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ENERGY TRANSITION IN SICILY: THE STRATEGIC ROLE OF GREEN HYDROGEN IN TECHNOLOGICAL INNOVATION AND MATERIAL CIRCULARITY*

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Abstract

The ecological transition represents one of the most urgent and complex challenges for Europe's sustainable future and, in particular, for insular regions such as Sicily, which are characterized by significant renewable energy potential but also by considerable infrastructural constraints. Within this framework, green hydrogen is positioned as a strategic instrument for decarbonization and for the revitalization of the regional energy system. This study focuses on the analysis of green hydrogen production alternatives in Sicily, evaluating their potential in relation to the availability of renewable resources, the existing regulatory framework, and the main environmental impacts, with particular attention to water electrolysis technology. Electrolysis enables the production of green hydrogen using only electricity and water, with no CO_2 emissions when powered by renewable sources. As a clean and sustainable process, it is a valuable pathway for the decarbonization of industrial and transport sectors. An additional innovative opportunity examined in this research concerns the reuse of industrial molybdenum waste, which, through cost-effective nanostructuring processes, can be employed as alternative materials for electrodes and catalysts. This approach reduces dependence on critical raw materials and fosters a circular economy within the green hydrogen sector. Finally, the study proposes several recommendations aimed at integrating the green hydrogen value chain into the regional ecological transition strategy, with a specific focus on infrastructure, materials research, and the regulatory framework.

Keywords: critical raw materials, decarbonization, ecological transiction, green hydrogen, membranes

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1. Introduction

The ecological transition represents one of the most complex and necessary processes of our time, particularly for a country such as Italy, where the interconnection between environment, economy, and society is especially pronounced. It is not merely a matter of replacing fossil fuels with renewable energy sources or planting trees to offset emissions: it entails a profound rethinking of our development model, as outlined in the Piano per la Transizione Ecologica (PTE) and in the objectives of the 2030 Agenda for Sustainable Development. It means envisioning cities where mobility is sustainable, industries operate without depleting natural resources, and agriculture works in harmony with biodiversity.

In Italy, the ecological transition holds a particularly urgent meaning due to the fragility of its territory: landslides, floods, droughts, and sea-level rise are tangible manifestations of climate change, which is strongly felt in this context. Moreover, Italy possesses a unique cultural and landscape heritage that risks being compromised unless effective adaptation and mitigation strategies are implemented, as foreseen by the PTE and by the international guidelines of the 2030 Agenda.

Sicily occupies a distinctive position within the national and European energy landscape. Its geographical location, at the center of the Mediterranean, together with the abundance of natural resources (particularly solar and wind), makes it one of the regions with the highest renewable potential in Italy (XXXIII Congresso Geografico Italiano, 2021). However, this favorable condition is intertwined with structural challenges that cannot be overlooked: insufficient electricity transmission capacity, limited integration with the continental grid, and an uneven distribution of energy infrastructures represent concrete barriers to the optimal exploitation of such potential.

In this context, green hydrogen emerges as a strategic lever to support the energy transition and to reduce greenhouse gas emissions. Green hydrogen refers to hydrogen produced through the electrolysis of water powered exclusively by renewable energy. This process separates water molecules into hydrogen and oxygen by means of an electric current, without generating carbon dioxide. Its inherent characteristics, combined with the possibility of storage and use in energy-intensive sectors, make it a technology capable of contributing both to decarbonization and to the management of renewable energy variability.

Electrolysis, indeed, makes it possible to obtain hydrogen without environmentally harmful emissions, and is therefore fundamental for the implementation of a sustainable energy model (Bahman et al., 2024). However, the efficiency and sustainability of electrolysis largely depend on the availability and properties of the materials employed, particularly membranes and catalysts. The latter, often based on critical raw materials such as platinum, iridium, and rare earth elements, present significant challenges in terms of supply and environmental impact. A thorough analysis of membranes highlights the necessity of developing alternative, more abundant, and lower-impact materials to ensure the scalability and accessibility of this technology. Green hydrogen also fosters energy independence by reducing reliance on fossil fuels. Furthermore, the hydrogen produced can be stored and used when required, thereby improving the management of intermittent renewable sources (Ponzio et al., 2021). Although electrolysis is a scientifically consolidated process, it requires specific materials for membranes and catalysts, which today are frequently based on rare and costly elements such as platinum and iridium. This dependency raises issues related to costs, supply security, and the environmental footprint of extractive industries. From this perspective, innovative solutions such as the reuse of industrial molybdenum waste acquire particular relevance. Through low-cost nanostructuring processes, these residues can be transformed into alternative materials for electrodes and catalysts, thereby reducing dependence on critical raw materials and promoting a circular economy approach applied to green hydrogen production (Costanzo et al., 2024).

