, taking care of the fact that the specific sub-criterion must be minimized or maximized (**Table 7**). In order to deliver a final suitability map, it is needed to collect the experts’ preferences to define the proper weightings for each criterion, so that the importance levels in achieving the objective are established. Concerning the AHP procedure, a pairwise comparison is required; to this end, the Saaty’s fundamental scale ranging from 1 to 9 is exploited (**Figure 77**).

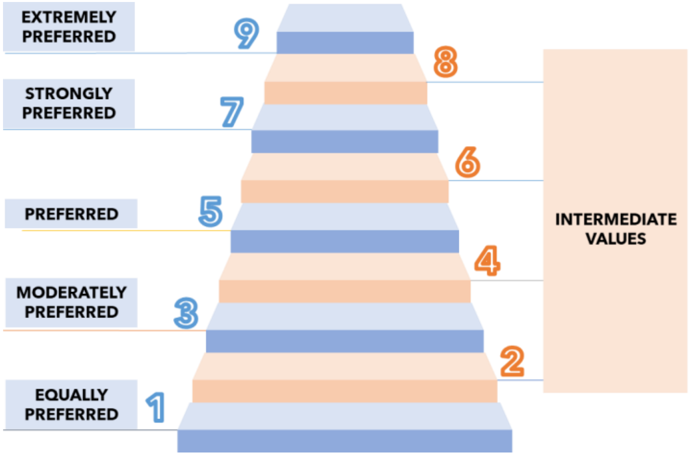


Figure 77: Saaty's fundamental scale for pairwise comparison.

With the possibility to range from “equally preferred” to “extremely preferred”, five experts are involved in the assessment: (i) an energy engineer as technical expert, (ii) an urban planner specialized in environmental impact assessment as environmental expert, (iii) a policy expert involved in energy policy activities and planning to assess the geopolitical field, (iv) an engineer specialized in economic evaluation for energy projects to deal with the economic criterion, and (v) a PhD student involved in sustainable development for developing countries as social expert. To obtain the weightings, the open source software Super Decisions is used (version 2.10); **Figure 78** is a snapshot of its main window, showing the hierarchical structure for the problem under assessment [211].

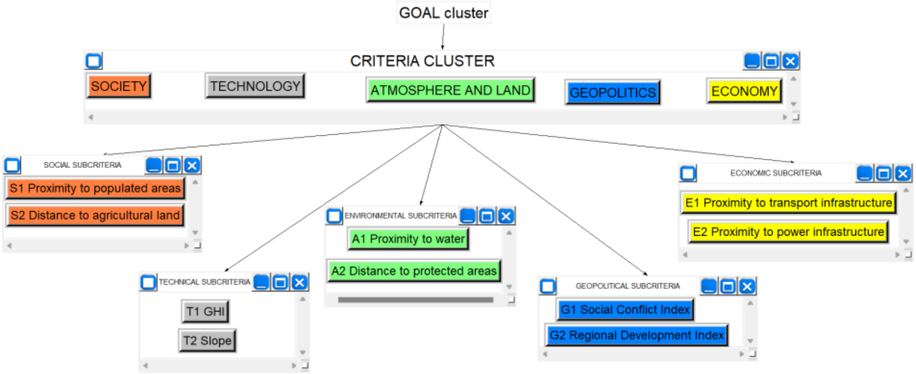


Figure 78: The hierarchical structure built on Super Decisions software (v 2.10) to enable experts' judgements [211].

At the criteria level, each expert is interviewed; **Figure 79** shows the final criteria weightings of this assessment, obtained by average of the individual experts' opinions on criteria priorities. Concerning the sub-criteria level, each expert is interviewed with respect to its domain of expertise, so that for each criterion the weightings associated to the sub-criteria are also determined; specifically, **Figure 80** indicates the preferences on Saaty's scale to be translated in percentages. In the weighting procedure, through the software calculations, the consistency of the matrices is verified (it is lower than 0.1).

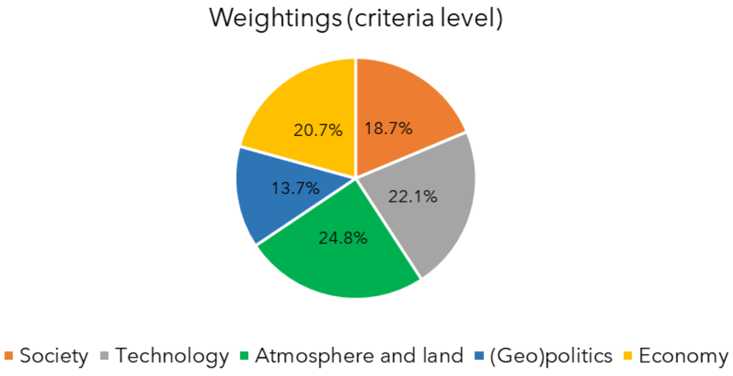
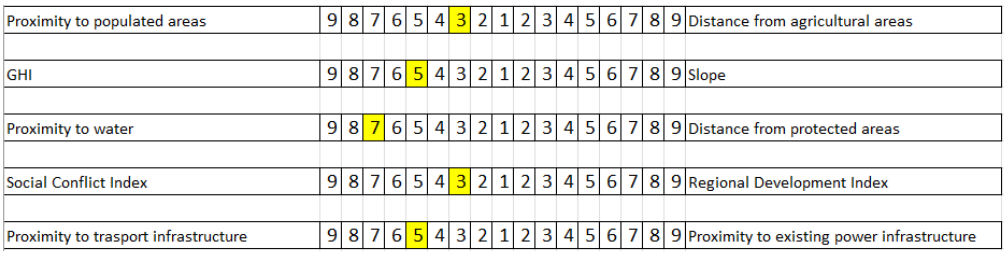


Figure 79: Weightings obtained by averaging the experts' preferences at criteria level.



Proximity to populated areas	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Distance from agricultural areas
GHI	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Proximity to water	9	8	**7**	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from protected areas
Social Conflict Index	9	8	7	6	5	4	**3**	2	1	2	3	4	5	6	7	8	9	Regional Development Index
Proximity to trasport infrastructure	9	8	7	6	**5**	4	3	2	1	2	3	4	5	6	7	8	9	Proximity to existing power infrastructure

Figure 80: Weightings at the sub-criteria level.

Table 9 summarises the final priorities for the criteria and sub-criteria, implemented to go on with the core step of the analysis, i.e. the elaboration of the suitability maps, which corresponds to the choice phase.

Table 9: Criteria and sub-criteria weightings.

Criterion	*Sub-criterion*	*Final priorities (criteria level)*	*Final priorities (sub-criteria level)*
Society	Proximity to populated places	18.7%	75%
	Distance from agricultural land		25%
Technology	GHI	22.1%	83.3%
	Slope		16.7%
Atmosphere and land	Proximity to coastline	24.8%	87.5%
	Distance to protected areas		12.%
(Geo)politics	Social Conflicts Index	13.7%	75%
	Human Development Index		25%
Economy	Proximity to transport infrastructure	20.7%	83.3%
	Proximity to existing infrastructure		16.7%

Being each map standardized and having properly defined the weightings at the criteria and sub-criteria levels, the choice phase consists of the elaboration of the suitability maps. Specifically, it is calculated a suitability index for each cell of the map according to the equation 3.7:

$$Suitability = S_j = \sum w_i \cdot X_i \tag{3.7}$$

S_j is evaluated through a weighted sum function and represents the suitability of the j-th cell of the map; it relies on the weight of the i-th factor and the standardized score of the i-th factor. For this specific purpose it is decided to distinguish among five different classes, corresponding to “very low suitability”, “low suitability”, “moderate suitability”, “high suitability”, “very high suitability”. It is also added the class of “excluded areas”, so the unsuitable ones, related to cities (4 km buffer), towns (2 km buffer), villages (1 km buffer), agricultural areas, slope (excluded values higher than 5°), waterways (500 m buffer), protected areas (500 m buffer), transport and power infrastructure, vegetation areas. To conclude, a sensitivity analysis is developed; it is chosen to analyse six different scenarios, shown in **Figure 81**, reporting also the corresponding weightings assigned. Discussing the results is the final step of the approach, according to which the final outcomes are analysed, starting from the suitability maps and then focusing on the results of the sensitivity analysis.

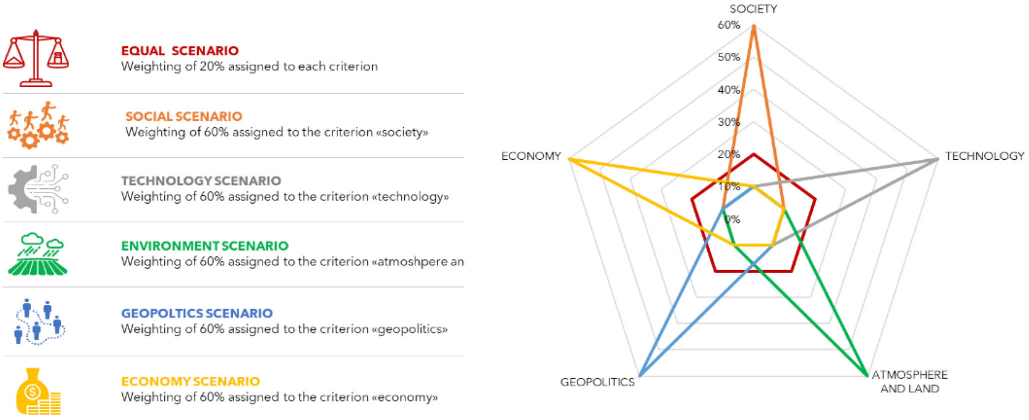


Figure 81: The six scenarios assessed to conduct a proper sensitivity analysis.

In the following sub-sections the methodological approach is applied on Tunisia, Algeria, Morocco and Western Sahara; the Tunisian case is better detailed as first example of application, than followed by the sub-sections dedicated to Algeria and Morocco which are more focused on results.

3.3.4.2 The Tunisian case

In this sub-section, all the steps are tailored on Tunisia, with respect to the problem definition already introduced, regarding the exploitation of solar PV panels to enable water electrolysis for green hydrogen production. In **Table 10** a tentative list of the involved stakeholders, at different levels and categories and with different objectives with respect to the problem statement, is reported (in the same form suggested by [117]), in this case tailored on the Tunisian institutions and associations.

Table 10: Type of stakeholders, related levels, resources, categories and expectations, tailored on Tunisia.

Stakeholders	*Level of action*	*Resources*	*Categories*	*Expectations*
Ministry of Economy and Planning	national	legal, political, economic, cognitive	political, bureaucrats	mobilization of investments; support to new efficient and high-quality projects (also referred to cross-border partnerships); improvement of energy policies and actions for sustainable development
Ministry of Finance	national	legal, political, economic, cognitive	political, bureaucrats	mobilization of investments; enhancement of new forms of public profits
Ministry of Social Affairs	national	legal, political, economic, cognitive	political, bureaucrats	improvement of economic health of the country; improvement of life quality, without compromising local activities
Ministry of Industry, Mines and Energy	national	legal, political, economic, cognitive	political, bureaucrats	more efficient energy systems; achievement of energy transition targets; strategic exploitation of local resources; improvement of cross-border energy partnerships
Ministry of Trade and Export Development	national	legal, political, economic, cognitive	political, bureaucrats	strategic exploitation of local resources; improvement of cross-border energy partnerships
Ministry of Agriculture, Water Resources and Maritime Fisheries	national	legal, political, economic, cognitive	political, bureaucrats	strategic exploitation of local resources; protection of areas of interest (terrestrial and maritime); assurance of water

				availability and agricultural activities
Ministry of Higher Education and Scientific Research	national	legal, political, economic, cognitive	political, bureaucrats	increase of interest in energy and environmental issues; development of Research and Innovation
Ministry of Transport	national	legal, political, economic, cognitive	political, bureaucrats	enhancement of existing infrastructure and support to new infrastructure development
Ministry of Environment	national	legal, political, economic, cognitive	political, bureaucrats	support to sustainable development; strategic exploitation of local resources; protection of areas of interest (terrestrial and maritime); assurance of water availability and agricultural activities
National Agency for Energy Management (ANME)	national	legal, economic, cognitive	political, expert	improvement of energy policies and actions for sustainable development
Comite Maghrebin de L'electricite (COMELEC)	intergovernmental	legal, economic, cognitive	political, expert, special interest	enhancement of existing infrastructure and support to new infrastructure development; support to new efficient and high-quality projects (also referred to cross-border partnerships)
Tunisian Company for Electricity and Gas (STEG)	national	legal, economic, cognitive	expert, special interest	enhancement of existing infrastructure and support to new infrastructure development; support to new projects (also referred to cross-border partnerships)
Regional Center for Renewable Energy and Energy Efficiency (RCREEE)	intergovernmental	cognitive	expert, special interest	enhancement of existing infrastructure and support to new infrastructure development; support to new efficient and high-quality projects (also referred to cross-border partnerships)
Tunisian Institute of Competitiveness	national	cognitive	Expert	support to efficient and high-quality projects

and Quantitative Studies (ITCEQ)				
Private investors	intergovernmental, national, regional, local	economic	special interest	support to profitable investments; mobilization of investments; enhancement of new forms of private profits
Private engineering services	local and foreign	economic, cognitive	expert, special interest	development of efficient and high-quality projects
Local citizens	local	cognitive	general interest	support to sustainable development; improvement of life quality, without compromising local activities; improvement of economic health of the country
Local associations for environment protection	local	cognitive	general interest	support to sustainable development; exploitation of local resources; protection of terrestrial and maritime areas of interest; assurance of water availability and agricultural activities
Universities	local and foreign	cognitive	expert	development of efficient and high-quality projects
Italian Ministry of Environment and Energy Security*	national (Italy)	legal, political, economic, cognitive	political, bureaucrats	establishment of new cross-border partnership; support to sustainable development
European Commission	Intergovernmental	legal, political, economic, cognitive	political, bureaucrats	establishment of new cross-border partnership; support to sustainable development

*Italy as direct potential importer.

From **Figure 82** to **Figure 91**, it is shown the mapping procedure elaborated on ArcGIS Pro [190], obtaining a standardized map per each sub-criterion, from step 3 – which covers data elaboration and maps creation – to step 5, consisting of standardization. Specifically, for each sub-criterion the following maps are showed: (i) initial map, (ii) intermediate map, if present (here consisting of the application of the Euclidean distance tool), (iii) standardization function to be exploited, (iv) standardized (0-to-1) map obtained.

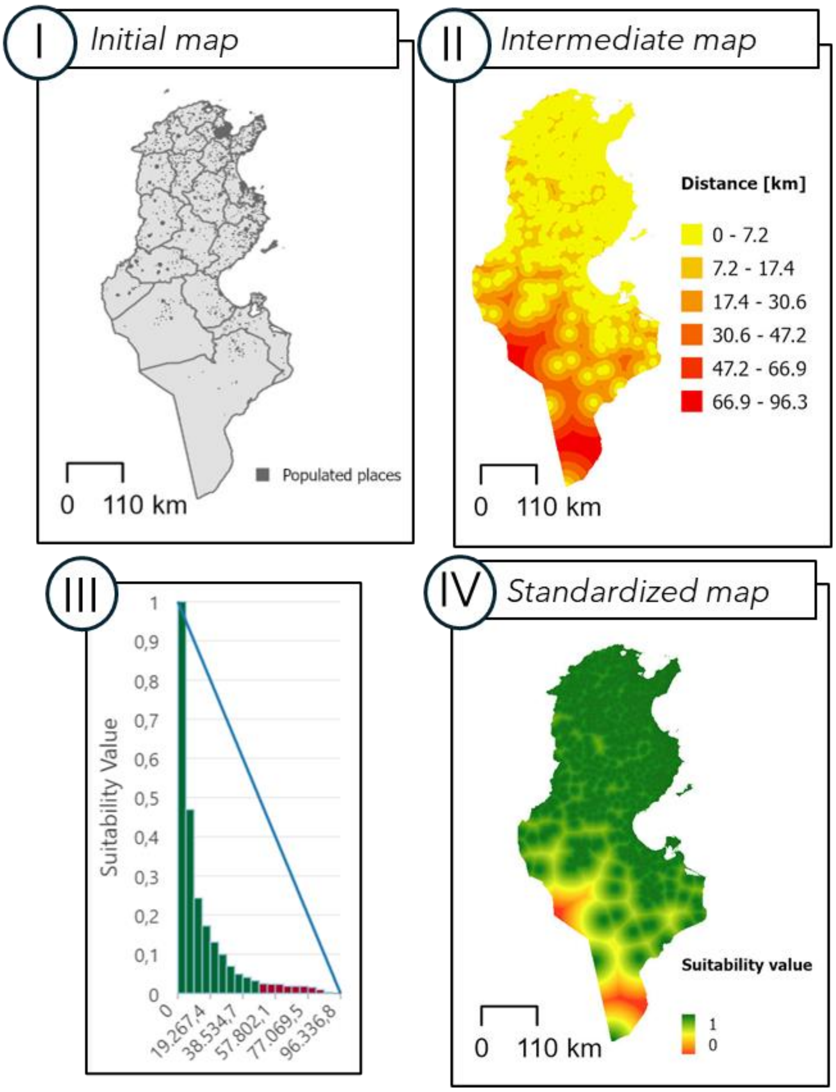


Figure 82: Tunisia, “Proximity to populated places” sub-criterion (from step 3 to 5).

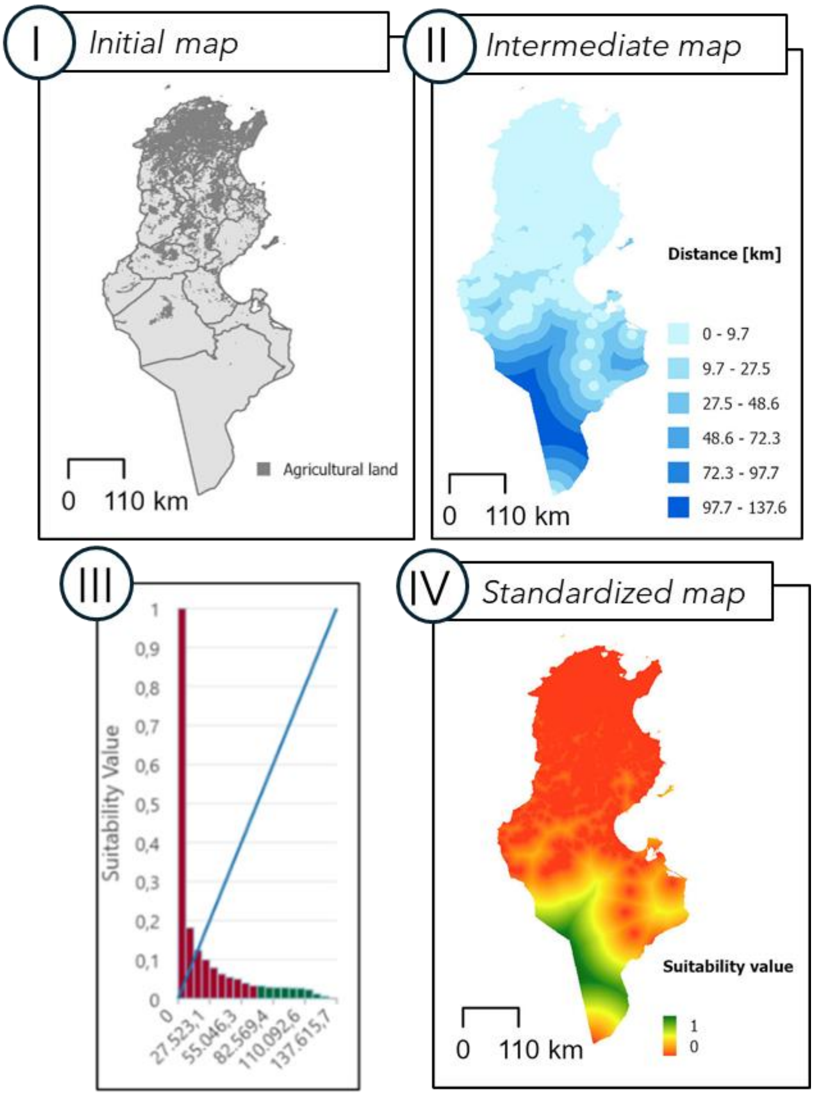


Figure 83: Tunisia, “Distance from agricultural areas” sub-criterion (steps 3 to 5).

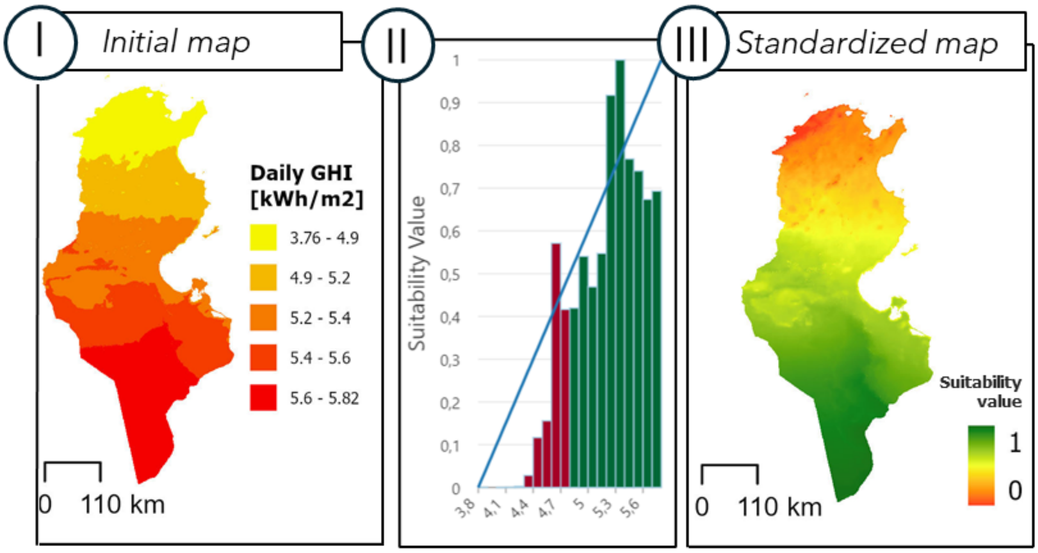


Figure 84: Tunisia, "GHI" sub-criterion (steps 3 to 5).

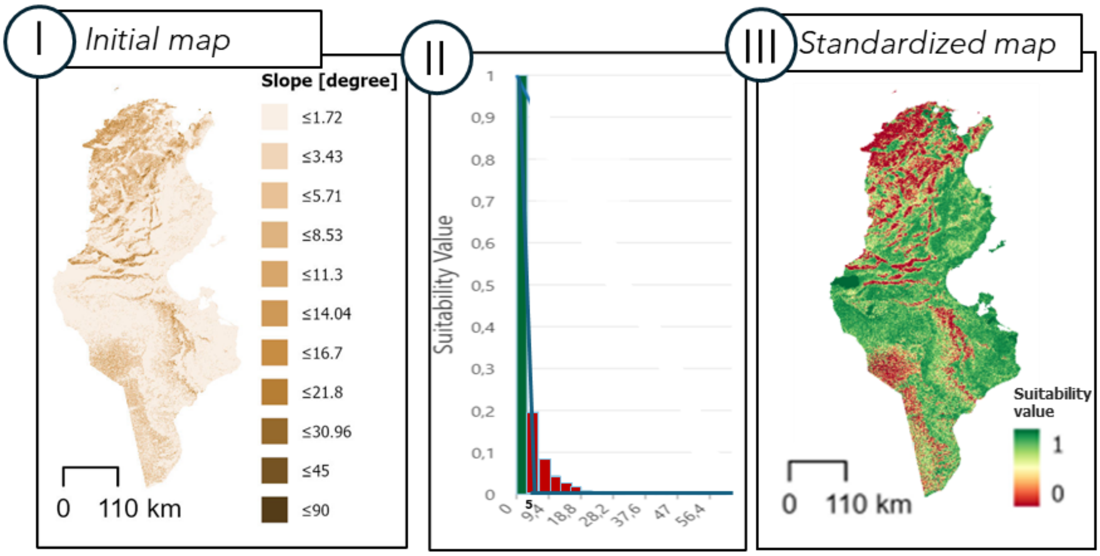


Figure 85: Tunisia, "Slope" sub-criterion (steps 3 to 5).

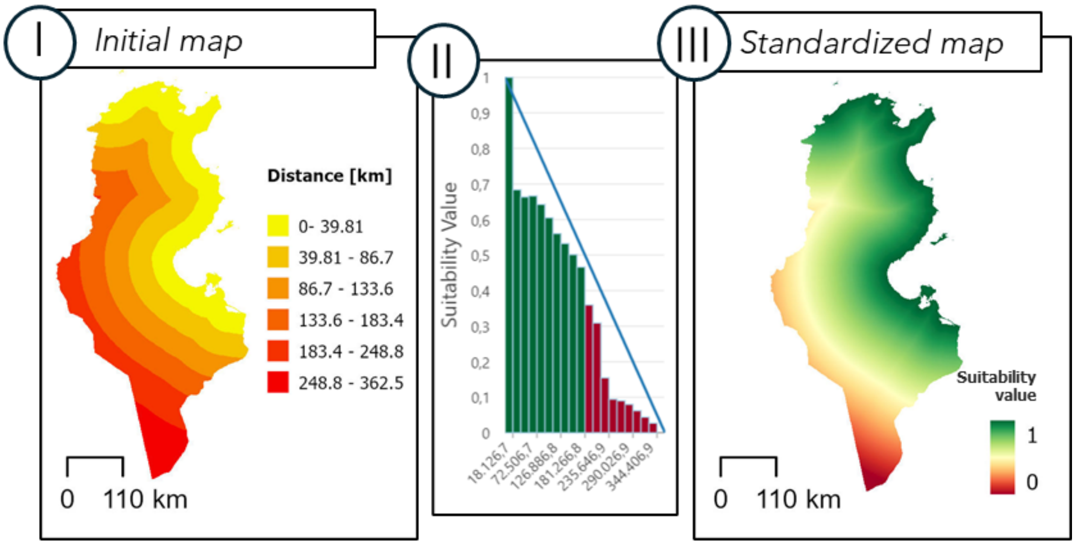


Figure 86: Tunisia, “Proximity to coastline” sub-criterion (steps 3 to 5).

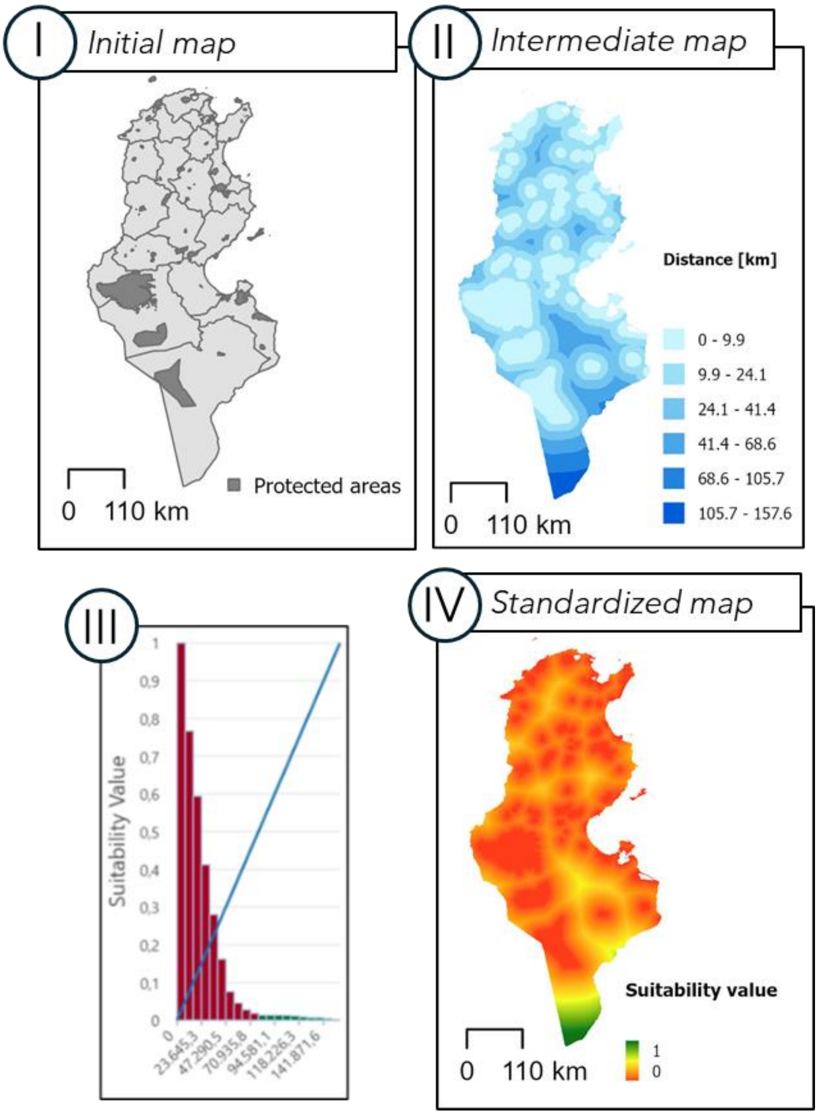


Figure 87: Tunisia, “Distance from protected areas” sub-criterion (steps 3 to 5).

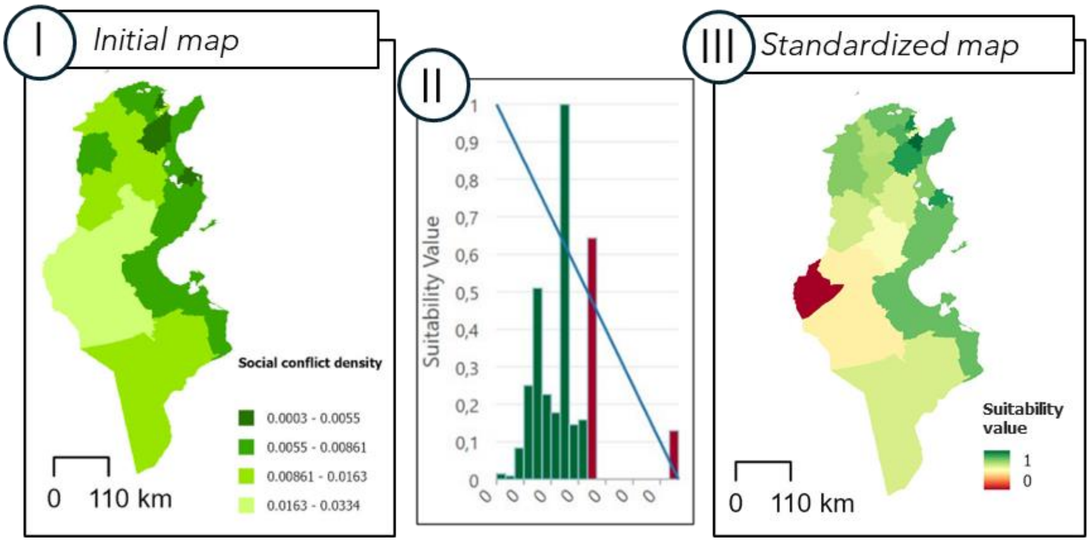


Figure 88: Tunisia, “Social conflicts density” sub-criterion (steps 3 to 5).

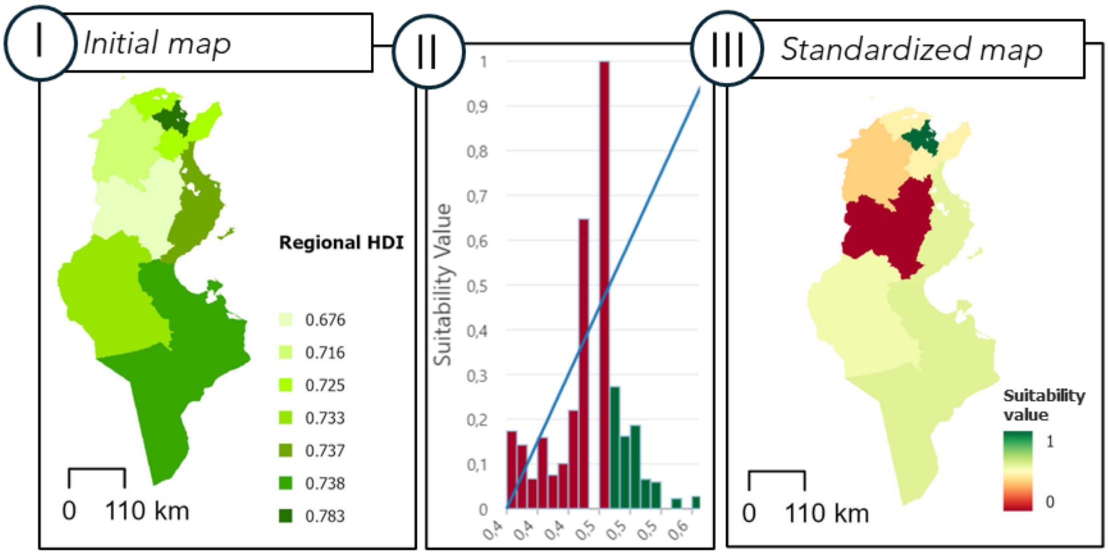


Figure 89: Tunisia, “Human Development index” sub-criterion (steps 3 to 5).

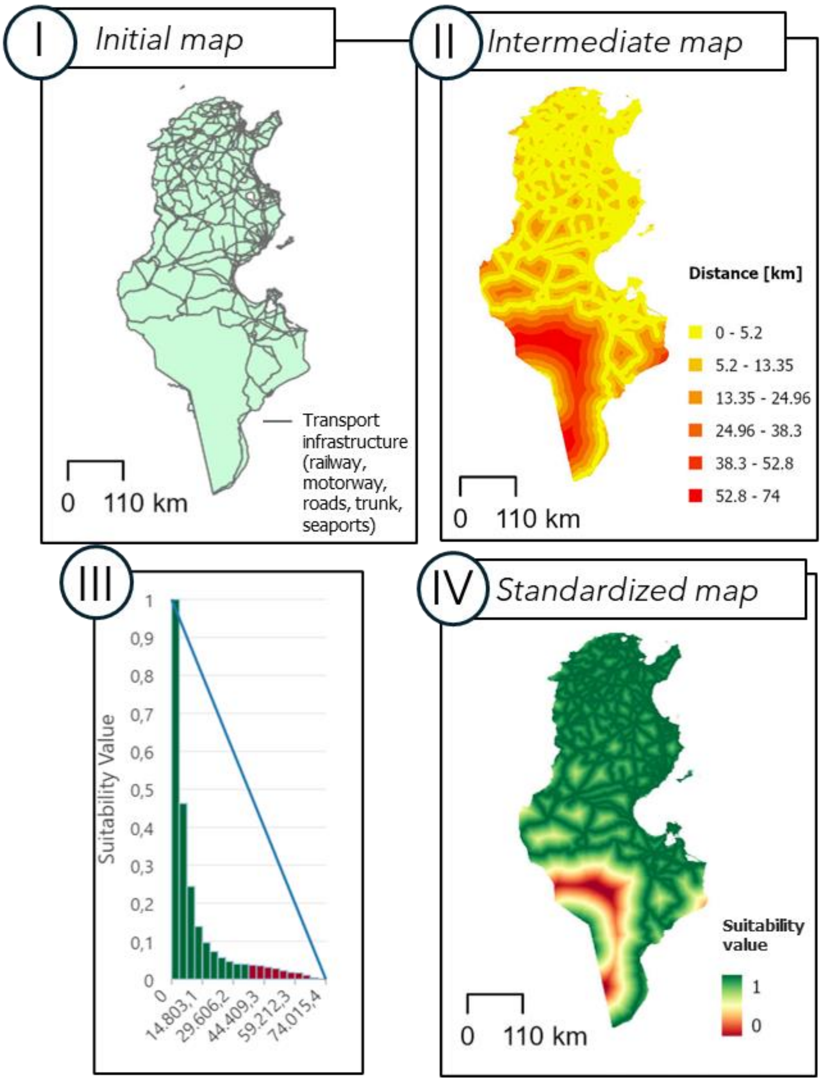


Figure 90: Tunisia, “Proximity to transport infrastructure” sub-criterion (steps 3 to 5).

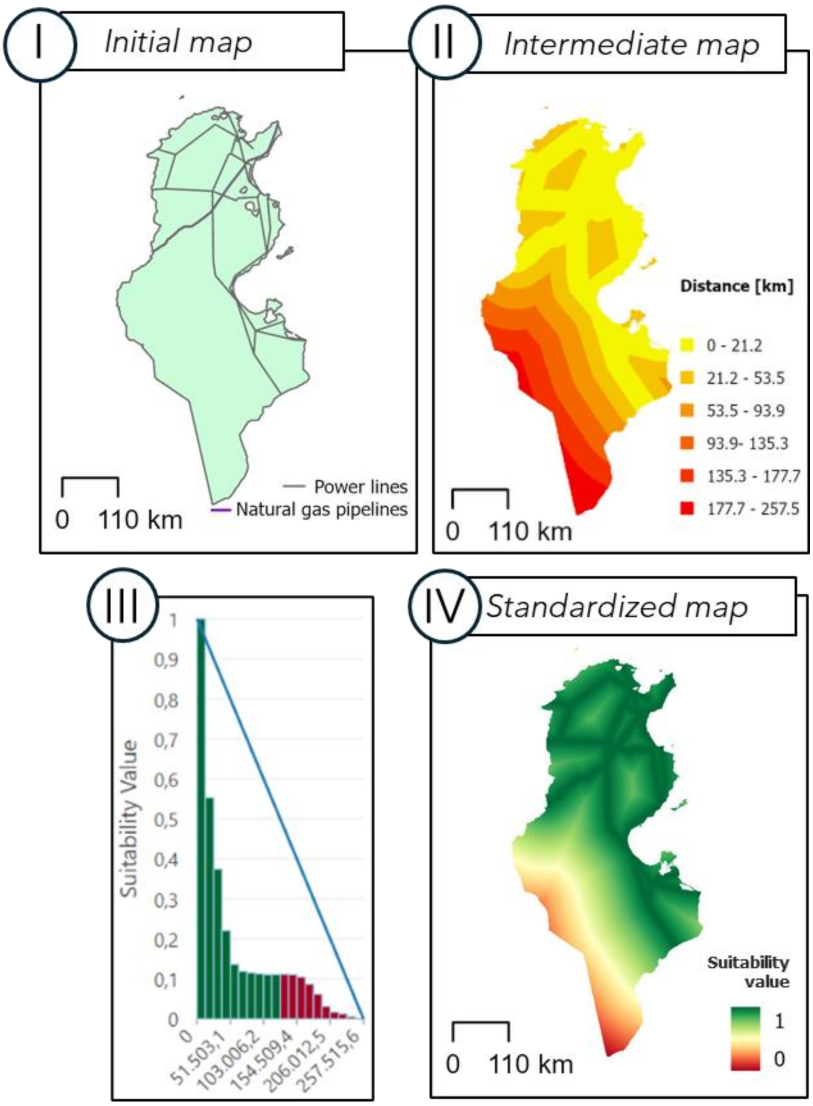


Figure 91: Tunisia, “Proximity to power infrastructure” sub-criterion (steps 3 to 5).

