

# Potential for Hydrogen Production Associated to Water and Food in Off-grid Communities of Southern Africa

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## Abstract

Solar energy is called to meet electricity demands for isolated, off-grid communities in Africa. However, solar electric energy is intermittent and can be stored, for a limited amount of time, in batteries, which are expensive and cause serious environmental impacts at the end of their lifetime. Conversion of the surplus electric energy to green hydrogen through water electrolysis and back to electricity, when needed, using electrolyser-fuel cells systems, is examined as a potential solution to meet the water-energy-food nexus in Southern Africa. In the framework of the Agrivoltaics concept, the main constraints, opportunities and parameters to consider its applicability are presented and discussed, in terms of its technical, economic, environmental and social impacts. In the second phase of this work the developing of a PEM electrolyser for connection to a solar PV power source and a fuel cell device, for a stand-alone application, is proposed, ensuring high reliability and energy conversion efficiencies, as well as adequate transient response and a competitive cost. It is intended as a low-carbon energy system, realising the potential for synergy in the Agrivoltaic concept, aligned with global and regional sustainability goals.

**Keywords:** Solar hydrogen production, Off-grid autonomous hydrogen systems, PEM electrolysis, Fuel cells, Agrivoltaic

## 1 Context and Potential for Hydrogen Production

Subsistence agriculture and pastoralism is one of the main economic activities in Southern Africa, particularly in off-grid communities. However, both activities are quite endangered by the growing desertification that the region is facing because of climate change, that leads to the scarcity of water and rainfall, essential for both activities. A virtuous combination of photovoltaic solar energy production and agriculture, Agrivoltaic, appears with an enormous potential to address these issues, including the use of photovoltaic in water irrigation systems [1],[2]. In fact, although photovoltaic electricity generation is seen as a source of clean energy, it demands extensive soil occupation, which might be in competition with arable soil [1]. The use of soils underneath the solar panel to perform activities related to agriculture and/or pastoralism, allows a better use of both resources, soil and sun, and synergistic gains: soil productivity increases due to the reduction of water evaporation, and energy conversion efficiencies increase due to refreshment of solar panels [2].

The relationship between climate change and increasing desertification has been recognized for a long time in vast regions of southern Africa [3],[4],[5]. The predictions of the United Nations (UN) Intergovernmental Panel for Climate Changes (IPCC) points out, for the southern Africa region, a significant drought in the dry season months, but no significant differences are projected in the rainfall for the wet season and no increased risk of drought events are reported [3]. However, despite the remaining uncertainty, combined evidence of current trends (increased rainfall variability and intensity of extreme events, including drought) with global climate model predictions of warming and drying across the region, add significant concerns that climate change will exacerbate land degradation and desertification [3]. Most of southern Africa is dry with assessments of the desertification potential pointing that all Namibia and Botswana, and in fact more than half of South Africa is rated as potential desert [5]. Moreover, according do United Nations Environmental Program (UNEP), one-third of Africa is affected by desertification and 73 % of the agriculturally used lands are degraded. In most southern Africa drylands, the failure of any seasonal rain in a year result in social and economic difficulties because most population is rural, depending on subsistence farming and/or direct exploitation of vegetative resources [4]. Indeed, two or three successive years of drought conduct to severe environmental stress that often culminates in serious food shortages, famine, and loss of both human and animal life. Behind this problem, the Southern Africa Development Community (SADC), that includes as member countries Tanzania, Zambia, Zimbabwe, Namibia, Angola, Botswana, Lesotho, Eswatini, Malawi, Mozambique, South Africa, Madagascar, Mauritius, and Democratic Republic of Congo, formulated and worked out mechanisms of implementing Regional and National Action Programs to correspond to the 1994 Convention to combat desertification [4].

On the other hand, it is well known that access to clean water, healthy food, cooking facilities and energy, particularly in the form of electricity, are still important aspects that need immediate attention throughout the continent [6].

According to the International Energy Agency (IEA), in 2019 only around 56 % of the population of Africa had access to electricity, and the situation is even worse in rural areas, with only 37 % compared with 81 % in urban areas [7]. In Sub-Saharan Africa the average rural electricity access rate is approximately 25% [8], and in South Africa, for example, around 1.3 million households have no access to grid connection [9]. Remote off-grid localities may benefit from electrification of the different activities, namely those related to agriculture, pastoralism, and small-scale industrial tasks, or in schools and clinics [9],[10], since the extension of the electricity grid may be simply prohibitive.