This publication proposes to investigate the potential of green hydrogen production in Sicily by integrating technological and environmental perspectives. Opportunities deriving from the abundance of renewable resources will be analyzed alongside the critical issues related to infrastructure, materials, and the regulatory framework, with the aim of outlining strategies to incorporate green hydrogen into the regional pathway toward a more resilient, competitive, and sustainable energy system.

2. Materials and methods

Sicily is a region that, due to its natural conditions, geographical location, and availability of resources, exhibits extraordinary potential to produce energy from renewable sources. Within this framework, green hydrogen emerges as a strategic energy carrier capable of absorbing excess renewable energy that cannot be immediately utilized, converting it into a molecule that is easily storable and deployable in hard-to-electrify sectors such as heavy industry, long-distance mobility, and maritime transport. Renewable-powered electrolysis, if integrated into a well-balanced system of production and consumption, may represent the missing link to ensure flexibility and security in the Sicilian energy system. In this context, technological innovation plays a decisive role: the reuse of industrial molybdenum waste to produce catalysts and electrodes can reduce dependence on critical raw materials and foster a circular economy, thereby strengthening the overall sustainability of the value chain.

The production of green hydrogen through electrolysis can be carried out using different technologies, which differ primarily in the type of electrolyzer employed, the materials used, the operating conditions, and the level of industrial maturity. At the core of all variants lies the same physico-chemical principle: electricity from renewable sources is used to split water into its two elemental components, hydrogen and oxygen, thereby avoiding the emission of CO_2 and other climate-altering substances (Matarazzo, 2024). The main differences concern efficiency, costs, durability, operational flexibility, and scalability.

The most historically established method is that of alkaline electrolyzers (AEL, Alkaline Electrolysis), which employ a potassium hydroxide or sodium hydroxide solution as a liquid electrolyte. This technology is characterized by simplicity, reliability, and relatively low costs, and can operate at moderate temperatures, generally between 60 and 80 °C. Their operational longevity is high; however, their energy efficiency does not reach the levels of more recent technologies, and their response to rapid load fluctuations is less immediate, an important limitation when operating with variable renewable sources such as wind and solar.

Proton Exchange Membrane electrolyzers (PEM) employ a solid polymer membrane that conducts protons while physically separating hydrogen from oxygen. This technology offers high current density, rapid start-up, and greater compatibility with intermittent renewable energy. However, the catalysts used in the electrodes often require noble metals such as platinum and iridium, which are both costly and scarce, and the membrane itself entails significant production costs. Current research is increasingly oriented toward the use of alternative materials, including the recovery of industrial waste, such as molybdenum residues, which, when properly processed, can partially or fully replace traditional catalysts, thereby reducing both economic and environmental impacts.

A third category is represented by Solid Oxide Electrolysis Cells (SOEC), which operate at high temperatures, generally between 650 and 850 °C, and use a solid ceramic electrolyte that conducts oxygen ions. Heat can be supplied by industrial processes, geothermal plants, or concentrated solar power, thereby reducing the electricity demand for water splitting (Flis, 2023). High conversion efficiency is one of the strengths of this technology; however, the elevated operating temperatures require resistant materials and careful management of thermal stresses, factors that still limit large-scale deployment.

In recent years, hybrid and innovative solutions have also begun to emerge. Anion Exchange Membrane electrolyzers (AEM), for example, combine features of both alkaline and PEM systems, employing a solid membrane that conducts OH^- anions instead of protons. This configuration makes it possible to avoid the extensive use of noble metals, thereby reducing costs, while offering a faster and more flexible response compared to traditional AEL, though the technology has not yet reached the same level of maturity. Experimental approaches have also been proposed, such as direct seawater electrolysis, which is still at the research stage but could potentially integrate desalination processes to produce hydrogen in coastal areas with abundant renewable energy yet limited freshwater availability.