At this step of the analysis the suitability maps are obtained. Specifically, as detailed in the previous sub-section about the methodology, the final suitability map (**Figure 92**) is elaborated through the assigned weightings level and according to the equation 3.7. This final suitability map (**Figure 92**) is based on the sub-criteria weightings proposed in **Table 9**. Assessed that the 49.25% of the country is excluded because of the constraints introduced, looking at **Figure 93** it is found that no “very low suitable” areas are assessed, with only the 0.01% classified as “low suitable”, while the majority of areas are found to be from moderate to very high suitable for solar hydrogen production.

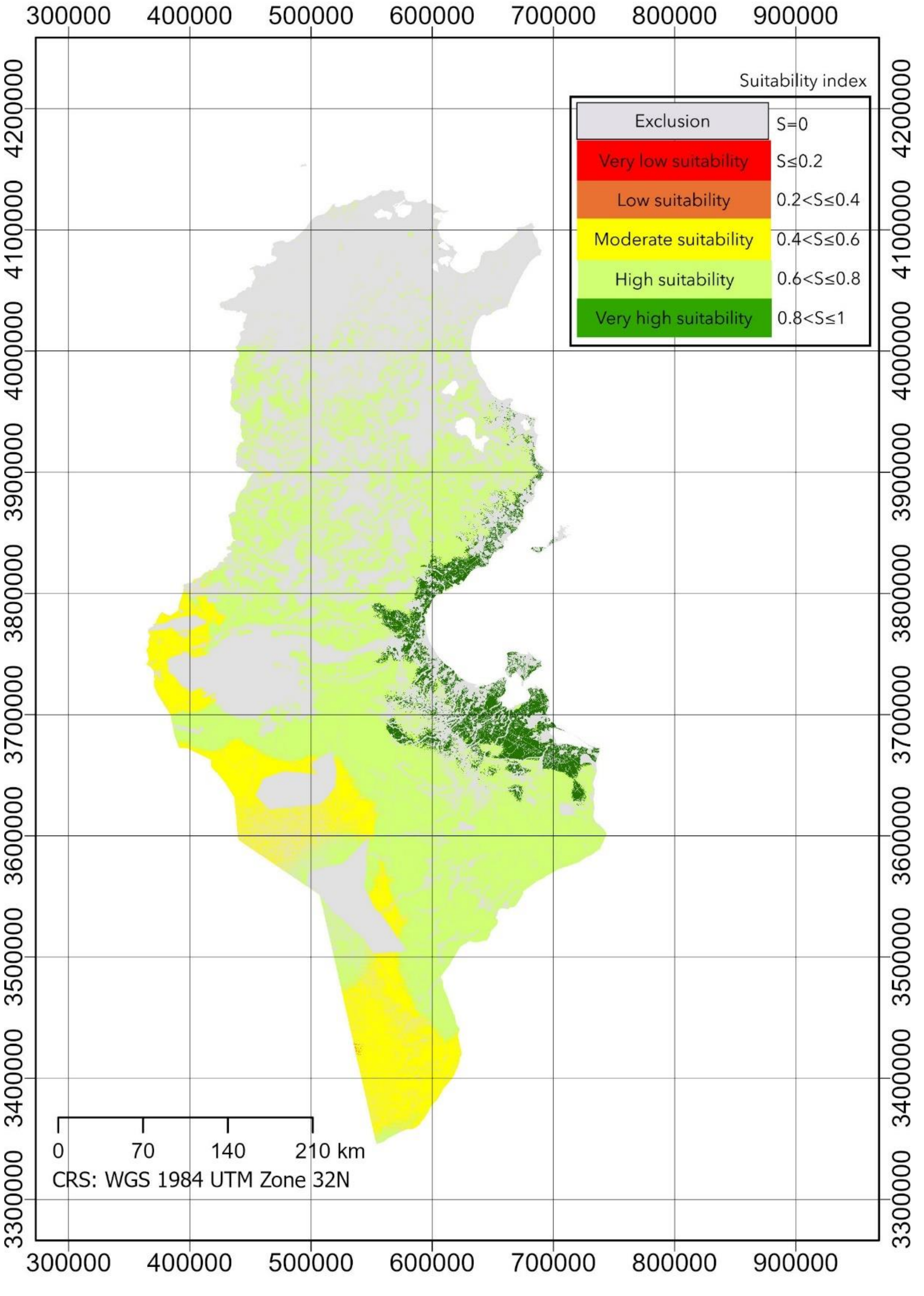


Figure 92: Tunisia, solar hydrogen: the final suitability map, ranging from exclusion areas to very highly suitable areas.

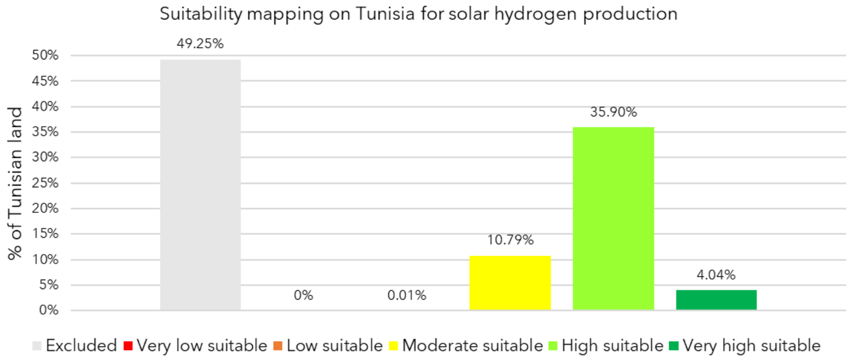


Figure 93: Tunisia, solar hydrogen: the share of land for the different classes of suitability.

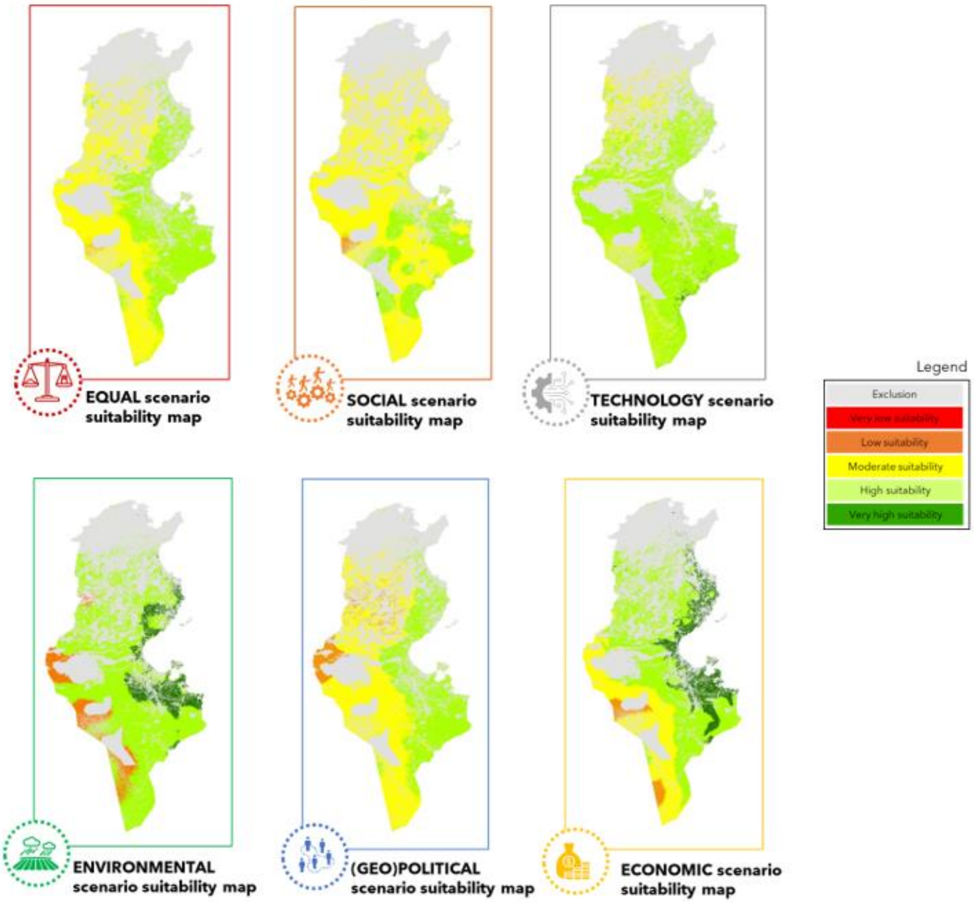


Figure 94: Tunisia, solar hydrogen: the suitability maps referring to the 6 scenarios of the sensitivity analysis.

Figure 94 introduces the six maps related to the application of the weightings for sensitivity (**Figure 81**). Looking at the final map of suitability (**Figure 92**), but also at the maps referred to the sensitivity analysis **(Figure 94**), the significance of the amount of moderately suitable areas and highly suitable areas is an important result; it highlights the high potentialities of Tunisia with respect to solar hydrogen production. For the equal case, there are not areas with very high suitability, neither with very low suitability. The social scenario presents the majority of the Tunisian area as moderately suitable, while for the technological scenario the majority of the area appears as highly suitable as expected. The economic scenario belongs to the pattern of the existing infrastructure, in line with the environmental sub-criterion strongly affected by the proximity to coastline.

3.3.3.3 The Algerian case

As for Tunisia, the integration of GIS and AHP is applied to Algeria, to classify the land suitability for solar hydrogen production (**Figure 95**). The same methodological procedure presented for Tunisia is followed, since it is built to be replicable to all the countries of interest, as presented in the previous section. After collecting and elaborating the Algerian dataset, **Figure 95** is obtained; it directly reports the final suitability map resulting from the application of the weightings introduced in **Figure 79** and **Figure 80**. It is found that only 18.61% of the country is excluded for the production of green hydrogen through solar PV, according to the exclusion criteria introduced. Looking in detail at the suitability map, the Algerian land is classified as moderately suitable for 29.36% and as highly suitable for about 52% (**Figure 96**). It is of interest to notice that according to the preferences applied, there are no areas classified as very low suitable or low suitable for solar hydrogen production.

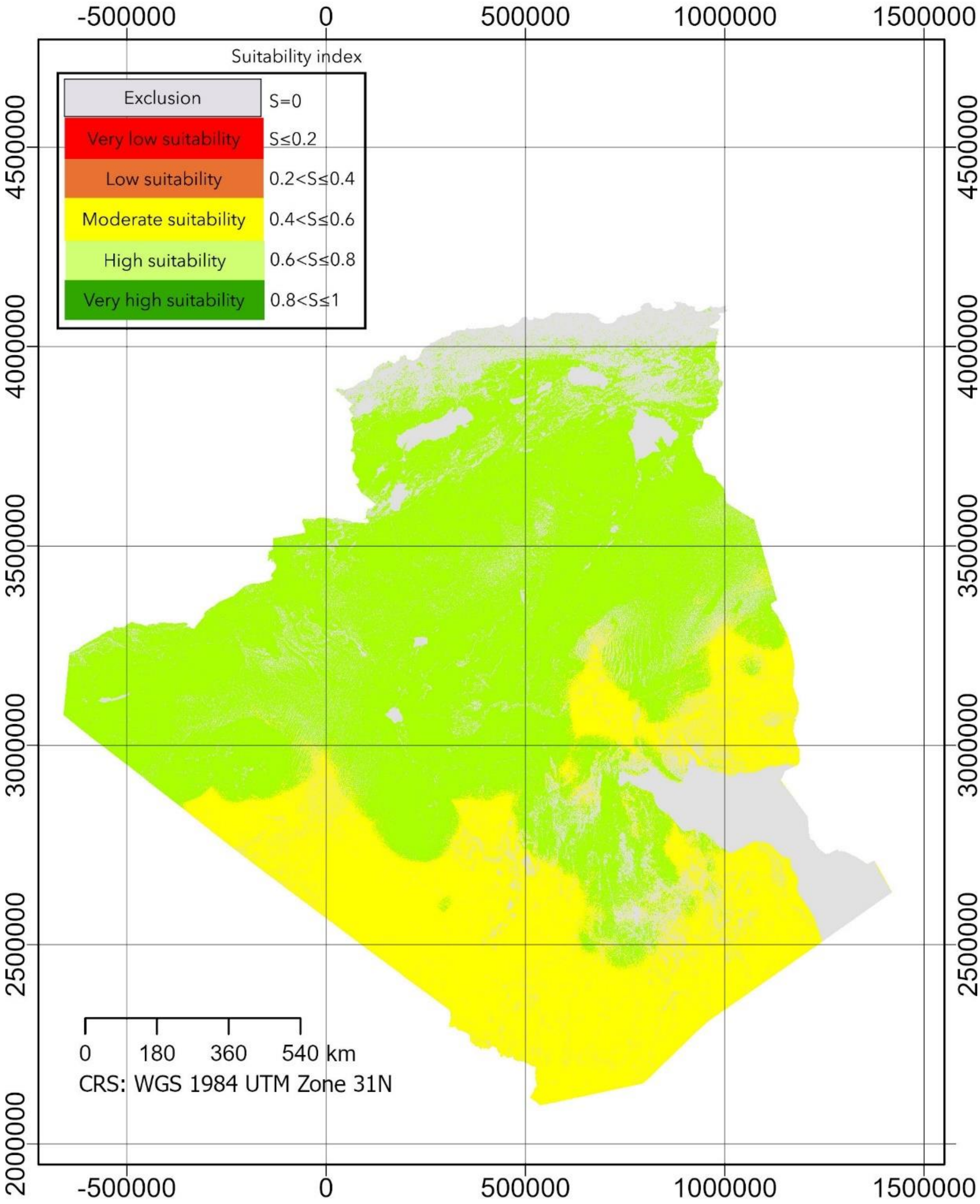


Figure 95: Algeria, solar hydrogen: the final suitability map, ranging from exclusion areas to very highly suitable areas.

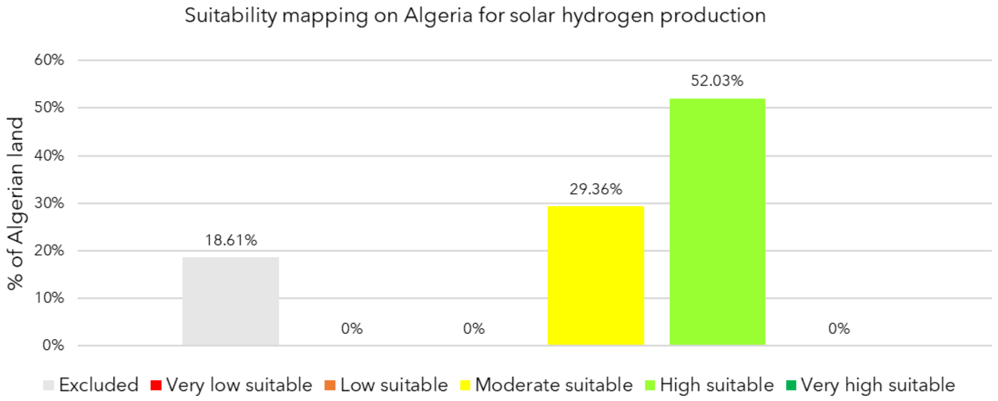


Figure 96: Algeria, solar hydrogen: the share of land for the different classes of suitability.

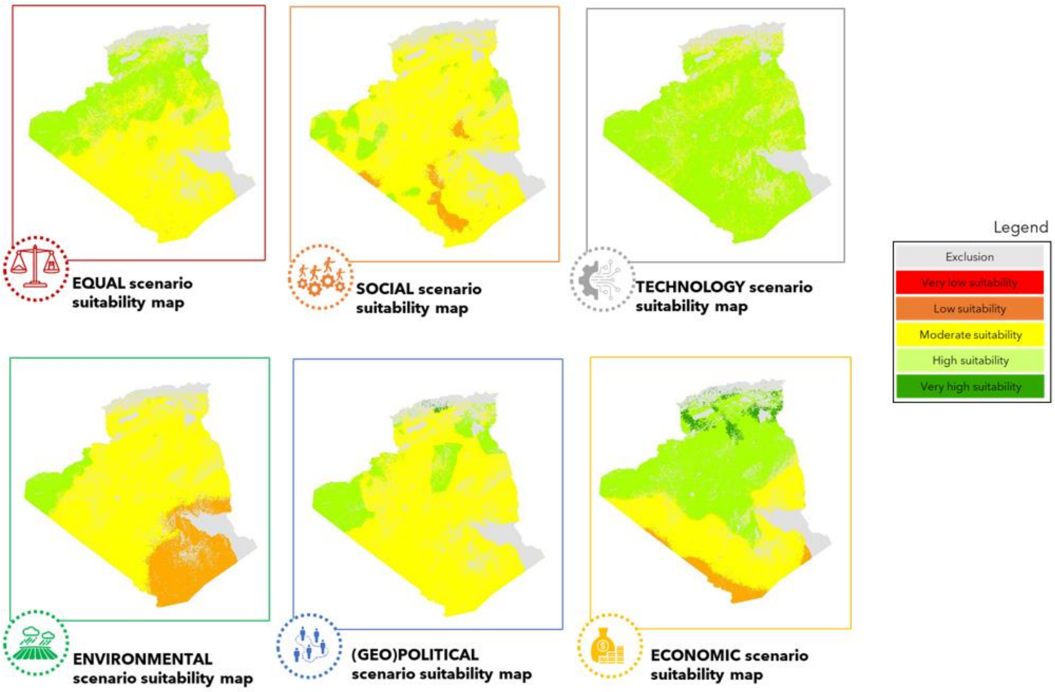


Figure 97: Algeria, solar hydrogen: the suitability maps referring to the six scenarios of the sensitivity analysis.

Figure 97 reports the results coming from the related sensitivity analysis in terms of suitability maps. As for Tunisia, there are no areas identified as very low suitable for the exploitation of solar energy for green hydrogen production and trade. As expected, the maps resulting from the sensitivity analysis put in evidence how the different sub-criteria influence the assessment (**Figure 97**); for the extreme technological scenario the most desertic areas are assessed as highly suitable, while it is the opposite for the extreme economic scenario which accounts for the lack of infrastructure in the Southern part of the country. It is important to notice that most of the territories are defined as highly suitable if the technological criterion is extremized – even if it could be of interest to add as criterion the challenges for PV related to sand and high temperatures. While looking at the extreme environmental scenario, an increase in low suitable areas is evident, specifically for the higher distance from the sea of the desertic areas in the Southern part. More generally, excluding the results of the technological scenario, all the others appear to be penalized in the desertic areas, being influenced by the higher distance from populated places, water resources and the absence of existing infrastructure.

3.3.4.4 The Moroccan case

As presented in the previous sub-sections referred respectively related to Tunisia and Algeria, here the nine steps of the MC-SDSS are applied to Morocco and Western Sahara. Even if these areas are of primary importance for what concerns the development of new projects involving green hydrogen, it is important to stress that the related dataset is not so easy to be implemented, so that more studies and research are required to apply the AHP and GIS methodology previously introduced. The two areas are considered as unique application in this section; in fact, a lot of data and details are not disaggregated for the Western Sahara region, specifically looking at the geopolitical dimension (see the focus in the next sub-section). For this reason, to have a useful mapping also of the Western Sahara areas and to better compare its suitability with respect to the Moroccan areas, it is decided to apply the MC-SDSS framework to both regions in an unique assessment. Moreover, it is important to specify that the maps used for some sub-criteria are different – because of some updates available – with respect to the ones used in the preliminary spatial analysis (sub-section 3.3.2). In the following figures the main results for Morocco and Western Sahara are reported and commented.

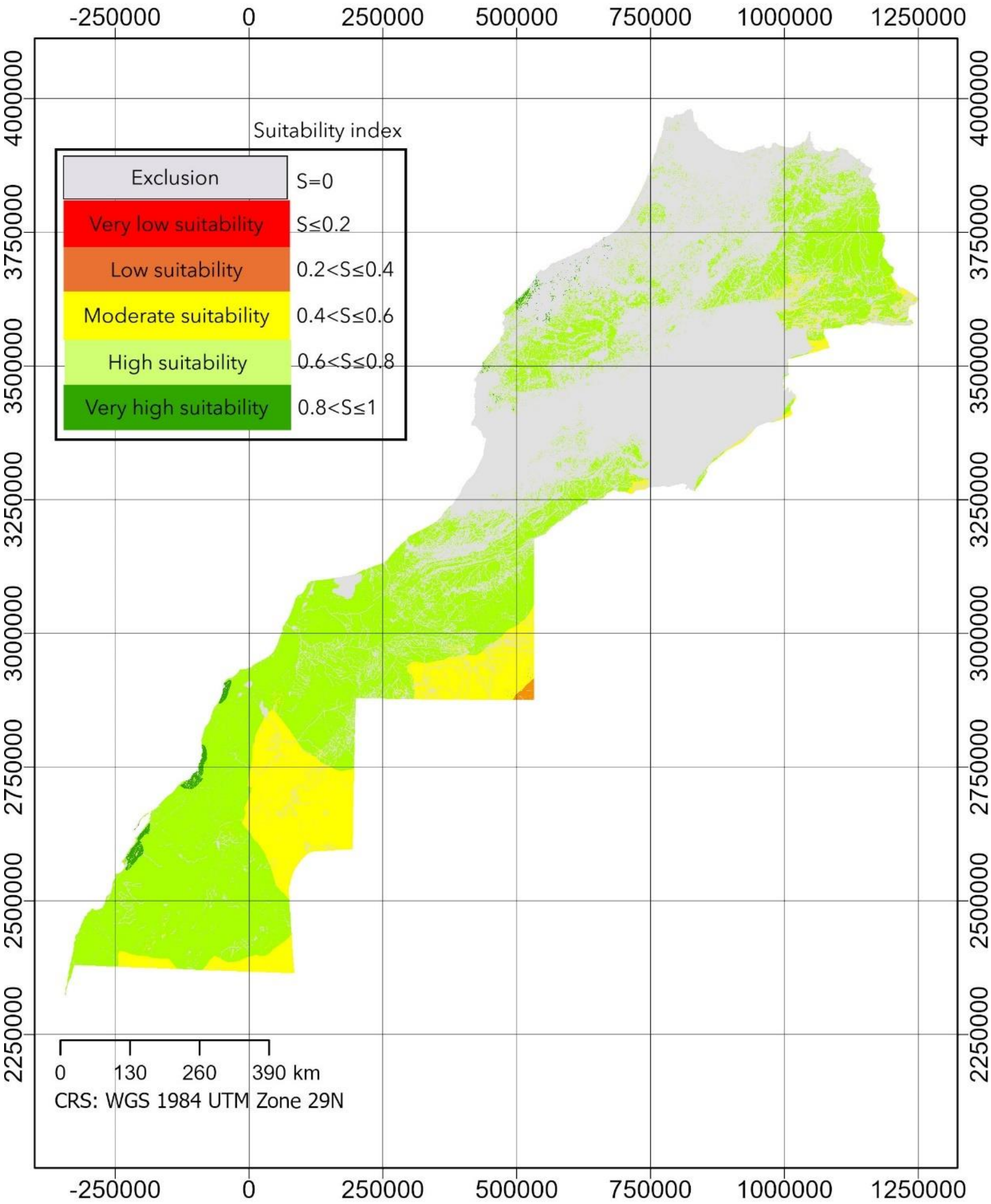


Figure 98: Morocco and Western Sahara, solar hydrogen: the final suitability map, ranging from exclusion areas to high suitable areas.

Looking at , it is evident how Morocco and Western Sahara show a huge difference in terms of land availability; if from one side it appears clear that the majority of the Moroccan areas are in the range of very high suitability, it is also true that the desertic areas in the Western Sahara region are mostly affected by very high GHI values and low values of slope, but are also interested by a lack of infrastructure and a few number of populated places. There are no areas characterized by very low suitability and only a few amounts of low suitable places, while 48.17% of the excluded land is mostly related to the Moroccan part, being the Western Sahara practically found to be exploitable everywhere, as expected (**Figure 99**).

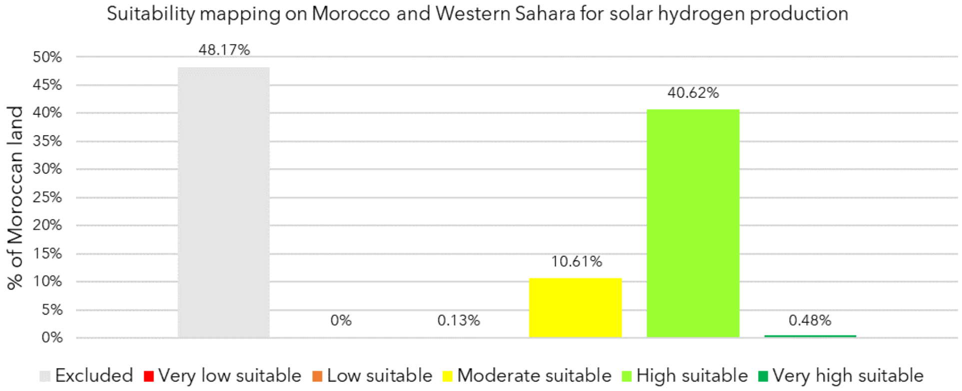


Figure 99: Morocco and Western Sahara, solar hydrogen: the share of land for the different classes of suitability.

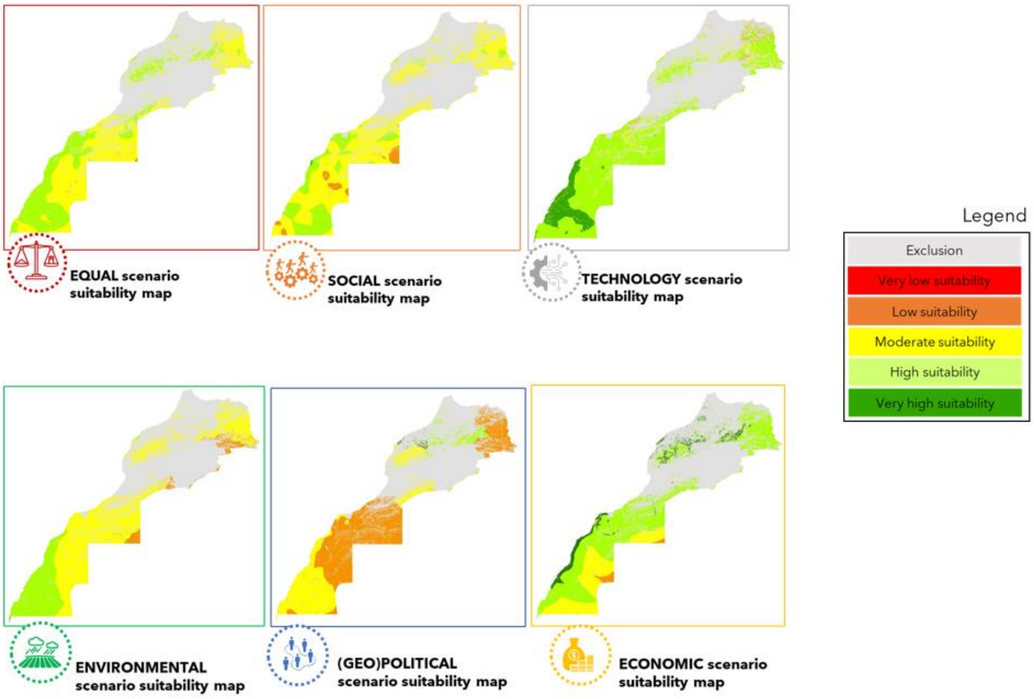


Figure 100: Morocco and Western Sahara, solar hydrogen: the suitability maps referring to the six scenarios of the sensitivity analysis.

The sensitivity analysis applied to Morocco and Western Sahara (**Figure 100**) highlights the favourable conditions in terms of GHI and slope in the Western Sahara region, while concerning the geopolitical criterion it is put in evidence how the Southern part, as expected, is affected by more social conflicts and lower values of social welfare, showing an increase of low suitable areas.

3.3.4.5 Limitations and future development of the work

The application of a MC-SDSS for the evaluation of the suitability with respect to solar hydrogen production in Tunisia, Algeria and Morocco, allows to highlight potentialities and drawbacks of this methodological approach related to this kind of assessment. If from one side maps as final outputs offer clear and transparent results for the multi-interest actors involved and specifically policymakers, it is also important to highlight that there are some criticalities concerning their specific elaborations. First, it is not trivial to find available datasets which are spatially defined; this can imply further work on the identification of criteria and sub-criteria involved or can also penalize the achievement of the objective and final results. In this case, the most difficult criteria to be evaluated is the geopolitical one; in fact, two indexes per macro-regions are used as sub-criteria, with the second self-elaborated based on a specific collection of data. In this latter case, it becomes crucial to specify the update year for the dataset involved. As already mentioned, for all these analyses the year of the exploited sources is an important factor that needs to be stated and that can affect the results. Moreover, this analysis can be better investigated through the exploitation of other datasets and tools to work with higher resolutions (i.e. tools like SAGA GIS); more details can be specifically collected on the techno-economic dimension (e.g. elevation, surface temperature). Focusing on the spatial analyses itself, it can be of interest – and also useful as sensitivity analysis on the obtained results –, to apply to the sub-criteria of the assessment different standardization functions; for this procedure the linear functions are applied to the maps, being the most suitable for this kind of applications. In addition, a crucial aspect which can improve the design phase regards the involvement of local people and institutions in assessment like this, since it was not possible during the PhD thesis to have a direct exchange with multi-interest actors directly from Tunisia, Morocco or Algeria.

3.3.5 The wind hydrogen production

In order to assess the production of green hydrogen exploiting wind energy, the same approach presented in sub-section 3.3.2 is used; specifically, the problem statement becomes: "Which are the suitable areas for green hydrogen production if onshore wind energy to enable water electrolysis is exploited?"

3.3.5.1 From the design phase to the review phase

With respect to the application already introduced, regarding solar hydrogen production, the difference relies on the first technological sub-criterion (GHI for solar energy), that in this case is related to the average wind speed at 100 m for the areas of interest, elaborated through the Global Wind Atlas dataset [212] (Table 3.5). The citations in the table again refers to the specific Tunisian areas, but the sources are valid for all the other countries analysed.

Table 11: Elaboration of spatial sub-criteria for the suitability assessment of wind hydrogen production.

Sub-criterion	*Dataset (map/table)*	*Source*	*Data type*
Proximity to populated areas	Populated places	Humanitarian Open Street Map [188]	shp file – Points; shp file - Polygons
Distance from agricultural areas	Land cover 32R, 32S	ESRI [189]	TIFF file
Wind speed	***@100 m***	***Global Wind Atlas [212]***	***TIFF file***
Slope	SRTM 38_05, 38_06, 39_05, 39_06	SRTM 90m DEM Digital Elevation Database [206]	TIFF file
Proximity to coastline	Coastline	GADM (Database of Global Administrative Areas) [207]	shp file - Lines
Distance from protected areas	Protected areas	World Database of Protected Areas (WDPA) [187]	shp file – Points; shp file - Polygons
Social conflicts density	Administrative borders	Database of Global Administrative Areas (GADM) [207]	shp file - Polygons
	2000-2021 conflicts	Armed Conflict Location & Event Data Project (ACLED) [205]	excel file

Human Development index	HDI	UNDP 2019 [149]	excel file
Proximity to transport infrastructure	Railways	Humanitarian Open Street Map [208]	shp file – Lines; shp file - Polygons
	Main roads	WFP Geonode (OSM) [209]	shp file - Lines
	Seaports	Humanitarian Open Street Map [208]	shp file – Points; shp file - Polygons
Proximity to existing power infrastructure	Electricity transmission network	energydata.info (from Arab Union of Electricity and country utility) [210]	GeoJSON
	Natural Gas pipelines	self-elaboration	shp file - Lines

In the following sub-sections, Tunisia, Algeria and Morocco are assessed with respect to the onshore wind hydrogen production, through the application of the MC-SDSS approach already introduced and detailed for the solar hydrogen production. Specifically, the same steps of **Figure 73** and detailed in sub-section 3.3.1 are elaborated, starting from the mapping of wind speed for each country of interest (**Figure 101**), which represents the technological criterion substituting the GHI used for the assessment of suitability for solar hydrogen. Considering the high weighting given to this criterion by stakeholders and experts (18.4%), a strong impact on the final results is expected. Looking at **Figure 101**, it appears evident that the locations with the highest speed are in the Western Sahara, reaching a maximum value of 18 m/s as wind speed at 100 m, but also desertic areas of Algeria and the Southern part of Tunisia are characterized by high values. For the analysis of maps and dataset, in order to elaborate the standardised maps, the cut-in velocity of 4 m/s is chosen as lower threshold value, so that lower values of speed would mean to assign a value of zero on the map. Looking instead at the highest values for wind speed, it is found that a very few amount is above 12 m/s, as shown in **Figure 101**, reporting the distribution according to natural breaks (jenks); according to this, it is important to have in mind that modifying the standardization function on this sub-criterion, through the setting of specific ranges of feasibilities (i.e. cell value equal to one for wind speed higher than 12 m/s), would mean to have a higher amount of areas belonging to the classes with high suitability (i.e. moderate and high suitability).

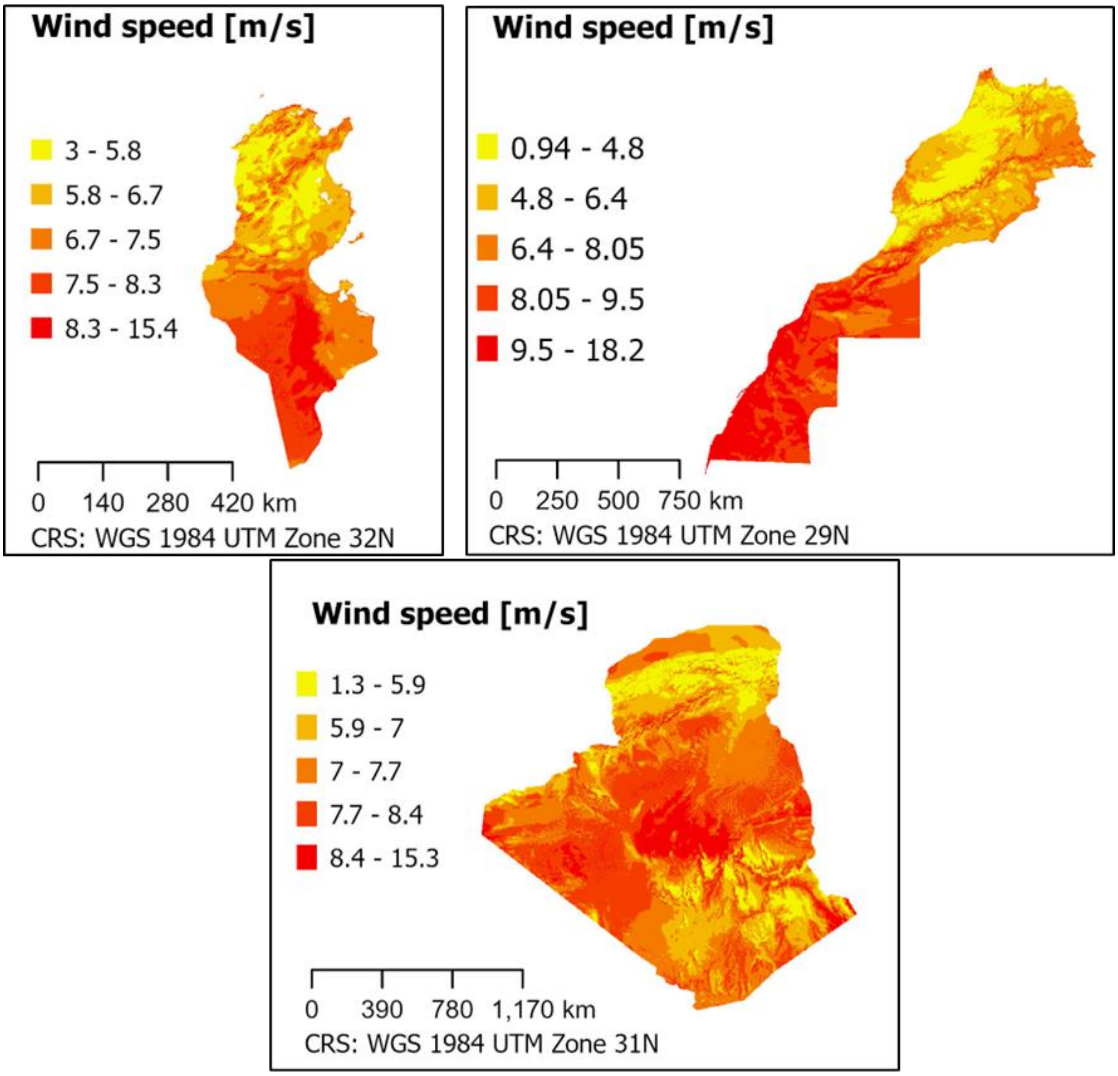


Figure 101: Values of wind speed (m/s) for Morocco and Western Sahara, Algeria and Tunisia at 100 m.

3.3.5.2 The Tunisian case

Working on suitable areas for hydrogen production by onshore wind **Figure 102** is obtained. It is found that, considering a 48.95% of the total land as not suitable at all because of the involved constraints, the majority of the Tunisian areas fall in the class of moderate suitability or high suitability (23.39% and 25.44%, respectively), while there are no very low suitable areas and only a few zones defined as very highly suitable (**Figure 103**).

