Comprehensive Analysis of the Energy Transition in Mozambique: Opportunities and Challenges for Achieving the Established Global Goals

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Abstract

This paper presents a comprehensive analysis of Mozambique's energy transition, focusing on integrating a hybrid solar-wind system with green hydrogen storage. It discusses Mozambique's renewable energy potential, particularly in solar and wind, and the country's efforts to meet increasing energy demands sustainably. The transition offers opportunities for sustainable development and job creation but requires careful management to prevent socio-economic disparities. Mozambique aims to be a key player in the renewable energy transition, emphasizing inclusivity and collaboration. The document also addresses the global context of energy transitions, the importance of renewable energy sources, and specific programs promoting clean energy. It provides detailed insights into Mozambique's solar and wind energy potential, the evolution of energy projects, and the technical aspects of designing solar and wind energy systems, including energy storage solutions like green hydrogen. The study aims to bridge the gap between stakeholders in Mozambique's energy transition and the academic community, raising awareness and influencing policy decisions based on local knowledge. In conclusion, the document highlights that Mozambique is actively transitioning towards renewable energy sources, focusing on integrating hybrid solar and wind energy systems with green hydrogen storage. The country's abundant solar and wind potential is being leveraged to meet domestic and industrial energy needs. Green hydrogen, emerging as a key storage solution, offers diverse applications across industries. The success of this transition depends on community engagement, education, and investments in research and financing for renewable energy installations. Despite the growth in the renewable energy sector, Mozambique still requires continued exploration and investment to fully realize its potential.

Keywords: Energy Transition, Renewable Energy, Solar Energy, Wind Energy, Green Hydrogen Storage

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1. Introduction

The concern about the rise in the global average temperature that causes climate change, whose effects negatively impact the ecology, felt more severely in developing countries with deficient structures. Considering that the effects of climate change slow down the development of nations, that create irreversible damage, there is concern for measures leading to the mitigation of climate change.

According to the Intergovernmental Panel on Climate Change (IPCC), a United Nations body, carbon is considered the biggest villain of climate change. The IPCC states that human activities are responsible for 90% of the causes of global warming. That is why the international measure is to reduce or eliminate human activities that may contribute to the emission of greenhouse gases.

However, international treaties and protocols were signed, the first meeting being held in 1992, during Eco 92, the International Conference on Environment and Development, in Rio de Janeiro. The most recent conference was the United Nations Climate Change Conference, COP28, in Dubai, United Arab Emirates (November 30 – December 13, 2023), which, in turn, calls on governments to accelerate the transition from fossil fuels to renewable energy such as wind and solar.

The demand for energy is growing around the world as people get richer and populations increase. If this increase in demand is not offset by improvements in energy efficiency elsewhere, our global energy consumption will continue to grow and the global temperature will continue to increase year after year (Ritchie, et al., 2020).

Energy demand growing makes the challenge of transitioning to low-carbon energy sources more difficult, as new clean energy sources need to meet this additional demand and try to replace existing fossil fuels in the energy mix. Fortunately, renewables energy projects have been growing rapidly. Countries are investing in clean sources to reduce dependence on fossil fuels and mitigate climate change (Ma et al., 2023).

Sustainable development actions that support decarbonization leading to climate change mitigation are the duties of all social, civilian, military, academic and political actors. The policies have already set out at various international conferences (Korolev et al.,2023). All are called to awareness to embrace any activity that may contribute to these purposes.

With the present study, the authors intend to contribute to the acceleration of the energy transition with the present literary subsidies. The research was conducted with a narrative bibliographic method. It seeks to bring together opportunities and challenges of the energy transition from fossil sources to clean energy with hydrogen storage system integration in Mozambique. The bibliographic consultation is carried out in documents available on the internet and Google Scholar and on other digital and physical platforms available and duly referenced.

This study aims to bridge the gap between the actors involved in the energy transition in Mozambique and the academic community and/or voters. The discussion on the energy transition is done at the level of conferences and workshops where the peaceful and academics are not included, few know about the climate emergency that the world is experiencing. With publication initiatives on the opportunities and challenges of the energy transition, both for the intervening sectors and for the general population, it is believed that more Mozambicans will be able to be knowledgeable about the subject and influence all coherent policy decisions based on local knowledge.

2. Contextualization

The energy transition of the 21st century is an international agreement that seeks to contain the imbalance of energy systems on the carbon cycle, controlling the impact of human activities on the climate. In this statement, solar energy, and wind energy were the main renewable energy sources. Due to the intermittency of these renewable resources, lithium batteries and hydrogen complement the environmental sustainability package for energy storage.

The energy transition program for clean carbon-free sources is one of the programs that succeed several programs carried out around the world, which aimed to promote clean energy for all for the good of the environment and sustainable development. Among so many programs, we can list some programs:

1. Energy Efficiency Program (EEP): This is a program of National Electric Energy Agency (ANEEL) of Brazil that aims to promote the efficient use of electricity, reducing waste and optimizing energy consumption in different sectors. The program encourages the adoption of technologies and practices that increase energy efficiency.
2. Conserve Program: It was the first action of the Brazilian government in 1981 to promote energy efficiency in industry.
3. Universal Access to Sustainable Energy: The UN initiative to ensure universal access to sustainable energy by 20303. However, the UN report suggests that universal access to sustainable energy will remain unattainable unless inequalities are addressed.
4. Sustainable Development Goal (SDG) 7: This is a United Nations goal to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030.
5. Transition to Renewable Energy: UN Secretary-General António Guterres highlighted the need to transition to renewable energy to avoid a climate catastrophe. He presented a five-point plan for a just transition.

These and more programs have been implemented in different urban and rural areas, in Brazil like Mozambique from SDG goal 7. With EU support, Mozambique launched the Energy for All programme and then, in 2020, launched the Renewable Energy Auction Programme in Mozambique (PROLER), developed by the Ministry of Energy and Mineral Resources (ALER, 2020). These programs have in common the democratization of access to and use of electricity, contributing to the fight against energy poverty, the promotion of social and productive inclusion of vulnerable communities. The discussion about these programs is done later.

2.1 State of the art of solar and wind energy

The main sources of renewable energy in Mozambique include solar, wind, hydropower, biomass, and geothermal (Cristóvão, et al., 2021; Hassane et al., 2024). However, technological innovations, incentive policies, and awareness of the importance of sustainability have driven the use of renewable energies worldwide. The table 1, shows the renewable energies currently more harnessed.

Table 1: Renewable energy more exploited in the world

Renewable energies currently exploited in the world	**Solar Energy**: Generated by sunlight, captured by solar panels, and converted into electricity
	Wind Energy: Generated by the wind, which drives wind turbines to generate electricity
	Hydroelectric Power: Generated by the power of water, which drives turbines to generate electricity
	Geothermal Energy: Uses heat from the Earth's interior to produce electricity or heating
	Biomass: Derived from organic matter such as agricultural waste, wood, and biofuels
	Tidal Energy: Obtained from the tides and waves of the ocean.