3. Case study

When considering the relationship between costs and environmental impact, the three main electrolysis technologies (alkaline, AEL; proton exchange membrane, PEM; and solid oxide, SOEC) present different advantages and limitations, and the optimal choice strongly depends on the application context. Alkaline electrolyzers are the most mature and widespread solution: they involve relatively low investment costs, employ common materials such as nickel and steel, and ensure good operational durability. From an environmental perspective, their limited reliance on critical raw materials reduces risks associated with extraction and supply, and the overall balance is favorable when powered by stable renewable sources. Their efficiency is good, though not the highest, and their response to rapid load fluctuations is slower, an important consideration when electricity comes from variable sources such as solar or wind (McKenzie et al., 2024). PEM technology offers excellent operational performance in terms of flexibility: it can start up and shut down rapidly, easily following the intermittent output of renewables. However, it requires catalysts based on platinum and iridium, rare and expensive metals whose extraction and refining cycles have significant environmental impacts. This makes the environmental profile of PEM less advantageous when considering the full life cycle, and production costs are also higher due to the material component.

SOECs operate at high temperatures and can achieve higher efficiencies than the other technologies, especially when the required heat is available at low cost from industrial processes, geothermal sources, or concentrated solar power. In such cases, the environmental impact can be very low, as renewable electricity consumption per unit of hydrogen produced is reduced. The main limitation is that SOECs are less mature, with higher costs and shorter operational lifetimes compared to AELs, mainly due to thermal stresses on ceramic materials.

If the immediate objective is to minimize costs and implement a robust system sustainable in terms of materials, alkaline electrolyzers currently represent the most balanced choice. If, instead, the priority is to track real-time variable renewable generation, PEMs are unsurpassed from an operational standpoint, though with higher economic and environmental costs due to their reliance on critical raw materials. In the long term, with improved durability and cost reductions, SOECs may offer the best environmental and economic compromise, particularly in contexts where renewable heat is readily available. For a region such as Sicily, a combination of AELs for continuous production and SOECs where high-temperature heat can be exploited appears to be the most promising strategy. The conditions established by DL 144/2022 for accessing renewable energy consumption incentives require that electrolyzers be powered exclusively by clean sources and that temporal correspondence between renewable electricity production and its consumption for electrolysis be guaranteed. This requirement favors technologies capable of rapidly modulating their operation according to intermittent solar and wind availability. In this regard, PEM electrolyzers are advantaged: their rapid start-up and operational flexibility allow even short renewable production windows to be exploited, maximizing the use of “certified” energy and reducing the risk of resorting to non-renewable grid electricity. While AELs offer lower costs and use less critical materials, their slower load response makes optimal compliance with temporal correspondence more challenging, unless constant renewable power or electricity storage systems are available. SOECs, owing to their high efficiency, could achieve significant environmental benefits when powered by renewable heat and clean electricity, but their current limited capability for rapid start-up/shutdown cycles makes them less suitable for variable generation without a stable energy profile.

Reform 3.2 of MASE (2025), on the other hand, through capital grants, contracts for difference, and streamlined permitting, lowers the entry barrier for all technologies but can shift preferences depending on medium- to long-term strategies. In industrial projects aiming for continuous operation with dedicated renewable sources (for example, photovoltaic and wind plants combined with storage), AELs become particularly competitive due to their low CAPEX and long lifetime. In contexts where high-temperature renewable heat is available (concentrated solar power, geothermal energy, or industrial waste heat recovery), SOECs can exploit their higher efficiency to reduce both electricity consumption and the levelized cost of hydrogen, while still benefiting from MASE (2025) incentives for infrastructure. In cases where hydrogen production is tightly coupled with variable renewable availability and large storage systems are not in place, PEMs remain the ideal candidates, despite higher costs and the use of noble metals, precisely because of their ability to maximize hydrogen production while meeting the requirements of DL 144/2022.