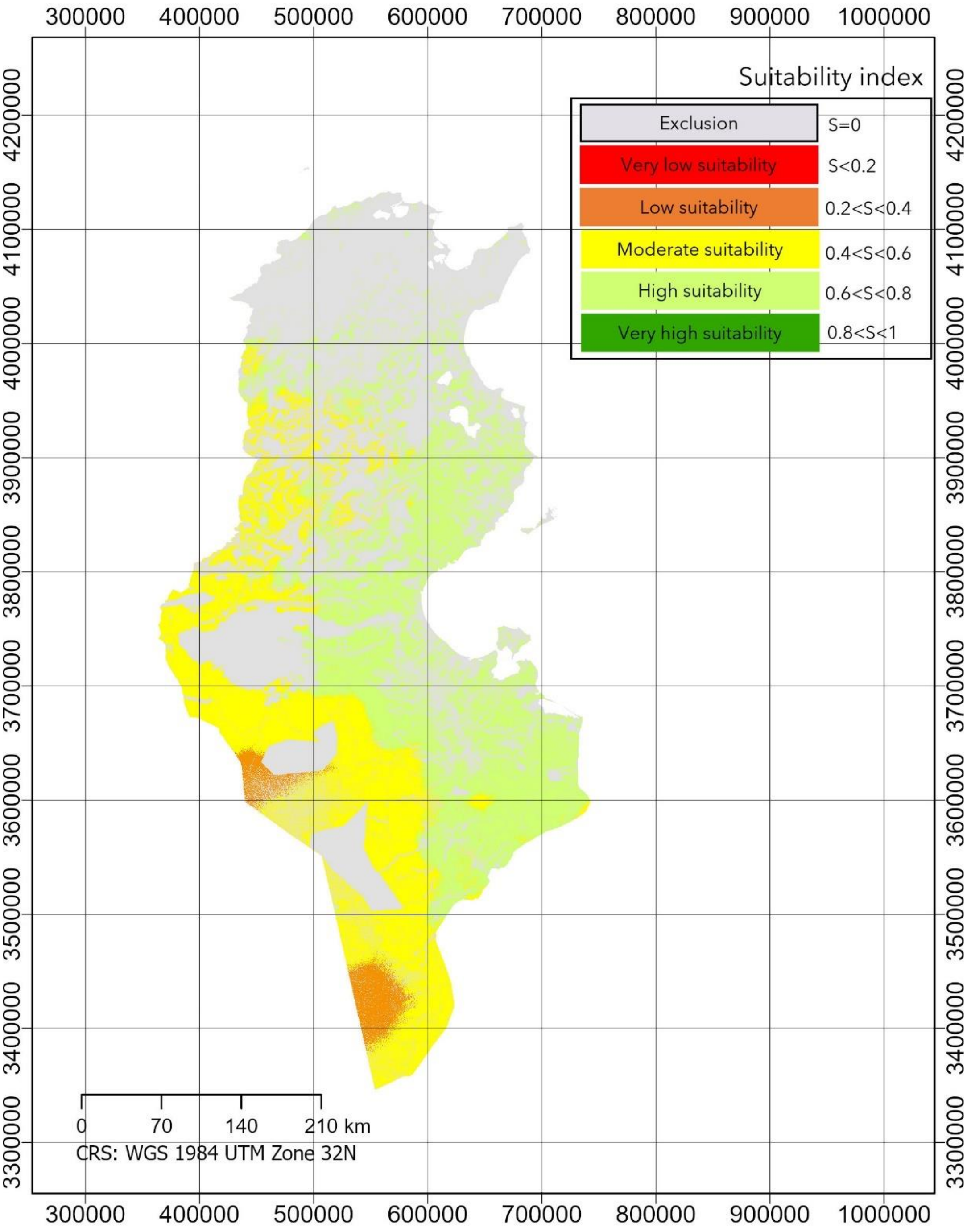


Figure 102: Tunisia, wind hydrogen: the final suitability map for the suitability of green hydrogen production by onshore wind.

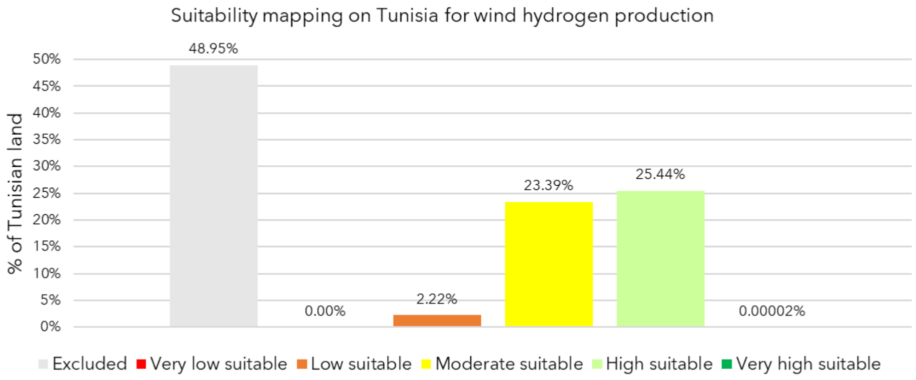


Figure 103: Tunisia, wind hydrogen: the share of land for the different classes of suitability.

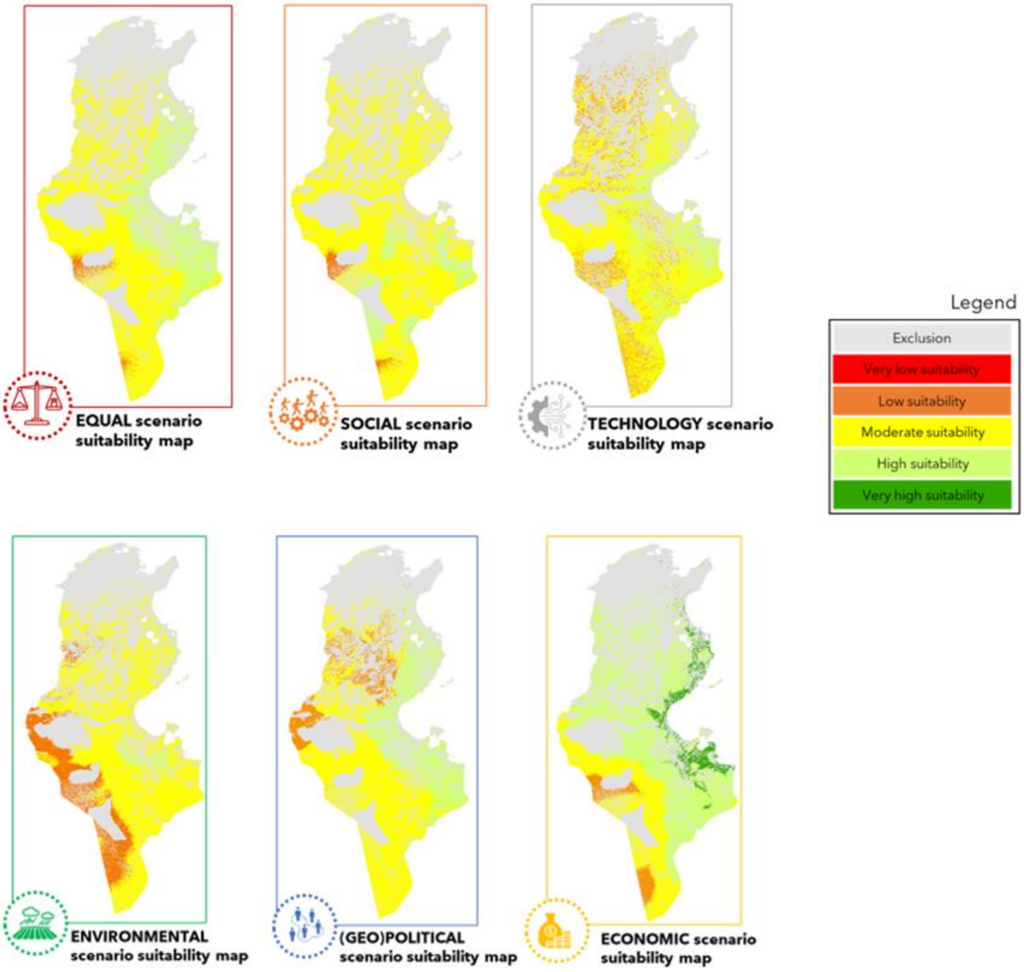


Figure 104: Tunisia, wind hydrogen: the suitability maps referring to the six scenarios of the sensitivity analysis.

According to the six different scenarios introduced in **Figure 81**, the sensitivity analysis for the onshore wind hydrogen production is conducted for Tunisia; the majority of the areas can be defined as moderately or highly suitable, but including a high percentage of low suitable areas, according to the extremization applied to the weightings (**Figure 104**). As already introduced for the solar hydrogen assessment, in this case the major role is played by the distance from coastline, urban areas and existing infrastructure; of course, in this case the wind source mapping has a strong impact, especially in reshaping the suitability assessment for the extreme technological scenario.

3.3.5.3 The Algerian case

As for Tunisia, the MC-SDSS is applied to the Algerian territories, to obtain a classification of land suitability in those areas, too. The same methodological procedure with respect to wind hydrogen production is exploited (criteria and sub-criteria defined in **Table 11**), since it is built in order to be replicable to all the countries of interest. **Figure 105** reports the final suitability map resulting from the application of the weightings introduced in the already presented applications, while **Figure 107** reports the results coming from the application of the sensitivity analysis. The percentage of excluded areas is very close to the one obtained for the solar hydrogen mapping, while the class of “very low suitability” is more populated (5.09%) in this case, then with about 45% of Algerian land identified as moderately suitable and more than 31% as highly suitable for wind hydrogen production (**Figure 106**).

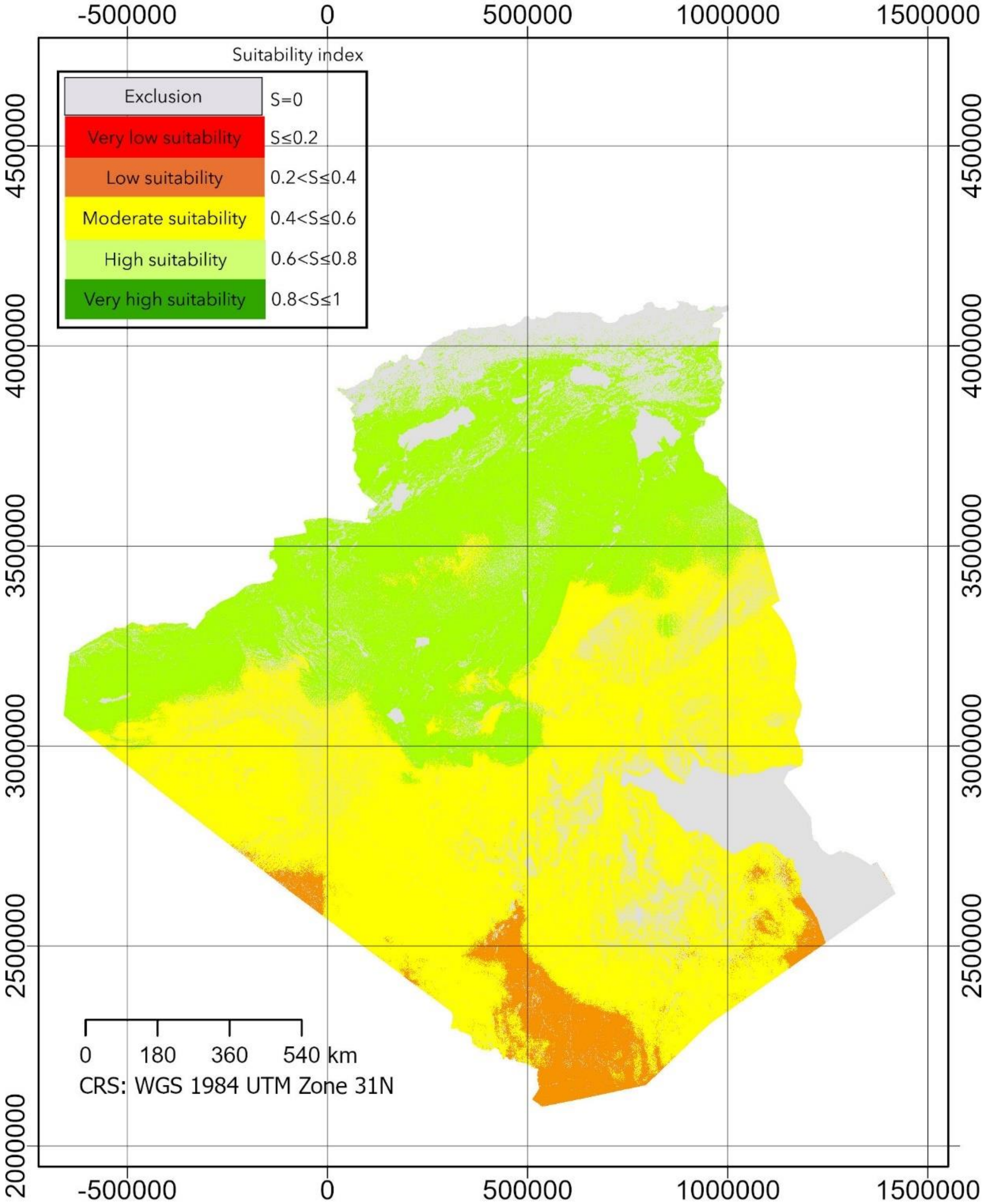


Figure 105: Algeria, wind hydrogen: the final suitability map for the suitability of green hydrogen production by onshore wind.

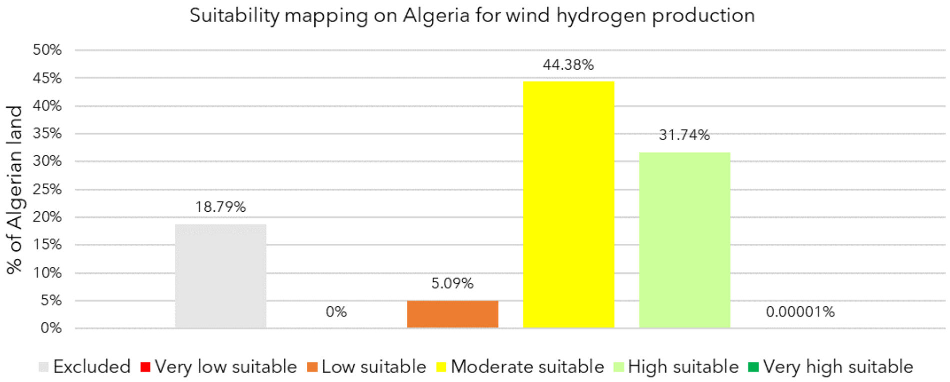


Figure 106: Algeria, wind hydrogen: the share of land for the different classes of suitability.

Looking at the sensitivity analysis (**Figure 107**), in this case it appears evident how on the technological and geopolitical side Algeria is widely suitable with respect to what happens extremizing the environmental, social, or economic scenario, as happened in **Figure 97** concerning solar hydrogen production. In fact, in both cases – having defined the same geopolitical sub-criteria – it appears evident how there is a homogeneous political situation in the different governorates.

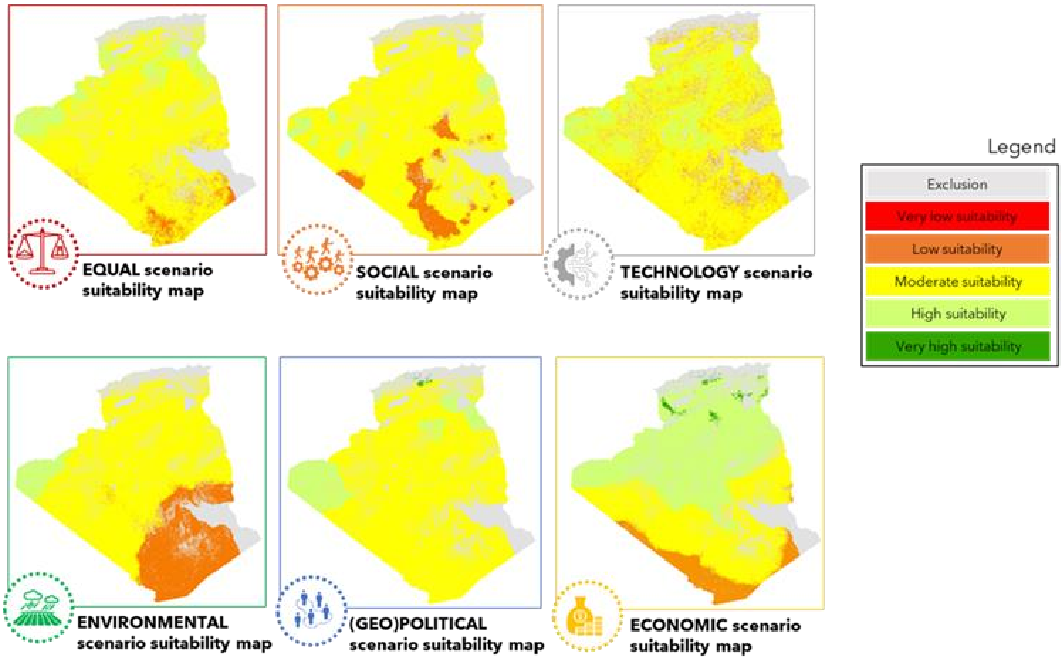


Figure 107: Algeria, wind hydrogen: the suitability maps referring to the six scenarios of the sensitivity analysis.

3.3.5.4 The Moroccan case

As already stressed in sub-section 3.3.1, Morocco and Western Sahara are analysed together in this application.

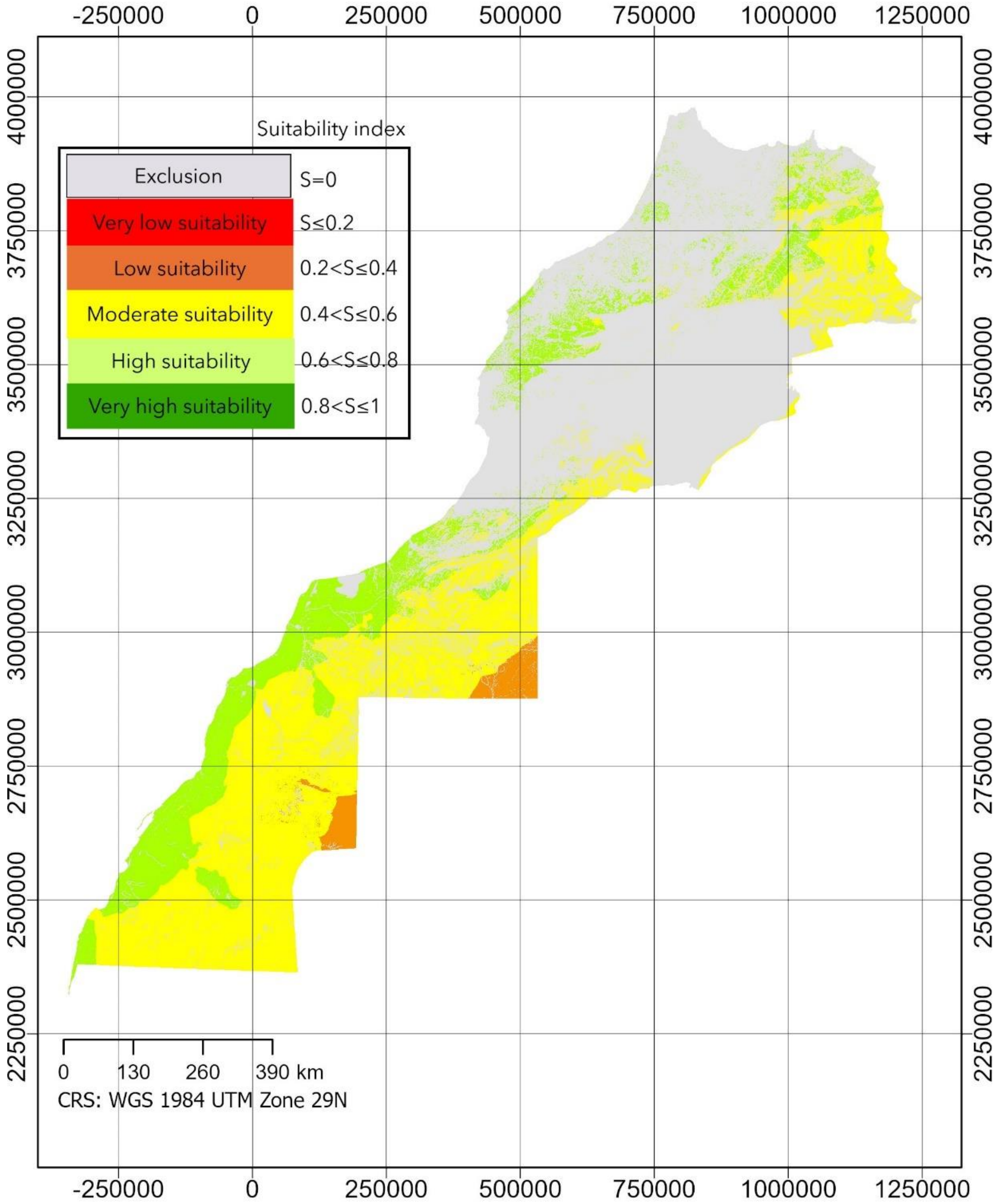


Figure 108: Morocco and Western Sahara, wind hydrogen: the final suitability map for the suitability of green hydrogen production by onshore wind.

Figure 108 shows the related suitability mapping for wind hydrogen production, while **Figure 109** focuses on the share of the different suitability classes. With a portion of excluded area very similar to the one obtained for solar hydrogen (i.e., 49%), it is found that the majority of land is moderately suitable for wind hydrogen exploitation, specifically for 34.3%, while 14.6% is found to be highly suitable. Even if there is a very high potential for wind hydrogen potential in Morocco, the MC-SDSS, through the involvement of the other criteria, points out that the percentage of highly suitable areas for solar hydrogen production is higher, being of 40.6%.

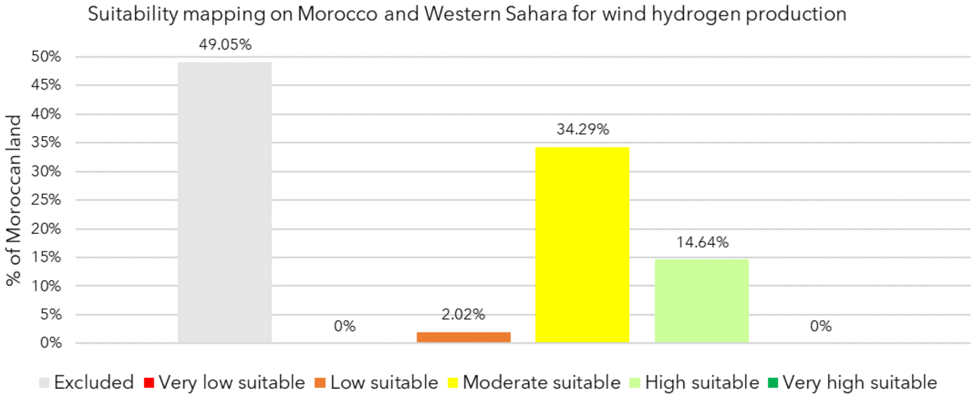


Figure 109: Morocco and Western Sahara, wind hydrogen: the share of land for the different classes of suitability.

As already commented for **Figure 100** related to solar hydrogen production, concerning the sensitivity analysis, the instability in Western Sahara strongly influences the extreme geopolitical mapping, while the social, environmental, and economic ones are affected by the distance from urban areas, from the coastline and from the existing infrastructure, respectively (**Figure 110**).

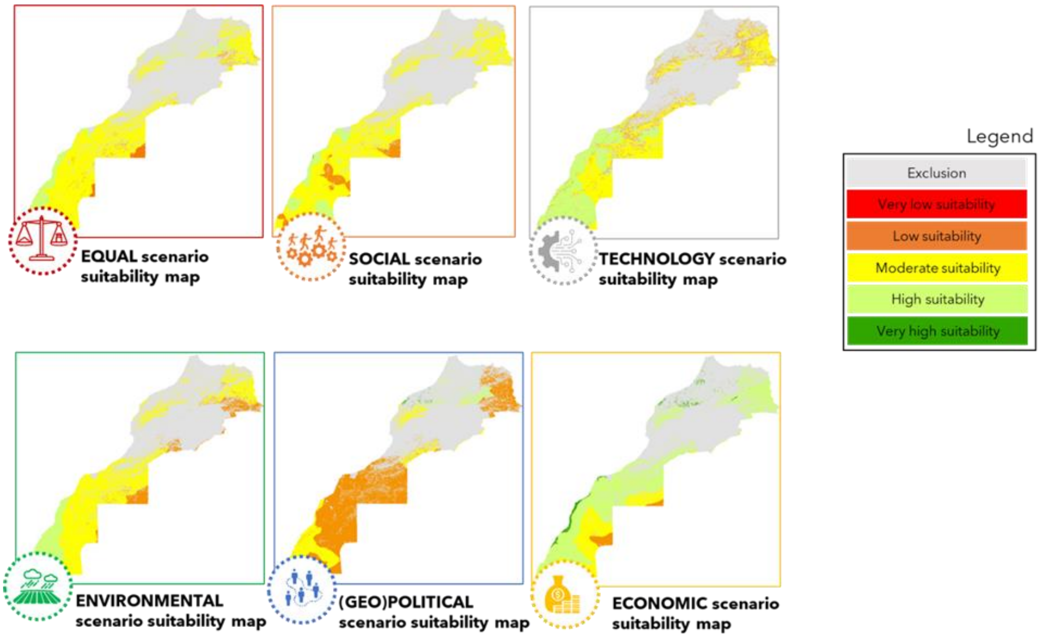


Figure 110: Morocco and Western Sahara, wind hydrogen: the suitability maps referring to the six scenarios of the sensitivity analysis.

3.3.5.5 Limitations and future development of the work

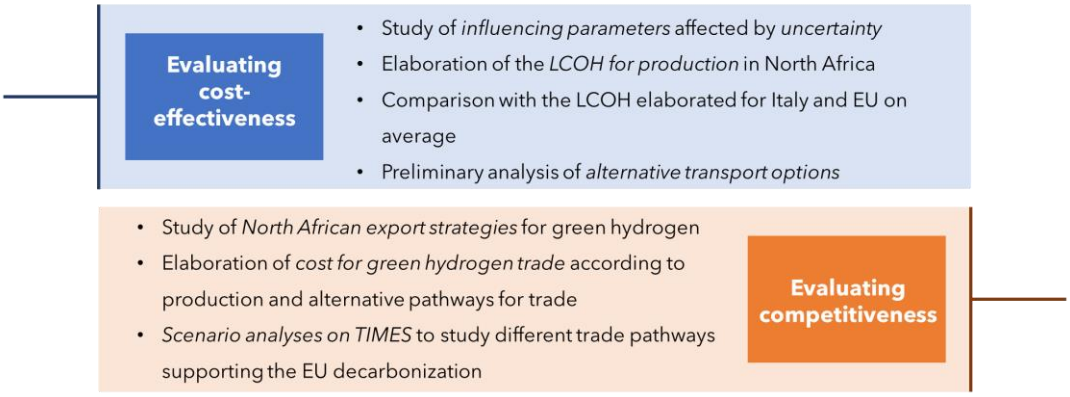
For the application in this sub-section 3.3.5, which investigates the role of wind energy in the hydrogen production framework, the same challenges analysed in 3.3.4.5 can be detailed, as for the solar hydrogen production. It is important to say that the main focus of the thesis is on the solar production – as also explained by the first map elaborations on the solar theoretical production; nevertheless, it is decided to explore also the wind potential of these areas, which can boost up the development of a hydrogen market in North Africa. An important change can involve the sub-criteria of wind speed – to which it is assigned in this application a simply linear function with the lower threshold of 4 m/s. More generally, it can be possible to apply changes on sub-criteria, specifically working on the technological dimension by adding ad-hoc new datasets for wind – spatially defined. Another way to proceed can be integrating both the solar and wind production in a unique application to have directly a map on renewable hydrogen; here it is decided to study both the assessments in parallel, with the possibility to compare them and focusing on specific aspects related to the two options separately for further applications. To conclude, about the application of the MC-SDSS for solar and wind hydrogen production, it is important to say that it would be important to add also the analyses on Egypt and Libya, not involved at this step of the research because of the ranking obtained in the assessment of predisposition but of course of interest for the development of a competitive hydrogen mapping in North Africa. In this case, specifically for Libya, it will be crucial to verify the availability of datasets and maps, which is often a limit for the application of the MC-SDSS, as already stated.

3.4 From predisposition to competitiveness: the role of green hydrogen imports from North Africa in the EU decarbonization

While the aim of the previous applications concerns the investigation and assessment of predisposition and suitability, the third level of the analysis deals with the assessment of cost-effectiveness and competitiveness of green hydrogen trade from North Africa to Europe. Having set that among Algeria, Egypt, Morocco, Tunisia and Libya, the most predisposed countries are Algeria, Tunisia and Morocco – for which the suitability maps offer also an overview on the high potentialities for renewable hydrogen production – the research is now devoted to the elaboration of specific costs for production, and of the optional affordable pathways for transport. Considering that there is still a lot of uncertainty concerning the different parameters affecting production and transport costs, but also the hydrogen demand and production capacities, the first part (sub-section 3.4.1) aims to address this uncertainty in parameters, focusing on production and transport pathways. Specifically, it is estimated the Levelized Cost of Hydrogen (LCOH) production in Algeria, Egypt, Morocco, Tunisia, Libya, Italy and Europe on average; it is decided to make the calculation also for Egypt and Libya in this case because the datasets required were available and also because this is a preliminary assessment before exploring the third step of the methodological approach concerning competitiveness. In fact, in these calculations also Italy and Europe are involved.

Having analysed different options to assess if and how green hydrogen can be cost-effective, especially in the long-term, then sub-section 3.4.2 allows to better investigate the concept of competitiveness through the exploitation of scenario analyses based on TIMES model generator. **Figure 111** summarises objectives, instruments and outputs belonging to this third step of the application. Concerning this part, there are two RdS deliverables, one published [213] and one under review

[214], and also it has been finalized a paper submission to the “International Journal of Hydrogen Energy” [215].



- Study of *influencing parameters* affected by *uncertainty*
- Elaboration of the *LCOH for production* in North Africa
- Comparison with the LCOH elaborated for Italy and EU on average
- Preliminary analysis of *alternative transport options*

- Study of *North African export strategies* for green hydrogen
- Elaboration of *cost for green hydrogen trade* according to production and alternative pathways for trade
- *Scenario analyses on TIMES* to study different trade pathways supporting the EU decarbonization

Figure 111: The evaluation of green hydrogen cost-effectiveness up to the competitiveness through scenario analyses.

The key instrument of this third level of the analysis consists of modelling energy scenarios through the integrated MARKAL-EFOM System (ETSAP-TIMES) model generator [216],[217]; to work with scenarios in the optimization framework, it is required a detailed analysis of different parameters competing for hydrogen deployment and its effectiveness among the carbon-neutral solutions in the long-term. In fact, there are several uncertainties and limitations to be considered while dealing with the development of future energy systems: (i) cost and efficiencies of existing technologies in the future, (ii) disruptive new technologies or energy carriers, (iii) demand, (iv) assumptions related to policies, foreign trade, market functioning and integration, (v) methodological limitations [65].

Specifically, the work elaborated in section 3.4.2 – concerning the evaluation of competitiveness through TIMES modelling – has been made possible thanks to Maria Gaeta, who allows the direct collaboration in Lisbon with Sofia Simões (National Laboratory of Energy and Geology, LNEG) and Patricia Fortes (NOVA School of Science and Technology, FCT NOVA), from February 2023 to July 2023.

3.4.1 The cost-effectiveness of green hydrogen: uncertainty on influencing parameters

To implement strategic pathways for an effective increase in green hydrogen uptake, there is a series of factors influencing its pace of development; significant differences in terms of hydrogen production potentials, hydrogen demand and costs are found in literature and technical studies. It is undoubted that there are several techno-economic challenges affecting cost trends of both renewable sources and electrolysers, together with the evolution of the hydrogen demand from the short- to long-term; moreover, a series of political, social and environmental issues are involved in the definition of costs and trends for hydrogen deployment [42]. The amount and heterogeneity of these influencing factors is reflected on several studies and scenarios estimating varieties of global hydrogen demand volumes up to 2050, as already discussed in sub-section 1.2. It is well known that different constraints and objective affect the results; specifically, the more ambitious and urgent the objectives of the transition process, the higher the penetration of hydrogen in the energy system, meaning that more stringent long-term emissions targets will require huge investments in hydrogen. Despite the different levels of hydrogen demand and supply, in any case there is a crucial role played by short- and long-distance trade; the new hydrogen game will require renewed trade routes or new ones, relying on resource availability, infrastructure potential, local demand and export potentials. To achieve the 1.5°C as rising temperature limit, IRENA models a quarter of total hydrogen demand as traded [9], while the REPowerEU accounts for a domestic production of 50% of the hydrogen needed by Europe [54]. To this end, infrastructure needs to be adapted or developed; by 2050 it is estimated that half of the available hydrogen will be transported by ships and pipelines – especially the repurposed ones, being cheaper than the newly constructed option [9]. In this context, there is huge uncertainty concerning the potential amount available for trade, the cost of renewable sources, the investment and maintenance for electrolysers and infrastructure, being the cost-effectiveness strongly affected by (i) technological readiness, (ii) market growth, (iii) financial risks [38],[49]. To this regard, it is envisioned a 50% reduction of future hydrogen costs, foreseeing innovation, optimization in supply chains and support from economies of scale [49]. While for the short-term it appears hard to obtain a competitive green hydrogen production with respect to the fossil fuel-based option, some studies report that a decrease of PV costs would mean a reduction of 35% for the LCOH [220]. Specifically, Pastore et al. [221] highlights how a Levelized Cost of Electricity (LCOE) lower than 30 €/MWh could determine a more competitive cost for green hydrogen [221]. It is clear that the cost of renewable sources is one of the most influencing factors for green hydrogen production; to this regard, an important parameter affecting both the cost of renewables and of the electrolysis process is the Weighted Average Cost of Capital (WACC); it could determine the export or import status of a country with respect to hydrogen trade [67], reflecting the stability of an economy and specific investments. Moreover, an important role is also played by the technology of the electrolyser itself, concerning investments, maintenance, efficiencies, performances, affected by a wide range of values from the short- to the long-term [222]. All these considerations allow to understand that it is needed to focus on the evolution of RES technology and costs, the financial risks associated to the projects, the technological development of electrolysers, to make an adequate analysis of the green hydrogen cost-effectiveness and competitiveness. Within this context, it is also required a focus on transport options, i.e., pipelines or ships, influenced by distances and volumes, with the latter to be preferred for longer distances and very large volumes [79]. Moreover, as highlighted recently by IEA [38], a series of projects considered feasible before mid-2022, are now reconsidered their financial plans because of an increase up to 50% of costs associated to inflation [38]. Also the EHB, on November 2023 has released a report concerning the potential increase in cost assumptions because of inflation and uncertainty in parameters and assumptions for the development of the five corridors [223].

Before focusing on the identification of scenarios to address the competitiveness of green hydrogen import from North Africa, ad-hoc analyses on all these parameters must be conducted, in order to make the proper assumptions and discuss the ranges of production and transport costs on different traded hydrogen volumes. The next sub-section (3.4.1.1) is devoted to the estimation of the LCOH for Algeria, Morocco and Tunisia, to be compared with the Italian case and the European average, while the sub-section 3.4.1.2 reviews the main transport options to make a preliminary focus on pipeline option.

3.4.1.1 The Levelized Cost of Hydrogen production in the Mediterranean areas

Concerning the evaluation of the costs for green hydrogen production, it is important to stress that it is a complex process, involving different technologies, and that can be addressed through different assumptions and implications with respect to the country where hydrogen is produced. To elaborate a coherent procedure for the estimations of costs, different sources are studied, considering how impactful some assumptions can be on the final results. For this analysis, it is decided to start from the methodology proposed by Nunez-Jimenez and De Blasio [73], according to which the LCOH is estimated. To evaluate this final cost, different variables are considered, as shown in **Table 12**. From equation 3.8 to the 3.11, the adopted formulas and related steps are summarised, considering specific assumptions to elaborate the LCOH for solar-to-hydrogen and wind-to-hydrogen in North Africa, Italy and European Union (average values in this last case). First of all, the Levelized Cost of Electricity from renewables ($LCOE_{RE}$) is computed according to the equation 3.8; for the final LCOH (equation 3.11), the estimation of the investment costs for hydrogen production (aggregated in the $CAPEX_{H2}$ value, equation 3.9) and the operational and maintenance costs (obtained through the $OPEX_{H2}$ calculation by equation 3.10) are elaborated. Matlab and Excel are used for the elaboration of the results. Specifically, the content discussed in this sub-section (3.4.1) is the core of the RdS deliverable of 2022 [213].

Table 12: The main variables introduced for the elaboration of the LCOH.

Variable	*Definition*	*Unit of measure*	*Source(s)*
I_{RE}	Investment cost for RES technology	[€/kW]	IEA [224]; IRENA [225],[226]
T_{RE}	RES plant lifetime	[y]	IEA [224]; IRENA [225],[226]
OM_{RE}	Operation and maintenance cost for RES technology	[€/kW]	IEA [224]; self-elaboration
FLH_{RE}	Full Load Hours of co-located RES plant	[h]	Global Solar Atlas [184]; Global Wind Atlas [212]; IEA [224]
η_{H2}	Electrolyser efficiency	[%]	IEA [45]; Schmidt et al. [222]; DEA [227]
I_{H2}	Investment cost for electrolysis plant	[€/kW]	IEA [45]; Schmidt et al. [222]; DEA [227]
OM_{H2}	Operation and maintenance cost for electrolyser technology	[€/kW]	Schmidt et al. [222]; DEA [227]
T_{H2}	Electrolysis plant lifetime	[y]	IEA [45]; DEA [227]
f_{H2O}	Specific water consumption per mass of hydrogen	[m^3_{H2O}/kg_{H2}]	Haider Ali Kan M. et al. [228]; Global Alliance Power Fuels – GEA [229]
c_{H2O}	Desalinated water cost	[€/m^3_{H2O}]	World Bank Group [230]
d	Discount rate / WACC	[%]	IEA [231]; IRENA [49],[67]

$$LCOE_{RE}\left[\frac{€}{kWh}\right] = \frac{I_{RE} + \sum_{t=1}^{T_{RE}} \frac{OM_{RE}}{(1+d)^t}}{\sum_{t=1}^{T_{RE}} \frac{FLH_{RE}}{(1+d)^t}} \tag{3.8}$$

$$CAPEX_{H2}\left[\frac{€}{kg_{H2}}\right] = \frac{LHV_{H2}}{\eta_{H2} * L_{H2}} * I_{H2} \tag{3.9}$$

$$OPEX_{H2}\left[\frac{€}{kg_{H2}}\right] = \frac{LHV_{H2}}{\eta_{H2} * L_{H2}} * \sum_{t=1}^{T_{H2}} \frac{OM_{H2}}{(1+d)^t} \tag{3.10}$$

$$LCOH\left[\frac{€}{kg_{H2}}\right] = LCOE_{RE} * \frac{LHV_{H2}}{\eta_{H2}} + CAPEX_{H2} + OPEX_{H2} + f_{H2O} * c_{H2O} \tag{3.11}$$

For the elaboration of the CAPEX and OPEX of the electrolysers system (equations 3.9 and 3.10) the parameter L_{H2} is introduced, defined as the hours that the electrolysis plant operates during its lifetime T_H, discounted over time with rate d; here as assumed in [73], for its calculation it is considered that the co-located renewable electricity plant has the same power rating of the electrolyser. To take into account the effective availability of the RES plant, we consider a reduction of the related electrolyser capacity which is expressed in the model as a 10% investment cost I_{H2} reduction for the electrolyser plant. A parameter playing an important role in the elaboration of costs, among the others, is the WACC; IRENA highlights how CAPEX and WACC represent two key drivers of costs and how they quickly change over time [67]. While today there is a wide spread of WACC values among countries worldwide, in the future it is assumed that there will be a lower gap, considering that technology risks would decrease through a major uptake and only some factors beyond technology would maintain some differences among regions [48]. It is important to say that differences in WACC today means to have a double cost of electricity; looking at shipping, a change from 15% to 5% of WACC will impact on decreasing the cost of shipping hydrogen by 25-45% [67]. Concerning the capital cost, it is a crucial component for defining the production cost of green hydrogen, especially if looking at the green one and then at the specific cost of the electrolysers [231]; now the variety worldwide relies on local labour costs, installation costs and economy of scale [48]. In **Figure 112** and **Figure 113**, the evolution of the investment cost (€/kW$_e$) for the alkaline electrolysers (ALK), polymer electrolyte membrane (PEM) and solid oxide electrolyser cell (SOEC) is reported, with respect to three different sources referred to specific datasets and assumptions for 2030, 2040 and 2050 trends [45],[227],[232]:

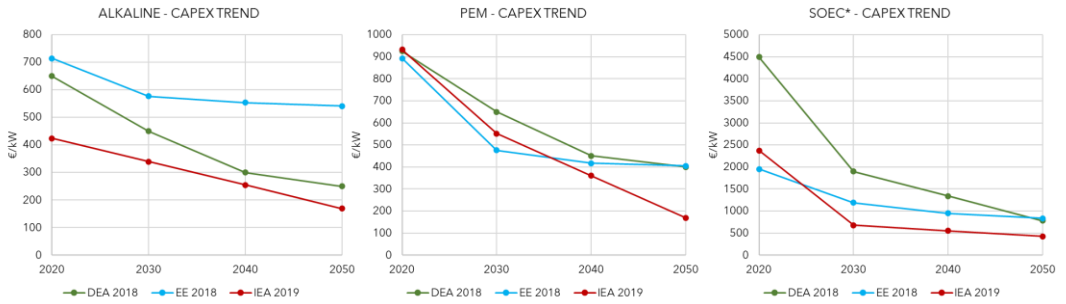


Figure 112: Electrolysers trends for CAPEX, adapted from [45],[227],[232], from the current state to 2050.