Source: Authors

The Mozambican energy matrix points to the highest consumption of imported fossil energy. Destined for the transport and industrial sector, the electricity produced, approximately 85% of electricity consumption in Mozambique is destined for industry, only 45% is consumed by the domestic sector. The lack of access to energy is a major factor in the slow progress in attainment of the sustainability development global (Chichango & Cristovão, 2021). Additionally, the country is gradually industrializing, which is expected to lead to a continuous increase in domestic energy demand. Member countries of the Southern African Development Community (SADC) are also anticipating higher demand for energy, which could be met with Mozambican exports (ITA, 2024).

According to IRENA (2023), Mozambique has a solar and wind energy potential that is well distributed across the country. The solar potential with the capacity to produce 1.4 to 1.8 MWh/kWp of solar energy annually is distributed in almost 40 to 60% of the country. Regarding the distribution of wind potential, the country has winds with an average energy density of 260W/m2 in an area of about 97% of the national territory. Figure 1 shows the distribution of solar and wind energy potential over the year.

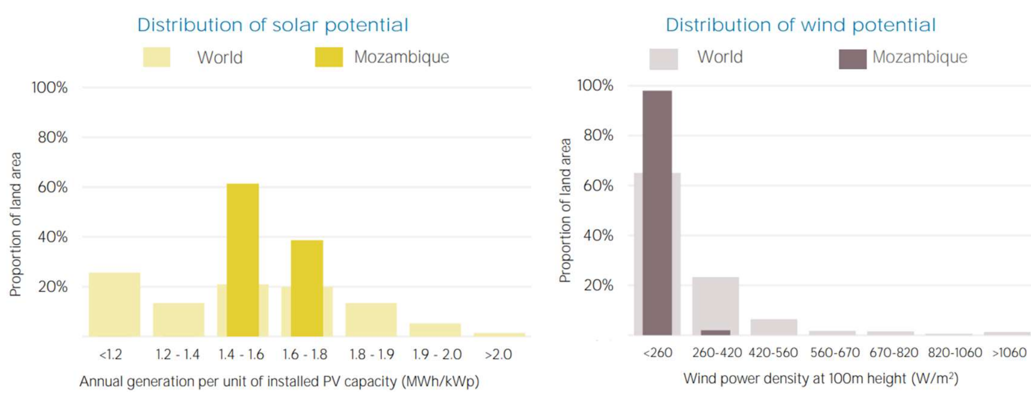

Figure 1: Distribution of solar and wind potential in Mozambique by land: Source: IRENA (2023)

2.2 Evolution of solar and wind energy

As a result of the strategies to promote renewable energy in the country, recommendations for the energy transition are visible, especially in the supply of clean energy to the domestic sector. The evolution of the electrification rate in Mozambique is evidenced by new solar plants in operation and others under construction, pre-qualification, tender to be launched, etc. Some of the plants are as follows:

1. Mecúfi Solar Power Plant - SM Solar PV Project, located in Pemba, Mozambique. It has a capacity of 26 megawatts (MW) and was inaugurated in October 2019.

2. Metoro plants Power Plant, located near the city of Pemba in Cabo Delgado province, has an installed capacity of 41 megawatts (MW). This plant was inaugurated in April 2022.

3. Tetereane Solar Power Plant located in the district of Cuamba, Niassa province. Generating capacity of 15 Mega Watts (MW). The Tetereane Solar Power Plant was officially inaugurated on September 14, 2023.

4. Mocuba Solar Power Plant, located in Zambezia province, Mozambique's first large-scale solar power plant. With an installed capacity of 40 megawatts (MW). The Solar Power Plant was officially inaugurated on August 10, 2019.

5. Cahora Bassa and Marávia Solar Power Plants in the districts of Cahora Bassa and Marávia, Tete province. The Cahora solar plant will have a capacity of 140MW and the Maravia one has been planned, but there are no specific details about its solar capacity yet.

The forecast and evolution of the electrification rate encourages rural communities to remain in rural areas, thereby reducing the rural exodus. The graph in Figure 2 shows the evolution of the electrification rate.

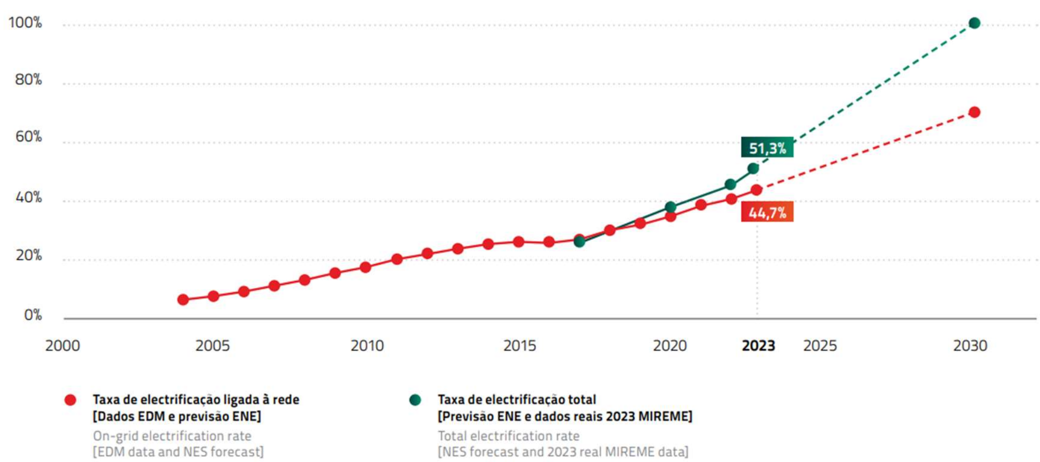

Figure 2: Evolution of on-grid electrification rate in Mozambique; Source ALER & AMER (2023)

In the energy forecast from 2022 to 20230, the energy resource that will increase the installed capacity will be solar in 5.4%, while the hydro resource may decrease by 7% and natural gas by 1.4% and there will also be a reduction in heavy oil exploration by 2,6 %, the installation and exploitation of wind energy will be 3% (ALER & AMER (2022). Figure 3 present the actual and prospective of renewable energy in Mozambique (2022 to 2030).