Ultimately, the regulations do not favor a single technology outright but instead create conditions that reward different approaches depending on context: the stringent traceability and temporal matching requirements of DL 144/2022 favor the flexibility of PEMs; the investment strategy and simplifications of Reform 3.2 allow AELs to fully express their cost-effectiveness in constant-operation plants; and SOECs to become the highest-yield choice where renewable heat is available. For a region such as Sicily, endowed with abundant solar and wind resources as well as opportunities to exploit geothermal and concentrated solar heat, a calibrated combination of the three technologies, selected on a site-specific basis, could maximize access to incentives and fully leverage the national and European support framework.

4. Results and discussion

The geographical location and natural characteristics of Sicily confer upon it a potential leading role within the Mediterranean energy landscape. The combination of abundant renewable resources, both solar and wind, and proximity to major maritime trade routes provides an opportunity to transform the island into a true hub for green hydrogen (NextEU, 2025). In this perspective, the energy produced locally could not only meet a significant share of domestic demand but also be exported to other European and North African countries, creating an energy corridor based on a fuel free from direct emissions. The connection with strategic ports, already equipped with industrial and logistical infrastructures, represents an additional competitive advantage that could support the development of an efficient and integrated distribution network. On the technological front, the adoption of innovative solutions in hydrogen production is a decisive factor for the competitiveness of the value chain. In particular, the use of electrodes and catalysts obtained from the recycling of industrial molybdenum waste, suitably processed through nanostructuring techniques, appears to be a promising pathway to reduce both costs and dependence on critical raw materials (U.S.

Geological Survey, 2024). This approach not only lowers the environmental impact associated with the extraction and processing of rare metals such as iridium and platinum, but also establishes a direct link with circular economy strategies, enhancing resources already available locally while stimulating new industrial supply chains in the region.

When comparing the different electrolysis technologies, it is not sufficient to assess only efficiency or operational costs: a crucial aspect is the reliance on critical raw materials such as platinum, iridium, and rare earth elements, whose limited availability and high costs represent a barrier to the large-scale diffusion of advanced electrolyzer technologies. To quantify this dimension, the Critical Raw Material Substitution Index (CRM-SI) has been introduced, a synthetic indicator that measures the capacity of a technology to reduce or replace the use of critical raw materials with more abundant, cost-effective, or recycled alternatives (Table 1). The index ranges from 0 (total dependence on critical raw materials) to 1 (complete substitution or total absence of CRM).

Table 1. Comparison of main water electrolysis technologies for green hydrogen production, highlighting key materials, involvement of critical raw materials, and the Critical Raw Material Substitution Index (CRM-SI)

Electrolysis technology	***Key materials***	***Critical raw materials involved***	***Crm – si (0-1)***
AEL (Alkaline Electrolysis)	Nickel, steel	Low dependence on CRMs	0.8
PEM (Proton Exchange Membrane)	Pt, Ir, Polymer Membrane	Platinum and Iridium (highly critical)	0.1
PEM with recycled Mo-based catalysts	Recycled Mo + reduced share of Pt/Ir	Partial substitution of noble metals	0.6
SOEX (Solid Oxide Electrolysis Cells)	Rare earth elements, advanced ceramics	Rare earth elements (moderate criticality)	0.4

Applying this indicator to the three main electrolysis technologies:

- Alkaline electrolyzers (AEL) use abundant materials such as nickel and steel and show minimal dependence on critical raw materials, resulting in a high CRM-SI value.
- PEM electrolyzers, while offering optimal performance in terms of flexibility and compatibility with intermittent renewable sources, are heavily dependent on platinum and iridium. Their CRM-SI value is therefore very low. However, with the introduction of catalysts derived from industrial molybdenum waste, the index increases significantly, thereby reducing the overall criticality of the value chain.
- Solid oxide electrolyzers (SOEC), although highly efficient, require advanced ceramic materials and rare earth elements, yielding an intermediate CRM-SI value.

This approach provides a clear and comparable representation of the contribution of different technological solutions not only to the energy transition but also to the development of a genuinely circular and sustainable value chain.