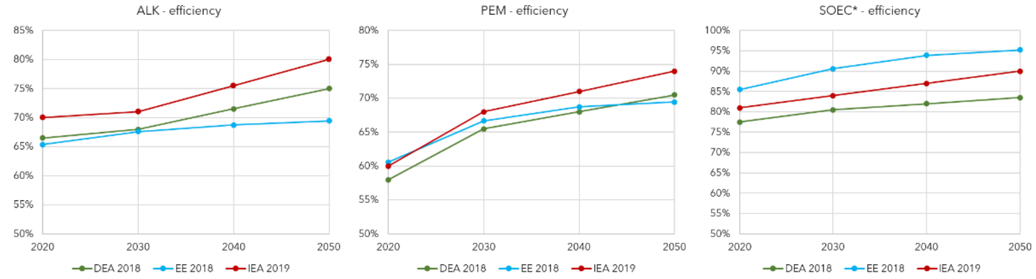


Figure 113: Electrolysers trends for CAPEX, adapted from [45],[227],[232], from the current state to 2050.

Concerning the size, for ALK and PEM technologies all values aim to assess costs and efficiency related to a large module size. The SOEC typology are still experiencing an ongoing process of research and development, so that it is not possible to assess large size plants as it is for ALK and PEM; specifically, the Danish Energy Agency (DEA) [227] has studied 1 MW plants for SOEC while elaborating the related investment costs, while for IEA [45] and Element Energy (EE) [232] it is assumed to have a larger size, so that it is not simple to conduct a real comparison. **Figure 112** highlights different evolutions for the investment costs according to different sources; specifically, the reported values by IEA refer to the minimum assumed cost for the investment cost ranges and the maximum assumed efficiency for the efficiency ranges [45]. For DEA [227], a 100 MW electrolyser plant exploiting ALK technology will reach an investment cost of 250 €/kW in 2050, starting from a value of 650 €/kW in 2020, while the base case of EE [232] reports higher values – from about 700 to 500 €/kW – and the most optimistic assumptions of IEA [45] – relates to a CAPEX below 200 €/kW for ALK in 2050. CAPEX trends for PEM are different; the most expensive scenario from 2030 to 2050 is envisioned by DEA [227], even if all the three sources agree for a CAPEX around 400 €/kW in 2040, which decreases strongly in 2050 according to IEA, reaching the same CAPEX of ALK [45]. Concerning SOEC technology, it is not possible to compare directly its trend with the ones of ALK and PEM, because of the different size; nevertheless it is important to notice how, as expected, strong improvements in R&D will strongly reduce the cost, achieving a CAPEX ranging from 500 €/kW [45] to 700 €/kW [232] by 2050. Looking at the efficiency trends (**Figure 113**) a technological improvement for all the three technology in the next decades is assumed, even if with different values according to the three dataset analysed [45],[227],[232].

While for ALK and PEM – which are already commercially available and widely used – it is decided to develop a LCOH elaboration following specific assumptions according to DEA and IEA, concerning the SOEC technology – not commercially available yet –the possibility to have three different scenarios is assumed, detailed in **Figure 114**. Through the development of these scenarios, three different technological evolutions from the current state (2020) to the long-term (2050) with respect to renewables market and SOEC systems are addressed. While the technologically steady scenario accounts for a very few variations in renewable costs and for minimum improvements concerning electrolysers (about efficiency and costs), the technologically advanced option implements a strong cost reduction, together with effective enhancement in performance. Also a scenario between the technologically steady and the technologically advanced is developed, i.e. the technologically moderate one (**Figure 114**).

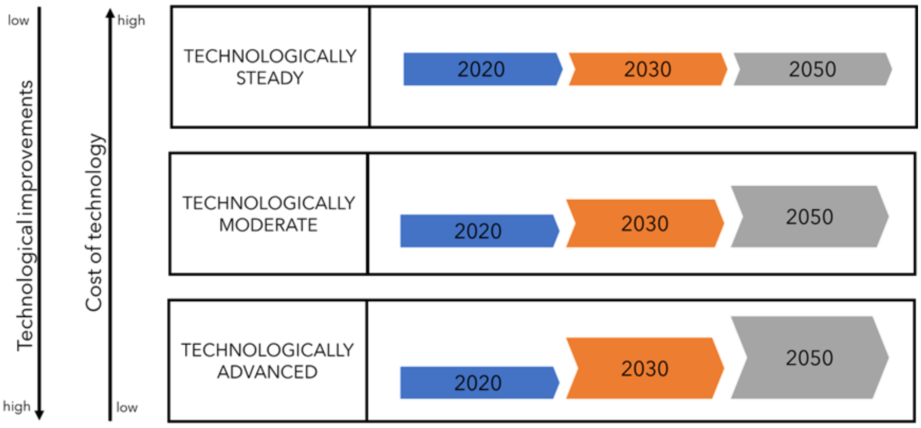


Figure 114: The three scenarios to evaluate different pathways for the evolution of hydrogen cost produced by SOEC.

Concerning the LCOH elaboration, for the basic case it is assumed a WACC of 8% for the North African countries, while 5% is considered for Italy and Europe. Moreover, with respect to water availability and use, the adopted data are related to the desalination process through reverse osmosis; specifically, the desalination market in the Mediterranean is considered a pioneer in the introduction of this technology for desalination [233]. Concerning desalinated water, in literature it is possible to find costs ranging from 0.64 €/m^3_{H2O} to 2.6 €/m^3_{H2O}; here for the specific values, the average of water costs of existing desalination plants which adopted reverse osmosis in North Africa is considered (i.e. about 0.84 €/m^3_{H2O}) [230], while specific water consumptions are associated to the different technologies of electrolysers (i.e. 11.2 l_{H2O}/kg_{H2} for ALK, 10 l_{H2O}/kg_{H2} for PEM, 9.1 l_{H2O}/kg_{H2} for SOEC) [227],[228], making reference to the amount required specifically by the electrolysis process. It is also assumed to have a fixed cost associated to the desalination process over time; for further analyses it could be of interest to assume a reduction over the next decades, considering that the cost of desalinated water has been decreasing over time because of technological improvement – despite the rise of energy prices [234]. Another important issue regards the electrolysis to renewables ratio, $\eta_{ely\text{-}to\text{-}RE}$, which represents the ratio between the nominal electric input power of electrolysis and the renewable power [235]. In fact, there is an optimal ratio mainly influenced by the renewable capacity factors, according to which the minimum LCOH is reached; if (i) the location exploits very favourable conditions for RES, thus reaching high full load hours, and (ii) the installed RES capacity is high, the higher the $\eta_{ely\text{-}to\text{-}RE}$, the lower the hydrogen production costs [235]. On the opposite, the worse the site, the lower the $\eta_{ely\text{-}to\text{-}RE}$ power ratio and the narrower the related optimal range [235]. Looking at different capacity factors through several locations, it is found that the power ratio ensuring the minimum LCOH will tend towards unity if RES allow to achieve high yearly capacity factors [49],[235]; for further assessments it can be of interest to better detail and analyse different ranges of this value for the different locations.

From **Figure 115** to **Figure 118** the results for the LCOH pf solar-to-hydrogen and wind-to-hydrogen obtained by ALK or PEM are shown, starting from the current state (2020) up to 2050. With respect to the dataset for electrolysers, it is decided to adopt the values from DEA [227], while data from IEA [45], Global Solar Atlas [184] and Wind Atlas [212] are elaborated to estimate the related LCOE (**Table 12**). Specifically, LCOH are estimated for Algeria, Egypt, Libya, Morocco (which stands for Morocco and Western Sahara), Tunisia, Italy and also for European Union on average; here the most relevant results and comparisons are reported, focusing on the cheapest and the most expensive options for each technology.

Figure 115 reports the LCOH for solar hydrogen produced by ALK; Tunisia presents the highest cost among the North African countries, while Egypt is the cheapest, ranging from a value of 5.13 €/kg$_{H2}$ (2020) to 1.9 €/kg$_{H2}$ for 2050. Italy is still more convenient, starting from a LCOH of 4.33 €/kg$_{H2}$ (2020) to a value of 1.69 €/kg$_{H2}$ calculated for 2050; this result is justified by the lower investment cost for PV in Europe with respect to North Africa [224] and the lower WACC assumed (5% versus 8%). **Figure 116** reports the elaboration of LCOH for solar hydrogen produced through PEM electrolysers; with respect to the alkaline typology, the cost in 2020 is higher. However, looking at the next decades, this cost will decrease, leading to a LCOH for 2050 of 2.38 €/kg$_{H2}$ in Italy and 2.51 €/kg$_{H2}$ in Egypt.

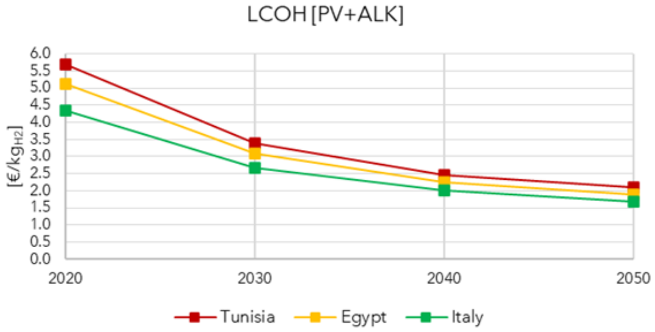


Figure 115: The LCOH for solar hydrogen by ALK electrolysers, for Tunisia, Egypt and Italy, from 2020 to 2050.

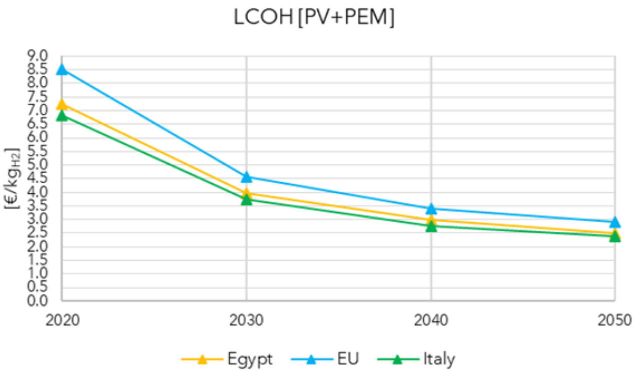


Figure 116: The LCOH for solar hydrogen by PEM electrolysers, for Egypt, EU, and Italy, from 2020 to 2050.

Concerning the production of wind hydrogen, it is evaluated as more convenient in North Africa, specifically in Morocco, where there is a very high potentiality for the exploitation of wind resources. Focusing on the alkaline technology (**Figure 117**), the LCOH ranges from 3.38 €/kg$_{H2}$ (2020) to 2.11 €/kg$_{H2}$ (2050) in Morocco, while for Italy the minimum cost is 3.29 €/kg$_{H2}$ in 2050. Looking at PEM technology (**Figure 118**), also for wind hydrogen the higher CAPEX of these electrolysers influences the overall results; the minimum cost is in fact evaluated in Morocco at 2.49 €/kg$_{H2}$ in 2050.

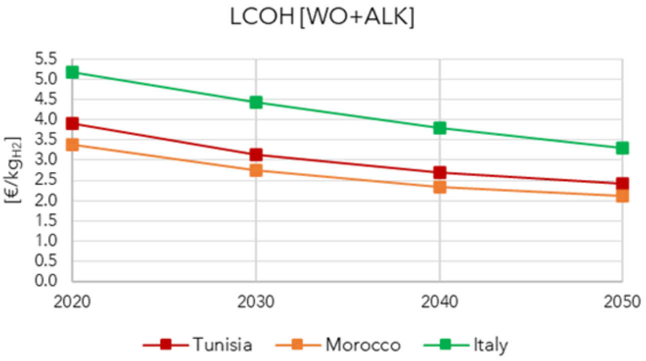


Figure 117: The LCOH for wind hydrogen by ALK electrolysers, for Tunisia, Morocco and Italy, from 2020 to 2050.

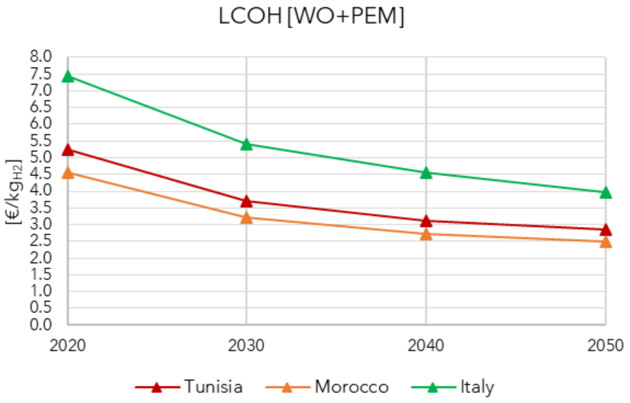


Figure 118: The LCOH for wind hydrogen by PEM electrolysers, for Tunisia, Morocco and Italy, from 2020 to 2050.

Focusing on SOEC, as already introduced by **Figure 114**, it is needed to analyse different scenarios, which are representative of optional pathways for technological development; as expected, the most convenient option matches the advanced technological scenario, representing the most optimistic evolution in technological and economic terms in the next decades. In these calculations, the variables affected by technological improvements are CAPEX, OPEX and the efficiency of the SOEC. In **Figure 119** and **Figure 120** the Italian case is compared with the most affordable North African option, Egypt for solar hydrogen and Morocco for wind hydrogen, respectively. Still in 2020, the technological status of SOEC is clearly uncertain, as shown by the LCOH for solar hydrogen, ranging in Italy from 9.46 €/kg$_{H2}$ (technological steady scenario) to 6.6 €/kg$_{H2}$ (technological advanced scenario) and in Egypt from 9.27 €/kg$_{H2}$ (technological steady scenario) to 6.74 €/kg$_{H2}$ (technological advanced scenario). In 2020 a wider range is also found for wind hydrogen by SOEC; in Italy from 9.33 €/kg$_{H2}$ (technological steady scenario) to 6.9 €/kg$_{H2}$ (technological advanced scenario) and in Morocco from 5.31 €/kg$_{H2}$ (technological steady scenario) to 4.01 €/kg$_{H2}$ (technological advanced scenario). In this regard, as clearly shown by **Figure 120**, the wind hydrogen produced in Italy in the technological advanced scenario is still less affordable than the one produced in Morocco by SOEC assessed in the technological steady scenario. In 2030, for both solar and wind hydrogen, a strong improvement for SOEC is envisioned, as demonstrated by the LCOH obtained. Italy remains more competitive than Egypt in 2030 and also in 2050 with respect to solar hydrogen (1.54 €/kg$_{H2}$ vs 1.69 €/kg$_{H2}$ in the technological advanced scenario, respectively), while Morocco is always more competitive than Italy concerning wind hydrogen (1.81 €/kg$_{H2}$ vs 2.85 €/kg$_{H2}$ in the technological advanced scenario, respectively).

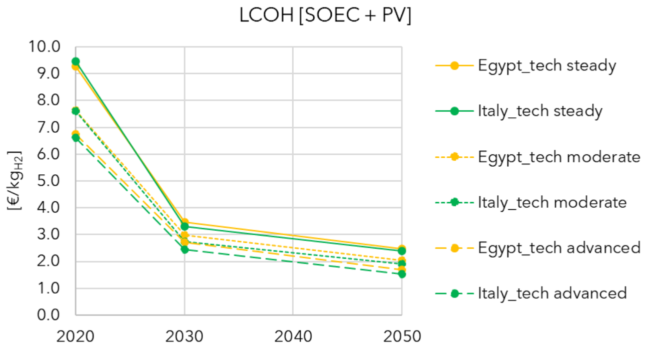


Figure 119: The LCOH for solar hydrogen by SOEC electrolysers, for Egypt and Italy, from 2020 to 2050, according to the technological scenarios.

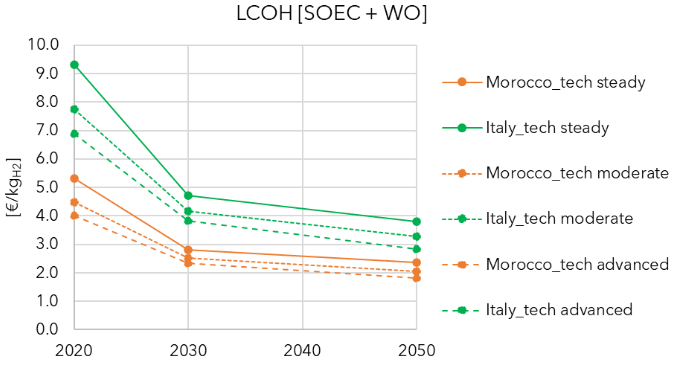


Figure 120: The LCOH for wind hydrogen by SOEC electrolysers, for Morocco and Italy, from 2020 to 2050, according to the technological scenarios.

To summarise, the main outputs for Morocco, Algeria and Italy are collected in **Figure 121**, **Figure 122**, **Figure 123**; the LCOH for solar and wind hydrogen and related to the exploitation of ALK, PEM and SOEC (in this case the technological moderate scenario is shown) are reported. All these values are calculated and available also for Egypt, Libya, Tunisia, and for the European Union (exploiting the average values by IEA [224]). Specifically, it is interesting to notice how Morocco is much more convenient for wind hydrogen production than the solar one, while for Italy it is the opposite, being the solar hydrogen production much more affordable, from 2030. Algeria (**Figure 122**) presents similar results of Morocco (**Figure 121**), with some differences because of specific capacity factors of the areas.

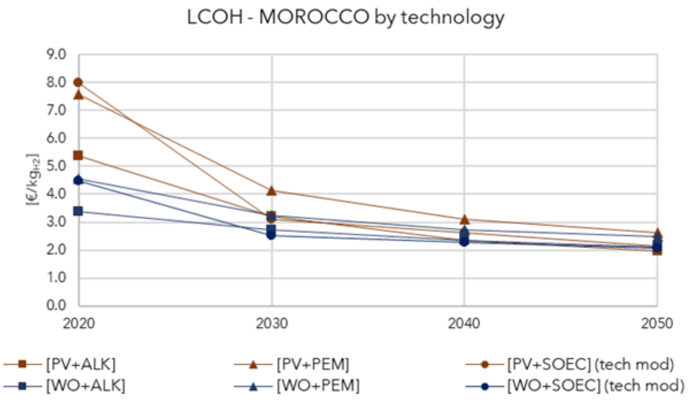


Figure 121: The LCOH for Morocco, according to different technological options, from 2020 to 2050.

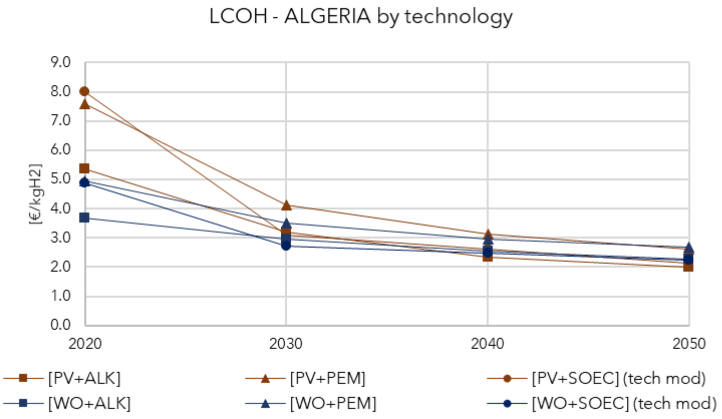


Figure 122: The LCOH for Algeria, according to different technological options, from 2020 to 2050.

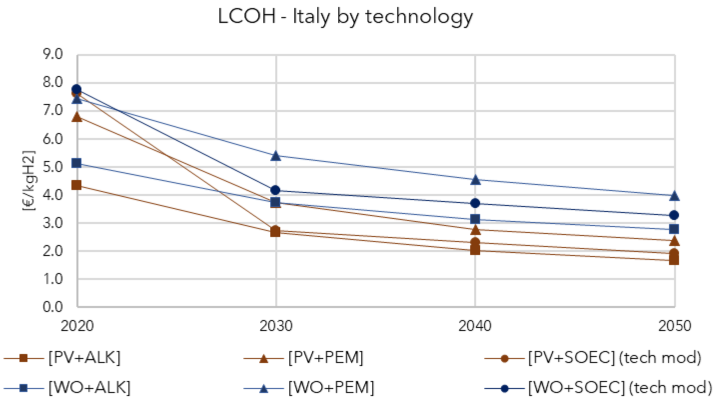


Figure 123: The LCOH for Italy, according to different technological options, from 2020 to 2050.

In the following figures the cost breakdown for the most affordable options is reported, which in terms of electrolysers means focusing on the Alkaline type; for solar hydrogen (**Figure 124**) the comparison is between Egypt and Italy, while on the wind side (**Figure 125**) between Morocco and Italy. It is evident how the highest impact on the final LCOH relies on the renewable electricity required for water electrolysis, which of course decreases along the decades up to 2050, and it is followed by the CAPEX of electrolysers. Instead, the impact of water cost appears negligible according to the assumptions adopted.

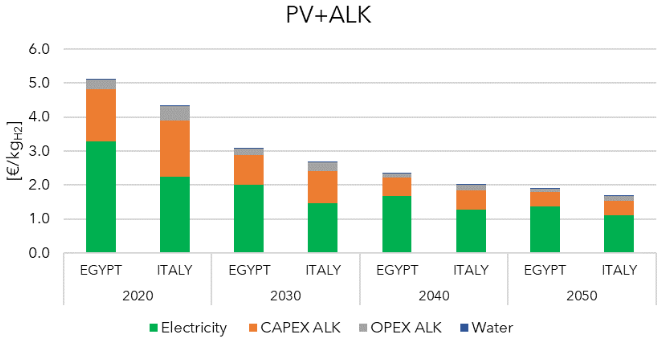


Figure 124: Cost breakdown for solar hydrogen produced in Egypt and Italy, by ALK, from 2020 to 2050.

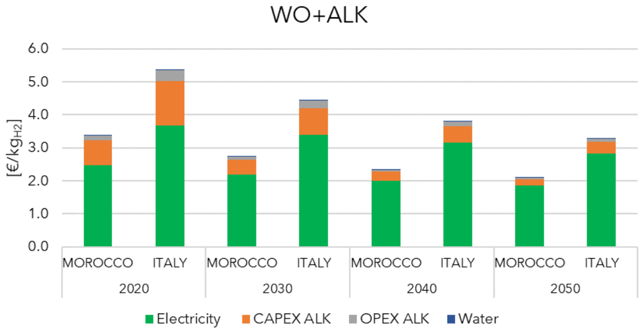


Figure 125: Cost breakdown for wind hydrogen in Morocco and Italy, by ALK, from 2020 to 2050.

In order to have a focus on the influence of WACC on the results, it is conducted a sensitivity analysis by ranging its value from 3% to 12%, which potentially represent the minimum and maximum projections for solar and wind technologies, even if there will be always outliers at country level [67]. The WACC analysis is elaborated only for ALK and PEM electrolysers, considering that the SOEC option involves more uncertainties. **Figure 126** and **Figure 127** highlight the influence of WACC on the final results obtained for the LCOH; in fact, in case of same WACC, the North African countries are more convenient in terms of LCOH for both solar and wind hydrogen production, which is not the case of the results reported before (highlighted through black points in **Figure 126** and **Figure 127**), when a WACC of 5% for Italy and of 8% for North Africa are assumed. It is found that with a 3% as WACC in 2050 the lowest LCOH is 1.33 €/kg$_{H2}$, which is associated to the production by PV and ALK in Egypt.

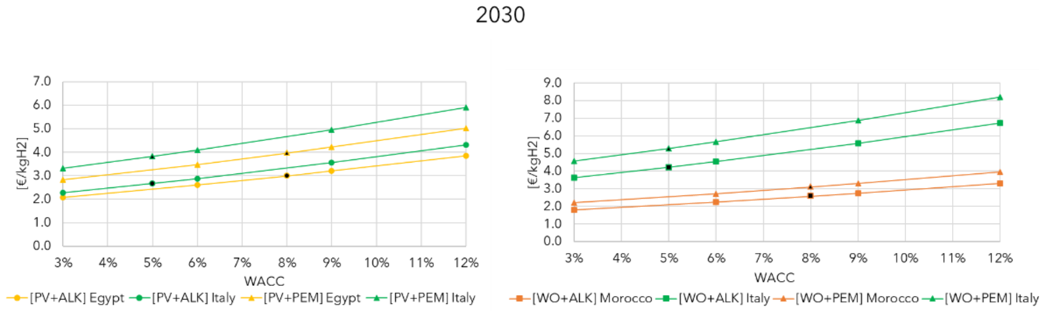


Figure 126: LCOH elaboration according to a WACC sensitivity analysis for 2030.

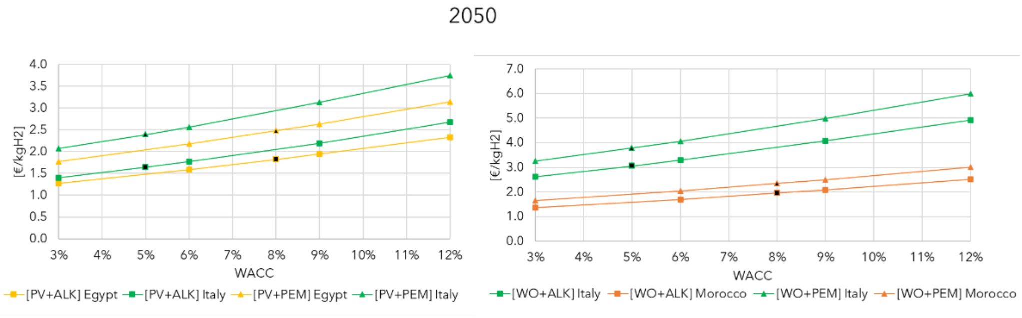


Figure 127: LCOH elaboration according to a WACC sensitivity analysis for 2050.

Looking at the overall results, it appears evident that while elaborating costs and potential options for trade, there are both criticalities and potentialities to be addressed and that can support different strategies in terms of development of new technologies. Concerning the production of green hydrogen in North Africa and potential cross-border cooperation, it is of interest to focus on how affordable the LCOH of solar-based hydrogen is in Italy, which is lower than the one elaborated for North Africa, because of the much lower costs of RES plants in Europe, due to a lower WACC. It is different for the production by wind generation; in this case the much higher availability in terms of wind power positively influences the performance in Morocco with respect to the Italian one. Within this framework, there is the strong impact of the discount rate, which can play a crucial role, supporting the local production or pushing for trade when there is a high availability of resources. In line with this, a key element for the assessment is represented by the local demand together with the capacities and infrastructure requirements in Italy. The crucial point to be addressed is the rate of diffusion of renewable energy; to satisfy the expected demand it is necessary to install more than 10 GW of electrolysers and more than 70 GW of PV plants on the Italian areas [236]. In this regard, the huge amount of renewable resources and land availability of North Africa, which means high potentialities in terms of production, can represent a viable solution, but with the need to elaborate a trade-off in terms of local production and use, investment and maintenance costs, financial risks and infrastructure requirements.

Concerning the number of assumptions and datasets to be investigated for the elaboration of the LCOH for production, it can be if interest to focus on some other studies to analyse the used data and the obtained outputs. According to IEA [47], in line with the cost reduction for both RES plants and electrolysers, by 2030 renewable hydrogen cost will range from 1.3 to 4.5 USD/kg$_{H2}$, with the lower range associated to the most renewable-rich countries and where green hydrogen can be structurally competitive against fossil fuels [236]. According to the optimistic 2030 scenario of

IRENA [67], in North Africa a LCOH between 1.5 and 2.5 USD/kg$_{H2}$ is estimated; looking at 2050, the optimistic scenario assigns to Morocco a LCOH of about 0.8 USD/kg$_{H2}$ while for Italy it is 1 USD/kg$_{H2}$, values that in case of a pessimistic scenario become 1.5 USD/kg$_{H2}$ and 1.6 USD/kg$_{H2}$, respectively [47]. IRENA [2] reports also an Italian economic potential below 2 USD/kg$_{H2}$ of 10.1 Mt$_{H2}$/yr, but if its achieved a reduction of capital costs by 60% for solar PV and by 30% for both onshore wind and electrolysers [2]. For the EHB [69], while assessing the specific North Africa and South Europe Corridor (**Figure 20**), in 2030 the cost of hydrogen produced will range from 2.1 to 3.8 €/kg$_{H2}$, and in 2040 there will be a reduction, going from 1.4 to 2.8 €/kg$_{H2}$.

3.4.1.2 Alternative hydrogen transport options

To take care of specific transport costs, it is important to consider that alternative options based on different technologies can be adopted according to the amount of hydrogen to be transported and the distance from the production site to the consumption site. The optional ways to transport hydrogen are summarised by **Figure 128**:

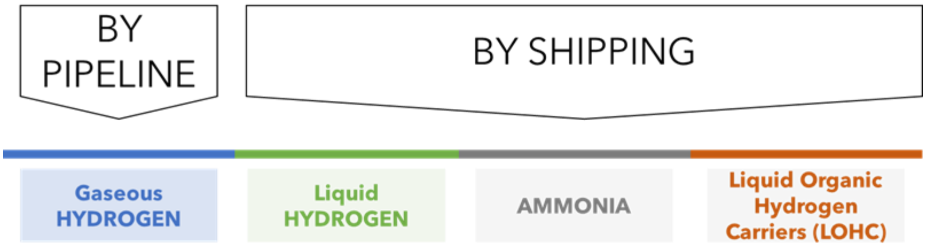
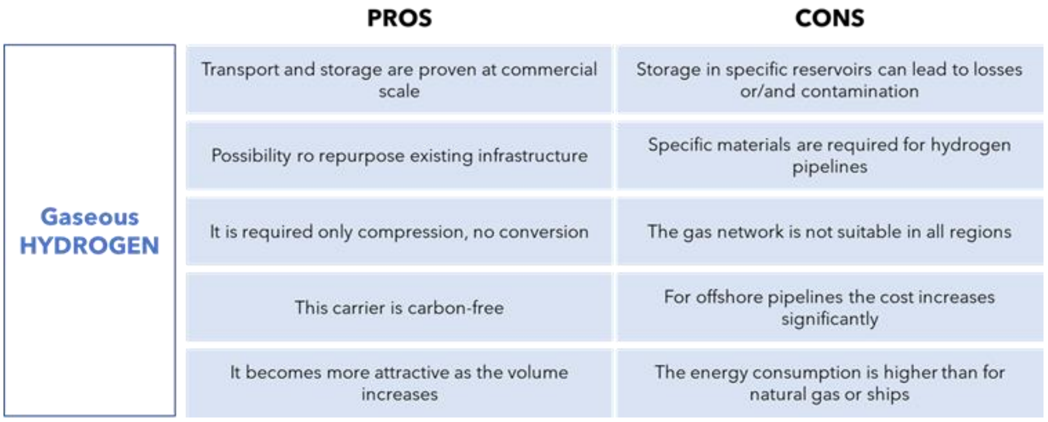


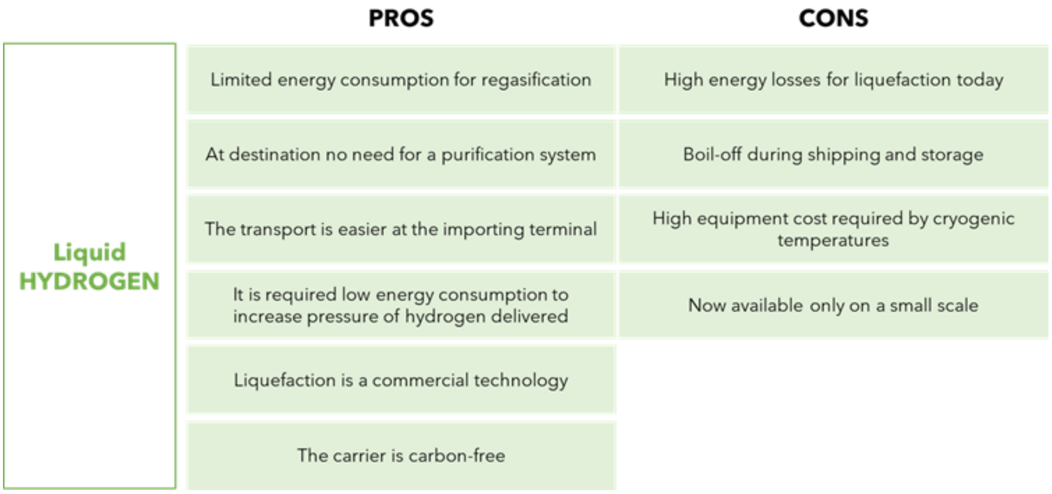
Figure 128: Optional ways for hydrogen transport.

There are advantages and disadvantages associated to all the options for transport (**Figure 128**), considering the limitations in terms of technology readiness, availability, costs or infrastructure readiness. From **Figure 129** to **Figure 132** the aspects belonging to each alternative transport are summarised, as collected by IRENA [79].



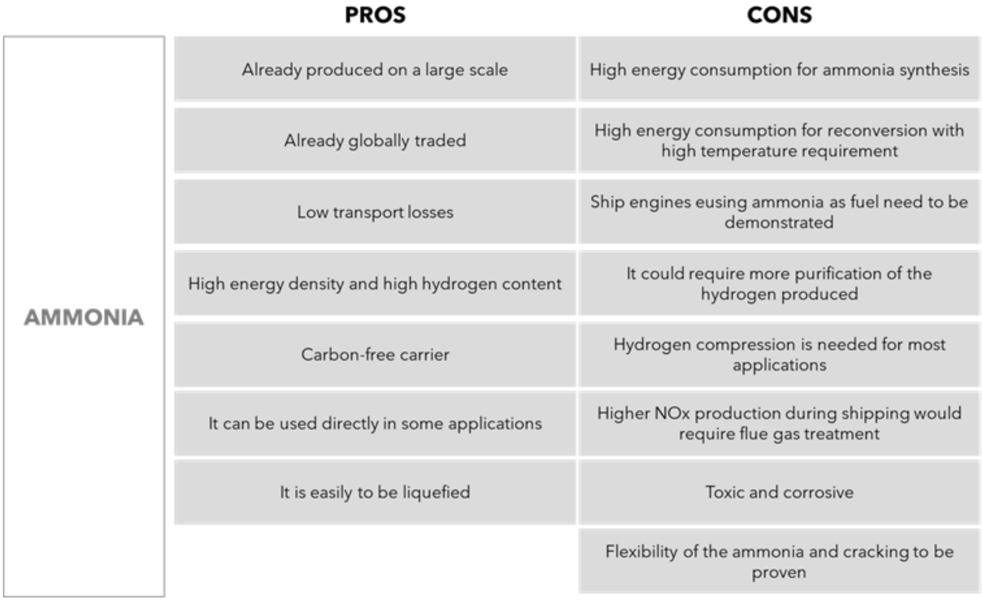
	PROS	CONS
Gaseous HYDROGEN	Transport and storage are proven at commercial scale	Storage in specific reservoirs can lead to losses or/and contamination
	Possibility ro repurpose existing infrastructure	Specific materials are required for hydrogen pipelines
	It is required only compression, no conversion	The gas network is not suitable in all regions
	This carrier is carbon-free	For offshore pipelines the cost increases significantly
	It becomes more attractive as the volume increases	The energy consumption is higher than for natural gas or ships

Figure 129: Advantages and disadvantages of transport by pipeline of gaseous hydrogen, adapted from [79].



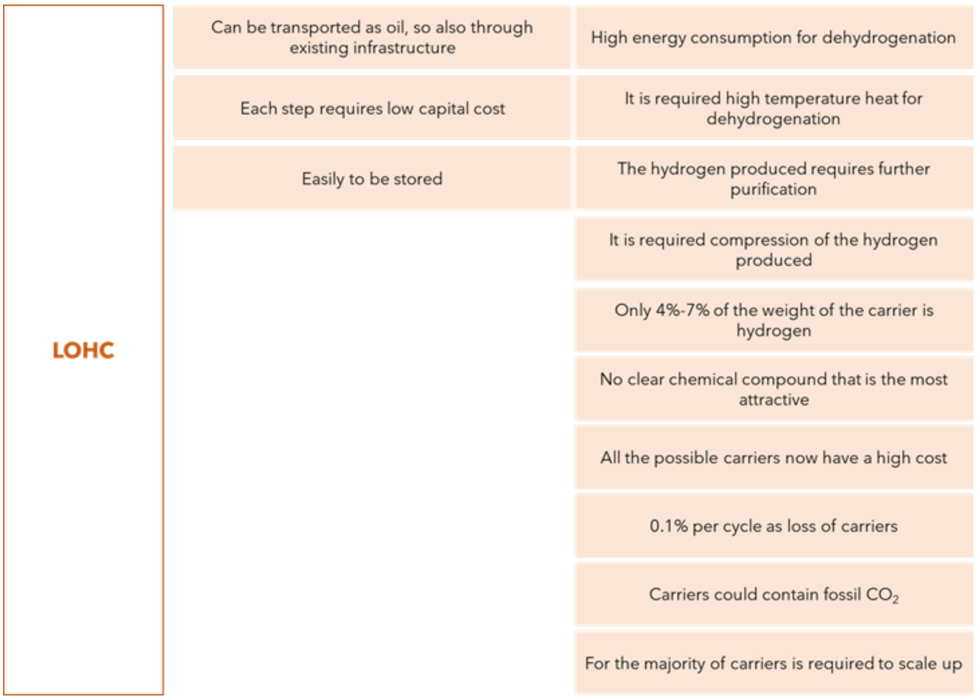
	PROS	CONS
Liquid HYDROGEN	Limited energy consumption for regasification	High energy losses for liquefaction today
	At destination no need for a purification system	Boil-off during shipping and storage
	The transport is easier at the importing terminal	High equipment cost required by cryogenic temperatures
	It is required low energy consumption to increase pressure of hydrogen delivered	Now available only on a small scale
	Liquefaction is a commercial technology	
	The carrier is carbon-free	

Figure 130: Advantages and disadvantages of transport by shipping liquid hydrogen, adapted from [79].