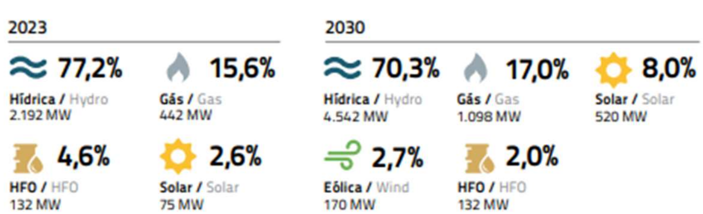

Figure 3: Installed capacity of Renewable energy in Mozambique; Sources: ALER & AMER (2022)

In this forecast, solar energy will have the highest growth, 5.3% compared to other energy sources. the wind energy will grow in 2.7%. The private sector, Globeleq, has started construction of the 120 MW wind farm in Namaacha, Maputo province (Perfil, 2024). In Inhambane province, a tender will be launched during the first half of 2024 for the construction of a 50MW wind farm (IREN & AMER 2023).

2.3 Hybrid solar – wind energy

A hybrid solar-wind energy generation system combines the benefits of both solar panels and wind turbines to generate electricity. The system is composed by:

1. Solar Panels (Photovoltaic Cells) to capture sunlight and convert it into electrical energy.

2. Wind Turbines to harness wind energy and convert it into electricity through rotational motion.

3. System stores excess energy generated by both solar panels and wind turbines for use during periods of low generation.

4. Charge Controller and wind controller to manage the charging process for both solar panels and wind turbines. The figure 4 presents the simplified Solar-wind hybrid system.

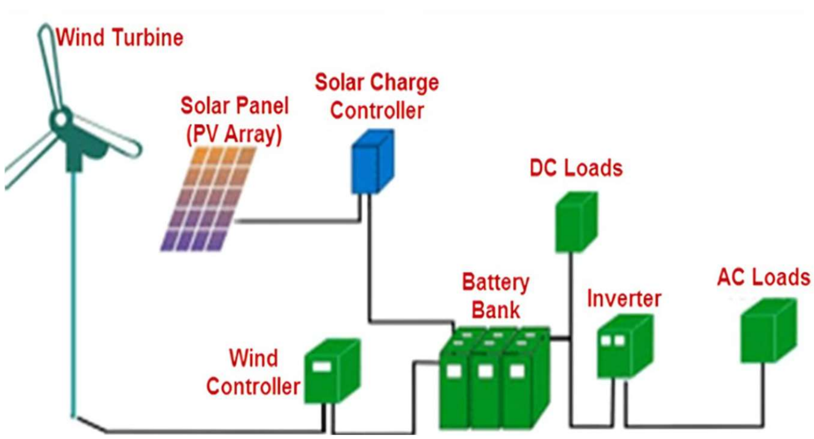

Figure 4: Representation of hybrid solar - wind system.

Source: https://www.suryashakthi.co.in/solar-power-generating-systemongrid-offgrid/ Accessed on 10 May 2020

The challenge of the solar – wind hybrid power generation is the intermittency. The solar energy is available only during daylight hours, and wind energy varies based on weather conditions. The storage systems are needed and proper sizing and integration of solar panels, wind turbines, and storage are critical for optimal performance. The battery storage system is already in use, further on, other storage systems are discussed.

2.4 Photovoltaic power design

To design the solar system, it is crucial to determine the number of demander energy. In this case, the simulation will focus on an energy demanded in a village isolated from the power grid. It is considered that the populations of (Ni- total number of inhabitants) inhabitants live in this village without access to the electricity grid.

$$N_A = \frac{N_i}{Nh} \qquad (01)$$

Where: N_A , number of houses, e N_i Total number of inhabitants, respectively; Nh-Average number of households.

2.4.1 Electricity demand

There are several procedures and standards for estimating the electricity demand in a single household, ranging from simple to complex methods, for example, the average energy consumed per month through energy purchase bills, number of specific and general outlets, area of compartments, or even by the rated power of existing appliances or expected to connect. However, considering grid-off houses it is reasonable to consider the load from the household appliances. Thus, the installation potential would be expressed by the formula (02) which is the multiplication of the individual power rate of the devices by their quantity.

$$P_{TI} = \sum_{i=1}^{n} Q_i P_i \quad (W) \tag{02}$$

Where: P_{TI} -total installed/needed power (kW); P_i - is the Power rated device (kW); Q_i - is the average number of devices with P_i in the house.

Consider the concurrency factor because not all loads work simultaneously all the time. Some of them are used at separate times. Therefore, the maximum concurrent demand will be less than the total estimated demand. Costa, & Moreno, (2004) present the range (0.2 to 0.8) of the factor simultaneously must be considered by using the formula (03).

$$P_{sim} = P_{TI} \cdot f_{sim} \tag{03}$$

Where: P_{sim} maximum potential considering simultaneously; f_{sim} factor of simultaneously.

The energy demand considers the use time of each device. To estimate the energy consumption the device potential e multiplied by time use as presented in formula (04).

$$E_T = \sum_{i}^{n} Q_i \cdot P_i \cdot t_i \tag{04}$$

Where: E_T - Total energy consumed in MWh/month. t_i - Charge period of each load (h). When considering simultaneous factor then the formula (05) is valid.

$$Energy\ demand_{\ sim} = f_{sim} * E_t \tag{05}$$

2.4.2 Sizing the PV solar modules

To generate the required energy using the solar photovoltaic system, it is important to size considering the month of the year with low irradiation to ensure the availability of energy throughout the year. In Mozambique, the weakest irradiance month typically occurs during the rainy season. The rainy season in Mozambique usually spans from December to March, during this period, cloud cover increases, leading to reduced solar irradiance and consequently, solar panels receive less sunlight, affecting their energy production (Chichango, et al., 2024). Figure 5 shows the average solar irradiance during the year.

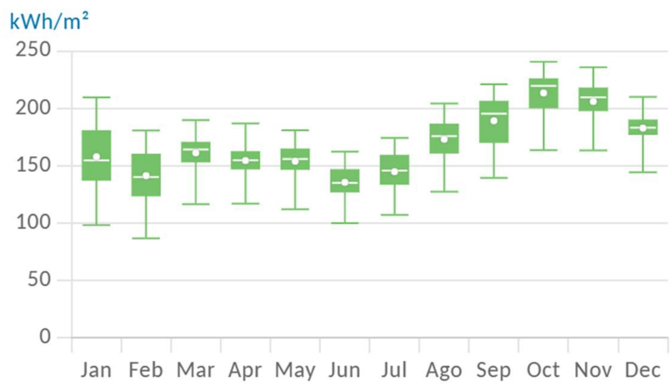

Figure 5: Solar Irradiance in Mozambique; Source: IRENA, 2024)

2.4.3 Choosing Solar PV panel

The amount of energy estimated in the previous point is used as a basis for the measurement and choice of solar panels. Hence, as the demand were estimated per month the formula (06) may reduce to Energy required per day.

$$E_{d,sim} = \frac{Energy\ demand_{\ sim}}{30} \quad (06)$$

Note: In formula the subscription *sim* is to remember the parameter consider the concept of simultaneous.

