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Technical and economic feasibility of green hydrogen production in Madagascar

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Abstract*—Madagascar is experiencing a severe energy deficit, which worsens the challenges of sustainable development and exacerbates the effects of climate change. An urgent action is required, especially in Africa, where the continent bears a disproportionate impact despite its minimal contribution to global emissions. Green hydrogen could be a promising solution for sustainable energy production in Madagascar. This research aims to explore the potential of green hydrogen as a sustainable energy solution for Madagascar by analyzing the feasibility, economic viability, and environmental impact of integrating green hydrogen into the national energy landscape. The results will support informed decision-making and strategic planning, and provide insights into a sustainable energy future for Madagascar.*

Keywords— Madagascar; green hydrogen; sustainable development; feasibility; economic viability; environmental impact.

1- Introduction

Madagascar is facing significant challenges in achieving reliable energy access, which is hindering its progress towards sustainable development. The nation is constrained by inadequate infrastructure and heavy reliance on fossil fuels, and is struggling with increased environmental degradation and energy insecurity. Supplying new technologies can create a base for the start of the hydrogen economy, providing an alternative fuel and energy carrier to reduce reliance on fossil resources. In this way, green hydrogen offers a back-up energy source that can promote sustainability and enhance energy independence.

This study aims to investigate the feasibility and impact of integrating green hydrogen into Madagascar's energy landscape. The research hypotheses are:

- Madagascar has the potential to produce green hydrogen on a significant scale, using renewable energy as the primary source.
- Adopting green hydrogen could significantly reduce greenhouse gas emissions compared to traditional energy sources, contributing to climate change mitigation efforts.
- While establishing green hydrogen production incurs high initial costs, the long-term economic benefits resulting from reduced operational costs and heightened energy efficiency may outweigh these expenses.
- Regulatory and policy constraints could impeach the widespread adoption of green hydrogen in Madagascar. To overcome these barriers, strategic adjustments and incentives may be necessary.
- Integrating green hydrogen into Madagascar's energy matrix could enhance energy source diversification and strengthen the resilience of the national energy system.

This article is divided into 7 sections to guide the research.

It begins by introducing the concept of green hydrogen and the role it plays in energy transition. It then discusses various methods of hydrogen production, including steam methane reforming and electrolysis of water using renewable energy sources. Fourthly, an analysis is conducted encompassing its economic viability in the current context. Fifthly, it analyzes its viability in different sectors especially in Madagascar frameworks. It then examines the potential environmental impacts by presenting environmental indicators. Finally, we provide recommendations and discuss ongoing efforts and strategies aimed at overcoming challenges in the adoption of clean hydrogen in Madagascar.

2- THE CONCEPT OF GREEN HYDROGEN AND THE ROLE IT PLAYS IN TRANSITIONING TO RENEWABLE ENERGY.

In 1766, the chemist Henry Cavendish identified hydrogen as a distinct chemical element. Hydrogen is the simplest chemical element, consisting of a single proton and a single electron. It is located at the top of the periodic table of elements and symbolizes the origin of matter. As the lightest atom, hydrogen plays a fundamental role in the elemental composition of the universe.

It is abundant in the cosmos, making up a significant fraction of the observable universe. The heart of stars, including our Sun, contains the core of this cosmic element. Fusion reactions transform hydrogen into helium, releasing vast amounts of energy and illuminating the solar system.

However, on Earth, hydrogen is rarely found in isolation in our atmosphere. Instead, it readily forms bonds with other atoms, creating a variety of chemical compounds. One of the most well-known examples is the water molecule H_2O, which consists of two hydrogen atoms and one oxygen atom. This compound is essential for life. Hydrogen is also a significant component of organic molecules, including hydrocarbons and natural gas (methane: CH_4, propane: C_3H_8, butane: C_4H_{10}), highlighting its importance in terrestrial chemistry.

Obtaining hydrogen requires specific chemical procedures to separate it from other atoms, each with a specific production spectrum in terms of greenhouse gas emissions and costs. This results in a diatomic molecule composed of two hydrogen atoms, known as dihydrogen (H_2) or simply hydrogen.