	PROS	CONS
AMMONIA	Already produced on a large scale	High energy consumption for ammonia synthesis
	Already globally traded	High energy consumption for reconversion with high temperature requirement
	Low transport losses	Ship engines eusing ammonia as fuel need to be demonstrated
	High energy density and high hydrogen content	It could require more purification of the hydrogen produced
	Carbon-free carrier	Hydrogen compression is needed for most applications
	It can be used directly in some applications	Higher NOx production during shipping would require flue gas treatment
	It is easily to be liquefied	Toxic and corrosive
		Flexibility of the ammonia and cracking to be proven

Figure 131: Advantages and disadvantages of transport by shipping ammonia, adapted from [79].



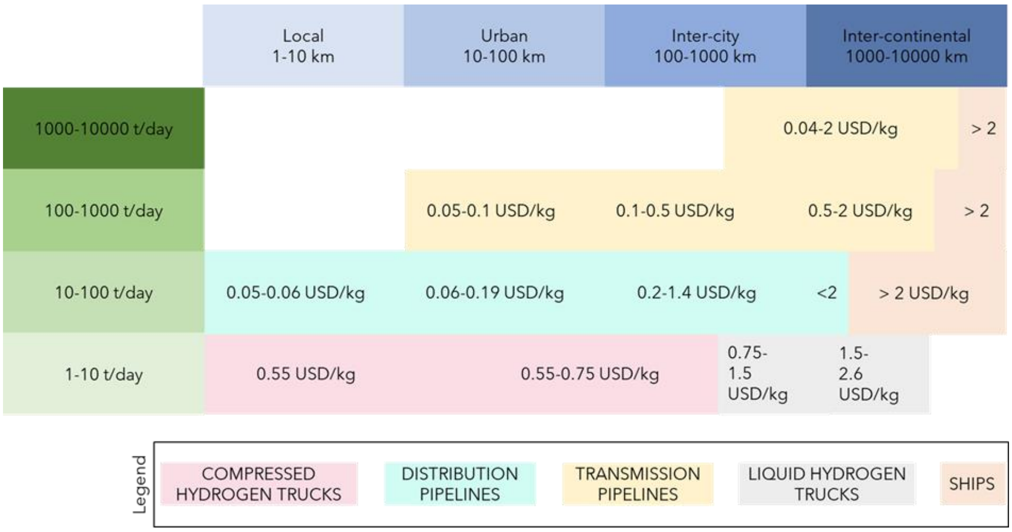
LOHC	Can be transported as oil, so also through existing infrastructure	High energy consumption for dehydrogenation
	Each step requires low capital cost	It is required high temperature heat for dehydrogenation
	Easily to be stored	The hydrogen produced requires further purification
		It is required compression of the hydrogen produced
		Only 4%-7% of the weight of the carrier is hydrogen
		No clear chemical compound that is the most attractive
		All the possible carriers now have a high cost
		0.1% per cycle as loss of carriers
		Carriers could contain fossil CO_2
		For the majority of carriers is required to scale up

Figure 132: Advantages and disadvantages of transport by shipping LOHC, adapted from [79].

To summarise the information detailed from **Figure 129** to **Figure 132**, ammonia is widely produced, stored and traded and its main challenge is related to the reconversion to hydrogen, which is a very energy-intensive process and the same limitation concerns the reconversion of LOHC and the liquefaction of hydrogen [79]. In the latter case, there is the need to get a scale up with respect to the current levels, concerning the liquefaction plants, the required commercial large-scale ships and the development of cryogenic technologies [79]. Considering these four alternatives for hydrogen transport, it is decided to focus on the first three (i.e. gaseous hydrogen, liquid hydrogen, ammonia), according to the technological status and related advantages and disadvantages. In this regard, it is important to analyse the constraints in terms of amount of hydrogen and distance to be addressed while considering a certain pathway for transport. **Table 13** and **Figure 133** summarise the cost-effectiveness of different transport options with respect to the amount of transported hydrogen and the distance from the production site to the consumption site, according to IRENA [48],[79].

Table 13: Cost-efficient transport options when considering volume and distance [48].

- Small volumes (e.g. 0.3 million tonnes of H_2 per year) - Distance below 1500 km	Pipelines cheaper than ships
- Large volumes (e.g. 1.5 million tonnes of H_2 per year) - Distance up to 4000 km	Newly built pipelines
- Large volumes (e.g. 1.5 million tonnes of H_2 per year) - Distance up to 8000 km	Repurposed pipelines
- Large volumes - Long distance	Shipping (for larger distance: ammonia shipping is more cost-effective than liquid hydrogen shipping)



	Local 1-10 km	Urban 10-100 km	Inter-city 100-1000 km	Inter-continental 1000-10000 km
1000-10000 t/day				0.04-2 USD/kg > 2
100-1000 t/day		0.05-0.1 USD/kg	0.1-0.5 USD/kg	0.5-2 USD/kg > 2
10-100 t/day	0.05-0.06 USD/kg	0.06-0.19 USD/kg	0.2-1.4 USD/kg	<2 > 2 USD/kg
1-10 t/day	0.55 USD/kg	0.55-0.75 USD/kg	0.75-1.5 USD/kg	1.5-2.6 USD/kg

Legend: COMPRESSED HYDROGEN TRUCKS | DISTRIBUTION PIPELINES | TRANSMISSION PIPELINES | LIQUID HYDROGEN TRUCKS | SHIPS

Figure 133: Transport options and costs based on volume and distance, adapted from [79].

According to [73], all the EU Member States can exploit pipelines to transport hydrogen, while for North Africa (Morocco and Egypt), island states (Iceland, Ireland, Malta, Cyprus) and long-distance exporters (Australia and United States) transportation by shipping is considered [73]. Other assumptions are elaborated by the EHB, according to which the hydrogen corridor between South Europe and North Africa would be accomplished by 2030, through the creation of 11000 km of large-scale pipelines, with 60% of them as repurposed [69]. In fact, EHB calculated that for places in Europe or near Europe that can exploit pipelines, a pipeline is a more cost-effective alternative than any shipping option, which is the appropriate choice to cover intercontinental distances [69]. To this regard, it is decided to firstly analyse pipelines as transport option; the diameters of 48 inch, 36 inch and 20 inch are addressed in order to consider the cases of large, medium and small size, respectively. For the assumptions, formulas elaborated by a technical brief of The Transition Accelerator are combined with the datasets exploited by the EHB, specifically oriented to the analysis of pipelines as transport option [69],[80]. While considering pipeline systems of large, medium or small size, it is required to include compressors, every 100-200 km. **Figure 134** and **Figure 135** report the evolution of specific costs of the pipeline system, made by the pipeline itself – which can be newly constructed or of repurposed type – and the required compressors. Specifically, the preliminary results concerning the operation of the pipeline system are shown, with a 75% and 25% capacity for the different sizes of pipelines. While pipelines of large and medium size (**Figure 134**) are suitable for transport lines, so for the interconnection among countries involving in trade activities, the 20-inch pipelines (i.e. small size) are mainly exploited to cover the distance from the production site to the transport lines or from the transport lines to the distribution ones (**Figure 135**).

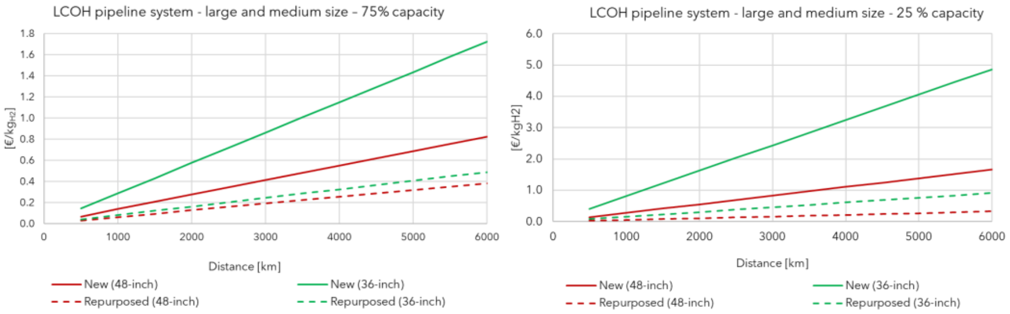


Figure 134: LCOH for pipeline system of large and medium size, operating at 75% and 25% of capacity.

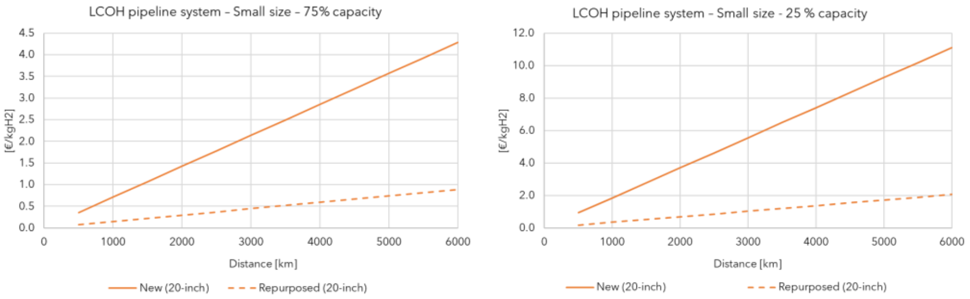


Figure 135: LCOH for pipeline system of small size, operating at 75% and 25% of capacity.

Repurposed pipelines are more convenient but there are some challenges to be addressed; material suitability, pipeline capacity and compression requirements may lead to some criticalities if not adequately managed [79]. Concerning the European infrastructure for pipelines, about 70% of the total pipeline length could be reused for onshore pipelines, while the remaining 30% could be retrofitted, even if huge advancements are required in terms of testing and updated standards [237]. Concerning storage options, hydrogen represents the appropriate complement of batteries in the transport sector; moreover, even if energy storage through batteries is dynamically developed, new types of storage are required, to fulfil the need of larger surplus amount of electricity [238]. In this regard, there are several options for storing hydrogen, which are distinguished between physical- and material-based [238], as summarised in **Figure 136**.

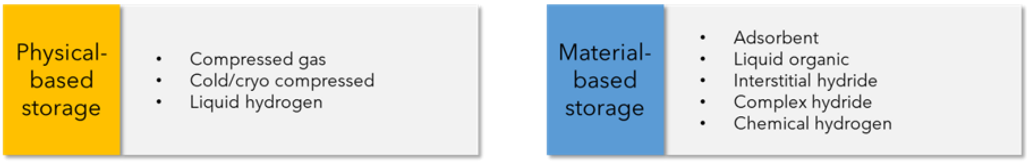
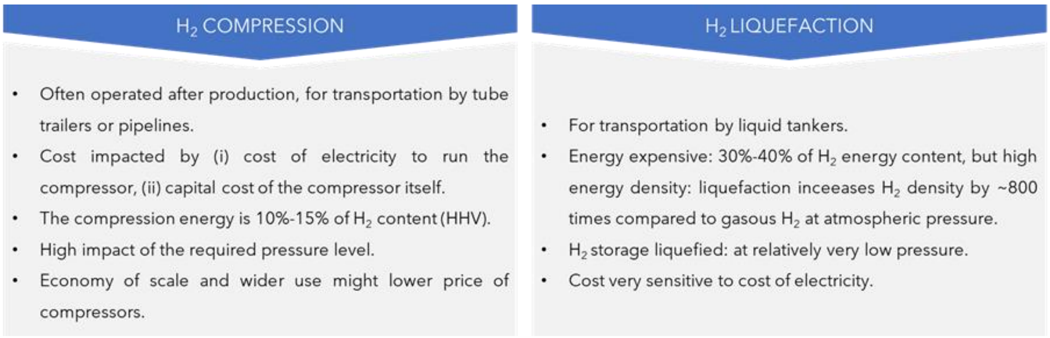


Figure 136: Methods for storing hydrogen, adapted from [238].

Considering that hydrogen has a mass-based energy density which is three times higher than the one of the other liquid hydrocarbons, and also considering that its volumetric energy density is comparatively low, it is required a huge increase of density for storage purposes. For what concerns physical-based storage, it is possible to store gaseous hydrogen in compressed state or liquefied hydrogen; liquefaction requires -253°C, meaning technical and economic challenges to be addressed. Moreover, it is possible to combine compression and cooling, so that the cooled hydrogen is compressed, obtaining a higher energy density than the one of only compressed hydrogen [238]. **Figure 137** compares hydrogen compression and liquefaction, according to a technical brief of IEA-ETSAP [239]:



H_2 COMPRESSION

- Often operated after production, for transportation by tube trailers or pipelines.
- Cost impacted by (i) cost of electricity to run the compressor, (ii) capital cost of the compressor itself.
- The compression energy is 10%-15% of H_2 content (HHV).
- High impact of the required pressure level.
- Economy of scale and wider use might lower price of compressors.

H_2 LIQUEFACTION

- For transportation by liquid tankers.
- Energy expensive: 30%-40% of H_2 energy content, but high energy density: liquefaction inceeases H_2 density by ~800 times compared to gasous H_2 at atmospheric pressure.
- H_2 storage liquefied: at relatively very low pressure.
- Cost very sensitive to cost of electricity.

Figure 137: Compressed vs liquefied hydrogen, adapted from [239].

On the other side, the material-based storage modes are mostly under development, still relying on not appropriate densities, costs and timing [238]. However, in this regard an interesting option consists of ammonia, which is already defined as one of the most promising potential carriers for hydrogen, having a volume which is nearly double of that of liquefied hydrogen [240]. As seen in the transport options and specifically in **Figure 131**, the ammonia option consists of converting hydrogen into ammonia, then transporting it to the final destination and at the end converting ammonia into hydrogen to use it; currently, ammonia cracking is still under development, in fact the conversion rate are now very low (i.e. around a third at best) [240].

While on the small- to mid-scale storage vessels of compressed hydrogen represent a valid option, underground storage through salt caverns, exhausted oil and gas fields or aquifers must be exploited for large-scale storage needs [238],[241]. Nevertheless, there are only few locations in the United States and Europe where hydrogen storage caverns exist; moreover, there are underground natural gas storage which could be available for hydrogen, but only a very small portion of these is really used as storage caverns, considering that the most common alternative for underground storage is represented by depleted gas reservoirs [238]. According to the HyUnder Study [242], salt caverns are the most suitable geological storage for hydrogen; the surface-near storage of gaseous hydrogen is not competitive if compared with salt caverns because of the high cost of pressure vessel containment [241]. In literature, different costs are associated to hydrogen storage through salt caverns, following appropriate assumptions and considering that there are a lot of costs which are site-specific and influenced by local factors and project requirements. To have a look at the several components required to assess the underground storage as option for hydrogen storage, **Figure 138** reports the breakdown of capital cost for a cavern of 2500 ft depth – with a minimum storage pressure of 35 atm, a maximum of 120 atm and a water volume of 78294 m^3 – distinguishing among construction costs, engineering costs, brine disposal costs, aboveground costs as detailed in [242]. The cushion gas percentage is widely estimated to be around 30% [242],[243].

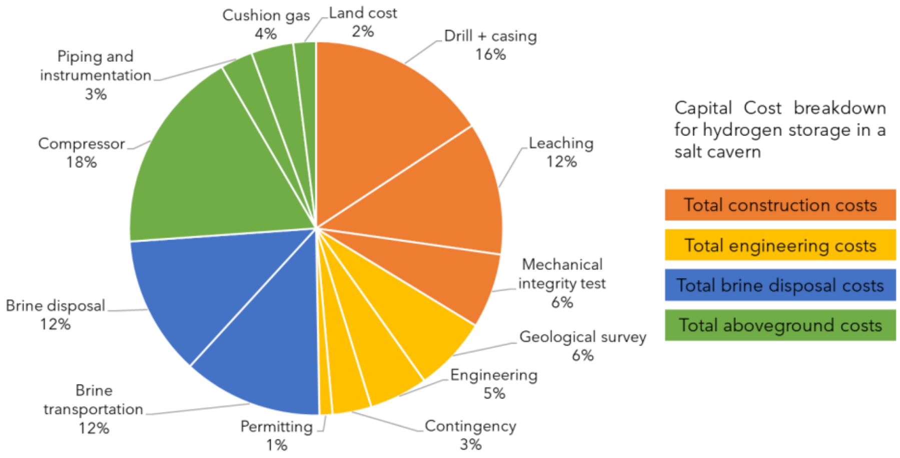
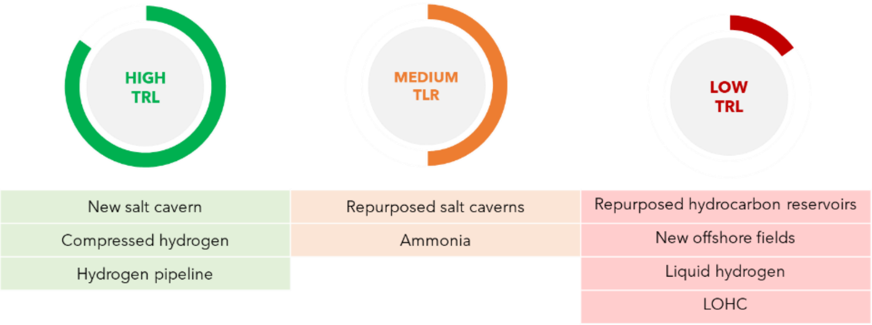


Figure 138: Capital cost breakdown for H_2 storage in salt cavern, adapted from [242].

Figure 139 shows the Technological Readiness Level (TRL) associated to the already introduced transport and/or storage options; salt caverns present a medium-to-high TRL, appropriate for multiple users among power, industrial and heat sectors, and with a low-to-medium hazard and toxicity level [237],[244].



HIGH TRL	MEDIUM TLR	LOW TRL
New salt cavern	Repurposed salt caverns	Repurposed hydrocarbon reservoirs
Compressed hydrogen	Ammonia	New offshore fields
Hydrogen pipeline		Liquid hydrogen
		LOHC

Figure 139: The TRL of several storage and transport options, adapted from [237],[244].

In the attempt to summarise the main features of transport and storage options for green hydrogen and to introduce some preliminary elaborations of costs concerning pipeline systems, this section represents the starting point for new and advanced analyses on green hydrogen and its development, to better investigate and considered the proper inputs and parameters for the scenario analyses to be developed on TIMES model.

3.4.2 Hydrogen trade scenarios to model competitiveness through uncertainty

Energy scenarios are alternative trajectories for the future energy system, which are likely to happen according to specific assumptions; in this way, it is possible to assess and study the evolution of the system if something happens or if something must be achieved. In fact, there are policy scenarios which deal with the effectiveness of different alternative policies towards the achievement of the neutrality target, or also there are normative scenarios providing what is needed by technology and by when to reach a desirable future. Nowadays, because of the urgent actions required to implement the ambitious decarbonization targets and the different alternative pathways and technologies available, with different costs, environmental impact and economic characterization, energy scenarios are a key instrument for policymakers to effectively support and promote ad-hoc strategies, which are locally applicable and efficient worldwide. In order to build scenarios, the whole energy system must modelled; to this end, optimization and simulation techniques can be developed, with the aim to estimate for all the decision variables the values leading to the optimal configuration, or to predict the response of a system for a given set of data, respectively [245]. Moreover, the different description and modelling of the energy system in terms of characterization of components and interactions lead to the distinction between top-down and bottom-up approaches. The former is based on macroeconomic modelling principles and techniques, the latter approach relies on disaggregation and inclusion of a large number of technical parameters. Specifically, bottom-up energy system optimization models are mostly exploited to overcome uncertainties based on modeler's perception of the energy system evolution, including detailed specifications for technologies both on supply and demand sides; linear programming algorithms are used to minimize the cost of the whole system. The integrated MARKAL-EFOM System (ETSAP-TIMES) model generator allows to perform this kind of system-wide optimization [216],[217]. It was built by IEA and ETSAP in the framework of energy models used for IEA analyses; through the combination of a technical engineering approach and an economic approach, it is possible to obtain a least-cost energy system, optimized with respect to specific user's constraints in the medium to long-term time horizon [216],[217]. The analysis of the hydrogen technologies through energy system model makes possible to focus on its interactions and integration within all the other components defined; the MARKAL-TIMES energy model family is among the most common used tool for hydrogen energy systems in energy modelling [246],[247]. Thanks to the period abroad spent in Lisbon with Sofia Simões and Patricia Fortes, the JRC-EU TIMES (JET) model is exploited [51],[248],[249], to analyse to what extent green hydrogen trade from North Africa can contribute to the European decarbonization by 2050. This is the work currently detailed in the RdS deliverable of 2023 under review [214] and a paper within the submission status [215]. **Figure 140** reports how the hydrogen value chain is structured on the JET model, as detailed in [246],[247].

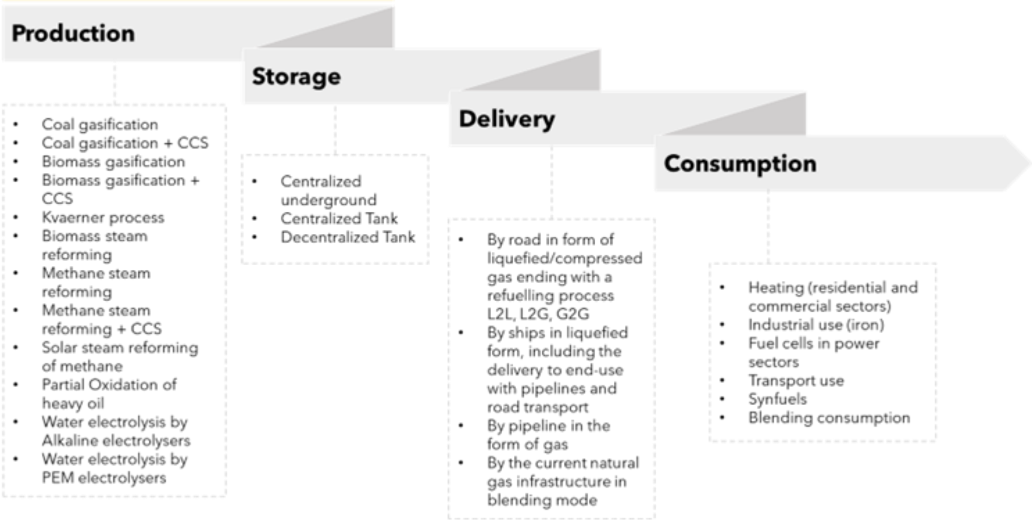


Figure 140: The structure for hydrogen value chain in JET, adapted from [246],[247].

In literature there are several studies focusing on the European potential for domestic production of hydrogen in a decarbonization perspective [65],[74]-[76]. Specifically, the work of Seck et al. [65] exploits the combination of three models, i.e. (i) MIRET-EU, which follows the setup of the JET model, (ii) Integrate Europe, as aggregated energy system model allowing to include technological learning curve, (iii) HyPE, a dedicated model for calculating hydrogen import options for Europe; through scenario analyses assessing different share of renewables, it is found that the growing role of hydrogen goes hand in hand with the increasing integration of RES into the energy system [65]. Moreover, it is highlighted the importance of off-grid plants to power electrolysers, having that the off-grid solutions cover up to the 95% of the total hydrogen production via electrolysers [65]. Another significant result concerns the reliance of Europe on hydrogen imports; according to [65], the imported volume can reach up to 10 to 15 Mt in 2050, considering as exporting countries North Africa, Russia, Ukraine and Middle East. As already discussed in the previous sections, it is undoubted the role that North Africa can play as favourable partners for hydrogen trade; especially focusing on the exploitation of existing pipelines, in blending mode or as repurposed [67],[77],[78]. Modelling pipelines as transport option, the work of Van der Zwaan et al. [77] investigates the potential export of electricity and hydrogen through the Integrated Assessment Model TIAM-ECN; the scenario analysis allows to assess the cost-effectiveness of hydrogen import, but that is decreasing when trade amounts are more constrained [77]. Nevertheless, merely techno-economic analyses are not enough to address the competitiveness of green hydrogen in this new hydrogen game; after studying the predisposition to production and mapping suitability for production plants, it is now important to involve the whole energy system and the parameters of uncertainty which could directly or indirectly affect its deployment to achieve climate-neutrality.

Starting from the datasets collected and the calculations elaborated in the previous sub-sections, specifically related to the production costs (3.4.1.1) and the transport options available (3.4.1.2), to evaluate the multi-level competitiveness of green hydrogen through scenario analyses the workflow in **Figure 141** is introduced and exploited.

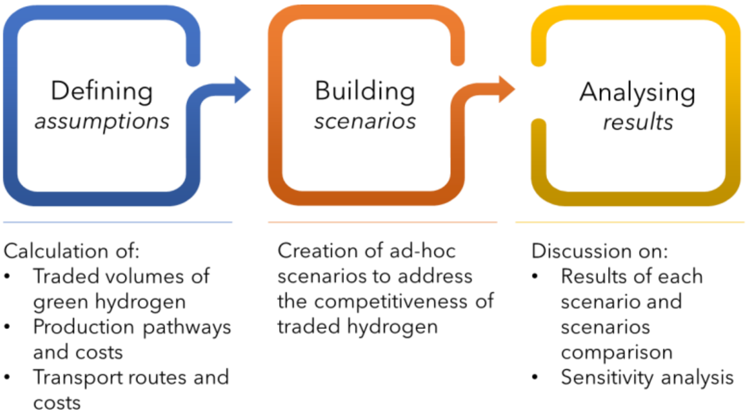


Figure 141: The workflow adopted for scenarios analyses on hydrogen trade on JET.

The first step is devoted to the definition of ad-hoc assumptions for scenario analyses on uncertainty in hydrogen trade and competitiveness, i.e. concerning the traded volumes of hydrogen, the alternative ways of production and related costs, the different transport routes and associated costs (sub-section 3.4.2.1). Having set the assumptions, the following step relates to the identification of specific scenarios able to address all the options available and ranging over the different costs and pathways elaborated (3.4.2.2). Finally, the analysis of the results of each scenario and the comparison among them, followed also by a detailed sensitivity analysis, help to deeply investigate the role of green hydrogen trade from North Africa in the EU decarbonisation (3.4.2.3 and 3.4.2.4).

3.4.2.1 Definition of the assumptions for the scenarios

First, it is required to work on hydrogen volumes available for trade; there are different technical reports or feasibility analyses that are often optimistic with respect to the potential hydrogen production. For this analysis it is decided to assess the national strategies and roadmaps of the involved countries, i.e. Algeria, Morocco and Tunisia, to determine the potential maximum volumes of green hydrogen that can be imported by Europe. **Table 14** summarises the documentations and strategies available to support local production and trade in the North African countries in the long-term.

Table 14: Strategies and roadmaps for hydrogen export in Algeria, Morocco, Tunisia.

Country	*Specific targets*	*Strategies/roadmaps*
Algeria	From 30 to 40 TWh of hydrogen and hydrogen-based fuels to be exported to Europe by 2040.	Government announcement related to a national hydrogen roadmap [250]
Morocco	From 46 to 92 TWh of hydrogen and hydrogen-based fuels to be exported to Europe by 2040; from 115 to 230 TWh of green hydrogen and hydrogen-based fuels to be exported to Europe by 2050.	Green hydrogen roadmap [178],[251]
Tunisia	From 180 to 200 TWh of hydrogen to be exported to Europe by 2050.	Government announcement based on the outputs of the EHB initiative [69],[252]

Specifically, Morocco appears to be ready to hydrogen revolution, making huge efforts in defining a specific roadmap for hydrogen since January 2021 [178],[251] and also giving an essential role to hydrogen in the context of its ambitious long-term low-carbon strategy for 2050 [177], confirming its potential role as hydrogen export-oriented country. Also Algeria is identified as key player for the European decarbonization; at this moment it is declared a strategy defining the commitment of Algeria to export to Europe from 30 to 40 TWh of hydrogen and hydrogen-based fuels by 2040 [250]. Concerning Tunisia, the final hydrogen strategy to be released on mid-March 2023 is not yet finalized while writing [253]. Nevertheless, the General director of the Electricity and Energy Transition at the Ministry of Industry, Mines and Energy, Belhassen Chiboub, making reference to the outputs of the EHB initiative [69], has recently confirmed the hydrogen vision of the country, which aims to strongly influence the hydrogen economy, specifically impacting on the European decarbonization target.

Concerning the costs for hydrogen production, it is decided to start from the calculations and assumptions shown in section 3.4.1, related to the elaboration of the LCOH. Specifically, in the calculation performed in the previous section a WACC of 8% is associated to each North African country; here to better investigate the role of financial risks and how this can impact the cost-effectiveness of trade, changing the level of competitiveness of hydrogen, the WACC for renewable projects recently summarised by IRENA is exploited [254]. Starting from these country-specific values, it is added a 5% to model a higher level of risk, while it is assigned a WACC of 3% to each North Africa countries to work on lower risk. Among the three countries analysed, it is found that the highest risks in renewable projects are associated to Algeria (around 11% of WACC), while Morocco has the lowest (around 6%) [254].

All data reported in the following tables and figures referred to 2010 currency; the calculations of green hydrogen production costs are based on [45],[227]; **Figure 142** reports CAPEX and efficiencies assumed for ALK and PEM electrolysers while working on North Africa and European production. Specifically, it is assumed that there is the same technological maturity and so related costs for electrolysers for all the countries, while potentialities and costs of renewable energy and financial risks in the form of WACC are country-specific.

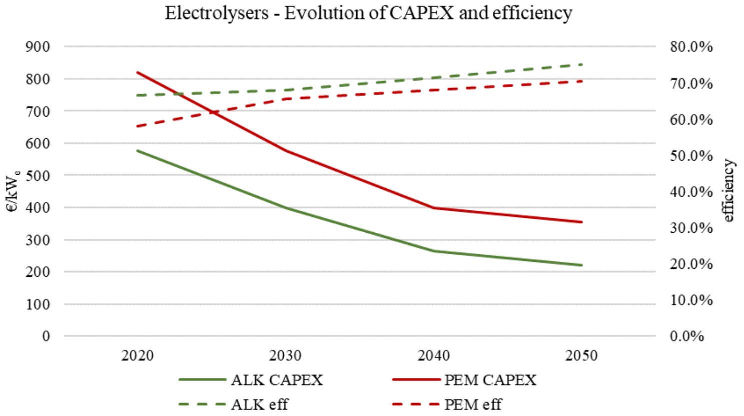


Figure 142: Inputs for CAPEX and efficiency of ALK and PEM, adapted from [45],[227].

Considering all these inputs and assumptions, the LCOH for green hydrogen produced in Algeria, Morocco and Tunisia is calculated for all the already introduced technological combinations, i.e. PV + ALK, PV + PEM, WO + ALK, WO + PEM. The charts below (**Figure 143**) report the different evolution of costs from 2030 to 2050.

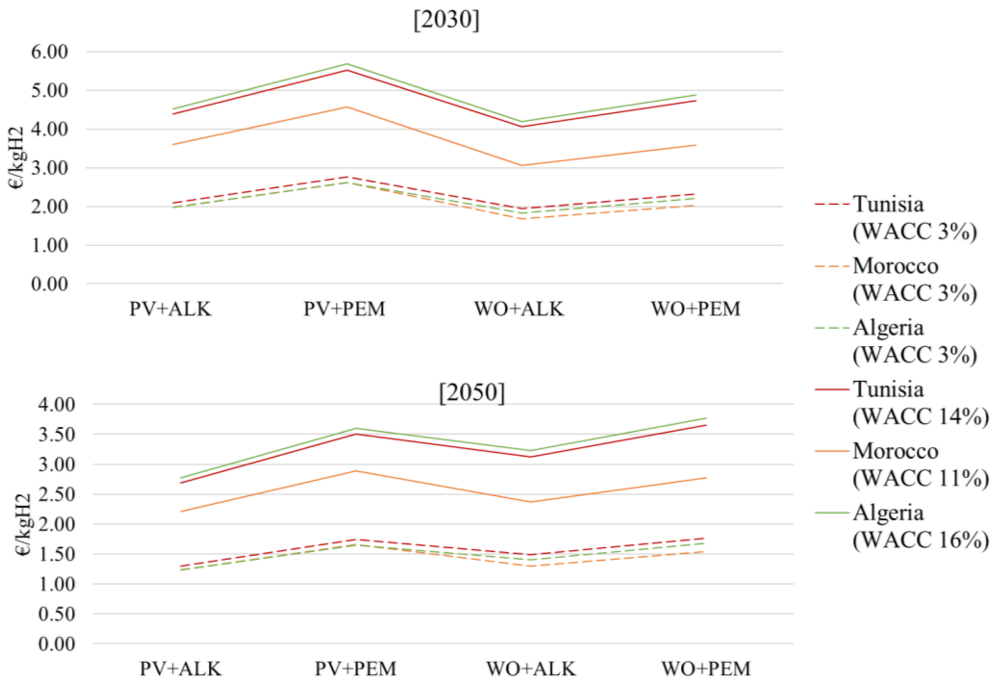


Figure 143: The LCOH assumed for different technologies and risks, in 2030 to 2050.

Concerning the transport options, pipelines, shipping by ammonia, liquefied hydrogen or LOHC are already discussed, detailing potentialities and criticalities (section 3.4.1.2). Specifically looking at the trade path North Africa-Europe, both the transport by pipelines or shipping can be developed [79]; this is because even if it is undoubted that even more for shorter distances pipelines are more affordable than ships, other influencing factors can make the latter more feasible. For instance, a pipeline as physical connection can last 40 years or more, while a ship can afford an offtake agreement of 10 years and change its target market afterwards [79]. Concerning the shipping option, it is decided to model liquefied hydrogen shipping in spite of ammonia; this choice relies on the fact that if electricity in the exporting country is abundant and sufficiently cheaper than in the importing one, liquid hydrogen shipping over ammonia can be the best option [79]. In the elaboration shown in the following figures, the study of IRENA [79] and of the EHB [80],[81] are exploited. **Figure 144** collects a pessimistic and an optimistic cost evolution respectively for onshore pipelines for gaseous hydrogen, offshore pipelines for gaseous hydrogen and liquefied hydrogen shipping; the two cases allows to account for the most and less favourable conditions for transport, as assessed by the cost ranges evaluated by [79],[80],[81]. Concerning pipelines, the values referred to the EHB study which works on the European volumes and capacity [80],[81], so that an average on new and repurposed pipelines is exploited [80]. The elaborations on shipping costs refer to the assumptions for very large projects (1.5 Mt/y) adopted by IRENA [79].

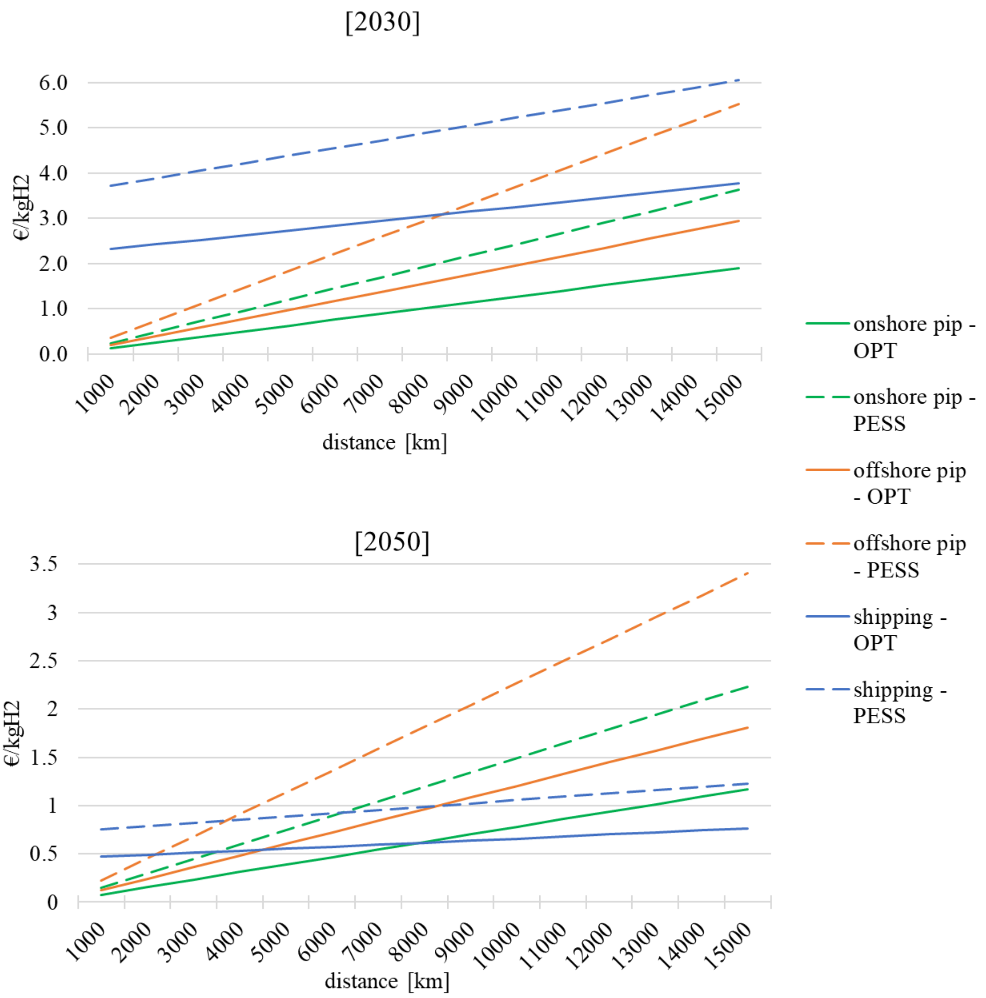


Figure 144: The cost over distance for hydrogen transport options in 2030 (up) and 2050 (down), elaborated starting from [79],[81].