Since the day has 24 hours, but the sun does not radiate all the time, there is the concept of solar peak time, which is the period of the day when solar radiation reaches its maximum intensity. There are many applications that help to determine or read the peak-sun times for different regions, such as: Global Atlas, Weather Atlas, Polarid, fusion-solar-energy, etc. Figure 6 presents an example of peak-sun times for Maputo province.

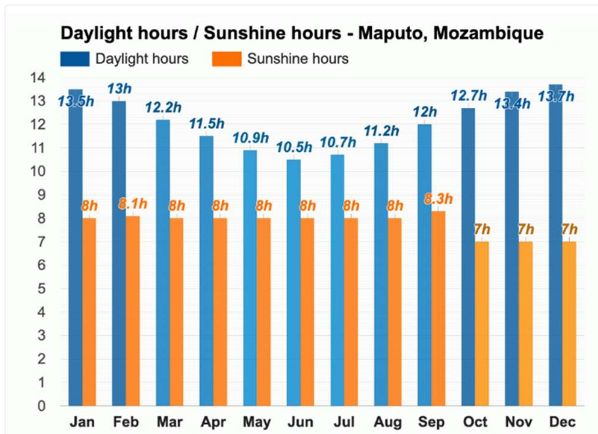

Figure 6: Average hours of peak-sun. Source: Weather Atlas, 2023.

Doe, (2021) the size of the solar system to meet the energy demand can be calculated by the expression (07) in which the efficiency factor can be calculated based on the area and power of the panel (08)

$$P_{r,day} = \frac{E_{d,sim}}{T_{HPS}} f_{PV} \quad (07)$$

Where: $P_{r,day}$ - Power required day; T_{HPS} Average Hours Peak Sun, and E_d energy demand per day, f_{PV} efficiency factor from supplier.

In this case is important to consider the nominal and real potential, the real potential is verified in short circuit (sc) case. In which when the PV panel is in short circuit (connected to load) it illustrates the real tension difference (V_{sc}) and current intensity (I_{sc}).

$$P_{PVm} = P_{real} = V_{sc} \cdot I_{sc} \quad (08)$$

To determine the number of PV module with the same capacity (nominal potential) can be estimated using the equation (09).

$$N_{PVm} = \frac{P_{rday}}{P_{real}} \quad (09)$$

Where: N_{PVm} - is the number of PV modules; P_{PmR} - is the production capacity required for all PV modules (kW); P_{PVr} - is the PV module rate of each device (kW).

2.4.4 PV power reserve

When sizing the solar panels by rounding the number of modules to integer, the power must be recalculated with the rounded number, the difference of the current power in relation to the initial potential is considered reserve power. Equation (10) shows the calculation of the reserve power.

$$P_{reserve} = P_{real} \cdot N_{PVm} - P_{rday} \quad (10)$$

Where: $P_{reserve}$ is reserve power.

2.3.5 PV panel connecting types

To meet the voltage or the current required is crucial to associate the PV panels in parallel or series as announced by Georg Simon Ohm and Kirchhoff for load or energy generation. Analytically or through app (Homer Pro app; Omni, etc.) is possible to optimize the layout of PV panels.

When connecting solar panels, there are two main types of configurations: series and parallel. In series connection the voltage increase. This is useful when you need a higher voltage for your system. The negative terminal of one panel is connected to the positive terminal of the next panel. The power generated by the module also increases with this series connection.

While in parallel connection the current increases. It is useful when you require higher current output. In this connection, the positive terminals of all panels are connected, and the negative terminals are also connected. The overall power remains the same, but the current capacity increases. The figure 7 presents the example of two types of PV panel connection.

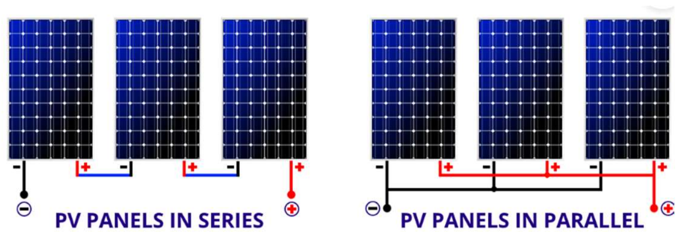

Figure 7: PV panel connecting types

Source: https://www.electricaltechnology.org/2013/07/how-to-calculatefind-rating-of.html

The layout of PV modules determines the field/space require to assembly de PV modules, so there is a need to reserve enough space for the generation of electricity in the desired quantities. To this end, it is essential to estimate the total area of electricity generation with PV, the chosen has dimensions of templates, associating with PV array dimensions is possible to estimate the overall area required.

2.5 Wind power system design

Wind turbines are equipment that generate electrical energy from the kinetic energy of the wind. Depending on the direction of the axis of rotation of the blades, wind turbines are classified into horizontal-axis turbines (HAWT) and vertical-axis turbines (VAWT). Figure 8 presents these two types of wind turbine. The HAWTs are the traditional wind turbines.

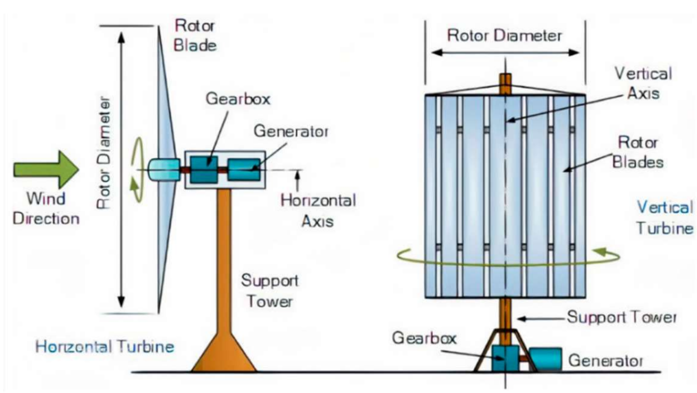

Figure 8: Types of wind turbines

Source: Hossain, 2019.

Wind turbines have different parameters, which gives them advantages and disadvantages to each other, Table 2 presents a comparison of the HAWT and VAWT parameters according to Hossain, (2019).

Table 2: Comparison of turbines common parameters

#	Parameter	HAWT	VAWT
1	Size	Relatively large	Relatively small
2	Maintenance	Difficult to maintain	Easy maintenance
3	Efficiency	High Efficiency	Low efficiency
4	Need for guidance system	Need guidance	No guidance system required
5	Power range	Use for large power range	Usually small in size

Source: Authors

Table 2 shows that the horizontal axis wind turbine (HAWT) has higher efficiency in relation to the vertical axis turbines (VAWT), this was the initial parameter used in the choice of turbines.