The most common method of producing hydrogen from chemicals is steam methane reforming, a process which produces hydrogen from natural gas which is called grey hydrogen as illustrated in figure 1.This method accounts for approximately 95% current hydrogen production worldwide. Despite its attractiveness from an efficiency and economic standpoint, steam methane reforming is not environmentally friendly, as the production of hydrogen from natural gas also produces CO_2. Approximately 9.3 metric tons of CO_2 are produced for every 1 ton of H_2 produced from steam methane reforming. This level of CO_2 is incompatible with the objective of using hydrogen as a "clean" fuel. The current and future restrictions on CO_2 emissions will prevent the use of this method on a larger scale. (Khan et al. 2021)

Figure 1: Production line of grey hydrogen [W1]

Compared to grey hydrogen, green hydrogen is produced from renewable electricity, such as solar or wind power, by electrolysis of water as illustrated in figure 2. It produces no carbon dioxide emissions during production, making it a clean source of hydrogen.

Figure 2: Production line of green hydrogen [W2]

3- THE ROLE OF HYDROGEN IN TRANSITIONING TO RENEWABLE ENERGY

Green hydrogen, offers a promising solution for decarbonizing sectors that have traditionally found it difficult to move away from fossil fuels such as:

3.1 Heavy industry: Industries such as steel, cement and chemical production require high-temperature heat, which is currently mainly produced using fossil fuels. Green hydrogen can be used as a clean alternative, either directly as a fuel or as a feedstock in processes such as hydrogen reduction of iron ore, leading to significant reductions in emissions.

3.2 Shipping: Maritime transport is one of the largest contributors to global emissions due to its reliance on heavy fuel oil. Green hydrogen can power fuel cells or be used in internal combustion engines to power ships, providing a zero-emission alternative to traditional fuels.

3.3 Aviation: Similarly, aviation currently relies heavily on fossil fuels, making it difficult to decarbonize. Green hydrogen could be used in fuel cells to power electric propulsion systems for smaller aircraft, or blended with synthetic fuels for larger aircraft, reducing emissions from the aviation sector.

3.4 Energy storage: Green hydrogen can serve as a form of energy storage, storing excess renewable energy generated during periods of low demand. This stored hydrogen can then be used to generate electricity or provide heat when renewable sources are unavailable, ensuring a stable and reliable energy supply.

3.5 Ammonia production: Green ammonia can be produced by combining the green hydrogen with nitrogen from the air. It offers a sustainable alternative to traditional ammonia production, reducing carbon emissions and the dependence on fossil fuels.

Overall, green hydrogen offers a versatile and scalable solution to decarbonize sectors that are difficult to convert to renewable energy, making a significant contribution to the efforts to combat climate change and achieve carbon neutrality. However, widespread adoption will require significant investments in infrastructure, technology development, and supportive policies to realize its full potential.

4 ANALYSIS OF THE ECONOMIC VIABILITY OF USING GREEN HYDROGEN IN THE GENERAL CONTEXT

In many instances, the higher cost of 'zero-carbon' solutions compared to their fossil fuel counterparts arises because the full environmental impact of fossil fuels is often not factored into their pricing. As a result, fossil fuels can appear more economically attractive.
These additional costs are termed 'green premiums' (Bill Gates, February 2023), representing the price difference attributable to environmental considerations. Occasionally, 'green premiums' can be negative, indicating that opting for environmentally friendly alternatives may actually be more profitable than sticking with fossil fuels.

However, it's important to note that despite these potential additional expenses, the overall trend in renewable energy is moving towards becoming a cost-competitive alternative to traditional energy sources. Technological advancements, increased production, and policies promoting renewable energy adoption have steadily reduced the premium costs associated with renewable sources, particularly solar panels, as depicted in Figure 3.

Likewise, the swift decline in renewable electricity costs is substantially narrowing the price gap between hydrogen production via electrolysis and fossil fuels. Green hydrogen has long been touted as a cornerstone for a global clean energy economy but has yet to fully meet expectations. Encouragingly, recent data indicates this narrative may be shifting

Optimizing electrolyzers—whether by enhancing efficiency, employing low-maintenance materials, or scaling up production—is crucial for reducing their initial investment costs. Moreover, increasing operational hours further decreases investment-related expenses, thereby lowering the overall production cost of green hydrogen.

As the cost of green hydrogen production falls and its use increases, the global imperative to provide clean energy alternatives and decarbonized intensifies.