3.4.2.2 Identification of the scenarios for trade competitiveness

In the attempt to study the effects of uncertainty on hydrogen trade competitiveness and to exploit the assumptions and elaborations already shown about production and transport costs and routes, different energy scenarios are built, as shown in **Figure 145**. Specifically, the identified scenarios allow to take into account (i) different traded hydrogen volumes, (ii) different financial risks affecting projects for green hydrogen production, (iii) alternative routes and costs for transport of hydrogen. **Table 15** reports the characterization of scenarios, with "optimistic" accounting for the most favourable conditions of market push and strength, i.e. higher importable hydrogen volumes at lower costs, while “pessimistic” refers to lower global coordination and higher risks, i.e. lower importable volumes at higher costs. In the following, the specific inputs are discussed and explained (**Table 15**).

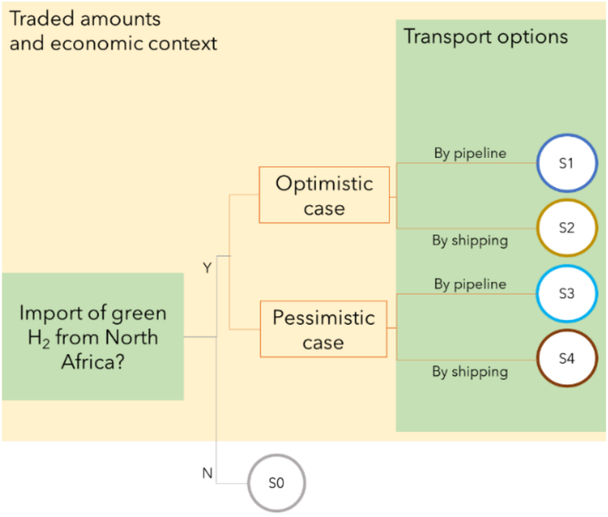


Figure 145: The identification of the alternative scenarios under assessment.

Table 15: The basic assumptions for each scenario analysed.

Scenario name	*Details on assumptions*
S0	No importable hydrogen volumes from North Africa; only local production and trade among EU countries available.
S1	Optimistic (higher) importable volumes from North Africa; optimistic (lower) costs for production in North Africa; transport by pipeline at optimistic (lower) cost to Spain, Italy, Portugal.
S2	Optimistic (higher) importable volumes from North Africa; optimistic (lower) costs for production; transport by ships at optimistic (lower) cost to each EU country having at least a terminal available.
S3	Pessimistic (lower) importable volumes from North Africa; pessimistic (higher) costs for production in North Africa; transport by pipeline at optimistic (higher) cost to Spain, Italy, Portugal.
S4	Pessimistic (lower) importable volumes from North Africa; pessimistic (higher) costs for production; transport by ships at pessimistic (higher) cost to each EU country having at least a terminal available.

As already introduced, the JET model [246],[247], as European-wide partial-equilibrium model with disaggregation at a country level, was developed and released in 2013 by the Joint Research Centre (JRC) of the European Commission and has been widely use to model EU's energy system decarbonisation, including hydrogen economy [51],[249]. According to the model setup, its spatial coverage is based on all the 27 Member States of the European Union, plus United Kingdom, Norway, Switzerland, and Iceland (namely EU+); each year is modelled through 12 time-slices, with an average of day, night and peak demand per season. The JET model is deeply described and analysed in [248],[249].

In the original setup of JET only the hydrogen trade among EU+ countries is available, according to the same trade links used for natural gas; to integrate the green hydrogen trade option from North Africa, six new processes are added (**Figure 146**). Each process is country-specific and address one of the two alternative options for transport, i.e. pipelines or liquefied hydrogen ships. In addition to this, on the domestic production side, the EU+ countries are allowed to produce green hydrogen through off-grid solar PV plants too.

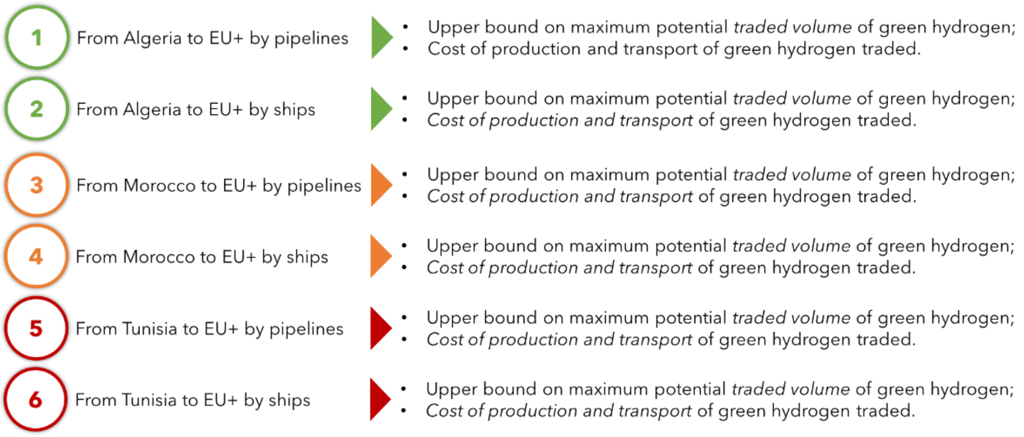


Figure 146: The six processes integrated in JET to model hydrogen import from North Africa.

All the scenarios shown in **Figure 145** are built upon the target of 95% reduction of EU-wide CO_2 energy-related emissions in 2050 with respect to the 1990 levels. To assign specific traded volumes and costs of green hydrogen to each process, the optimistic and pessimistic cases are exploited. Specifically, the production costs are calculated as the average of the LCOH per technology already detailed and explained by **Figure 142** and **Figure 143**, while for the elaboration on transport **Figure 144** is followed. The assumptions leading to the definition of scenarios (**Table 15**) are numerically detailed in **Table 16**.

Table 16: The numerical assumptions collected for the elaboration of scenarios.

	Traded H_2 volumes [Mt_{H2}]		*Production cost [$€_{2010}/kg_{H2}$]*		*Transport cost [$€_{2010}/kg_{H2}$]*	
	2030	*2050*	*2030*	*2050*	*2030*	*2050*
S0	-	-	-	-	-	-
S1	ALG: 0.30 Mt$_{H2}$ MOR: 0.65 Mt$_{H2}$ TUN: 0.5 Mt$_{H2}$	ALG: 3.0 Mt$_{H2}$ MOR: 6.89 Mt$_{H2}$ TUN: 5.5 Mt$_{H2}$	ALG: 2.15 €/kg MOR: 2.08 €/kg TUN: 2.28 €/kg	ALG: 1.49 €/kg MOR: 1.43 €/kg TUN: 1.57 €/kg	On. pip.: 0.13 €/kg/1000km Off. pip.: 0.20 €/kg/1000km	On. pip.: 0.08 €/kg/1000km Off. pip.: 0.12 €/kg/1000km
S2					LH2 ships: @1000 km: 2.61 €/kg @6000 km: 3.19 €/kg	LH2 ships: @1000 km: 0.53 €/kg @6000 km: 0.65 €/kg
S3	ALG: 0.23 Mt$_{H2}$ MOR: 0.31 Mt$_{H2}$ TUN: 0.2 Mt$_{H2}$	ALG: 2.25 Mt$_{H2}$ MOR: 2.75 Mt$_{H2}$ TUN: 2.8 Mt$_{H2}$	ALG: 4.82 €/kg MOR: 3.7 €/kg TUN: 4.67 €/kg	ALG: 3.34 €/kg MOR: 3.44 €/kg TUN: 3.24 €/kg	On. pip.: 0.24 €/kg/1000km Off. pip.: 0.37 €/kg/1000km	On. pip.: 0.15 €/kg$_{H2}$/1000km Off. pip.: 0.23 €/kg$_{H2}$/1000km
S4					LH2 ships: @1000 km: 4.18 €/kg @6000 km: 5.12 €/kg	LH2 ships: @1000 km: 0.85 €/kg @6000 km: 1.04 €/kg

Concerning the transport options, the cost for pipelines is elaborated according to the already known distances of the natural gas pipelines – Medgaz, Maghreb and Transmed – connecting Algeria with Spain, Algeria and Morocco with Portugal and Spain, Algeria and Tunisia with Italy (**Table 17**).

Table 17: The green hydrogen costs for the scenarios S1 and S3 (transport by pipelines, optimistic and pessimistic).

From	*to*	*Green hydrogen cost (production + transport) [€/kg$_{H2}$]*			
		S1		*S3*	
Country 1	*Country 2*	*2030*	*2050*	*2030*	*2050*
Algeria	Italy (IT)	2.30	1.58	5.10	3.51
	Portugal (PT)	2.36	1.62	5.16	3.55
	Spain (ES)	2.24	1.54	4.98	3.44
Morocco	Portugal (PT)	2.18	1.50	3.91	3.37
	Spain (ES)	2.12	1.46	3.78	3.29
Tunisia	Italy (IT)	2.33	1.61	4.77	3.31

For the liquefied hydrogen shipping three selected terminals in Algeria, Morocco and Tunisia (respectively, Oran, Jorf Lasfar, Sfax) are accounted to calculate the distances from the countries where there is an LNG terminal at least. Specifically, for the EU+ countries where more than one terminal is under operation or construction or planned, the average distance is exploited to elaborate the final costs; the accounted terminals (status 2022) are elaborated starting from [255], as shown in **Figure 147** from the European Commission, while the final costs for S2 and S4 are summarised in **Table 18**, highlighting that twenty countries are modelled as potentially connected by shipping options to North Africa.

Figure 147: The European LNG infrastructure (status 2022), by EU Commission [255].

Table 18: The green hydrogen costs for the scenarios S2 and S4 (transport by ships, optimistic and pessimistic).

From	*to*	*Green hydrogen cost (production + transport) [€/kg$_{H2}$]*			
		S2		*S4*	
Country 1	*Country 2*	*2030*	*2050*	*2030*	*2050*
Algeria	Belgium	4.19	1.78	7.93	3.70
	Croatia	4.15	1.77	7.87	3.69
	Cyprus	4.19	1.78	7.93	3.70
	Estonia	4.42	1.83	8.30	3.78
	Finland	4.42	1.83	8.31	3.78
	France	4.09	1.76	7.77	3.67
	Germany	4.23	1.79	8.00	3.72
	Greece	4.15	1.77	7.87	3.69
	Ireland	4.14	1.77	7.85	3.69
	Italy	3.98	1.74	7.60	3.64
	Latvia	4.41	1.83	8.28	3.77
	Lithuania	4.37	1.82	8.22	3.76
	Malta	4.03	1.75	7.68	3.65
	Netherlands	4.19	1.78	7.94	3.70
	Norway	4.46	1.84	8.37	3.79
	Poland	4.34	1.81	8.18	3.75
	Portugal	3.96	1.74	7.57	3.63
	Spain	3.98	1.74	7.60	3.64
	Sweden	4.32	1.81	8.14	3.74
	UK	4.17	1.78	7.91	3.70
Morocco	Belgium	4.08	1.73	6.88	3.00
	Croatia	4.14	1.74	6.97	3.02
	Cyprus	4.19	1.75	7.04	3.03
	Estonia	4.31	1.77	7.25	3.07
	Finland	4.33	1.78	7.28	3.08
	France	4.02	1.71	6.77	2.98
	Germany	4.13	1.74	6.95	3.01
	Greece	4.15	1.74	6.99	3.02
	Ireland	4.03	1.72	6.80	2.98
	Italy	4.06	1.72	6.84	2.99
	Latvia	4.30	1.77	7.23	3.07
	Lithuania	4.26	1.76	7.17	3.06
	Malta	4.03	1.72	6.80	2.98
	Netherlands	4.09	1.73	6.89	3.00
	Norway	4.36	1.78	7.32	3.09
	Poland	4.24	1.76	7.13	3.05
	Portugal	3.86	1.68	6.52	2.93
	Spain	3.92	1.69	6.62	2.95
	Sweden	4.21	1.75	7.08	3.04
	UK	4.07	1.72	6.85	2.99
Tunisia	Belgium	4.44	1.89	8.02	3.66
	Croatia	4.14	1.83	7.54	3.56
	Cyprus	4.17	1.83	7.59	3.57
	Estonia	4.66	1.93	8.39	3.74
	Finland	4.68	1.94	8.42	3.74
	France	4.30	1.86	7.80	3.62

Germany	4.48	1.90	8.09	3.67
Greece	4.15	1.83	7.56	3.57
Ireland	4.39	1.88	7.94	3.64
Italy	4.08	1.82	7.44	3.54
Latvia	4.65	1.93	8.37	3.73
Lithuania	4.62	1.92	8.31	3.72
Malta	4.03	1.81	7.36	3.53
Netherlands	4.44	1.89	8.03	3.66
Norway	4.71	1.94	8.46	3.75
Poland	4.59	1.92	8.27	3.71
Portugal	4.21	1.84	7.66	3.59
Spain	4.21	1.84	7.65	3.59
Sweden	4.56	1.91	8.22	3.70
UK	4.42	1.88	7.99	3.66

3.4.2.3 Scenario analyses: discussion on results

To investigate the outputs of the modelled scenarios, this section addresses step by step the following questions: 1) How much will EU+ rely on green hydrogen trade from North Africa? How do the transport options affect the trade? 2) How EU+ countries are impacted by green hydrogen trade from North Africa? 3) Which EU+ economic sectors are affected by this trade? 4) What does this trade mean in terms of mitigation for EU+?

According to the modelled scenarios, from 2030 to 2050 different amounts cover the whole EU+ hydrogen demand (**Figure 148**). In the short-term (2030), only Morocco exports hydrogen into Spain via pipeline in the optimistic case (S1) – the 22% of the hydrogen amount available for trade is imported by Spain. From 2040 on, all the hydrogen available for trade from North Africa is imported by EU+ in each modelled scenario, i.e. by pipelines and ships, in both optimistic and pessimistic cases.

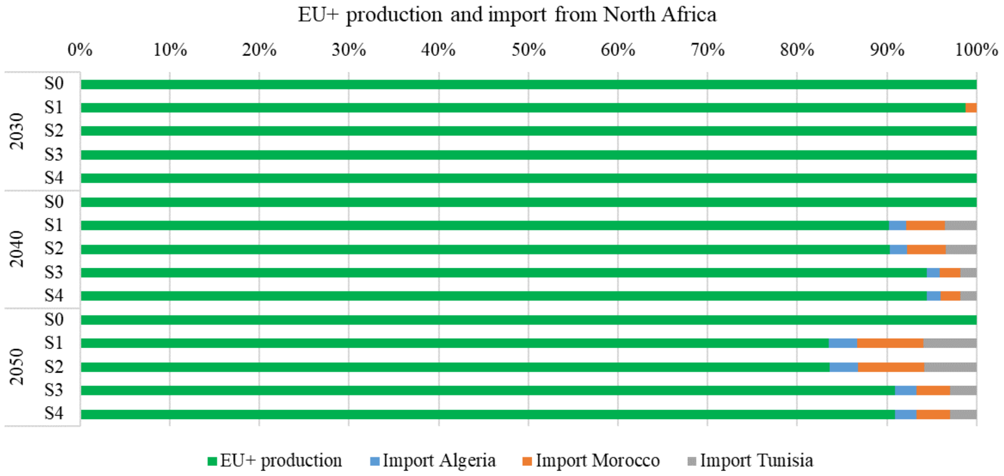


Figure 148: The contribution to the EU+ hydrogen demand of the local production and of the North African import.

Having that in 2040 and 2050 all the available amount is imported (**Figure 148**) even if EU+ can afford to locally satisfy the majority of its hydrogen demand, Morocco, Algeria and Tunisia can be identified as major players in the context of hydrogen trade, supplying it at lower energy system costs in the long-term. Specifically, it is important to stress that also in case of pessimistic scenarios, when higher risks and lower global market coordination is modelled through higher costs and lower available amounts (i.e. in S3 and S4), all the trade to Europe is affordable by the energy system modelled. In each case, the traded hydrogen amounts by 2050 cover only around 16.5% of the EU+ demand in scenarios S1 and S2 (i.e., the optimistic cases) and only around 9% in scenarios S3 and S4 (i.e., the pessimistic cases). It is relevant to mention that hydrogen from Morocco is responsible of almost half of this trade. This is in line with the fact that Morocco is the only country among the three analyzed to have a structured hydrogen roadmap, which carefully addresses exports [179]. **Figure 149** and **Figure 150** detail the flows of trade from Algeria, Morocco and Tunisia through a Sankey diagram built for each scenario in 2040 and 2050.

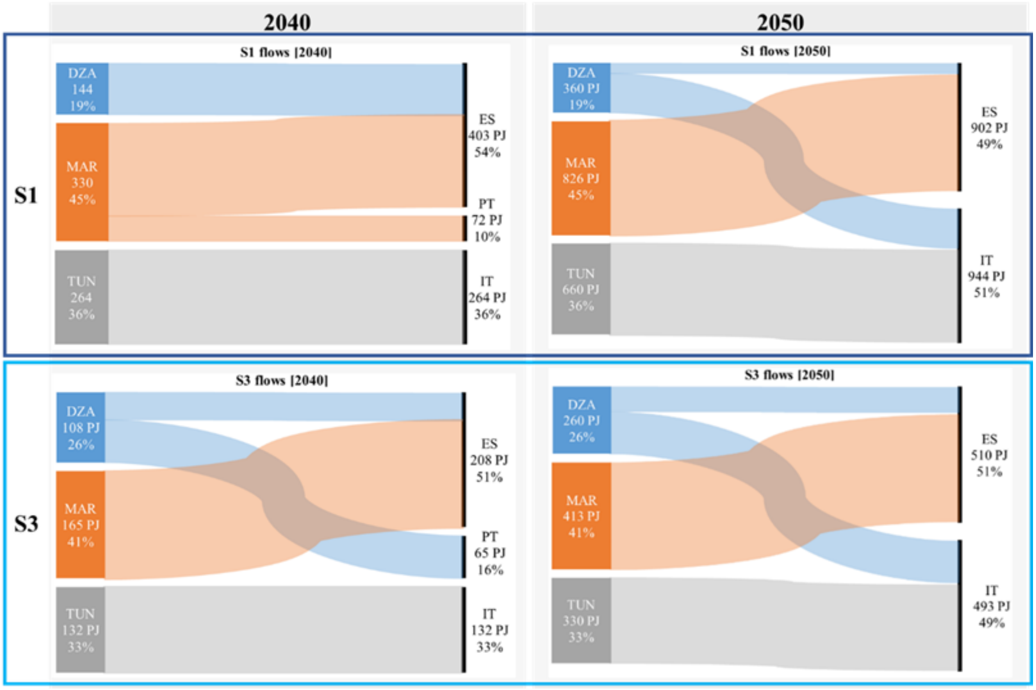


Figure 149: Trade flows in the form of Sankey diagram for S1 and S3, by 2040 and 2050.

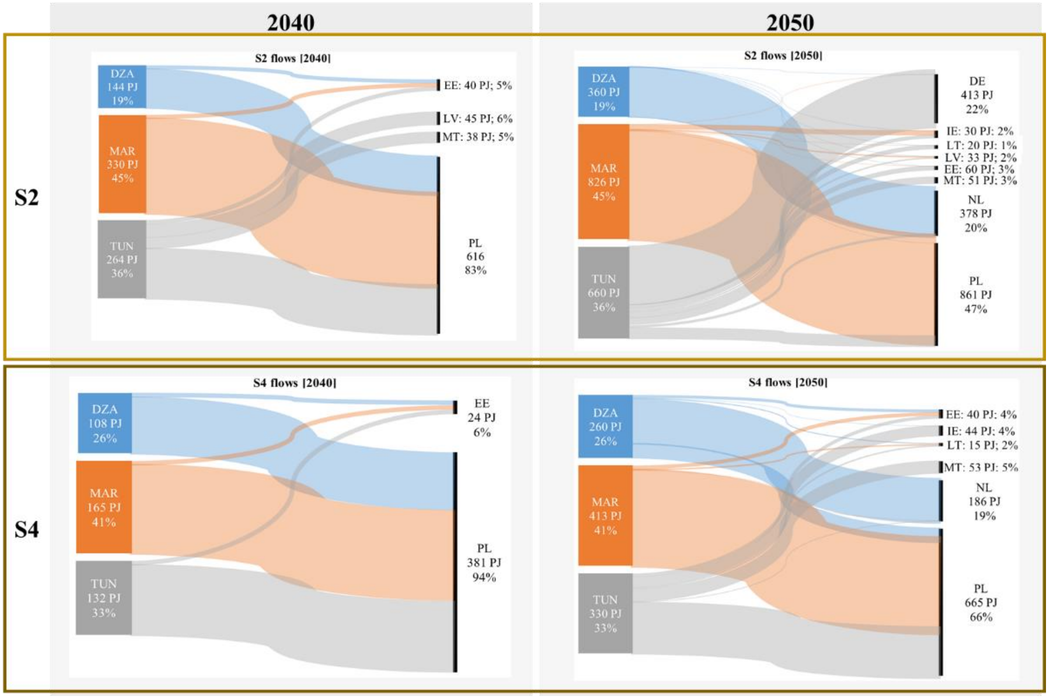


Figure 150: Trade flows in the form of Sankey diagram for S2 and S4, by 2040 and 2050.

Looking at the transport options, while pipelines have the possibility to become competitive also in the short-term, the liquefied hydrogen shipping, as expected, is exploited directly from 2040 and specifically only by countries that have not the option of pipelines. In other words, Spain, Italy and Portugal are not involved in the trade when the shipping options are available, confirming that this transport option is consistent with the hydrogen market only for longer distances. On the other side, the fact that different countries are involved in trading when ships are modelled highlights the need of diversification for trade pathways, allowing the selection of different countries which can directly benefit from green hydrogen coming from North Africa. Focusing on the scenarios modelling pipelines (i.e. S1 and S3, in **Figure 149**), Italy and Spain are the predominant importers. Notably, Portugal plays a marginal role in trade, importing hydrogen only by 2040, primarily from Morocco in S1 and from Algeria in S3. However, when using liquid hydrogen shipping, additional nations like Poland, the Netherlands and Germany start to be involved in trade. In 2050 other countries such as Malta, the Baltic nations, and Ireland also import renewable hydrogen by shipping, but their volumes are comparatively smaller. These findings highlight the significance of addressing uncertainties related to costs and trade routes within the EU+ hydrogen trade. Examining the results for shipping options (**Figure 150**), it is noteworthy that in 2040 Poland emerges as the primary importer of the majority of available hydrogen, in both optimistic and pessimistic scenarios. Moving into 2050, in scenario S2 Germany takes the role of major importer from Tunisia, while the Netherlands assume this position for Algeria. Even in S4, the Netherlands continues to be the major importer of most hydrogen produced in Algeria.

In addition to this, it is important to consider that each EU+ country has the capacity to either locally produce or engage in hydrogen trade within the other EU+ countries to meet its individual demand. **Table 19** and **Table 20** outline diverse percentage ranges by rows, representing the deviation from scenario S0 for each country in 2050, focusing on hydrogen production and consumption respectively. Analyzing the European average, it is observed that, due to the imports from North Africa, EU+ hydrogen production decreases by up to 15% compared to S0, particularly in S1. In contrast, EU+ hydrogen consumption sees an increase up to 3% in S2, and 2.3% in S1. This implies that the EU+ relies on North African hydrogen to reduce its own overall hydrogen production. However, the additional imported hydrogen is not directly consumed in its original form (see **Figure 154**). Despite this overarching trend, specific countries exhibit varying responses to the trade of hydrogen from North Africa, showcasing different levels of sensitivity to surplus availability.

Table 19: % difference with respect to S0 for local production of hydrogen in 2050.

Production by country – delta wrt S0 [2050]

<table>
<tr><th></th><th><i>S1 wrt S0</i></th><th><i>S2 wrt S0</i></th><th><i>S3 wrt S0</i></th><th><i>S4 wrt S0</i></th></tr>
<tr><td>> 75%</td><td colspan="4">CZ, DK, SK</td></tr>
<tr><td>35% to 75%</td><td colspan="2">BE, BG</td><td colspan="2">-</td></tr>
<tr><td rowspan="2">5% to 35%</td><td colspan="4">CH, HU</td></tr>
<tr><td>EE, LT, LU, LV, PT, RO, UK</td><td>NO, PT, RO</td><td>BE, BG, LT, LV, UK</td><td>BE, BG, PT, RO</td></tr>
<tr><td rowspan="2">-5% to 5%</td><td colspan="4">AT, CY, EL, FI, SE</td></tr>
<tr><td>NO, MT</td><td>IT, LU, UK</td><td>DE, EE, LU, NO, PT, MT</td><td>DE, IT, LU, NO, UK</td></tr>
<tr><td rowspan="3">-35% to -5%</td><td colspan="4">ES, HR, IS, NL, <i>EU+</i></td></tr>
<tr><td>PL</td><td>LT</td><td>PL, RO</td><td>LT, LV</td></tr>
<tr><td colspan="2">DE</td><td colspan="2">FR</td></tr>
<tr><td>-75% to -35%</td><td>FR, IT</td><td>FR, LV, PL</td><td>IE, IT, SI</td><td>PL</td></tr>
<tr><td rowspan="2">< -75%</td><td></td><td>EE, MT</td><td rowspan="2">-</td><td rowspan="2">EE, IE, MT, SI</td></tr>
<tr><td colspan="2">IE, SI</td></tr>
</table>

Concerning local production, countries such as Austria, Cyprus, Greece, Finland, and Sweden consistently exhibit no impact from North African hydrogen in all scenarios, with variations in local production ranging from -5% to 5%. On the other hand, Germany, the United Kingdom, Italy and Norway are unaffected by the available trade in specific modelled scenarios. Notably, Czechia, Denmark, Slovakia, Ireland and some Baltic countries are more sensitive to trade, experiencing a higher degree of impact on their national hydrogen production.

Table 20: % difference with respect to S0 for local consumption of hydrogen in 2050.

Consumption by country - delta wrt S0 [2050]

<table>
<tr><th></th><th><i>S1 wrt S0</i></th><th><i>S2 wrt S0</i></th><th><i>S3 wrt S0</i></th><th><i>S4 wrt S0</i></th></tr>
<tr><td>> 75%</td><td colspan="2">BG</td><td colspan="2">-</td></tr>
<tr><td>35% to 75%</td><td colspan="2">AT</td><td>-</td><td>BG</td></tr>
<tr><td rowspan="2">5% to 35%</td><td colspan="4">LV</td></tr>
<tr><td colspan="2">EE, PT, RO</td><td>BG, AT</td><td>IE, PT, RO, AT</td></tr>
<tr><td rowspan="2">-5% to 5%</td><td colspan="4">BE, CH, CY, CZ, DE, DK, EL, ES, FI, FR, HR, HU, IT, LT, LU, MT, NL, PL, SE, SI, SK, UK, <i>EU+</i></td></tr>
<tr><td colspan="2">IE</td><td>EE, IE, NO, PT</td><td>NO</td></tr>
<tr><td rowspan="2">-35% to -5%</td><td colspan="4">IS</td></tr>
<tr><td>NO</td><td>-</td><td>RO</td><td>EE</td></tr>
</table>

-75% to -35%	-	NO	-
< -75%	-		

Across all the scenarios, Spain, Italy and the Netherlands consistently reduce their domestic production. Conversely, on the consumption side, Norway experiences a decrease in its national hydrogen consumption when starting trade with North Africa. Additional nations emerge, such as Austria, where despite maintaining similar levels of local production, an increase in consumption is noted due to indirect imports from North Africa. In contrast, countries like Bulgaria experience an increase in both production and consumption. These observations underscore the potential impact of trading hydrogen with North Africa on the dynamics of intra-EU hydrogen interactions.

Looking at country level, it can be of interest to focus on the impact that hydrogen have on different local economies; specifically, in the following figures it is detailed the hydrogen balance for specific nations, considered the related demand of the reference scenario modelled. In fact, in 2050 Germany has the highest share of hydrogen demand in Europe (32% of the total), followed by Spain (10%), Poland (8%), France, Italy and the Netherlands (7%). Figures below are grouped according to the magnitude of the delta that each country experiences when dealing with the different trades by scenarios. Specifically, **Figure 151** shows how Spain and Italy share the same ranges in terms of delta when focusing on the terms of the hydrogen balance, i.e., production, consumption, European import and export, North African import. On one side, Italy is strongly impacted just in S1 and S3 – when pipelines are modelled – by a decrease in production that does not affect consumption, being replaced by the additional amounts from North Africa. On the other side, the role of corridor played by Spain influences the results of S2 and S4, too. In all the scenarios there is a decrease in Spanish production that has different impacts on the right side of the balance; in S1 the imported amounts from North Africa make possible to increase the export in S1 without changing the behavior in consumption, while in S2 and S4 it happens that the EU export from Spain to Europe decreases, being substituted by the direct trade with North Africa.

According to **Figure 152**, Germany is able to have a slight increase in consumption without changing its local production trend; in S2, while benefitting directly from North African hydrogen, there is a huge decrease in local import and a smaller decrease in local export. While looking at France, the local export decreases more than the local import, to leave unchanged the consumption when the production is strongly decreasing.

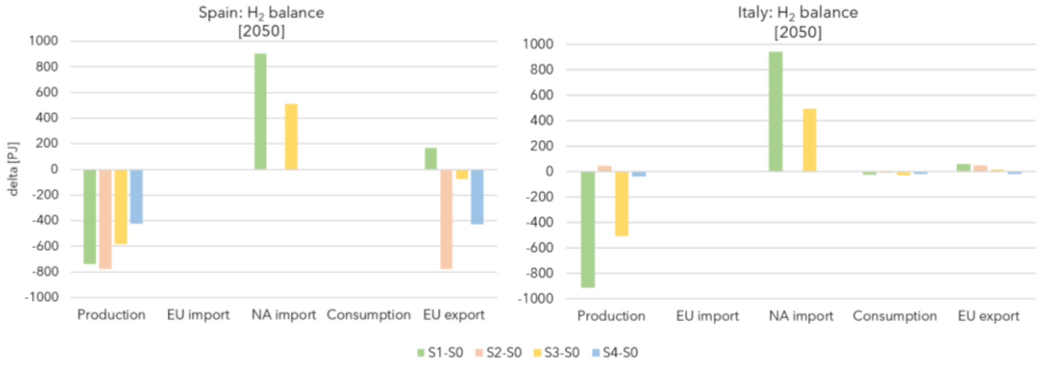


Figure 151: Hydrogen balance in terms of delta with respect to S0 for Spain and Italy; year: 2050.

Figure 152: Hydrogen balance in terms of delta with respect to S0 for Germany and France; year: 2050.

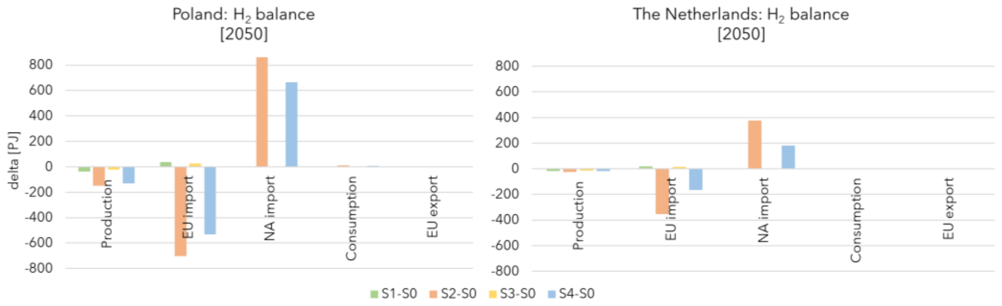


Figure 153: Hydrogen balance in terms of delta with respect to S0 for Poland and the Netherlands; year: 2050.

The hydrogen balances shown in **Figure 153** for Poland and the Netherlands – which play a crucial role in S2 and S4 as major importers of hydrogen by North Africa – highlight how the extra-EU volumes substitute the European import, ensuring at the same time no changes in the consumption behavior of these countries. In more general terms, these country-specific graphs (**Figure 151**, **Figure 152**, **Figure 153**) allow to stress the competitiveness of North African hydrogen in supporting the European decarbonization, specifically reducing the local production but without impacting the consumption trends. However, as already stressed, each country reacts differently to the different scenarios modelled, in terms of local production, extra and intra-EU trade.

Focusing on hydrogen consumption and distinguishing between its direct and indirect usage, even in scenario S0, the majority of hydrogen is consumed by the transport sector. The introduction of additional imports from North Africa results in minor variations in the overall hydrogen consumption compared to the baseline scenario, having that it is mostly substituted the local production. However, although the differences are modest, more noticeable impacts are observed in indirect hydrogen consumption, particularly in terms of hydrogen conversion into synfuels and heat (refer to **Figure 154** and **Table 21**). Specifically, **Figure 154** shows the extent to which the scenarios deviate from the base case scenario S0 (without import options), with S0 hydrogen consumption represented by a grey bar, and the relative differences in consumption in other scenarios are illustrated as specific points with different shapes and colors.

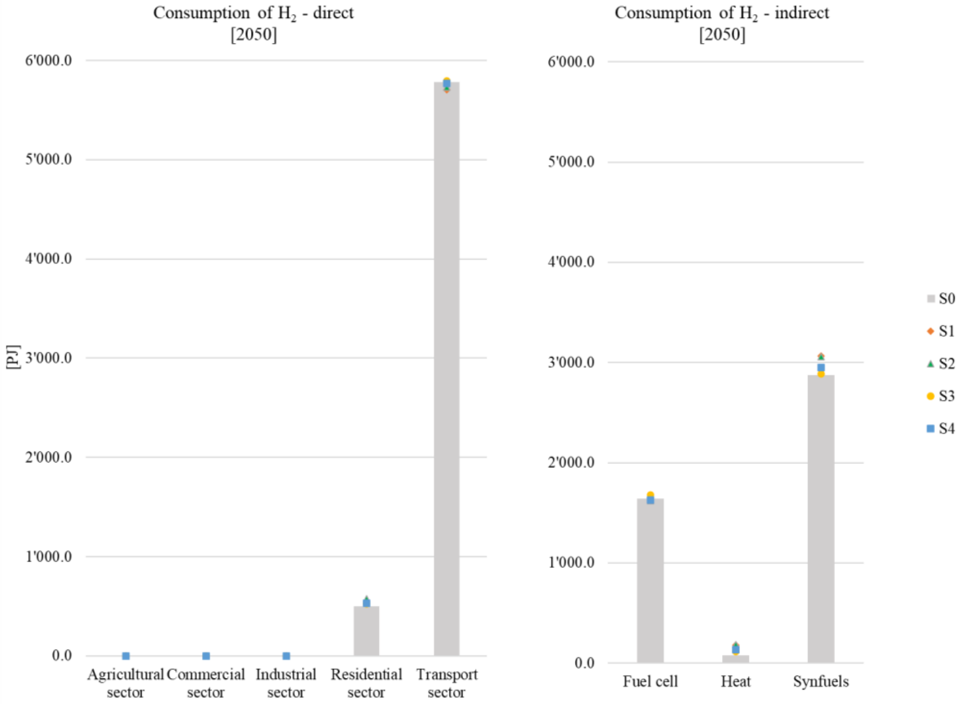


Figure 154: Consumption of hydrogen for S0 compared to the trade scenarios; year: 2050. a) Direct consumption of hydrogen by sectors; b) conversion of hydrogen into fuels, heat, electricity.

As previously mentioned, most of the imported hydrogen undergoes conversion into synfuels, primarily to be used in the transport sector. As a consequence, this sector experiences the most significant impact from the additional trade. **Table 21** provides a more detailed view on the relative differences in import scenarios compared to S0. Unsurprisingly, the most substantial variations are associated with S1 and S2, which assumes the highest importable amounts. It is worth noting that hydrogen imports also influence hydrogen consumption via fuel cells, undergoing an increase in S1 and S3, while decreasing in S2 and S4. Another sector affected is the industrial one, particularly in terms of hydrogen converted into heat, with consumption more than doubling in S1 and S2 compared to the absolute value of S0. In the context of the transport sector, the decrease in the direct use of hydrogen with respect to S0 corresponds to a simultaneous increase in the use of hydrogen through synfuels, particularly pronounced in S1 (i.e., trade by pipelines in the optimistic case). This shift is attributed to the increase in cost-effectiveness of consuming decarbonized synfuels, in spite of using hydrogen directly, as highlighted by **Table 21**.

Table 21: Relative difference between S0 and the trade scenarios for the hydrogen consumption per sector, through direct use and conversion options; year: 2050.

	H_2 direct use [PJ]				H_2 converted into heat [PJ]				H_2 into synfuels [PJ]			
	S1-S0	*S2-S0*	*S3-S0*	*S4-S0*	*S1-S0*	*S2-S0*	*S3-S0*	*S4-S0*	*S1-S0*	*S2-S0*	*S3-S0*	*S4-S0*
Agricultural sector	0.0	0.0	0.0	0.0	0.3	0.3	0.1	0.2	8.3	7.8	-0.3	3.3
Commercial sector	0.0	0.0	0.0	0.0	9.1	9.4	3.1	5.0	0.0	0.0	0.0	0.0
Industrial sector	1.7	0.0	0.0	0.0	61.8	65.1	21.3	35.2	28.4	26.6	-1.0	11.1
Residential sector	23.5	75.2	22.2	30.4	14.3	15.0	5.0	8.1	0.0	0.0	0.0	0.0
Transport sector	-70.9	-49.1	17.8	-8.0	–	–	–	–	140.5	132.4	2.9	50.8

	H_2 converted into electricity [PJ]			
	S1-S0	*S2-S0*	*S3-S0*	*S4-S0*
Fuel cell use	9.4	-27.4	39.3	-3.6

With respect to the decarbonization target, it is crucial to analyze the effects on emissions mitigation resulting from the additional trade of green hydrogen from North Africa to Europe. As anticipated, scenarios modelling imports demonstrate that EU+ decarbonization becomes more cost-effective. Specifically, it is observed that by 2040, the CO_2 marginal cost relative to scenario S0 decreases by up to 4% in the optimistic cases (S1 and S2), where the imported volumes of hydrogen are higher and cheaper. By 2050, the decrease in CO_2 marginal cost ranges from -10% (for S3 and S4) to -16% reduction in S1 and S2.

3.4.2.4 The sensitivity analysis

Considering that the scenario modelling aims to assess the significance of uncertainty in parameters affecting hydrogen development, it is useful to perform a sensitivity analysis to better investigate the impact of varying hydrogen trade volumes and associated costs. It is decided to run sixteen different scenarios, to replicate for each basic scenario (i.e. S1, S2, S3, S4) the increase or decrease of 50% of hydrogen amounts or costs (**Figure 155**).