Besides, it is recognized that Africa has an abundance of renewable energy sources that can help the continent to meet its needs for electricity, to promote the needed economic growth while meeting the global targets for carbon dioxide emissions reduction [11]. Therefore, Africa is also a well suitable place to produce green hydrogen, i.e., hydrogen produced through water electrolysis using electricity from renewable sources, since the needed electricity may be generated at low cost from abundant renewable sources, in particular solar energy, see Fig 1. Due to the relatively high solar radiation potential of large extensions of the African territory, solar energy is seen as the main source for the electrification of the entire continent and to produce green hydrogen for auto-consumption and exportation [6]. Hydrogen may play an important role in this context of renewable energy harnessing [11],[12] and in the decentralized generation of electricity, particularly in remote off grid African communities, since it can be produced and consumed locally, compensating for the fluctuations related to the availability of renewable sources [12],[10].

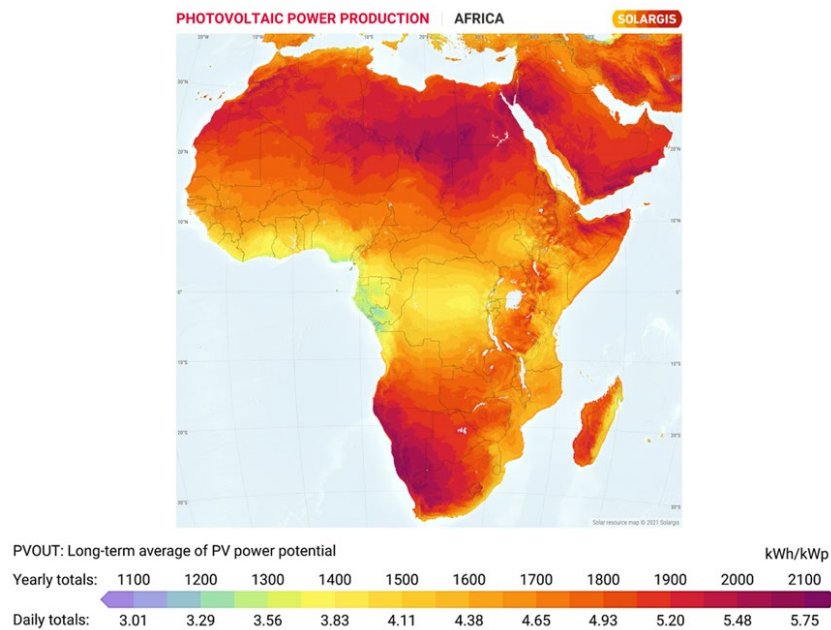


Fig. 1 Africa long-term average of PV power potential, period 1994-2020. Map © 2021 Solargis

To ensure a sustainable hydrogen economy in Africa it is also vital to address water sources for hydrogen production via electrolysis, considering the whole dimensions of the Water-Energy-Food Nexus. Furthermore, a coherent policy and regulatory framework is necessary to harvest synergies between the goals of energy poverty alleviation, food provision, decarbonisation and safeguarding water resources and ecosystems.

## 2 Projects and Strategies

Despite some major green hydrogen projects foreseen for some African regions, mainly confined to the North, West, Namibia, and South Africa [6],[11],[13],[14],[15], especially pointed to the exportation to Europe [16], only a reduced number of African countries have designed, till now, a comprehensive strategy to combine renewable energy harnessing with green hydrogen and synthetic gases production. In fact, South Africa established its HySA (Hydrogen South Africa) strategy in 2008 to take better advantage of the country's huge platinum group metal (PGM) resources, providing a clear direction for effective deployment of hydrogen and fuel cell technology, and to produce green hydrogen from clean and renewable resources for meeting the electricity and transportation gap in the country, especially in the rural settings [9],[11],[12]. South Africa has indeed announced plans to support a pipeline of green H<sub>2</sub> worth about US\$17.8 billion over next decade [17].

In Egypt, an agreement between the Egypt Sovereign Fund and two foreigner companies was reached an agreement for the development of 50 - 100 MW electrolyzers to produce green hydrogen, and lately, green hydrogen was even introduced in the Egypt's 2035 Energy Strategy [11]. In 2020, a partnership between Moroccan and Germany governments was launched to improve the production of green hydrogen through power-to-X and power-to-power type projects [11]. In Nigeria, short-, medium- and long-term strategies were designed to facilitate the implications of green hydrogen energy in the country [11]. In Uganda a project was implemented to store overabundant energy generated by solar panels through the production of green hydrogen, to warrant constant supply of electricity at night [11].