The VAWTs will be integrated into the photovoltaic system. The choice of these VAWT turbines was based not only on efficiency, but also on operational capacity (Szyk, 2024). According to the PV power required per day, which means the total power required to generate energy per day, estimated in the formula (07) the number of turbines can be obtained in the formula (08):

$$N_w = \frac{P_{r,day}}{P_w} \tag{11}$$

Where: N_w number of Wind turbine; $P_{r,day}$ Wind Power required in kW; Turbine generate capacity in kW output power with loses.

Overall losses in wind power generation are inevitable, some due to neighbouring topography and turbines, others in mechanical blades and gearboxes; and other electrical losses within the generator, transformer and wires, and others, are due to failures, malfunctions, maintenance (Szyk, 2024).

According to Szyk, (2024), the power generated by a wind turbine can be calculated by the following formulas:

1) Sweep area.

$$A = \pi \cdot L^2 \tag{16}$$

where: L — Blade length (the radius of the horizontal-axis turbine).

2.4.1 Available wind power

Available wind power according to the formula (17):

$$P_{wind} = 0.5 \cdot \rho \cdot v^3 \cdot A \tag{17}$$

where: P_{wind} available wind power; A sweep area; ρ air density; v wind speed, the figure 8, presents the relation between the density and the temperature.

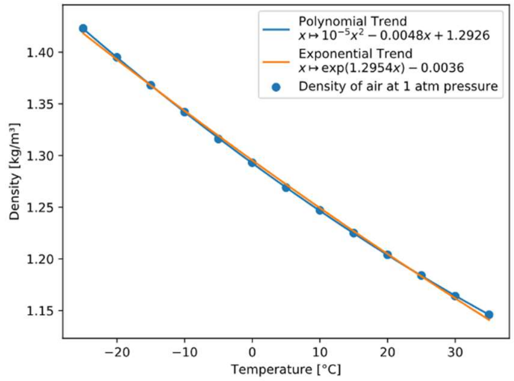

Figure 9: Air density vs. temperature.

Source: ISO 2533:1975, 1975 and https://planetcalc.com/9989/?P=101.325&T=20.

However, the available power wind turbine considering the coefficients relates is estimated by formula (18):

$$Power(W) = 0.5 \cdot \rho \cdot \pi r^2 \cdot V^3 \quad (18)$$

where: πr^2 is the swept area of the turbine, and V is the wind speed in m/s. ρ is the wind density in kg/m³ which varies according to graphic in figure x in kg/m³.

Location specific wind speed data can be found on different forecasting platforms and historical weather on the internet. as Weather-Atlas, Global Wind Atlas; Global Atlas for renewable energy. Meteoblue, Wind-finder, etc. the figure 10 present the example of wind speed through the year.

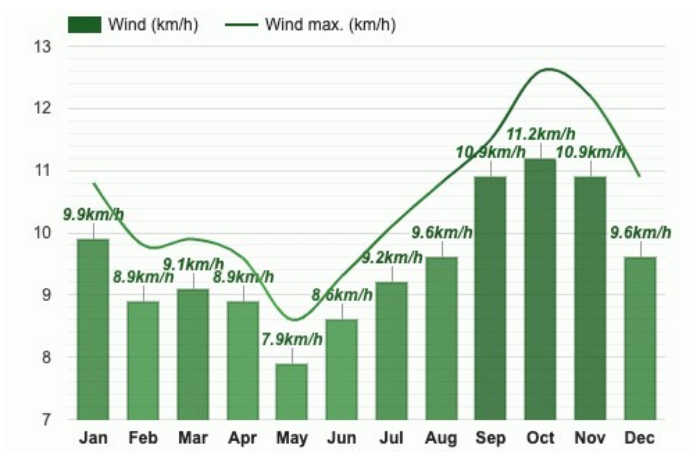

Figure 10: Wind speed profile, Dondo Sofala province.

Source: Weather Atlas (2023)

In figure x the average monthly wind speed is about 7.2 to 11.2 km/h during the year. The low value occurs in the month of May and the maximum in October.

2.5.2 Efficiency of the turbine

According to Szyk (2024), the total efficiency of the turbine considers coefficients as expressed in formula (19):

$$\mu = (k_m - 1) \cdot (1 - k_e) \cdot (1 - k_{e,t}) \cdot (1 - kt) \cdot (1 - kw) \cdot C_p \quad (19)$$

Where: μ - real efficiency; Cp - Turbine efficiency according to Szyk (2024) it must be lower than the Betz limit (59.3%), and is typically between 30-40%); kw - wake losses due to neighbouring turbines and the terrain topography typically valuers (3 – 10%) ; km - mechanical losses of the blades and gearbox (0%-0.3%;); ke - electrical losses of the turbine (1%-1.5%); $k_{e,t}$ electrical losses of transmission to the grid (3%-10%); kt percentage of time out of order due to failure or maintenance (2 – 3%).

Hence, the wind turbine power considering all loses is expressed by the formula (20):

$$P_{out} = \mu \cdot P_{wind} \tag{20}$$

The quantities of wind turbines will be calculated by formula (21)

$$N_{Wt} = \frac{Power\ required}{P_{out}} \tag{21}$$

Where: N_{wt} is the number of HAWT units required to provide the total energy demanded per day, and P_{out} is the rate power generation by a single HAWT unit, including all losses.

Where: backup days is the number of days a battery can provide power without being recharged.

2.6 Energy storage systems

According to U.S. Department of Energy (2020) The energy storage can be categorized in three ways: Mechanical Storage; Electrochemical Storage and Chemical Storage. Each type of storage as ways to store and dispatching the stored energy:

1. **Bidirectional Electrical Storage** technologies absorb, store, and dispatch electric energy. They include electrochemical, mechanical, and electrical storage systems. Electrochemical systems use chemical reactions, mechanical systems use physical methods, and electrical systems use specialized materials. Thermal and chemical energy storage systems can also be used for bidirectional electrical storage.
2. **Chemical and Thermal Energy Storage** harnesses energy for conversion to/from electricity. Thermal storage uses high/low-temperature reservoirs like molten salt, concrete, geothermal resources, phase change materials, and building thermal mass. Chemical storage uses hydrogen and other energy-dense chemicals from diverse sources for long-duration storage and grid decoupling, addressing power, industrial, and transportation sectors. Hydrogen-rich carriers can be synthesized for various applications and bidirectional storage.
3. **Flexible Generation and Controllable Loads** include technologies that enhance production or consumption flexibility. They aid in quick adjustment of power output, shift energy demand to match generation, enhance grid service provision, and integrate dispersed load with storage and behind-the-meter generation.

Green hydrogen falls under the category of Chemical and Thermal Energy Storage as a chemical energy carrier, enabling long-lasting storage and high energy density, and can be used in a variety of industries. Figure 11 presents a comparison of stored capacity and duration for different types of technologies.