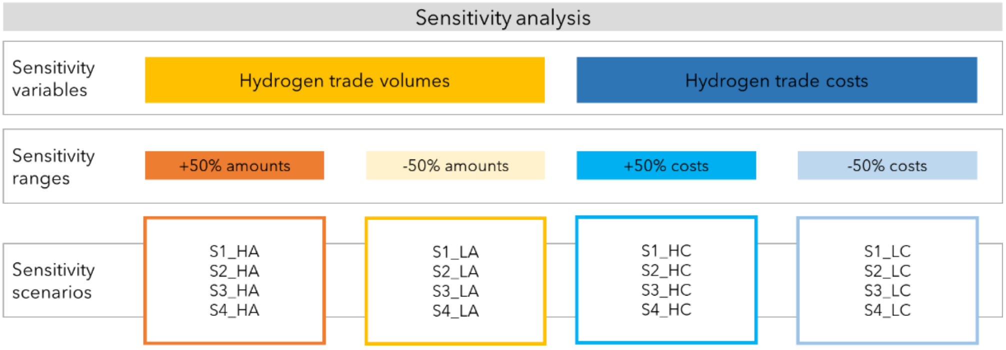


Figure 155: Sensitivity analysis: variables, ranges and scenarios to be analyzed.

As a result, by adjusting the amounts of the imported hydrogen by Morocco, Algeria and Tunisia, by 50% increase or decrease, the study reveals that by 2050 a 50% increase in imports from North Africa would result in a reduction of EU+ domestic production ranging from just under 4% to nearly 12% with respect to the basic importing cases, respectively in the pessimistic and optimistic cases. The same percentage but with an opposite meaning are found in case of a decrease by 50%, obtaining, as expected, an increase in local production. Focusing on consumption, a higher amount of hydrogen from North Africa would mean to increase the indirect consumption (i.e. by heat and synfuels). By applying the sensitivity analysis on production and transport cost of hydrogen from North Africa, it is found that a cost decrease of 50% unlocks the import by 2030 also from Algeria and Tunisia in S1, while in S2 (i.e. by exploiting liquefied hydrogen shipping) Algeria and Morocco start being involved in trade (this is not the case of Tunisia). By 2040, only Morocco is still competitive while increasing costs by 50% in S3 and S4. In 2050 EU+ will import all the North African hydrogen available, even if at higher cost (+50% of the costs of the basic scenarios) in all the scenarios. This means that the EU+ will always exploit green hydrogen from North Africa by 2050, as a helpful solution to achieve its carbon-neutrality target.

Concerning sensitivity, it is also important to stress the influence that the assumptions on renewable costs on the European side can have on the final results; specifically, it is found that a more competitive renewable production in Europe would mean an increase in local production of green hydrogen but without reducing the imported amounts from North Africa. In other words, it is estimated that a 50% decrease of off-grid PV technology for the electrolysis process would mean to increase hydrogen production (+5%) and related demand among EU+ countries. The fact that there is an increase in production that is not substituting the hydrogen import from North Africa stresses the significant contribution of green hydrogen trade to achieve the decarbonization, exploiting in each case all the amount available and also confirming the key role of hydrogen in the energy systems in the long-term.

3.4.2.5 Limitations and possible development of the work

There are limitations in the model to be taken into account while analysing results and for future possible development of the work. Concerning the grid modelling, the expansion capacity of the power grid is very limited, while also off-grid wind plants need to be modelled, since in the current model only PV panels represent the off-grid option to supply directly with renewable electricity the electrolysers. In addition to this, at this stage of the analysis Direct Air Capture (DAC) technologies are not considered in detail; also, in the current JET model version direct hydrogen consumption in industry is not possible yet.

As future development of the work, it could be of interest to overcome some limitations of the model, for instance including the role of DAC, looking at the interplay of hydrogen and DAC for decarbonization purposes and also it can be of interest to focus on specific hard-to-abate sectors. In addition, the model can be modified in terms of technological inputs for the electrolysis processes, to better investigate how the technological status and maturity have an impact on both domestic production in EU+ and production costs in North Africa. Moreover, specific assumptions can be developed on different constraints on the EU demand, in order to see how the model reacts in terms of production, consumption and trade to satisfy the demand over ranges of uncertainty. In any case, this study confirms the key role of hydrogen in the decarbonization process, assessing how hydrogen availability is crucial also through the exploitation of new routes and alliances and addressing the uncertainty of parameters.

Chapter 4

Conclusions

The current energy transition is a transition at all, involving the broader social, political, environmental, and economic dimensions; even if energy-related, this complex process towards carbon-neutrality and against climate change require a holistic approach allowing to tackle the multi-dimensionality of the several topics and actors involved. To address the complex challenges related to the shift from traditional energy systems to sustainable ones, it is crucial to enhance integration among different fields – like engineering, economics, policy, environmental science, technology – and in parallel to ensure collaboration among several experts in these areas. To this end, this PhD thesis aims to develop a science-based decision-making approach able to support informed intervention and actions of policymakers in the framework of strategic energy planning. Being strictly affected by the availability of resources, e.g. renewable sources, water, raw materials, the transition will reshape countries' identities and relationships worldwide. To this regard, it is required to consider the geopolitics of this transition and the role that different countries and strategies can have on the achievement of the final targets. Focusing on the decarbonization plans in the long-term, green hydrogen is identified among the key carbon-neutral solutions to be developed; the more ambitious the targets, the higher the amount of hydrogen required. Hydrogen can create new global leaders and alliances, enhancing the role of areas with very high availability of resources and space for infrastructure; nevertheless, there is a series of criticalities to be addressed to effectively pave the way to its deployment, encouraging in parallel the adoption of new pathways for trade.

In the framework of technological development and new strategic collaboration towards sustainability, three research questions are addressed: (i) How to assess strategic pathways to enable climate-neutral solutions? (ii) How to qualify and quantify multi-dimensional drivers and barriers for strategic energy planning? (iii) How to elaborate clear and usable outcomes for policymakers to allow informed strategies? Having set this research framework, the potential outcomes to be delivered concern the elaboration of a strategic multi-dimensional methodological framework that – through the adoption of qualitative and quantitative indicators, spatial analyses, multi-criteria assessment methods, energy modelling and scenario analyses – can deliver a structured science-based decision-making approach, supporting policymakers and citizens and being replicable for different case studies and scales. In fact, policy (i.e. policymakers' decisions), mindset (i.e. citizens' behaviour) and Research & Development (i.e. researchers' studies) are identified as key target subjects of the research, representing clearly and effectively the multi-layered structure of the issues involved and the integrated solutions required. To effectively enhance the uptake of new technology and support strategic energy planning, it is developed a three-stepped methodological approach on the STAGE of the transition; specifically, each analysis must be built on Society, Technology, Atmosphere and Land, Geopolitics and Economy. The integration of these different dimensions and the combination of several instruments and tools represents the key enabler of the research, to deeply investigate (i) predisposition/readiness, (ii) multi-dimensional suitability and (iii) multi-level competitiveness of a specific technology, strategy, or energy planning process. Firstly, it is required to preliminarily assess if and how a country, a society and/or an economy is predisposed and ready. The second step is based on a higher level of detail, mapping specific areas to study the multi-dimensional suitability, i.e. the suitability with respect to the STAGE of the transition. Finally, to tackle the complexity of the whole energy system, it is required a focus on the concept of multi-level competitiveness, to discuss to what extent predisposition and suitability can address a competitive pathway. The elaboration of this methodological approach requires a detailed analyses on the specific role played by scenario modelling, multi-criteria decision methods and indicators in the context of the transition and strategic energy planning. Providing alternative evolutionary pathways for energy systems, scenario analyses are widely recognized as effective instruments to help policymakers in anticipating and planning uncertainties, facing risks, and providing informed decisions. On the other side, multi-criteria assessments allow to analyse and rank different alternatives according to a set of criteria related to specific objectives to be achieved. To this regard, there are several methodological approaches that, following the common procedure of each multi-criteria analysis, can be applied to study a problem referring to multi-dimensional criteria and multi-actors' perspective. In addition to this, considering that the energy transition is a geographically-constituted process, there is the need to explore a more detailed spatial planning process to effectively address the complexity in space for strategic energy planning. Covering the spatial aspects of the transition, the GIS environment can be combined with multi-criteria analyses, which can perfectly fit with a strategic planning process, to assess simultaneously both the technical and social perspectives. Within this framework, scenarios, multi-criteria analyses, spatial decision support systems, indicators represent the powerful instrument to enhance evaluation processes, also allowing comparability analyses.

This methodological approach, making use of qualitative and quantitative indicators, GIS environment, multi-criteria analyses and scenario modelling, is exploited to study green hydrogen development and potentialities for trade between North Africa and Europe. Mentioned among the potential global hydrogen export-oriented regions because of the availability of resources, North Africa is experiencing an unprecedent moment of social, political, economic changes that strongly affect and will affect the energy landscape of the involved countries. To this regard, there are lots of studies dealing with the possibility to trade renewable electricity and/or renewable hydrogen from North Africa to Europe, to exploit the resources potential of these countries and on the other side to support the decarbonization targets and hydrogen strategies of the European Union. After analysing Algeria, Egypt, Libya, Morocco and Tunisia through the lens of specific indicators – like the Energy Trilemma Index or the Environmental Performance Indicator –, these five countries are assessed with respect to their predisposition to green hydrogen production, exploiting different indicators belonging to the STAGE view. The PROMETHEE II method as outranking multi-criteria method, allows to rank these alternative countries in terms of predisposition/readiness, according to different criteria, which correspond to indicators extracted by literature or self-elaborated. Different energy experts' preferences are exploited to assign specific weightings to the criteria; Morocco, Tunisia and Algeria are ranked as the most predisposed for green hydrogen deployment. Having set this, the multi-dimensional suitability mapping is applied to these three countries, related to both solar and wind hydrogen production; the Multi-criteria Spatial Decision Support System combining AHP and GIS techniques is developed through a nine-step process. It is obtained that most of the areas are moderately or highly suitable, even if the most favourable areas in terms of availability of resources are often negatively influenced by the geopolitical or economic assessment. For the assessment of both predisposition and multi-dimensional suitability, it is important to focus on the choice of the criteria to be analysed or elaborated, with respect to their estimation, availability, and limitations. Specifically, one of the main challenges is related to the year the indexes belong; it would be required an update of the criteria assessed year by year, considering also that this update could lead to different results. In other words, it is important to stress which is the year of the elaboration, having that the all the exploited datasets –

specifically the spatial one – can change over time. The application shown in this work is based mostly on 2020 and 2021 datasets, 2022 when available. In fact, another issue relies on the availability of data; there are countries or years for which there is no information available, mostly when specific spatial analyses must be developed. Moreover, for this methodological approach is also crucial the involvement of stakeholders and experts to better investigate the objective, define criteria and assess the proper prioritization of them according to a specific participatory environment. Looking at the application of North African countries, it will be needed a major involvement of local people, in form of institutions, organizations and citizens, to effectively convey priorities and needs of their own country. Concerning the evaluation of multi-level competitiveness as final step of the methodological framework developed, the aim is to investigate to what extent the additional trade of green hydrogen from North Africa can support the European decarbonization. To do this, it is conducted an analysis on specific parameters that because of their uncertainty can affect the trade. After studying local policies and strategies, the technological status of both production and transport options, and the financial risks in terms of investments and economic viability, different scenarios are modelled, starting from the JRC-EU TIMES model setup. Different options for importing hydrogen from Algeria, Morocco and Tunisia are integrated into the JET model; ad-hoc assumptions referred to specific parameters define the different scenarios to be analysed in terms of competitiveness. While S0 refers to the basic case without import, other four scenarios are analysed, distinguishing among transport options and the case of market push and strength (i.e. the optimistic case) in contraposition to the less favourable conditions for trade (i.e. the pessimistic one). It is found that in the short-term (2030) the only affordable option consists of pipelines in case of positive predisposition of market, while in 2050 all the options are accepted to achieve the decarbonization. Covering around the 16% of the EU+ hydrogen demand, the additional trade from North Africa represents part of the solution to totally decarbonized, with conversion into synfuels for transport and into heat for industry as the most affected consumption processes. Even if there are European countries more sensitive than others with respect to North African imports (e.g. Italy, Spain, Poland, the Netherlands), it is undoubted that the exploitation of this green hydrogen trade can accelerate the transition to carbon-neutrality and can make it more cost-effective in the long-run, if specific spatial constraints, social and geopolitical issues, different level of uncertainty in production costs and transport options, are considered.

Focusing on the role of green hydrogen in the long-term, the PhD research studies the potential green hydrogen trade from North Africa to Europe, applying the methodological proposal of a science-based decision-making process, able to assess the STAGE of the transition from the concept of predisposition to the competitiveness level. Through the use of different instruments and expertise, this research activity allows to point out the importance of a structured science-based approach that, recognizing the intrinsic multi-disciplinary of the current transition and its strong dependence on space and cross-border cooperations, support policymakers through specific analyses and assessments on different level of details but with the aim of addressing how what happens "on STAGE" must be taken into account to achieve the ambitious objectives of decarbonization.

With respect to the complexity of the topics and on the heterogeneity of instruments exploited in this work, it is undoubted that this PhD thesis does not claim to be exhaustive or to provide an absolute approach appropriate in each case. Conversely, recognizing the multi-dimensionality of the current transition and the connected challenges, this study aims to develop an approach able to tackle the different dimensions involved according to different points of view, highlighting the need to integrate instruments like spatial analyses, multi-criteria assessments, and scenario analyses for strategic energy planning. In this sense, the research paves the way to further analyses; each step of the methodological approach can be better investigated and also exploited for or adapted to other specific case studies. Specifically, to address the predisposition/readiness, other multi-criteria decision methods could be introduced, or also the PROMETHEE II methods could involve other criteria or preference functions to test the results. The same attention on criteria, sub-criteria and standardization functions can be adopted for the assessment of suitability through the Multi-Criteria Spatial Decision Support Systems, for which different assumptions or methods can lead to more detailed results or conversely confirm the robustness of the obtained outputs. Furthermore, concerning the TIMES modelling for scenario analyses to introduce the concept of competitiveness, alternative scenarios can be built, working on other assumptions or variables of uncertainties, or focusing on specific consumption sectors. In addition to this, it can be useful to integrate the multi-criteria approach with the scenario analyses to provide robust decision support in strategic planning. Another useful analysis to be combined to the whole methodological approach proposed within the PhD thesis concerns the specific role of multi-dimensional indicators and their evolution with time; it can be of interest to address how certain parameters evolve over time and which is the related impact on strategic planning. Another important aspect for further work concerns the involvement of new and more involved actors in this kind of strategic procedures, being their role essential for a correct implementation of the procedure and to get reasonable and useful outputs.

To conclude, having set that the current transition is a very complex puzzle, there are lots of optional pathways to be analysed through powerful tools, offering potential strategies for a sustainable development towards a decarbonized word. To this end, it is important to take into account that "ensuring the availability and accessibility of energy services in a carbon-constrained world will require developing new ways – and new geographies – of producing, living, and working with energy [13]."

References

[1] Intergovernmental Panel on Climate Change (IPCC). Climate change 2014: Synthesis Report, 2014.

[2] International Renewable Energy Agency (IRENA). Accelerating the energy transition through innovation. Working paper based on global REmap analysis, Abu Dhabi, 2017.

[3] International Energy Agency (IEA). World Energy Outlook, Paris, 2021.

[4] Worland, J. The Energy Transition Is in Full Swing. It's Not Happening Fast Enough, 2021. [Online]. Available: https://time.com/6106341/green-energy-transition-iea/.

[5] United Nations (UN) - Climate change. The Paris Agreement, December 2015. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement.

[6] United Nations (UN). The Climate Pact COP26, 2021. [Online]. Available: https://ukcop26.org/the-glasgow-climate-pact/.

[7] United Nations (UN) - Climate Change. Events: COP27, November 2022. [Online]. Available: https://unfccc.int/event/cop-27.

[8] United Nations (UN) - Climate change. COP28 – UAE, December 2023. [Online]. Available: https://www.cop28.com/.

[9] International Renewable Energy Agency (IRENA). World Energy Transitions Outlook: 1.5°C Pathway, Abu Dhabi, 2021.

[10] York, R., Bell, S. E. Energy transition or addition? Why a transition from fossil fuels requires more than the growth of renewable energy, *Energy Research and Social Science*, vol. 51, pp. 40-43, 2019; https://doi.org/10.1016/j.erss.2019.01.008

[11] Kraan, O., Chappin, E., Kramer, G. J., Nikolic, I. The influence of the energy transition on the significance of key energy metrics, *Renewable and Sustainable Energy Reviews*, vol. 111, pp. 215-223, 2019; https://doi.org/10.1016/j.rser.2019.04.032

[12] Chabrol, M. Re-examining historical energy transitions and urban systems in Europe, *Energy Research and Social Science*, vol. 13, pp. 194-201, 2016; https://doi.org/10.1016/j.erss.2015.12.017

[13] Bridge, G., Bouzarovski, S., Bradshaw, M., Eyred, N. Geographies of energy transition: Space, place and the low carbon economy, *Energy Policy*, vol. 53, pp. 331-340, 2013; DOI: 10.1016/j.enpol.2012.10.066

[14] Arias, A., Feijoo, G., Moreira, M. Advancing the European energy transition based on environmental, economic and social justice, *Sustainable Production and Consumption*, vol. 43, pp. 77-93, 2023; https://doi.org/10.1016/j.spc.2023.10.013

[15] Miller, A., Iles, A., Jones, C.F. The social dimensions of energy transitions: Introduction to the special issue, *Science and Culture*, vol. 22, pp. 135-148, 2013.

[16] Svobodova, K., Owen, J. R., Harris, J., Worden, S. Complexities and contradictions in the global energy transition: a re-evaluation of country-level factors and dependencies, *Applied Energy*, vol. 265, no. 114778, 2020; https://doi.org/10.1016/j.apenergy.2020.114778

[17] World Economic Forum, "Fostering effective energy transition," 2019.

[18] Defeuilley, C. Energy transition and the future(s) of the electricity sector, *Utility Policies*, vol. 57, pp. 97-105, 2019; https://doi.org/10.1016/j.jup.2019.03.002

[19] Ulli-Beer, S. Conceptual grounds of socio-technical transitions and governance, *Dynamic Governance of Energy Technology Change*, pp. 19-47, 2013; DOI:10.1007/978-3-642-39753-0_2.

[20] Vakulchuk, R., Overland, I., Scholten, D. Renewable energy and geopolitics: A review, *Renewable and Sustainable Energy Reviews*, vol. 122, no. 109547, 2020; https://doi.org/10.1016/j.rser.2019.109547

[21] Lee J. and Yang, J.S. Global energy transition and political systems, *Renewable and Sustainable Energy Reviews*, vol. 115, no. 109370, 2019; DOI:10.1016/j.rser.2019.109370

[22] Mata Perez, M.E., Scholten, D., Stegen, K.S. The multi-speed energy transition in Europe: Opportunities and challenges for EU energy security, *Energy Strategy Reviews*, vol. 26, no. 100415, 2019; https://doi.org/10.1016/j.esr.2019.100415

[23] Gielen, D. Boshella, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorinia, R. The role of renewable in the global energy transformation, *Energy Strategy Reviews*, vol. 24, pp. 38-50, 2019; https://doi.org/10.1016/j.esr.2019.01.006

[24] Eitan, A., Hekkert, M.P. Locked in transition? Towards a conceptualization of path-dependence lock-ins in the renewable energy landscape, *Energy Research & Social Science*, vol. 106, 2023; https://doi.org/10.1016/j.erss.2023.103316

[25] Halttunen, K., Slade, L., Staffell, I. Diversify or die: Strategy options for oil majors in the sustainable energy transition, *Energy Research & Social Science*, vol. 104, 2023; DOI:10.1016/j.erss.2023.103253

[26] D'Orazio, P. Charting the complexities of a post-COVID energy transition: emerging research frontiers towards a sustainable future, *Energy Research & Social Science*, 2023; DOI:10.1016/j.erss.2023.103365

[27] Roberts, C., Geels, F.W., Lockwood, M., Newell, P., Schmtiz, H., Turnheim, B., Jordan, A. The politics of accelerating low-carbon transitions: towards a new research agenda, *Energy Research & Social Science*, vol. 44, pp. 304-311, 2018.

[28] International Energy Agency (IEA), Net Zero by 2050, Paris, 2021.

[29] Schlindwein, L., Montalvo, C. Energy citizenship: Accounting for the heterogeneity of human behaviours within energy transition, *Energy Policy*, vol. 180, 2023; https://doi.org/10.1016/j.engeos.2023.100257

[30] World Energy Council (WEC), World Energy Scenarios: Composing energy futures to 2050. Project Partner Paul Scherrer Institute (PSI), Switzerland, Project Partner Paul Scherrer Institute (PSI), Switzerland, 2013.

[31] World Energy Council (WEC), World Energy Issues Monitor 2021: Humanising energy, 2021.

[32] Zhang, F., Zhao, P., Niu, M., Maddy, J. The survey of key technology in hydrogen energy storage, *International Journal of Hydrogen Energy*, vol. 41, pp. 14535-14552, 2016; DOI:10.1016/j.ijhydene.2016.05.293

[33] Momirlan, M., Veziroglu, T. The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet, *International Journal of Hydrogen Energy*, vol. 30, pp. 795-802, 2005; https://doi.org/10.1016/j.ijhydene.2004.10.011

[34] Pinto, M.C., Boccardo, P., Gaeta, M., Gelmini, A. Achieving decarbonization: challenges and opportunities of hydrogen, REHVA Journal, Vol.1 2022.

[35] Dawood, F., Anda, M., Shafiullah, G. Hydrogen production for energy: an overview, *International Journal of Hydrogen Energy*, vol. 45, pp.3847-3869, 2020; https://doi.org/10.1016/j.ijhydene.2019.12.059

[36] Usuelli, M. L'idrogeno è la soluzione all'emergenza climatica?, 2021 (in Italian). [Online]. Available: https://www.lenius.it/idrogeno-e-decarbonizzazione/

[37] Belmans, R., Vingerhoets, P. (EUI, RSCAS and FSR). Molecules: Indispensable in the Decarbonized Energy Chain. Policy Papers, 2020.

[38] International Energy Agency (IEA). Global Hydrogen Review, Paris, 2023.

[39] International Energy Agency (IEA), Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach - 2023 Update, Paris, 2023.

[40] Hyhurst, R. CCS can't solve the climate crisis new report, 2021. [Online]. Available: https://drillordrop.com/2021/01/11/ccs cant solve the climate crisis new.

[41] Nikolaidis, P., Poullikkas, A. A comparative overview of hydrogen production processes, *Renewable and Sustainable Energy Reviews*, vol. 67, pp. 597-611, 2017; DOI:10.1016/j.rser.2016.09.044

[42] Fuel Cells and Hydrogen 2 Joint Undertaking, Fraile, D., Altmann, M., Barth, F. et al., Study on hydrogen from renewable resources in the EU – Final report, 2016, https://data.europa.eu/doi/10.2843/28276

[43] International Renewable Energy Agency (IRENA). Green hydrogen: a guide to policy makers, 2020.

[44] International Renewable Energy Agency (IRENA). Green hydrogen: A Guide to Policymakers, 2021.

[45] International Energy Agency (IEA). The future of hydrogen, Paris, 2019. [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen, License: CC BY 4.0.

[46] International Energy Agency (IEA). Global Hydrogen Review, IEA, Paris, 2021.

[47] International Energy Agency (IEA). Global Hydrogen Review, Paris, 2022.

[48] International Renewable Energy Agency (IRENA). Geopolitics of the Energy Transformation: The Hydrogen Factor, Abu Dhabi, 2022.

[49] International Renewable Energy Agency (IRENA). Global hydrogen trade to meet the 1.5°C climate goal: Part III – Green hydrogen costs and potentials, Abu Dhabi, 2022.

[50] World Energy Council (WEC). Working paper: Hydrogen Demand and Costs Dynamics, 2021.

[51] Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo M., Thiel, C. How far is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system, *International Journal of Hydrogen Energy*, 2016; https://doi.org/10.1016/j.ijhydene.2015.09.004

[52] Tarvydas, D. The role of hydrogen in energy decarbonisation scenarios: views on 2030 and 2050. JRC Technical Report, 2022.

[53] European Commission. EU Hydrogen Strategy, 2020. [Online]. Available: https://eur-lex.europa.eu/TodayOJ/.

[54] European Commission. REPowerEU Plan {COM(2022) 230 final}. Brussels: European Commission, 2022. [Online].

[55] European Commission. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions, 2021. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541.

[56] European Commission, RED III 2023/2413, Bruxelles, 2023.

[57] Hydrogen Europe. Clean Hydrogen Monitor 2023, 2023.

[58] European Parliament. ReFuelEU Aviation initiative: Sustainable aviation fuels and the 'fit for 55' package, 28 November 2023. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2022/698900/EPRS_BRI(2022)698900_EN.pdf.

[59] European Council of the European Union. FuelEU maritime initiative: Council adopts new law to decarbonise the maritime sector, 25 July 2023. [Online]. Available: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/.

[60] European Council of the European Union. Alternative fuels infrastructure: Council adopts new law for more recharging and refuelling stations across Europe, 25 July 2023. [Online]. Available: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/alternative-fuels-infrastructure-council-adopts-new-law-for-more-recharging-and-refuelling-stations-across-europe/.

[61] European Commission. EU Emissions Trading System (EU ETS) - Directive 2003/87/EC, 5 June 2023. [Online]. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

[62] European Commission, Carbon Border Adjustment Mechanism, [Online]. Available: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

[63] European Commission, Carbon Border Adjustment Mechanism (CBAM) starts to apply in its transitional phase, 29 September 2023. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4685.

[64] European Commission. ETS 2: buildings, road transport and additional sectors, 2023. [Online]. Available: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/ets-2-buildings-road-transport-and-additional-sectors_en.

[65] Seck, G., Hache, E., Sabathier, J., Guedes, F., Reigstad, G., Straus, J., Wolfgang, O., Ouassou, J., Askeland, M., Hjorth, I., Skjelbred, H.,

Andresson, L., Douguet, S., Villavicencio, M., Truby, J., Brauer, J., Cabot, C. Hydrogen and the decarbonization of the energy system in Europe in 2050: A detailed model-based analysis, *Renewable and Sustainable Energy Reviews*, vol. 167, 2022; https://doi.org/10.1016/j.jclepro.2023.140473

[66] International Renewable Energy Agency (IRENA). International trade and green hydrogen: supporting the global transition to a low-carbon economy, December 2023.

[67] International Renewable Energy Agency (IRENA). Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward, Abu Dhabi, 2022.

[68] Kneebone, J. The Mediterranean as a leader in the clean hydrogen economy: production, transmission, end-use, 22 December 2022. [Online]. Available: https://fsr.eui.eu/the-mediterranean-as-a-leader-in-the-clean-hydrogen-economy-production-transmission-end-use/.

[69] European Hydrogen Backbone (EHB). Five hydrogen supply corridors for Europe in 2030, 2022.

[70] De Blasio, N., Pflugmann, F. Geopolitical and Market Implications of Renewable Hydrogen: New Dependencies in a Low-Carbon Energy World, 2020.

[71] Tonelli, D., Rosa, L., Gabrielli, P., Caldeira, K., Parente, A., Contino, F. Global land and water limits to electrolytic hydrogen production using wind and solar resources, *nature communications*, vol. 14, no. 5532, 2023; https://doi.org/10.1038/s41467-023-41107-x

[72] International Renewable Energy Agency (IRENA). Water for hydrogen production, December 2023.

[73] Nunes-Jimenez, A., De Blasio, N. The future of renewable hydrogen in the European Union. Market and Geopolitical Implications, 2022.

[74] Sens, L., Piguel, Y., Neuling, U., Timmemberg, S., Wilbrand K., Kaltshmitt, M. Cost minimized hydrogen from solar and wind - production and supply in the European catchment area, *Energy Conversion and Management*, vol. 265, 2022; DOI:10.21203/rs.3.rs-3164444/v1

[75] Kaoukulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., Jäger-Waldaua, A. Green hydrogen in Europe – A regional assessment: substituting existing production with electrolysis powered by renewables, *Energy Conversion and Management*, vol. 228, no. 113649, 2021; DOI:10.1016/j.enconman.2020.113649

[76] Wolf, A., Zander, N. Green hydrogen in Europe. Do strategies meet expectations?, *Review of European Economic Policy*, vol. 56, no. 6, pp. 316-323, 2021; DOI:10.3390/su15010303

[77] Van der Zwaan, A., Lamboo, S., Della Longa, F. Timmermans' dream: An electricity and hydrogen partnership between Europe and North Africa, *Energy Policy*, 2021; https://doi.org/10.1016/j.enpol.2021.112613

[78] Timmeberg, S., Kaltschmitt, M. Hydrogen from renewables: Supply from North Africa to Central EU as blend in existing pipelines Potentials and costs, *Applied Energy*, vol. 237, pp. 795-809, 2019; DOI: 10.1016/j.apenergy.2019.01.030

[79] International Renewable Energy Agency (IRENA). Global hydrogen trade to meet the 1.5°C climate goal: Part II – Technology Review of Hydrogen Carriers, Abu Dhabi, 2022.

[80] European Hydrogen Backbone (EHB), Analysing future demand, supply, and transport of hydrogen, 2021.

[81] European Hydrogen Backbone. A European hydrogen infrastructure vision covering 28 countries, 2022.

[82] Van de Graaf, T., Overland, I., Scholten, D., Westphal, K. The new oil? The geopolitics and international governance of hydrogen, *Energy Resource & Social Science*, vol. 70, no. 101667, 2020; https://doi.org/10.1016/j.erss.2020.101667

[83] Scott, M., Powells, G. Towards a new social science research agenda for hydrogen transitions: Social practices, energy justice, and place attachment, *Energy Research & Social Science*, vol. 61, no. 101346, 2020; https://doi.org/10.1016/j.erss.2019.101346

[84] Acar, C., Dancer, I. Review and evaluation of hydrogen production options for better environment, *Journal of Cleaner Production*, vol. 218, pp. 835-849, 2019; https://doi.org/10.1016/j.jclepro.2019.02.046

[85] Ouedragogo, N.S. Transition pathways for North Africa to meet its (intended) nationally determined contributions ((I)NDCs) under the Paris Agreement: a model-based assessment, *Climate Policy*, vol. 20, pp. 71-94, 2020; https://doi.org/10.1080/14693062.2019.1685449

[86] Griffiths, S. A review and assessment of energy policy in the Middle East and North Africa region, *Energy Policy*, vol. 102, pp. 249-269, 2017; https://doi.org/10.1016/j.enpol.2016.12.023

[87] Van De Graaf, T., Sovacool, K. Thinking big: politics, progress and security in the management of Asian and EU energy megaprojects, *Energy Policy*, vol. 74, pp. 16-27, 2014; DOI: 10.1016/j.enpol.2014.06.027

[88] Schmitt, T. (Why) Desertec fail? An interim analysis of a large-scale renewable energy infrastructure project from a Social Studies of Technology perspective, *Local Environment*, vol. 23, pp. 1-30, 2018.

[89] European Commission. Critical Raw Materials for strategic technologies and sectors in the EU, 2020.

[90] International Renewable Energy Agency (IRENA). Geopolitics of the transition: critical materials, Abu Dhabi, 2023.

[91] World Bank Group. Sufficiency, sustainability, and circularity of critical materials for clean hydrogen, 2022.

[92] European Commission. Critical Raw Materials: ensuring secure and sustainable supply chains for EU's green and digital future, 16 March 2023. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661.

[93] European Commission. COM(2023) 160 - Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials, 2023.

[94] Hydrogen Europe. Critical Raw Materials Act to unlock hydrogen revolution, 2023. [Online]. Available: https://hydrogeneurope.eu/critical-raw-materials-act-to-unlock-green-revolution/.

[95] Hydrogen Europe, World Bank. Sufficiency, Sustainability, and Circularity of Critical Materials for Clean Hydrogen, 2022.

[96] Spyridaki, N., Flamos, A. A paper trail of evaluation approaches to energy and climate policy interactions, *Renewable and Sustainable Energy Reviews*, vol. 40, pp. 1090-1107, 2014; DOI:10.1016/j.rser.2014.08.001

[97] Horschig, T., Thran, D. Are decisions well supported for energy transition? A review on modelling approach for renewable energy policy evaluation, *Energy, Sustainability and Society*, vol. 7, no. 5, 2017; https://doi.org/10.1186/s13705-017-0107-2

[98] Krog, L., Sperling, K. A comprehensive framework for strategic energy planning based on Danish and international insights, *Energy Strategy Reviews*, vol. 24, pp. 83-93, 2019; https://doi.org/10.1016/j.esr.2019.02.005

[99] Wilson, I. From Scenario Thinking to Strategic Action, *Technological Forecasting & Social Change*, Vol.67, 2000; https://doi.org/10.1016/S0040-1625(99)00122-5

[100] Borjeson, L., Hojer, M., Dreborg, K., Ekvall, T., Finnveden, G. Scenario types and techniques: Towards a user's guide, *Futures*, vol. 38, pp. 723-739, 2006; https://doi.org/10.1007/s40309-017-0121-9

[101] Van Notten, P., Rotmans, J., Van Asselt, M., Rothman, D. An update scenario typology, *Futures*, vol. 35, pp. 423-443, 2003.

[102] Alcamo, J. Chapter Six The SAS Approach: Combining Qualitative and Quantiative Knowledge in Environmental Scenarios, Developments in Integrated Environmental Assessment, vol. 2, pp. 123-150, 2008.

[103] Fortes, P., Alvarnega, A., Seixas, J., Rodrigues, S. Long-term energy scenarios: Bridging the gap between socio-economic storylines and energy modeling, *Technological Forecasting & Social Change*, vol. 91, pp. 161-178, 2015; DOI: 10.1016/j.techfore.2014.02.006

[104] Weimer-Jehle, W., Buchgeister, J., Hauser, W., Kosow, H., Naegler, T., Poganietz, W.R., Pregger, T., Prehofer, S., Von Recklinghausen, A., Schippl, J., Vogele, S. Context scenarios and their usage for the construction of socio-technical energy scenarios, *Energy*, vol. 111, pp. 956-970, 2016; https://doi.org/10.1016/j.energy.2016.05.073

[105] Kok, A., van Vliet, M., Barlund, I., Dubel, A., Sendzimir, J. Combining participative backcasting and exploratory scenario development: Experiences from the SCENES Project, *Technological Forecasting & Social Change*, vol. 78, pp. 835-851, 2011; https://doi.org/10.1016/j.techfore.2011.01.004

[106] Kowalski, A., Stagl, S., Madlener, R., Omann, I. Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis, *European Journal of Operational Research*, vol. 197, pp. 1063-1074, 2009; https://doi.org/10.1016/j.ejor.2007.12.049

[107] Serdeczny, O., Waters, E., Chan, S. Non-economic loss and damage in the context of climate change, Bonn: German Development Institute, 2016.

[108] Wang, Q., M'Ikiugu, M.M., Kinoshita, I. A GIS-based approach in support of spatial planning for renewable energy: a case study of Fukushima, Japan, *sustainability*, vol. 6, pp. 2087-2117, 2014; https://doi.org/10.3390/su6042087

[109] Tsoutsos, T., Drandaki, M., Frantzeskaki, N., Iosifidis, E., Kiosses, I. Sustainable energy planning by using multi-criteria analysis application in the island of Crete, *Energy Policy*, vol. 37, pp. 1587-1600, 2009; https://doi.org/10.1016/j.enpol.2008.12.011

[110] Kumar, A., Sah, B., Singh, A. R., Deng, Y., He, X., Kumar, P., Bansal, R. A review of multi criteria decision-making (MCDM) towards sustainable renewable energy development, *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 569-609, 2017; https://doi.org/10.1016/j.rser.2016.11.191

[111] Simon, H. The New Science of Management Decision, Harper & Row. Retrieved from https://archive.org/details/newscienceofmana00simo., 1960.

[112] Simon, H. Bounded rationality and organizational learning, *Organizational Science*, vol. 2, no. (1), pp. 125-134, 1991.

[113] Stoegleher, G., Niemetz, N., Kettl, K. Spatial dimensions of sustainable energy systems: new visions for integrated spatial and energy planning, *Energy, Sustainability and Society*, vol. 1 (1), 2011; https://doi.org/10.1186/2192-0567-1-2

[114] Ferretti, V., Montibeller, G. Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems, *Decision Support Systems*, vol. 84, pp. 41-52, 2016; https://doi.org/10.1016/j.dss.2016.01.005

[115] Ferretti, V. A Multicriteria Spatial Decision Support System Development for Siting a Landfill in the Province of Torino (Italy), *Journal of Multi-Criteria Decision Analysis* 18(5-6):231-252, 2011; DOI:10.1002/mcda.493

[116] Malczewski, J. GIS-based multicriteria decision analysis: a survey of the literature, *International Journal of Geographical Information Science*, vol. 20, pp. 703-726, 2006; https://doi.org/10.1080/13658810600661508

[117] Caprioli, C., Bottero, M. Addressing complex challenges in transformations and planning: A fuzzy spatial multicriteria analysis for identifying suitable locations for urban infrastructures, *Land Use Policy*, vol. 102, no. 105147, 2021; https://doi.org/10.1016/j.landusepol.2020.105147

[118] Witt, T., Dumeier, M., Geldermann, J. Combining scenario planning, energy system analysis and multi-criteria analysis to develop and evaluate energy scenarios, *Journal of Cleaner Production*, vol. 242, no. 118414, 2020; https://doi.org/10.1016/j.jclepro.2019.118414

[119] Yu, A., Xue, B., Stuckrad, S., Thomas H., Cai, G. Indicators for energy transition targets in China and Germany: A text analysis, *Ecological Indicators*, vol. 111, no. 106012, 2020; https://doi.org/10.1016/j.ecolind.2019.106012

[120] Krikstolaitis, R., Bianco, V., Martisauskas, L., Urboniene, S. Analysis of electricity market and natural gas security. A case study for Germany, France, Italy and Spain, *energies*, 2022; https://doi.org/10.3390/en15031000

[121] Elbassoussy, A. European energy security dilemma: Major challenges and confrontation strategies, *Review of Economics and Political Science*, vol. 4, p. 321–343, 2019; DOI:10.1108/REPS-02-2019-0019

[122] Rodriguez-Fernandez, L., Carvajal Fernandez, A.B., Fernandez de Tejada, V. Improving the concept of energy security in an energy transition environment: application to the gas sector in the European Union, *The*

Extractive Industry and Society, 2022; https://doi.org/10.1016/j.exis.2022.101045

[123] Gunnarsdottir, I., Davidsdottir, B., Worrel, E., Sigurgeirsdottir, S. Review of indicators for sustainable energy development, *Renewable and Sustainable Energy Reviews*, vol. 133, no. 110294, 2020; https://doi.org/10.1016/j.rser.2020.110294

[124] Colla, M., Iannou, A., Falcone, G. Critical review of competitiveness indicators for energy projects, *Renewable and Sustainable Energy Reviews*, vol. 125, 2020; DOI: 10.1016/j.rser.2020.109794

[125] World Energy Council (WEC). Transition toolkit. World Energy Trilemma Index, 2022. [Online]. Available: https://www.worldenergy.org/transition-toolkit/world- energy-trilemma-index.