The lack of strong hydrogen energy policies and strategy in Southern Africa certainly hinders the region vision for a green hydrogen economy. The recent project regarding the production of a H<sub>2</sub> Atlas-Africa, a joint initiative between the German Federal Ministry of Education and Research and African partners in the Sub-Saharan region, namely, SADC and ECOWAS, provides a decision support tool for the concept and design of pilot hydrogen plants. It focusses on detailed technological, environmental, economic, and social feasibility assessment, taking present and future local energy demands into consideration and assessed the availability and suitability of land and water resources, while considering land use for agriculture and local demand for water across a total of 31 sub-Saharan countries [9],[11], among them 12 from the SADC region [18]. H<sub>2</sub> Atlas Africa intends to map out these locations on an interactive atlas to show hydrogen production hotspots, and demonstrate through pilot projects how the production, distribution and export of green hydrogen can be performed in an economically efficient manner [9].

A recent study into Africa's green hydrogen potential, commissioned by the European Investment Bank, International Solar Alliance and the African Union highlights the benefits of harnessing solar power to generate green H<sub>2</sub> in four African hubs: Mauritania, Morocco, Southern Africa, and Egypt [19]. The study concludes that Africa can secure access to clean and sustainable energy, accelerate low-carbon economic growth across the continent, reduce greenhouse gas emissions by 40%, and become a global energy player through green H<sub>2</sub> exports. According to this study, Africa may produce 50 million tons of green H<sub>2</sub> per year around 2035 through solar energy, supplying about 7 EJ of energy, more than 1/3 of the 19.9 EJ consumed across the continent in 2021.

Imasiku *et al.* [18] reviewed the policy for green H<sub>2</sub> in the southern Africa. Besides the already referred south African HySA strategy for H<sub>2</sub>, the review mentions an additional restricted action plan in Namibia that includes the production of green H<sub>2</sub> and ammonia. Some green and grey H<sub>2</sub> productions were identified in Zimbabwe and South Africa related to the production of fertilizers and fossil fuels that may contribute to foster the green H<sub>2</sub> industry development in both countries. The authors concluded that most of the green H<sub>2</sub> projects implemented in southern Africa are either privately founded or funded by international players [18].

Within the Hydrogen energy policies and strategy in Southern Africa apart from support to projects, investment in R&D and capacity building is required, aligned with the demonstration of commercial viability of hydrogen-agriculture-photovoltaic systems as a potential solution to meet the water-energy-food nexus in Southern Africa, in order to stimulate innovation and achieve a cost-competitive hydrogen value chain, in the path towards a future carbon-neutral economy.

### 3 The Agrivoltaics concept

It is well known that photovoltaic solar energy capturing demands for a large share of land occupation [2], and with the mentioned foreseen megaprojects for green hydrogen production in Africa, mainly based on electricity generated from sun energy, the land occupation problem will be intensified, certainly conflicting with food production [1]. Land is, indeed, a vital asset for any economy based on agriculture such as most of the Southern Africa countries [1]. Agrivoltaic involves a compromise between agriculture and photovoltaic energy generation that contributes to the increase of the Land Equivalency Ratio (LER). The system, known also as "agrophotovoltaics" (APV), "solar sharing", or "PV agriculture", provides mutual benefits across the food-energy-water nexus [1]. Rainwater harvesting from PV systems may bring improved access to useable water, along with the diversion of the same water for PV surface cleaning and irrigation. Reduction in water extracted for irrigation can also support improvements in environmental outputs and input cost management. On the other hand, this approach provides off-grid farms with energy for productive uses such as pumping water, operating small-scale machinery, raising poultry, and producing fodder, as well as for value adding processes, such as grinding, drying, packing, etc. [20].

Despite these advantages and its rapid increase in popularity in many countries, Agrivoltaic systems did not yet gained the need traction in Africa [20]. In fact, only few projects and studies have been till now undertaken to explore or assess the benefits of

Agrivoltaic systems in Africa. A research project is underway in Ghana to develop an Agrivoltaic system to bolster the national resilience of renewable energy and food production security to a changing climate [21]. The economic potential of agrophotovoltaics in South Africa was assessed through the case study of a grape farm in West Cape [22]. The results show an optimistic potential of implementing APVs in South Africa to help to target the 6000 MW solar energy increase by 2030 without giving up land for agriculture and minimizing other land conflicts related to the acquisition of land for energy production.

The economic feasibility of Agrivoltaic systems in Food-Energy-Nexus context was modelled and assessed through a case study in Niger [6],[23]. Croplands, grasslands, and wetlands in Southern Africa are considered among the best places for capturing solar energy using photovoltaic panels (PVP) since they combine coolness with high irradiance, and these are places where typical crops would normally grow [24]. But even in arid and semiarid regions Agrivoltaic may be applied to cultivate certain crops that would not normally grow there, PVPs promotes shading and moisture preservation. It is shown that significant quantities of food and jobs may be created in Africa if Agrivoltaic systems can increase their surface area by securing large energy offtakers, whether in the form of off-grid industrial clients, via on-grid feed-in tariff schemes, or large-scale PV-to-fuel intercontinental export operations expected for the next years [24].