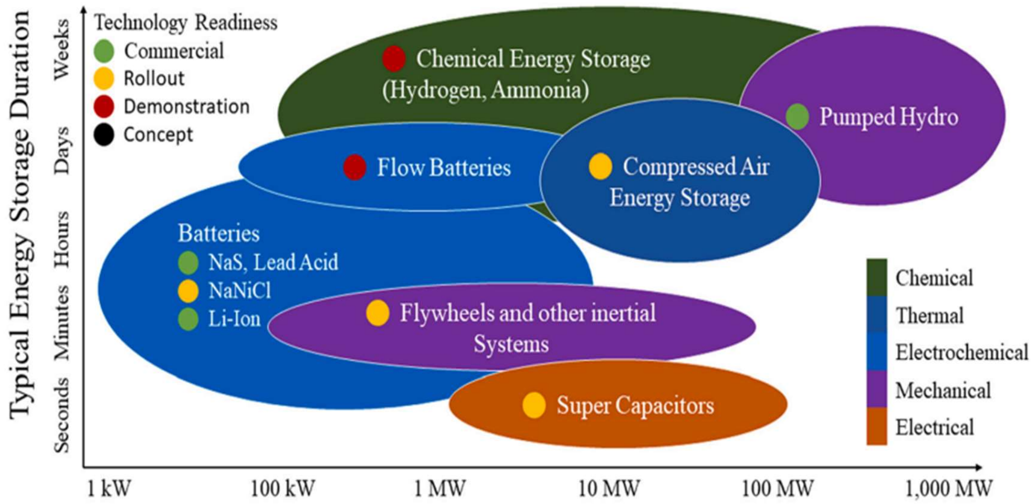

Figure 11: Time and energy associated with different storage system technologies. Source: Otto et al., (2022).

Figure 10 shows that Chemical Energy Storage technology, using hydrogen and ammonia, has a greater capacity to store large amounts of energy for longer.

2.5.1 Battery Storage system

Many studies show significant improvements in cost-effective and more autonomous battery solutions, the International Energy Agency (IEA), states that the sustainability of each solution is assessed by the equivalent CO2 emissions over the entire product life cycle. Among several solutions on the market, lithium batteries are in commercial phase, they can offer higher energy density, life cycle, low weight, and volume, compared to other technologies (Gomes, 2019).

However, to select adequate battery is important to consider some aspect as power rating, battery size and usable storage capacity, full cycle efficiency, battery life, safety as protection against overheating or short circuit, and battery quality which can be guaranteed by the manufacturer's reputation.

2.6.1. Battery selecting capacity

To estimate de battery capacity for energy storage Ohm's Law formula is need. Ohm's Law is describing the relationship between voltage, amperage (otherwise known as current) and resistance.

Battery Power is estimated as any electrical devices,

$$P = V \cdot I \tag{22}$$

Where: P – battery power (W); V - Voltage of the battery; I -is the current of the battery.

Battery Energy (E) is power P multiplied by time (T):

$$E = P \cdot T = V \cdot I \cdot T \tag{23}$$

Where: E – battery Energy (Wh); V - Voltage of the battery; I -is the current of the battery.

Battery capacity (Q) can be obtained by formula (24) as:

$$Q = \frac{E}{V} = I \cdot T \quad (24)$$

Where: E – Energy stored in a battery, expressed in watt-hours (Wh); V – Voltage of the battery(V); and Q – Battery capacity, measured in amp-hours (Ah).

Other battery parameters related to capacity are C-rate of the battery, which indicate how fast is the battery to charges and discharges. Charging or Discharge current (I), and Runtime (T) to full capacity or to discharge the battery when using the discharge current, measured in minutes. The relation between them is

$$I = C \cdot Q \quad (25)$$

$$t = \frac{1}{C} \quad (26)$$

Where: I – current (A); C is the rate of the charging or discharging battery (c); t is the time (h) and Q – capacity of the battery (Ah). The other fundamental parameters to be consider has to do with the battery autonomy and the deep of discharge (DOD).

Battery autonomy represents the time it can provide electric current without being recharged.

$$Battery\ Autonomy = \frac{Q}{I} \quad (27)$$

Where: Q- Battery capacity, measured in amp-hours (Ah) and current (A), Battery capacity (h).

While Depth of discharge is a measurement that indicates the amount of energy drawn from a battery, expressed as a percentage of total capacity.

$$DOD = 100\%\ of\ charge - SOC \quad (28)$$

Where: DOD – Deep of Charge (%); SOC – State of Charge (%).

DOD limit is given by the battery supplier (typical 20 to 50%), and it is highly recommended to comply with DOD for battery durability. The durability of batteries is not only controlled by deep discharge cycles, but also by overcharging. Batteries should also be limited to the maximum load voltage.

The devices used to control the load are called Charge Controllers, these devices are programmed to control the voltage, they have two limiting points of adjustment, maximum charge voltage (coming from the source) and minimum voltage that must remain in the battery (SOC) during operation. The figure 12 presents a typical Charger Controller.

Figure 12: Charger Controller.

Source: Available on https://www.ensko-intl.com/html_products/Solar-chager-controller-371.html

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2.5.2 Green hydrogen storage

Hydrogen is a chemical element that differs in colour names by the process used to obtain it and the energy source used. Table 3 shows the colours assigned to hydrogen based on the process and source used to obtain it.

Colour	Hydrogen Brown	Grey Hydrogen	Blue Hydrogen	Turquoise	Green Hydrogen
Process	Gasification without combustion	Steam methane reforming without pollutant capture	Steam methane reforming with pollutant capture	Pyrolysis	Electrolysis
Source	Coal gas	Methane or Coal	Methane or Coal	Methane or Coal	Reenable energy
CO2 Emission	Highly polluting	Polluting	Low Polluting	Low polluting	No polluting

Source: Adapted form Giovannini, 2020; Hematpur et al., 2023.

Green hydrogen (GH) has stood out as a key energy resource for the transition to a low-carbon economy. The production process is considered environmentally friendly as it does not emit any greenhouse gases. Production and store hydrogen involve high-pressure compression, liquefaction, and storage in solid materials such as metal hydrides. Figure 13 shows the phases of the green hydrogen production and storage process.