[126] World Economic Forum. Energy Transition Index: country overview, May 2022. [Online]. Available: https://www.weforum.org/publications/fostering-effective-energy-transition-2023/global-dashboard/.

[127] Singh, H., Bocca, R., Gomez, P., Dahlke, S., Bazilian, M. The energy transitions index: An analytic framework for understanding the evolving global energy system, *Energy Strategy Reviews*, vol. 26, 2019; https://doi.org/10.1016/j.esr.2019.100382

[128] Yale University. Environmental Performance Index, 2020. [Online]. Available: https://epi.yale.edu/.

[129] Ernst & Young. Renewable Energy Country Attractiveness Index, 2021. [Online]. Available: https://www.ey.com/en_gl/recai. [Accessed September 2021].

[130] The Heritage Foundation. Index of Economic Freedom, 2021. [Online]. Available: https://www.heritage.org/index/about.

[131] Ricerca sul Sistema Energetico (RSE). Un vettore energetico per la decarbonizzazione, 2021.

[132] Haddad, B., Dìaz-Cuevas, P., Ferreira, P., Djebli, A., Pèrez, J.P. Mapping concentrated solar power site suitability in Algeria, *Renewable Energy*, vol. 168, pp. 838-853, 2021; https://doi.org/10.1016/j.renene.2020.12.081

[133] Habib, S.M., Suliman, A.E..E., Assan Al-Nahry, A., El Rahman, E.A. Spatial modeling for the optimum site selection of solar PV power plant in the northwest coast of Egypt, *Remote Sensing Applications: Society and Environment*, vol. 18, 2020; https://doi.org/10.1016/j.rsase.2020.100313

[134] Tazi, G., Jbaihi, O., Ghennioui, A., Alami Merrouni, A., Bakkali, M. Estimating the Renewable Energy Potential in Morocco: solar energy as a

case study, IOP Conference Series: Earth and Environment Science, vol. 161, 2018.

[135] Alami Merrouini, A., Elalaoui, F.E., Ghennioui, A., Mezrhab, A. A GIS-AHP combination for the sites assessment of large-scale CSP plants with dry and wet cooling systems. Case study: Eastern Morocco, *Solar Energy*, 2018; https://doi.org/10.1016/j.solener.2018.03.038

[136] Zelt, O., Kruger, C.B.M., Bohm, S., Far, S. Long-term electricity scenarios for the MENA region: assessing the preferences of local stakeholders using multi-criteria analysis, *Energies*, vol. 12, 2019; https://doi.org/10.3390/en12163046

[137] Papapostolou, A., Karakosta, C., Apostolidis, G., Doukas, H. An AHP-SWOT-Fuzzy TOPSIS Approach for Achieving a Cross-Border RES Cooperation, *Sustainability*, vol. 12, 2020; https://doi.org/10.3390/su12072886

[138] EST and ESL@EnergyCenterLab – Politecnico di Torino and SRM, MED & Italian Energy Report: The new game of hydrogen in the Euro Mediterranean region. Annual Report 2021, Giannini editore, 2021.

[139] Pinto, M.C., Gaeta, M. Analysis on potential of green hydrogen production in North Africa: challenges and opportunities up to 2050, Ricerca sul Sistema Energetico (RSE), RdS Deliverable n. 21009853, December 2021.

[140] Visual PROMETHEE, VISUAL PROMETHEE SOFTWARE, [Online]. Available: www.promethee-gaia.net.

[141] Brans, J., Mareschal, B. The PROMCALC & GAIA decision support system for multi-criteria decision aid, *Decision Support Systems*, 1994.

[142] Brans, J., Mareschal, B., Vincke, P. PROMETHEE: A New Family of Outranking Methods in Multi-criteria Analysis, *Operational Research*, 1984.

[143] Brans, J., Vincke, P. A preference ranking organization method: the PROMETHEE method for MCDM, *Management Science*, vol. 31, p. 647–656, 1985.

[144] Brans, J., Vincke, P., Mareschal, B. How to select and how to rank projects: The Promethee method, *European Journal of Operational Research*, vol. 24, pp. 228-238, 1986.

[145] Behzadian, M., Kazemzadeh, R., Albadvi, A., Aghdasi, M. PROMETHEE: A comprehensive literature review on methodologies and applications, *European Journal of Operational Research*, vol. 200, pp. 198-215, 2010; https://doi.org/10.1016/j.ejor.2009.01.021

[146] Taherdoost, H., Madanchian, M. Using PROMETHEE Method for Multi-Criteria Decision Making: Applications and Procedures, Iris Journal of

Economics & Business Management, 2023; DOI:10.33552/IJEBM.2023.01.000502

[147] Figueira, J., Roy, B. Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure, *European Journal of Operational Research*, vol. 139, pp. 317-326., 2002; DOI:10.1016/S0377-2217(01)00370-8

[148] Software online DecSpace (Pre-Alpha), [Online]. Available: http://app.decspacedev.sysresearch.org/#/

[149] United Nations Development Program, UNDP. Human Development Report 2020, 2020. [Online]. Available: http://hdr.undp.org/sites/default/files/hdr2020.pdf.

[150] Kaufmann, D., Kraay, A. Worldwide Governance Indicators (WGI), 2020. [Online]. Available: https://info.worldbank.org/governance/wgi/Home/Documents. [Accessed 14 September 2021].

[151] World Intellectual Property Organization (WIPO). Global Innovation Index 2021. Tracking innovation through the Covid-19 Crisis, 2021. [Online]. Available: https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2021.pdf.

[152] World Bank. TCdata360, The World Bank, [Online]. Available: https://tcdata360.worldbank.org/indicators/3aa2eb70?country=LBY&indicator=40712&countries=SYR&viz=line_chart&years=2013,2016.

[153] World Bank Group and Energy Sector Management Assistance Program (ESMAP), [Online]. Available: https://rise.esmap.org/indicators.

[154] International Energy Agency (IEA). Policies, 2021. [Online]. Available: https://www.iea.org/policies/about. [Accessed 2021].

[155] IEA, Hydrogen Projects Database, IEA, Paris, 2020. [Online]. Available: https://www.iea.org/reports/hydrogen-projects-database .

[156] UN-Water SDG 6 Data Portal. Level of water stress: freshwater withdrawal as a proportion of available freshwater resources (FAO), [Online]. Available: https://sdg6data.org/tables.

[157] UN-Water SDG 6 Data Portal, Degree of integrated water resource management implementation (IWRM Data Portal, UNEP), [Online]. Available: https://sdg6data.org/tables.

[158] Transparency International. Corruption Perceptions Index," 2021. [Online]. Available: https://www.transparency.org/en/cpi/2020/index/nzl.

[159] International Monetary Fund (IMF). International Monetary Fund (IMF) dataset, 2019. [Online]. Available: https://data.imf.org/?sk=F8032E80-B36C-43B1-AC26-493C5B1CD33B.

[160] Ullah, H. Tunisia aims for the export-oriented hydrogen industry, February 2021. [Online]. Available: https://www.h2bulletin.com/tunisia-export-hydrogen-industry/.

[161] Republique Tunisienne. Contribution Déterminée au niveau National (CDN) actualisée, 2021 (in French).

[162] UNDP and ANME. L'élaboration de la Stratégie Nationale Bas Carbone dans le secteur de l'énergie en Tunisie, 2021 (in French).

[163] Nouicer, A. (ISPI). What a green transition means for Tunisia, 25 January 2022. [Online]. Available: https://www.ispionline.it/en/pubblicazione/what-green-transition-means-tunisia-32905.

[164] International Renewable Energy Agency (IRENA). Renewables Readiness Assessment: the Republic of Tunisia. (Executive summary), 2021.

[165] World Bank Group. Climate Risk Country Profile: Morocco, 2021.

[166] World Bank Group. Climate Risk Country Profile: Tunisia, 2021.

[167] International Energy Agency (IEA). Data and statistics/Algeria, 2020. [Online]. Available: https://www.iea.org/countries/algeria.

[168] Zahraoui, Y., Khan, M.R.B., Alhamrouni, I., Mekhilef, S.; Ahmed, M. Current status, scenario and perspective of renewable energy in Algeria: a review, *energies*, vol. 14, 2021; https://doi.org/10.3390/en14092354

[169] Haddoum, S., Bennour, H., Zaid, T.A. Algerian energy policy: perspectives, barriers and missed opportunities, Global Challenges, vol. 2, 2018; https://doi.org/10.1002/gch2.201700134

[170] Sibel, R., Terrapon-Pfaff, J. Sustainable transformation of Algeria's energy system, 2021.

[171] Boukhatem, I. The challenges of energy transition in fossil-fuel- exporting countries. The case of Algeria," 2022. [Online]. Available: https://longreads.tni.org/the-case-of-algeria.

[172] International Renewable Energy Agency (IRENA). South Africa country analysis – The renewable energy transition in Africa, March 2021.

[173] International Energy Agency (IEA), Energy Policies beyond IEA Countries: Morocco, Paris, 2019. [Online]. Available: https://www.iea.org/reports/energy-policies-beyond-iea-countries-morocco-2019.

[174] Schinke, B., Klawitter, J. Background Paper: Country Factsheet Morocco - Energy and development at a glance, 2016.

[175] Directorate-General for Climate Action. The EU and Morocco form a Green Partnership on energy, climate and the environment ahead of COP 26, 28 June 2021. [Online]. Available: https://ec.europa.eu/clima/news-your-

voice/news/eu-and-morocco-form-green-partnership-energy-climate-and-environment-ahead-cop-26-2021-06-28_en.

[176] Liga, A. (Istituto per gli Studi di Politica Internazionale, ISPI), «Transizione green: le ambizioni del Marocco.,» 6 August 2021 (in Italian). [Online]. Available: https://www.ispionline.it/it/pubblicazione/transizione-green-le-ambizioni-del-marocco-31349.

[177] Royaume du Maroc - Ministère de la Transition Energètique et du Developpment Durable, department du Developpement Durable. Stratègie Bas Carbone à Long Terme: MAROC 2050, October 2021 (in French).

[178] Royaume du Maroc - Ministère de la transition Energètique et du Développment Durable. Hydrogène Vert: vecteur de transition ènergètique et de croissance durable, 21 August 2021 (in French). [Online]. Available: https://www.mem.gov.ma/Pages/actualite.aspx?act=278.

[179] Royaume of Morocco. Feuille de route: Hydrogène Vert, Vecteur de Transition Energetique et de Croissance Durable, January 2021 (in French).

[180] Nait Mensour, O., El Ghazzani, B., Hlimi, B., Ihlal, A. A geographical information system-based multi-criteria method for the evaluation of solar farms locations: A case study in Souss-Massa area, southern Morocco, *energy*, no. 182, pp. 900-919, 2019; https://doi.org/10.1016/j.energy.2019.06.063

[181] Taoufik, O., Fekri, A., Laghlimi, M. Land suitability analysis for solar farms exploitation using the GIS and AHP - a case study of Morocco, *Energy Policy*, 2021; DOI:10.33223/epj/133474

[182] Sedrati, M., Maanan, M., Rhinane, H. PV power plants sites selection using GIS-FAHP based approach in North West Morocco, in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-4/W19, PhilGEOS x GeoAdvances 2019, Manila, Philippines, 2019.

[183] Tahri, M., Hakdaoui, M., Maanan, M. The evaluation of solar farm locations applying Geographic Information System and Multi-Criteria Decision-Making methods: Case study in southern Morocco, *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1354-1362, 2015; https://doi.org/10.1016/j.rser.2015.07.054

[184] The World Bank and the International Finance Corporation. Long-term yearly average of global horizontal irradiation - Morocco - Global Solar Atlas 2.0, 2019. [Online]. Available: https://globalsolaratlas.info/download.

[185] CGIAR - Consortium for Spatial Information (CGIAR-CSI). SRTM 90m DEM Digital Elevation Database, [Online]. Available: https://srtm.csi.cgiar.org/.

[186] openAFRICA by Code for Africa. [Online]. Available: https://africaopendata.org/dataset/morocco-maps/resource/30e9259b-02c9-4f8e-a337-44738de874cf.

[187] UNEP-WCMC WDPA/OECM. World Database on Protected Areas (WDPA), May 2019. [Online]. Available: https://www.unep-wcmc.org/resources-and-data/wdpa.

[188] Humanitarian Data Exchange. HOTOSM Morocco Populated Places (OpenStreetMap Export), [Online]. Available: https://data.humdata.org/dataset/hotosm_mar_populated_places.

[189] Esri, Sentinel-2 Land Use / Land Cover Downloader [Online]. Available: https://www.arcgis.com/apps/instant/media/index.html?appid=fc92d38533d440078f17678ebc20e8e2..

[190] ESRI, ArcGIS Pro software, 2022.

[191] Touili, S., Alami Merrouini, A., Azouzoute, A., El Hassouani, Y., Amrani, A. A technical and economical assessment of hydrogen production potential from solar energy in Morocco, *International Journal of Hydrogen Energy*, vol. 43, pp. 22777-22796, 2018; https://doi.org/10.1016/j.ijhydene.2018.10.136

[192] Rahmouni, S., Negrou, B., Settou, N., Dominguez, J., Gouareh, A. Prospects of hydrogen production potential from renewable sources in Algeria, *International journal of hydrogen energy*, vol. 42, pp. 1383-1395, 2017; https://doi.org/10.1016/j.ijhydene.2016.07.214

[193] Charabi, Y., Gastli, A. PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation, *Renewable Energy*, vol. 36, pp. 2554-2561, 2011; https://doi.org/10.1016/j.renene.2010.10.037

[194] Chen, S. et al., The Potential of Photovoltaics to Power: the Belt and Road Initiative, Joule, vol. 3, no. 8, pp. 1895-1912, 2019.

[195] Sabo, L.M., Mariun, N., Hizam, H., Radzi, M.A.M., Zakaria, A. Spatial energy predictions from large-scale photovoltaic power plants located in optimal sites and connected to a smart grid in Peninsular Malaysia, *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 79-94, 2016; https://doi.org/10.1016/j.rser.2016.07.045

[196] Doljak, D., Stanojevic, G. Evaluation of natural conditions for site selection of ground-mounted photovoltaic power plants in Serbia, *Energy*, vol. 127, pp. 291-300, 2017; https://doi.org/10.1016/j.energy.2017.03.140

[197] Asakereh, A., Soleymani, M., Sheikhdavoodi, M.J. A GIS-based Fuzzy-AHP method for the evaluation of solar farms locations: case study in Khuzestan province, Iran, *Solar Energy*, vol. 155, pp. 342-353, 2017; https://doi.org/10.1016/j.solener.2017.05.075

[198] Ruiz, H., Sunarso, A., Ibrahim-Bathis, K., Murti, S., Budiarto, I. GIS-AHP Multi-Criteria Decision Analysis for the optimal location of solar energy plants at Indonesia, *Energy Reports*, vol. 6, pp. 3249-3263, 2020; https://doi.org/10.1016/j.egyr.2020.11.198

[199] Zupi, M. – Osservatorio di Politica Internazionale. La questione del Sahara Occidentale: origine e sviluppi, 2021.

[200] Saaty, T. The Analytic Hierarchy Process, 1980.

[201] Steinitz, C. Geographical information systems: a personal historical perspective, the framework for a recent project, and some questions for the future, in European Conference on Geographic Information Systems, 1993.

[202] Malczewski, J. GIS and Multi-criteria Decision Analysis, John Wiley & Sons, 1999.

[203] Schuwirth, N., Reichert, P., Lienert, J. Methodological aspects of multi-criteria decision analysis for policy support: a case study on pharmaceutical removal from hospital wastewater, *European Journal of Operational Research*, vol. 220, no. (2), pp. 472-483, 2012; https://doi.org/10.1016/j.ejor.2012.01.055

[204] M.C. Pinto, M. Gaeta, E. Arco, P. Boccardo, S.P. Corgnati (2023). Mapping suitability of North Africa for green hydrogen production: development of a Multi-criteria Spatial Decision Support System applied to Tunisia. *Status: under review for the journal Energy, Sustainability and Society*.

[205] Armed Conflict Location & Event Data Project (ACLED). ACLED Portal - Available data, 2020. [Online]. Available: https://acleddata.com/data-export-tool/.

[206] SRTM. SRTM 90m - DEM Digital elevation Database, [Online]. Available: https://srtm.csi.cgiar.org/.

[207] GADM, GADM on Humanitarian Data Exchange, [Online]. Available: https://data.humdata.org/dataset/geoboundaries-admin-boundaries-for-tunisia.

[208] Humanitarian Data Exchange. HOTOSM (OpenStreetMap Export), 2020. [Online]. Available: https://data.humdata.org/dataset/.

[209] Open Street Map. WFP GeoNode (OSM) - Tunisia Road network, 2017. [Online]. Available: https://geonode.wfp.org/layers/geonode:tun_trs_roads_osm.

[210] World Bank Group, Energydata.info. Tunisia – Electricity Transmission Network, 2017. [Online]. Available: https://energydata.info/dataset/tunisia-electricity-transmission-network-2017.

[211] SuperDecisions software. [Online]. Available: www.superdecisions.com.

[212] World Bank Group - ESMAP - VORTEX – DTU. Global Wind Atlas, [Online]. Available: https://globalwindatlas.info/en.

[213] Pinto, M.C., Gaeta, M., Gelmini, A. Potential of green hydrogen in North Africa: suitability and costs up to 2050. Report RdS n.22014071, 2022.

[214] Pinto, M.C., Simões, S., Fortes, P. Green hydrogen from North Africa to Europe: impact and competitiveness through long-term scenario analyses, Ricerca sul Sistema Energetico (RSE), RdS Deliverable n. 23012300, 2023. *Status: under review.*

[215] Pinto, M.C., Simões, S., Fortes, P. How can green hydrogen from North Africa support EU decarbonization? Scenario analyses on competitive pathways for trade. 2023. *Status: submitted to the journal International Journal of Hydrogen Energy.*

[216] Loulou, R., Remme, U., Kanudia, A., Lehtila, A., Goldstein, G. Documentation for the TIMES model - Part I: Energy Technology Systems Analysis Programme (ETSAP), 2005.

[217] Loulou, R., Remme, U., Kanudia, K., Lehtila, A., Goldstein, G. Documentation for the TIMES model - Part II: Energy Technology Systems Analysis Programme, 2005.

[218] World Energy Council (WEC). Working paper: Hydrogen Demand and Costs Dynamics, 2021.

[219] European Commission. European Green Deal: Commission proposes transformation of EU economy and society to meet climate ambitions, 2021. [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_3541.

[220] Vartiainen, C., Breyer, M.D., Roman Medina, E., Busto, C., Masson, G., Jager-Waldau, A. True cost of solar hydrogen," *Solar RRL*, vol. 6, no. 5, 2022.

[221] Pastore, L.M., Basso, G., De Santoli, M. Technical, economic and environmental issues related to electrolysers capacity targets according to the Italian Hydrogen Strategy: a critical analysis, *Renewable Sustainable Energy Reviews*, vol. 166, 2022; https://doi.org/10.1016/j.rser.2022.112685

[222] Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., Few, S. Future cost and performance of water electrolysis: an expert elicitation study,

International Journal of Hydrogen Energy, vol. vol. 42, pp. 30470-30492, 2017; https://doi.org/10.1016/j.ijhydene.2017.10.045

[223] European Hydrogen Backbone (EHB). Implementation Roadmap – Cross border projects and costs update, November 2023.

[224] International Energy Agency (IEA). Power generation technology costs and assumptions in the WEO-2021 Stated Policies and Net Zero Emissions by 2050 scenarios, 2021.

[225] International Renewable Energy Agency (IRENA). Future of solar photovoltaic, 2019.

[226] International Renewable Energy Agency (IRENA). Future of wind, 2019.

[227] Danish Energy Agency (DEA). Technology Data for energy carrier generation and conversion. 2022. [Online]. Available: https://ens.dk/en/our-services/technology-catalogues/technology-data-renewable-fuels

[228] Haider Ali Khan, M., Heywood, P., Kuswara, A., Daiyan, R., MacGill, I. Amal, R. An integrated framework of open-source tools for designing and evaluating green hydrogen production opportunities, *Communications Earth & Environment*, vol. 3, no. 309, 2022; https://doi.org/10.1038/s43247-022-00640-1

[229] Global Alliance Powerfuels - German Energy Agency (GEA). Water consumption of powerfuels: demand, supply and policy recommendations to foster environmental sustainability, 2021.

[230] World Bank Group. The role of desalination in an Increasingly Water-Scarce World, 2019.

[231] International Energy Agency (IEA), "Energy Technology Perspectives 2023," Paris, 2023.

[232] Element Energy (EE). Hydrogen supply chain evidence base, November 2018.

[233] Cosin, C., Magazine, S.W., The evolution of rates in desalination (Part I), 15 01 2019. [Online]. Available: https://smartwatermagazine.com/blogs/carlos-cosin/evolution-rates-desalination-part-i.

[234] Institute for European Environmental Policy. Potential impacts of desalination development on energy consumption, 2008.

[235] Hofrichter, A., Rank, D., Heberl, M., Sterner, M. Determination of the optimal power ratio between electrolysis and renewable energy to investigate the effects on the hydrogen production costs, *International Journal of Hydrogen Energy*, vol. 48, pp. 1651-1663, 2023; https://doi.org/10.1016/j.ijhydene.2022.09.263

[236] Armaroli, N., Barbieri, A. Il dilemma dell'idrogeno nella transizione energetica italiana. 9 September 2021. [Online]. Available: https://www.nature.com/articles/d43978-021-00110-w.

[237] Hydrogen Europe. Clean H2 Monitor, 2022.

[238] Hydrogen Europe. Technical overview: Hydrogen storage, 2021.

[239] International Energy Agency (IEA) – ETSAP. Technology Brief, 2014.

[240] Willige, A. Four ways of storing hydrogen from renewable energy, 30 November 2022. [Online]. Available: https://spectra.mhi.com/4-ways-of-storing-hydrogen-from-renewable-energy.

[241] Reuss, M., Grube, T., Robinius, M., Stolten, D. A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany, *Applied Energy*, vol. 247, pp. 438-453, 2019; https://doi.org/10.1016/j.apenergy.2019.04.064

[242] Papadias, D., Ahluwalia, R. Bulk storage of hydrogen, *International Journal of Hydrogen Energy*, vol. 46, pp. 34527-34541, 2021;

[243] Chen, S., Ma, Z. Nasrabadi, H., Chen, B., Mehana, M., Van Wijk, J.W. Technical and Economic Feasibility Analysis of Underground Hydrogen Storage: A Case Study in Intermountain-West Region USA," 2022.

[244] Det Norske Veritas group (DNV). Hydrogen Forecast to 2050, 2022.

[245] Lund, E., Arler, F., Østergaard, P., Hvelplund, F., Connolly, D., Mathiesen, B., Karnøe, P. Simulation versus Optimisation: Theoretical Positions in Energy System Modelling, *Energies*, vol. 10, no. 840, 2017; https://doi.org/10.3390/en10070840

[246] Bolat, P., Thiel, C. Hydrogen supply chain architecture for bottom-up energy system models. Part 1: developing pathways, *International Journal of Hydrogen Energy*, vol. 39, pp. 8881-8897, 2014; https://doi.org/10.1016/j.ijhydene.2014.03.176

[247] Bolat, R., Thiel, C. Hydrogen supply chain architecture for bottom-up energy system models. Part 2: techno-economic inputs for hydrogen production pathways, *International Journal of Hydrogen Energy*, vol. 39, pp. 8898-8925, 2014; https://doi.org/10.1016/j.ijhydene.2014.03.170

[248] Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel C., Peteves, S. The JRC-EU-TIMES model: assessing the long-term role of the SET Plan Energy Technologies. Report EUR 26292 EN., 2013.

[249] Simoes, S., Nijs, W., Ruiz-Castello, P. Sgobbi, A., Thiel, C. Comparing policy routes for low-carbon power technology deployment in EU – an energy system analysis, *Energy Policy*, vol. 101, p. pp. 353–365. , 2017; https://doi.org/10.1016/j.enpol.2016.10.006

[250] Collins, L. Algeria aims to supply Europe with 10% of its clean hydrogen needs by 2040 in new national H2 roadmap, March 2023. [Online]. Available: https://www.hydrogeninsight.com/policy/algeria-aims-to-supply-europe-with-10-of-its-clean-hydrogen-needs-by-2040-in-new-national-h2-roadmap/2.

[251] Royaume du Maroc - Ministère de la transition Energètique et du Développment Durable. Hydrogène Vert: vecteur de transition ènergètique et de croissance durable. (in French), August 2021. [Online]. Available: https://www.mem.gov.ma/Pages/actualite.aspx?act=278.

[252] Agency Tunis Afrique Press, Tunisia can export over 5.5mln tonnes of green hydrogen to Europe by 2050.," 26 May 2023. [Online]. Available: https://www.zawya.com/en/world/africa/tunisia-can-export-over-55mln-tonnes-of-green-hydrogen-to-europe-by-2050-ojl8873x.

[253] Bouafif, A. Tunisia's National Green hydrogen roadmap to be ready by mid-March 2023, according to the German Development Agency « GIZ », March 2023. [Online]. Available: https://www.tunur.tn/tunisias-national-green-hydrogen-roadmap-to-be-ready-by-mid-march-2023-according-to-the-german-development-agency-giz/.

[254] International Renewable Energy Agency (IRENA). The cost of financing for renewable power (Data Appendix), Abu Dhabi, 2023.

[255] European Commission. EU-US LNG trade: US liquefied natural gas (LNG) has the potential to help match EU gas needs, 2022. [Online]. Available: https://energy.ec.europa.eu/system/files/2022-02/EU-US_LNG_2022_2.pdf.

List of abbreviations

ACLED	Armed Conflict Location & Event Data Projects
AF	Area Factor
AFIR	Alternative Fuels Infrastructure Regulation
AHP	Analytic Hierarchy Process
ALK	Alkaline electrolysers
ANME	National Agency for Energy Management
ANP	Analytic Network Process
APS	Announced Pledges Scenario
BE	Belgium
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Usage
COMELEC	Comite Maghrebin de L'electricite
COP	Conference of Parties
CSP	Concentrated Solar Power
CY	Cyprus
DAC	Direct Air Capture
DE	Germany
DEM	Digital Elevation Model
EE	Estonia
EFI	Economic Freedom Index
EHB	European Hydrogen Backbone
EL	Greece
EPI	Energy Performance Index

ES	Spain
ESA	Energy System Analysis
ESMAP	Energy Sector Management Assistance Program
ESRI	Environmental System Research Institute
ETS	Emissions Trading System
ETSAP	Energy Technology Systems Analysis Program
FAO	Food and Agricultural Organization of United Nations
FCT NOVA	Faculdade de Ciências e Tecnologia da Universidade NOVA - Lisboa
FDI	Financial Development Index
FI	Finland
FLH	Full Load Hours
FR	France
GADM	Global Administrative Areas
GDP	Growth Domestic Production
GHG	Greenhouse Gas Emission
GHI	Global Horizontal Irradiation
GHR	Global Hydrogen Review
GII	Global Innovation Index
GIS	Geographic Information System
HDI	Human Development Index
HHV	Higher Heating Value
HR	Croatia
IE	Ireland
IEA	International Energy Agency
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
IT	Italy

ITCEQ	Tunisian Institute of Competitiveness and Quantitative Studies
IWRM	Integrated Water Resource Management
JET	Joint Research Centre European TIMES
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LCOH	Levelized Cost of Hydrogen
LHV	Lower Heating Value
LNEG	Laboratório Nacional de Energia e Geologia - Lisboa
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
LT	Lithuania
LV	Latvia
MAVT	Multi-Attribute Value Theory
MCA	Multi-criteria Analysis
MCDM	Multi-criteria Decision Making
MC-SDSS	Multi-criteria Spatial Decision Support Systems
MT	Malta
NDC	Nationally Determined Contribution
NELD	Non-Economic Loss and Damage
NES	National Energy Strategy
NL	Netherlands
NO	Norway
OM	Operation and Maintenance
PEM	Proton Exchange Membrane/Polymer Electrolyte Membrane
PERG	Moroccan Rural Electrification Programme
PET	Pan-European TIMES

PL	Poland
PROMETHEE	Preference Ranking Organisation METhod for Enrichment of Evaluations
PT	Portugal
PV	Photovoltaic
RCF	Recycled Carbon Fuels
RCREEE	Regional Center for Renewable Energy and Energy Efficiency
RdS	Ricerca di Sistema
RECAI	Renewable Energy Country Attractiveness Index
RED	Renewable Energy Directive
RES	Renewable Energy Sources
RFNBO	Renewable Fuels of Non-Biological Origin
RISE	Regulatory Indicators for Sustainable Energy
RSE	Ricerca sul Sistema Energetico
SDG	Sustainable Development Goal
SE	Sweden
SOEC	Solid Oxide Electrolyser Cell
SP	Scenario Planning
SRTM	Shuttle Radar Topography Mission
STAGE	Society, Technology, Atmosphere and land, Geopolitics, Economy
STEG	Tunisian Company for Electricity and Gas
SWOT	Strength Weakness Opportunities and Threats
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TRL	Technological Readiness Level
TSO	Transmission System Operator
UK	United Kingdom

UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WACC	Weighted Average Cost of Capital
WDPA	World Database of Protected Areas
WEC	World Energy Council
WFP	World Food Programme
WGI	Worldwide Governance Indicators
WIPO	World Intellectual Property Organization
WO	Wind Onshore

Appendix

Here are reported the activities (i.e. contributions published or under review, conference attendances and publications, attended courses, other activities) during the three years of PhD.

Contributions

- *M.C. Pinto*, S.G. Simões, P. Fortes (2023). “Green hydrogen trade from North Africa to Europe: optional long-term scenarios with the JRC-EU-TIMES model”. Abstract presented at IEA-ETSAP Workshop 2023, 16-17 November 2023, Turin (Italy), session “Bioenergy and hydrogen in future energy system”, 17th November 2023.
- *M.C. Pinto*, M. Gaeta, E. Arco, P. Boccardo, S.P. Corgnati (2023). “Mapping Suitability of North African Countries for Green Hydrogen Production: A Multi-Criteria Spatial Decision Support System”. Paper presented at 18th SDEWES Conference, session “Renewable energies and energy efficiency technologies for industrial applications, transportations and infrastructure 2”, 26th September 2023.
- *M.C. Pinto*, G. Crespi, F. Dell’Anna, C. Becchio (2023). “Combining energy dynamic simulation and multi-criteria analysis for supporting investment decisions on smart shading devices in office buildings”, Applied Energy.
- *M.C. Pinto*, M. Gaeta, A. Gelmini (2022). “Potential of green hydrogen production in North Africa: suitability and costs up to 2050”, Ricerca sul Sistema Energetico (RSE), RdS Deliverable n. 22014071.
- *M.C. Pinto*, E. Arco, M. Gaeta (2022). “Combination of AHP and GIS to select suitable sites for green hydrogen production in North Africa”. Abstract presented at the International Conference EURO2022, session “AHP/ANP”, 4th July 2022.
- *M.C. Pinto*, G. Crespi, F. Dell’Anna, C. Becchio (2022). “A multi-dimensional Decision Support System for choosing solar shading devices in office buildings”. Paper presented at the Conference NMP2022, session “Energy transition: citizens’ active role, processes and impact”, 27th May 2022.

- I. Abbà, C. Becchio, S. Corgnati, P. Pasquali, *M.C. Pinto*, E. Roglia, S. Viazzo (2022). “Insights of the DYDAS Project: The Use Case Energy”. Paper presented at the International Conference CLIMA2022, session “Energy”, 23rd May 2022.
- *M.C. Pinto*, P. Boccardo, M. Gaeta, A. Gelmini (2022). “Achieving decarbonization: challenges and opportunities of green hydrogen”, REHVA Journal 01/2022, pp. 32-37.
- *M.C. Pinto*, M. Gaeta (2021). “Analysis on potential of green hydrogen production in North Africa: challenges and opportunities up to 2050”, Ricerca sul Sistema Energetico (RSE), RdS Deliverable n. 21009853, December 2021.
- E. Bompard, M. Cavana, S. Corgnati, F. Dolci, D. Grosso, P. Leone, A. Mazza, P. Moretto, *M.C. Pinto* (2021). “Trends, policies and geo-political implications of hydrogen exploitation in the Mediterranean”, Chapter 2 in “MED & Italian Energy Report: The new game of hydrogen in the Euro Mediterranean region”, EST-ESL@ EnergyCenterLab – Politecnico di Torino and SRM. Giannini Editore, 2021.
- *M.C. Pinto*, G. Crespi, F. Dell’Anna, C. Becchio (2021). “Proposal of a multi-step methodological approach for evaluating the performances of solar shading devices in office buildings”. Paper presented at the International Conference ICAE2021, session “Intelligent energy systems”, 4 December 2021.
- G. Crespi, F. Dell’Anna, *M.C. Pinto*, C. Becchio (2021). “A multi-criteria model to support shading devices selection in a real office building”. Abstract presented at the International Conference EURO2021, session “Urban and Territorial Planning in MCDA”, 14 July 2021.
- C. Becchio, S. Corgnati, G. Crespi, *M.C. Pinto*, S. Viazzo (2021). “Exploitation of dynamic simulation to investigate the effectiveness of the Smart Readiness Indicator: application to the Energy Center building of Turin”, Science and Technology for the Built Environment.

Contributions – in progress

- *M.C. Pinto*, S. Simões, P. Fortes (2023). “Green hydrogen from North Africa to Europe: impact and competitiveness through long-term scenario analyses”, Ricerca sul Sistema Energetico (RSE), RdS Deliverable n. 23012300, RT-LA 1.03-2. Status: *under review.*

- *M.C. Pinto*, S. Simões, P. Fortes (2023). How can green hydrogen from North Africa support EU decarbonization? Scenario analyses on competitive pathways for trade. *Status: submitted to the journal International Journal of Hydrogen Energy.*
- *M.C. Pinto,* M. Gaeta, E. Arco, P. Boccardo, S.P. Corgnati (2023). Mapping suitability of North Africa for green hydrogen production: development of a Multi-criteria Spatial Decision Support System applied to Tunisia. *Status: under review for the journal Energy, Sustainability and Society.*

Period abroad

- 13/02/2023 – 30/07/2023: LNEG (National Laboratory of Energy and Geology) and NOVA University – Science and Technology, Lisbon (Portugal): period abroad to focus on PhD research activities, with respect to energy scenario modelling on TIMES, in order to study and analyze the green hydrogen competitiveness in the Mediterranean area.

Attended conferences and workshops

- IEA-ETSAP Workshop 2023, 16-17 November 2023, Turin (Italy). Speaker in the session “Bioenergy and hydrogen in future energy system”, 17th November 2023. Abstract presented: “Green hydrogen trade from North Africa to Europe: optional long-term scenarios with the JRC-EU-TIMES model”, M.C. Pinto, Simões, S.G., Fortes, P.
- 18th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES Conference), 24-29 September 2023, Dubrovnik (Croatia). Speaker in the session “Renewable energies and energy efficiency technologies for industrial applications, transportations and infrastructure 2”, 26 September 2023. In Conference Proceedings: “Mapping Suitability of North African Countries for Green Hydrogen Production: a Multi-Criteria Spatial Decision Support System”, M.C. Pinto, M. Gaeta, E. Arco, P. Boccardo, S.P. Corgnati.
- 32th European Conference on Operational Research (EURO2022), 3-6 July 2022, Espoo (Finland). Chair and speaker in the session “AHP/ANP” in the area “Decision Support”, 4 July 2022. Abstract presented: “Combination of AHP and GIS to select suitable sites for

green hydrogen production in North Africa", M.C. Pinto, E. Arco, M. Gaeta.
- 5th Conference on New Metropolitan Perspectives (NMP2022), 25-27 May 2022, Reggio Calabria (Italy). Speaker in the session "Energy transition: citizens' active role, processes and impact", 27 May 2022. In Conference Proceedings: "A multi-dimensional Decision Support System for choosing solar shading devices in office buildings", M. C. Pinto, G. Crespi, F. Dell'Anna, C. Becchio.
- 13th International Conference on Applied Energy (ICAE2021), Nov 29 – Dec 2, 2021 (online). Speaker in the session "Intelligent energy systems", 4 December 2021. In Conference Proceedings: "Proposal of a multi-step methodological approach for evaluating the performances of solar shading devices in office buildings", M.C. Pinto, G. Crespi, F. Dell'Anna, C. Becchio.

Attended courses

- *Hard skills:*
  - Advanced geospatial data management (15 h)
  - Behavioural theories (15 h)
  - Energy sustainability and security (16 h)
  - Global energy trends and outlook (10 h)
  - Multicriteria analysis and strategic assessment (15 h)
  - Open geospatial data (15 h)
  - Problem structuring methods for facing urban uncertainty (15 h)
  - Socio-technical urbanization: quantitative and qualitative methodologies in urban studies (15 h)
  - Socio-technical urbanization: social sciences approach to urban studies (15 h)
  - Sustainable development goals: sustainability assessment methods and global challenges (16 h)
  - Telerilevamento (90 h)

- *Soft skills:*
  - All you need to know about research data management and open access publishing (15 h)

- Public speaking (5 h)
- Public speaking II (12 h)
- The Hitchhiker’s Guide to the Academic Galaxy (15 h)
- Thinking out the box (1 h)
- Time management (2 h)
- Time management II (4 h)

Other activities

- 20/04/2023 – 15/09/2023; Collaboration with Links Foundation for the LEED Certification assessment of a dormitory in Turin: Work on energy dynamic simulation of the building (Design Builder software to obtain the LEED Certification).
- 13/02/2023 – 30/07/2023: Collaboration with LNEG (National Laboratory of Energy and Geology) and NOVA School of Science and Technology, Lisbon, Portugal: Period abroad to focus on PhD activities belonging to TIMES modelling in order to study the competitiveness of green hydrogen in terms of local production and potential trades through cross-border cooperations.
- February 2021 – March 2023; Collaboration with ITHACA on the European project DYDAS: Working, meeting, and reporting, participation to dissemination conferences
- 26/09/2022 – 29/09/2022; Florence School of Regulation (FSR, EUI), Florence, Italy: Participation to the “Summer School for Young Researchers on Energy Systems: Heating in a decarbonised energy system”, organized by Florence School of Regulation, Robert Shuman Centre for Advanced Studies, European University Institute.
- 18/07/2022 – 29/07/2022; Bilkent University, Ankara, Turkey: Participation to the 14th EURO PhD Summer School on MCDA/MCDM.
- December 2017 – December 2022; Politecnico di Torino: Participation to the “EcòPoli” group, with the aim to create a sustainable campus, by promoting activities involving waste management, mobility and sustainability.

  Member of the “Team Waste” student team, evolved in “Threekeco” project, based both on a new and better design of the waste management at Politecnico di Torino, aiming to increase awareness among students.