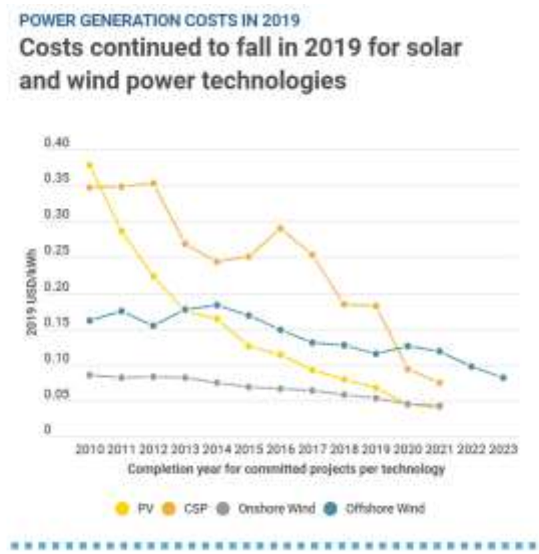

Figure 3: Renewable energy dropping costs. {W3}

5 THE VIABILITY OF GREEN HYDROGEN ON DIFFERENT SECTORS IN MALAGASY FRAMEWORKS:

At present, the use of green hydrogen in Madagascar is constrained by the absence of supportive key sectors necessary for its adoption. Specifically, these sectors are currently nonexistent

5.1 In terms of clean electricity production:

In the energy sector, the current energy mix in Madagascar presents a significant challenge to the development of the green H2 sector. Indeed, more than 75% of Madagascar's electricity is generated by thermal power, while less than 25% comes from renewable sources. (EDBM, January 2018). Therefore, the most effective way to facilitate an effective transition is to promote the direct use of electricity through renewable energies such as solar, hydroelectricity and wind power. Green hydrogen should be considered as a secondary solution, serving as a valuable fallback to strengthen energy resilience by enabling extended energy storage, thus functioning as a reliable source of backup power during hurricanes or power outages. This strategic approach will ensure a continuous supply of energy for critical infrastructures and emergency services.

However, it should be noted that the production of one kilogram of green hydrogen requires between 48 and 60 kWh of electricity. Marcel Lacroix, affiliated with the Université of Sherbrooke, estimates this consumption at around 50 kWh per kJ, equivalent to around 180,000 kJ per kg of hydrogen. However, when hydrogen is burned, it releases only 141,000 kJ. Consequently, the production of electricity from green hydrogen appears to be a loss-making operation, when considered in relation to the amount of electricity consumed and the amount produced. If this inherent loss cannot be mitigated by technological means, it must be reflected in the overall cost of the electricity. (GUYON & all, January 2022).

5.2 Green hydrogen for Malagasy industry

Hydrogen has the potential to replace natural gas in several industrial sectors, especially in processes requiring high temperatures for material transformations.

Currently, Madagascar's industrial infrastructure does not include critical facilities such as cement plants, steel mills, or aluminum foundries that could utilize green hydrogen. However, advancing technologies and increasing concerns about climate change are expected to drive a significant transition toward cleaner and sustainable industrial practices in developing countries like Madagascar in the near future.

5.3 Green hydrogen for Malagasy agriculture

Agriculture forms the foundation of Madagascar's economy, employing 80% of the workforce and serving as a crucial pillar of the Malagasy economy. It contributes significantly, accounting for 30% of GDP, which rises to 43% when including agri-food (GARRUCHET, January 2023).

However, Madagascar's agricultural sector grapples with issues like erosion, soil depletion, climate risks, inadequate infrastructure, and insecurity for farmers, all contributing to low productivity. These challenges directly affect food security, impacting a significant portion of the population. Approximately 35% of rural communities, along with economically vulnerable urban populations, face food insecurity.

Most rural communities in Madagascar rely on subsistence farming, primarily centered around rice cultivation. However, cash crops like lychees, vanilla, and spices are also important for generating valuable export revenue. The introduction of green ammonia-based fertilizer has the potential to greatly enhance agricultural yields in these regions.

Madagascar possesses ample renewable energy resources, making it well-positioned to produce green ammonia. This ammonia can be used to manufacture fertilizer, thereby bolstering the country's agricultural productivity.