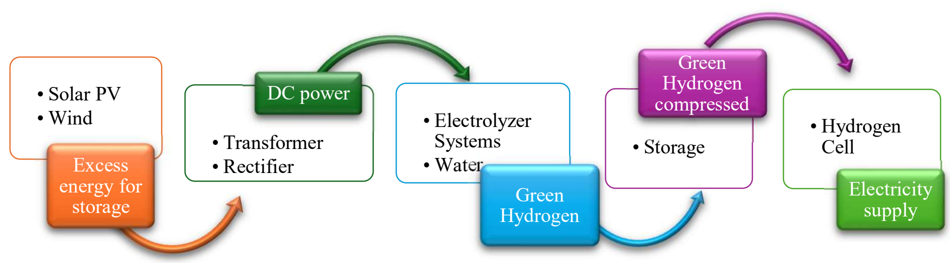

Figure 13: Phases of the green hydrogen process

2.6.2 Electrolysis phase

As a general definition, electrolysis is a process in which electric current is used to separate components of a substance affecting its chemical composition. In this specific case of hydrogen production, pure water is used as electrolyte, the result of electrolysis is decomposition of water and release of hydrogen and oxygen molecules. The minimum energy required for pure water electrolysis is about 1.23V (Wikipedia, 2014). The formula (24) resumes the chemical reaction. For this propose excess electrical generation from hybrid solar wind is used.

$$H_2O_{(l)} + energy \rightarrow H_{2(g)} + \tfrac{1}{2}O_{2(g)} \quad (24)$$

The hydrolysis process occurs under controlled environment conditions due to high energy density of hydrogen. According to Hernández-Gómez (2020), IRENE, (2023), and Franco & Giovani (2023) distinct types of electrolysis technologies exists including low-temperature and high- temperature, each with precise advantages figure 14 present de Alkaline (ALK) and Polymer Electrolyze Membrane (PEM) electrolysis technologies, they are more feasible for development regional countries.

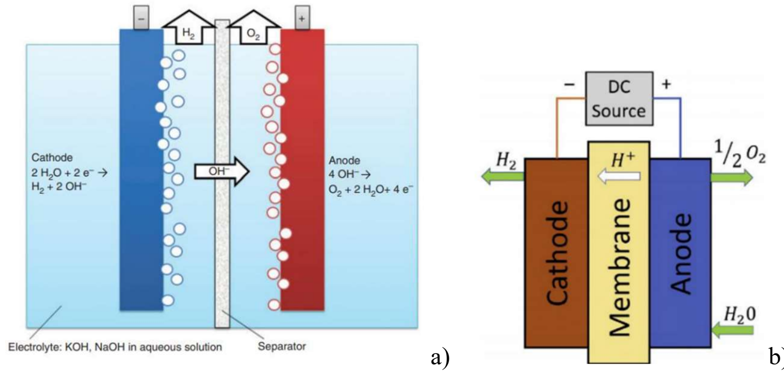

Figure 14: Most used types of electrolyzes a) ALK and b) PEM electrolyze.

Source: Hernández-Gómez (2020)

In electrolysis process there are steps to consider in step 1): In anode (negative electrode) there is the oxidation of hydrogen (H2) with the formation of protons (H+), which pass through the electrolyte, and electrons that move in the outer circuit. In step 2): In cathode (positive electrode) the oxygen, which is absorbed from the air, is reduced when it receives electrons from the external circuit. This movement of loads constitutes electric current; 3) At the electrolyte level, the positive (H+) and negative (O^{2-}) ions that arise from the reactions that occur at the interface between electrodes and the solution, bind together to form water. And finally, 4) it presents the overall chemical reaction of the process (Hernández-Gómez, 2020).

There are two main options of hydrogen storage currently used: which are tanks, and underground geologic formations (IRENA, 2021). Green hydrogen has a mass density of 141.9 $MJ.kg^{-1}$ but a low volumetric density of 12.75 $MJ.m^{-3}$, for its storage it is convenient to be compressed (Ferreira, 2003). According to IRENA (2021) tanks of several sizes and pressures are now used in industry. The thanks may store up to around 10 000 m^3, and high operating pressures around 1000 bar. In other hand, storage underground using salt caverns, they are used to great volumes of hydrogen and for long timeframes weeks to seasons, the operation pressure is around 50–250 bar.

Hematpur et al., (2023) in their comprehensive article, they discuss with more details the advantages and disadvantages of underground hydrogen storage and its role for energy transitions. The technical challenges are related to prevent leaked of the storage gas, the accessibility and the number of injection and withdrawal and the economic viability.

2.6.3 Hydrogen Appliances phase

Green hydrogen has a range of potential applications, including as a fuel for vehicles, heating, for energy and for feedstock in the chemical industry. Figure 15 presents some appliance of green hydrogen.

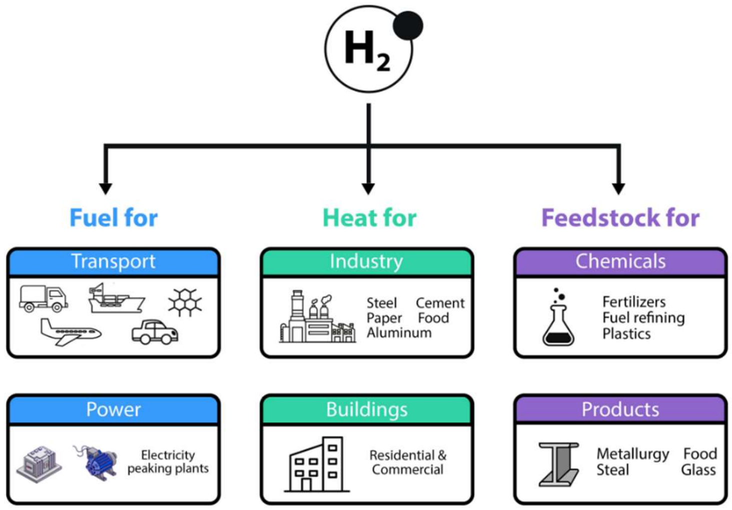

Figure 15: The main uses of hydrogen as a clean fuel (Kobina and Gil, 2022) Source: Hematpur (2023)

Considering the day-to-day applications of green hydrogen energy in different sectors presented in figure 14, the use of this secondary energy resource can be a step forward on the path of transition from clean energy to carbon-free environmental sustainability, and with the possibility of transforming the global economy, particularly in countries dependent on fossil fuel imports.

The solar-wind hybrid power generation scheme, with integration of storage systems, can be summarized as shown in figure x presented by Otto et al., (2022) in the study they carried out "Optimal hydrogen carrier: Holistic evaluation of hydrogen storage and transportation concepts for power generation, aviation, and transportation" the figure 16 presents the schematic summary.