The molybdenum market in 2024 is experiencing a phase of growth, albeit with some tensions linked to global supply and demand dynamics. Global production increased by about 6% compared to the previous year, signaling a consolidation of supply, mainly driven by China, followed by Chile, Peru, the United States, and Mexico. These five countries account for over 90% of global production, confirming the strong geographical concentration of this metal.

During 2024, prices in Europe remained high, ranging between €21,000 and €30,000 per ton depending on the product type (raw ore, oxides, ferromolybdenum, or chemical compounds). This relatively elevated level reflects the strategic importance of the metal and the growing attention toward critical raw materials required for energy and industrial transitions. The year 2024 has thus been marked by a strengthening of global molybdenum supply, relatively high European market prices, and sustained demand from the energy sector. Although Italy is not a producer, it remains a relevant actor as an importer and processor, thereby confirming its dependence on international dynamics in this strategic market.

Environmental aspects related to green hydrogen production play a significant role in the overall assessment of the project. The sustainability of this technology does not depend solely on the renewable origin of the electricity used for electrolysis but also on material management, plant life-cycle considerations, and the ability to integrate the process into a circular economic system. The adoption of technical solutions that reduce the use of critical raw materials, the reuse of industrial by-products, and the optimization of energy efficiency are all elements that contribute to minimizing the overall ecological footprint, making the supply chain more resilient and less exposed to commodity market fluctuations.

From an economic perspective, Sicily presents conditions that could attract substantial investments in the green hydrogen sector. The competitive cost of local renewable resources, combined with the availability of suitable areas for production and storage facilities, creates a favorable context for the development of large-scale projects. Integration with existing industrial clusters, particularly those with high energy consumption and significant emissions, offers the opportunity to initiate targeted decarbonization processes, thereby reducing dependence on fossil fuels and improving the competitiveness of products on international markets. In addition, the presence of incentives and support measures, such as those provided by DL 144/2022 and MASE Reform 3.2, can accelerate the implementation of investments, supporting both the initial installation phase and long-term operations (MASE, 2025).

In this vision, Sicily would not only be able to meet a growing share of its own energy demand through sustainable sources but could also export hydrogen and related technologies, consolidating its strategic role within the European and Mediterranean energy landscape.

The analysis shows that no single solution is universally valid: the different electrolysis technologies (alkaline, proton exchange membrane, and solid oxide) each find their own area of excellence, and in Sicily, a carefully tailored combination of approaches adapted to site-specific characteristics can deliver the best results. Integration with renewable heat, the use of recycled materials such as molybdenum waste, and the adoption of circular economy principles further strengthen the sustainability of the entire value chain, reducing both costs and dependence on critical raw materials.

5. Conclusions

Sicily occupies a unique and rare position within the European energy landscape: a territory capable of generating a significant amount of renewable energy and transforming it into an economic and environmental opportunity of strategic importance. Green hydrogen does not emerge as a mere technological option, but rather as the connecting element between natural resources, industrial innovation, and decarbonization policies.

The island’s geographical location, abundance of solar and wind resources, and proximity to major Mediterranean energy routes position it as a potential hub for the production, storage, and distribution of green hydrogen. By integrating renewable energy generation with advanced electrolysis technologies, Sicily can play a decisive role in the creation of a circular and sustainable hydrogen economy. Moreover, the valorization of local industrial by-products, such as molybdenum residues reused for catalyst production, strengthens the link between clean energy and material circularity, reducing dependence on critical raw materials while fostering new industrial value chains.

To fully realize this potential, coordinated action between research, industry, and public institutions is essential. Stable regulatory frameworks, infrastructure modernization, and targeted financial support can enable large-scale deployment of electrolyzers powered exclusively by renewables. In parallel, investment in research and innovation will be crucial for improving the efficiency, durability, and environmental performance of emerging electrolysis technologies.

If supported by stable policies, adequate infrastructure, and targeted investments, green hydrogen production on the island can evolve from a local initiative into a project of international relevance, capable of powering industrial processes, decarbonizing transport and manufacturing sectors, and enabling exports to other Mediterranean markets. In this way, Sicily could become a cornerstone of the European hydrogen strategy, a model of how insular regions, through technological innovation and resource optimization, can lead the transition toward a resilient, low-carbon, and circular energy system.

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