This option offers considerable economic and technical benefits, making it possible to:

- Boost agricultural production and guarantee food security by reducing dependence on imported nitrogen fertilizers.
- Simplify the transport and storage of green hydrogen by transforming it into ammonia, a stable and easily transportable product.

However, effectively harnessing these resources requires careful management due to their inherent variability. Extensive storage systems are crucial to ensure a reliable supply of green ammonia for agricultural needs.

While exploiting Madagascar's natural resources is important, it is crucial to do so sustainably. There's ongoing research into large-scale ammonia storage solutions, but this is still an area under development.

5.4 Green hydrogen for exportation

The transportation and storage of hydrogen present ongoing challenges, primarily due to its low energy density at atmospheric pressure, efficiency losses during pressurization and liquefaction, and stringent safety requirements. These challenges result in high transportation costs. For instance, compressed hydrogen has only 15% of the energy density of diesel and requires seven times more volume for the same energy content.

To make sea transport economically and technically viable, hydrogen must be converted into ammonia (NH3), which offers higher energy density. However, safety risks, especially in case of shipwreck, remain significant without proper precautions (GUYON & others, January 2022). Therefore, exporting green hydrogen becomes feasible only when production scales up significantly and becomes highly profitable.

6 ANALYSIS OF THE ENVIRONMENTAL IMPACT OF GREEN HYDROGEN PRODUCTION

With the global focus on mitigating climate change and the increasing regulatory scrutiny, the significance of green hydrogen has become paramount. Nations are now compelled to adopt low-emission technologies that can reliably meet their escalating energy demands, reflecting an unprecedented dedication to addressing climate challenges. Green hydrogen's potential to provide clean, sustainable energy aligns perfectly with the evolving landscape of climate consciousness, facilitating the transition towards a greener, more sustainable energy future. Notably, producing hydrogen from renewable sources like wind and solar ensures a process with zero direct carbon emissions.

Green hydrogen production, achieved by using renewable energy sources to electrolyze water and produce hydrogen, is widely seen as an environmentally friendlier method compared to producing hydrogen from fossil fuels like natural gas. However, it's important to recognize that green hydrogen production still affects the environment. It's crucial to consider the following key environmental impact indicators:

6.1 Carbon footprint: This indicator measures the amount of greenhouse gas emissions, in particular carbon dioxide (CO_2), released throughout the hydrogen production process. The objective of green hydrogen production is to minimize or to eliminate carbon emissions, thereby making it a low-carbon or carbon-neutral energy source. When used, the product emits no pollutants or greenhouse gases. The combustion process produces only water as a byproduct. This is why it is known as hydrogen (hydro = water / gene = product). However, when we analyze the entire life cycle of a green hydrogen project, we find that it emits a total of around 2 $kgCO_2eq/kgH_2$, which is far less than the emissions produced by hydrogen produced from fossil fuels.

6.2 Energy efficiency: This indicator assesses the overall efficiency of the green hydrogen production process, taking into account the energy input required and the hydrogen production. High energy efficiency means that less energy is wasted during production, which translates into a lower environmental impact.

6.3 Water use and pollution: The production of green hydrogen is dependent on water, which offers a flexibility of sources, such as seawater, treated wastewater, surface water or groundwater, depending on local availability. It is therefore essential to emphasize the importance of maintaining a clean, high-quality water supply in order to ensure the efficiency and sustainability of green hydrogen production. The water consumption for 1kg of hydrogen produced by electrolysis is approximately 9kg of water as illustrated in figure 4. A variety of water sources, including seawater and brackish wastewater, can be employed to meet this demand. However, specific treatment technologies, such as natural flocculation, reverse osmosis, filtration and post-treatment disinfection, are required, depending on the type of electrolysis unit used. It is important to note that obtaining this quantity of water is not a straightforward process. The availability of pure water for power generation is uncertain, and the cost and complexity of supplying clean, demineralized water varies according to the quality of the water source. This is because the cost and complexity of supplying clean, demineralized water varies according to the quality of the water source, whether it comes from the sea, tertiary wastewater, surface water or

Figure 4: Water consumption for the production of 1kg of hydrogen

groundwater.