Even though Agrivoltaic may substantially has the potential to increase land use efficiency, technical and economic viabilities of the integrated concept need to be demonstrated in rural communities, moreover with added storage capability using Hydrogen.

#### **4 Hydrogen in stand-alone energy systems**

Hydrogen stand-alone energy systems will be discussed in the context of the proposed application (Fig. 2). The interest on the concept of integrating renewable energy sources with hydrogen storage systems, for these applications, has increased in the past decade. Results have been reported in the literature focusing on system performance and viability [25],[26], simulation studies centring on system energy management, control strategies, sizing and modelling [27],[28],[29],[30],[31],[32].

With the increasing share of renewable energy sources, new requirements to access less costly electrical energy feedstock are emerging, and the markets for electrolytic hydrogen require more flexible electrolysis plants, which call for electrolysers to be operated dynamically. With the inherent variability and intermittency of the sources, flexibility, and reactivity to changes in the input conditions and loading effects are paramount. Within those with high readiness level, the PEM electrolysis technology is considered the one that better supports transient part load transitions, when connected with renewable energy [33],[34].

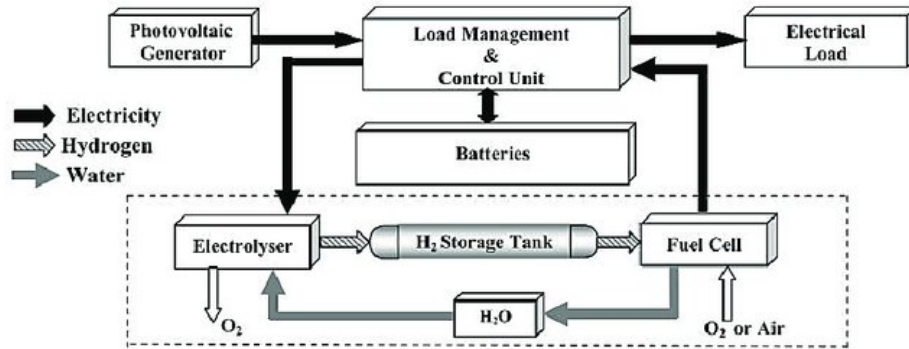


Fig. 2 Schematic diagram showing stand-alone system with flows of electricity, water, and Hydrogen [35].

Regarding the numerous end uses of hydrogen, the re-electrification pathway by employing a fuel cell will be discussed as well as the advantages that support the use of green hydrogen for isolated locations. Hydrogen-based power systems will be compared against main competitors such as batteries and diesel generators, which, presently, are the conventional options in off-grid scenarios. The system will be optimized for sizing and power control strategy, with the assistant of smart management systems that will consider not only the production variability but also consumption estimations from the stand-alone profiles. The influence of the location and the impact of different load energy consumption profiles will be explored. Optimal configurations will be also ascertained, also from an economic viewpoint.

The main barrier to implementation of hydrogen-based technologies is the high cost of the system and the scarce availability of commercially competitive off-grid electrolyzers, especially incorporating designs that work under variable renewable power inputs. System characteristics and advantages for the envisaged application will be discussed.

## 5 Final remarks

Increasing demand for photovoltaics, as a key element in the energy transition, entails land use issues as well as concerns on landscape and biodiversity, which has called for new approaches, considering integrated perspectives. Among these, Agrivoltaic, as a viable dual-land use, appear very promising as a potential solution to meet the food-energy-water nexus.

It is crucial to understand what are the most influential parameters that allow for an optimal design and overall performance of Agrivoltaic systems and Agrivoltaic integrated with hydrogen. Key performance indicators and the investigation of new innovative models, able to include additional activities, community functions and tasks, that may be developed in the defined context, are being addressed.

Inherent variability and intermittency of the renewable power sources require electrolyser's flexibility and reactivity to changes in the input conditions and loading effects. There is a lack of systematic studies to quantify the impact of operating parameters linked to the durability of critical components in the hydrogen production system. Understanding of degradation mechanisms, namely under dynamic operation, will be tackled.

Apart from the technical challenges, the economic feasibility of the proposed systems and expected cost-competitiveness along the value chain are to be demonstrated. Capacity building is required and is identified to be implemented at various levels, in order to establish the basis for educational and training strategies to ensure specialist skills and knowledge can be acquired in a timely manner. Also, to be considered, is the fact that implementing a new technology on agricultural land, which is highly valued, involves law and planning challenges.

The integration of hydrogen and its storage capability with Agrivoltaic in stand-alone energy systems have yet to demonstrate their significant potential to enable the transition to clean energy in off-grid locations, ensuring climate change mitigation and energy supply reliability.

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