7 STRATEGIES AND RECOMMENDATIONS FOR OVERCOMING CHALLENGES IN ADOPTING CLEAN HYDROGEN IN MADAGASCAR

To enhance the economic and technical viability of green hydrogen production, it is essential to consider a number of strategies.

7.1 Strategy 1: Promoting economies of scale and commercial usage nationally

In order to achieve the necessary scale, it is essential to minimize green premiums, which means to reduce the additional costs associated with green hydrogen. This can be achieved by initially subsidizing the economic deficit until the break-even point is reached. This subsidy should be viewed as an investment in the transition of the entire national energy system to low-carbon technology, rather than as a cost. Consumers, industry and governments can assist in offsetting this premium cost by implementing feed-in tariffs and other compensation schemes, similar to those used for solar photovoltaic and wind power. The government should provide tax incentives and policies that encourage companies to invest in renewable energy, grid modernization and green hydrogen, thereby reducing risk for producers and increasing security of energy supply.

7.2 Strategy 2: Use of a hydrogen micro-power station to meet local needs.

This strategy involves implementing a more straightforward solution that can be adapted to a local scale. Green hydrogen will be used as an energy carrier to optimize the utilization of renewable energies in a smart grid. The process incorporates power-to-gas-to-power applications to effectively manage surplus renewable energy. In the event of excess energy production, an electrolyzer will be employed to generate green hydrogen, which will be stored in a tank. In the event of low or non-existent photovoltaic energy production, a fuel cell will convert hydrogen into electrical energy, reducing dependence on the traditional electricity grid and the carbon footprint.

7.3 Strategy 3: Encouraging prospection and exploitation of white hydrogen in Madagascar

The term "white hydrogen", sometimes referred to as "gold hydrogen", refers to hydrogen that forms and occurs naturally in certain geological formations, notably hydrocarbon deposits such as oil and natural gas. Unlike conventional hydrogen, which is mainly produced by industrial processes, natural hydrogen is already present in the environment and requires no energy-intensive manufacturing.

From an economic standpoint, natural hydrogen is highly advantageous. Its extraction cost is potentially lower than that of industrial hydrogen, which could open up attractive economic prospects for its large-scale use. One of the main advantages of this hydrogen source is its ease of use. Unlike its industrially-produced counterpart, white hydrogen does not require heavy storage infrastructures, which considerably reduces the costs and complexities often associated with the hydrogen supply chain.

The direct use of hydrogen emitted from geological sources can be achieved through the implementation of flow capture techniques, pipelines and fuel cells. The elimination of costly storage processes simplifies the process of adding value to this resource, making it directly accessible for a variety of industrial and energy uses.

8 Conclusion

Climate change is reshaping the very fabric of our world, affecting every corner, every nation and every living being on the planet. Developing countries like Madagascar are particularly vulnerable, which is why it is imperative to prepare for and adapt to its effects. Access to energy is one of the key factors in this adaptation, because before we can fight climate change, we must first fight poverty. Giving priority to the development of renewable energies is a strategic opportunity for the country. Indeed, the mass adoption of renewable technologies and the gradual integration of green hydrogen into our energy mix are essential steps towards ensuring Madagascar's resilience.

Despite current economic uncertainties surrounding green hydrogen—especially in its production for clean energy or export—its use in ammonia production already represents a strategic choice for Madagascar in the short term. Looking ahead, the exponential rise in global and local energy demand, coupled with the imperative to reduce greenhouse gas emissions, makes green hydrogen increasingly attractive in the long term. This suggests that green hydrogen will become competitive across all sectors on an international scale in the near future, despite initial high investment costs. Continued technological progress and international collaboration can effectively mitigate these challenges.

Furthermore, the potential of this clean, sustainable energy source is vast and offers promising prospects for a greener, more prosperous future for the country. Madagascar holds a significant advantage with its abundant renewable natural resources, particularly solar and wind energy. By investing in research, development, and necessary infrastructure for green hydrogen production and utilization, Madagascar can position itself as a leader in the energy transition amidst a rapidly changing climate. This strategy not only addresses the country's energy needs but also creates new jobs and stimulates economic growth.

However, the technical and economic feasibility of green hydrogen in Madagascar hinges on advancements in technology, pricing, and supportive public policies. Through a proactive and ambitious approach, Madagascar can harness green hydrogen as a driving force in its energy transition and overall development.

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