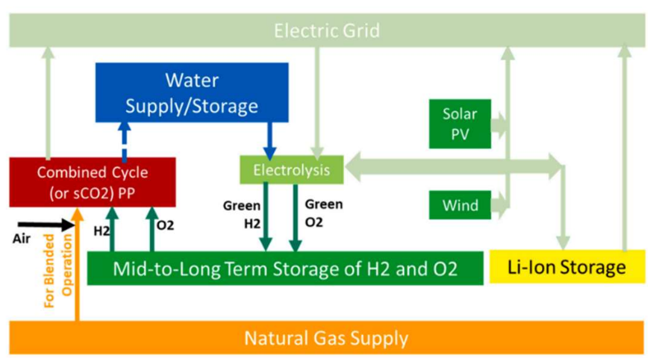

Figure 16: Scheme for the integration of renewable energy into the electricity grid with a storage system. Source: Otto et al., (2022)

The schematic shown in Figure 16 is a typical clean energy transition situation. Natural gas is still considered renewable, but in a short period of time it could be replaced by other, cleaner energy sources. This is a global challenge for decarbonizing the environment.

3. Opportunities and Challenges

The implementation of hybrid solar-wind energy systems with green hydrogen storage in Mozambique presents significant opportunities for the country's sustainable and economic development. It opens the opportunity for individuals and private companies to trade energy, demonopolizing EDM, which was responsible for producing, transporting, distributing, and marketing.

With vast potential for renewable energy generation, including solar, wind, and hydropower, Mozambique has the capacity to transform its energy landscape and spur economic growth. The transition to cleaner, renewable energy sources can create jobs, foster technological innovation, and reduce dependence on fossil fuels.

Additionally, expanding access to energy can significantly improve the quality of life for Mozambicans, many of whom still do not have access to the electricity grid. The energy transition can also promote social inclusion by involving local communities in the planning and implementation of renewable energy projects, ensuring that the benefits of development are shared fairly.

With the launch of the energy transition strategy at COP28 (on 23 December 2023), Mozambique affirmed its intention to emerge as a relevant player in the dynamics of the energy transition from renewable energy sources. The goal of raising the national electrification rate to 100% by 2030 with a production capacity of 68% through renewable sources is seen as ambitious, however, with the strategies adopted for the energy transition it seems to be working, given the rapid growth in the contributions of renewable energies (Solar and Wind) that since the launch of the Energy for All Program in 2019, coordinated by MIREM, the current installed capacity is 75MW, which represents 2.6% of the Mozambican energy matrix (ALER & AMER, 2023).

To meet the challenge of initial investment in renewable energy projects, which is high, the Government of Mozambique is looking for national and international partnerships that support sustainable development, such as the Swedish Embassy, the World Bank supporting Mozambique, the French Development Agency (FDA) through the European Union-Africa for Infrastructure, the European United is also supporting the establishment of a Renewable Energy Tariff (REFIT) and a Resource Centre. Above all, public-private partnerships and government incentives can make energy transition projects even more viable.

With the National Energy Strategy (2018-2030) launched on November 12, 2018, through the energy for all program and the energy auction program in Mozambique (PROLER) launched on September 30, 2020, coordinated by MIREM, electrification rate increased, for instance in 2022 was 44% and increased to 51.3% of the installed capacity of 2,841MW in 2023, of which 62% was generation from renewable sources, an increase resulting from new grid-connected solar plants with an installed capacity of 75MW and 6.6 MW from off-grid sources (ALER & AMER, 2023; EY, 2024 and Oeconomico2024). However, challenges related to investment, infrastructure, technology, and regulation must be carefully managed to ensure the success of these initiatives.

After the consolidation of hybrid systems in Mozambique, it will be necessary to make the energy transition from natural gas and fossil fuels to the production, storage, and consumption of green hydrogen. But at this stage, there will be a need and large investments due to the relative complexities of hydrogen storage and transportation technologies. As an example, the World Economic Forum (2022) presents a list of countries with advances in this sector, as well as related investments, among which lists:

1. China, it consumes and produces more hydrogen than any other country. While most of its production is “grey” hydrogen (generated using fossil fuels like coal), it has been actively working on “green” hydrogen projects since 2019. China issued its first hydrogen roadmap in 2016 and has a significant fuel cell electric vehicle (FCEV) fleet.
2. European Union (EU): The EU recognizes hydrogen as a key technology for achieving its policy goals, such as the European Green Deal. The EU’s strategy focuses on emissions-free green hydrogen, with a target to install 40 gigawatts of renewable hydrogen electrolyze capacity by 2030.

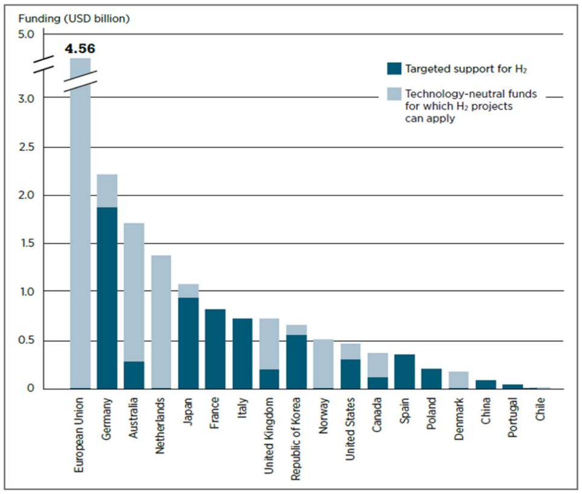

Figure 17: Annual funds available for hydrogen projects in Europe Source: World Economic Forum (2022)

3. Germany: Germany has the highest potential underground storage capacity for hydrogen in Europe. As of 2021, it had a working gas capacity of 255 terawatt hours, which could potentially translate into a hydrogen storage capacity of 61.4 terawatt hours (Statista, 2024).

However, it is crucial that this transition is managed in a way that respects the socio-economic reality of the country and ensures that disparities or exclusions are not created. Collaboration between government, civil society and international partners will be key to fully seizing the opportunities that the energy transition offers.

The energy transition in Mozambique cannot be seen only at the level of environmental sustainability, as decarbonization and the effects it causes directly affect the standard of living of communities (Junior, 2022). However, this transition represents a significant opportunity to drive sustainable social and economic development.

One of the examples of social exclusion was the implementation of a similar program in Brazil. "National Program for the Universalization of Access and Use of Electricity – Light for All" in Foz do Iguaçu, which became one of the largest social programs ever developed in this area (2004 to 2008), was not successful in carrying out specific actions programmed for the use of electricity to leverage social and economic development, thus contributing to the reduction of poverty and increase of family income (Bittencourt, 2010).

In addition, it is essential to involve and educate the local community about the benefits of renewable energy and how to use it efficiently. The participation of civil society and community leaders in the energy transition in Mozambique is necessary, as well as in the creation of mechanisms and tools to promote and regulate renewable technologies, capacity building in rural areas, including gender of education as strategy mentioned by Chichango et al, 2023, and Junior, 2022). Training programs can enable residents to maintain and operate the systems, because sustainable use of resources has become an issue in each food supply chain segment (Chichango, et al., 2023).

4. Final Consideration

The research paper provides a comprehensive analysis of Mozambique's energy transition, focusing on the integration of a hybrid solar-wind system with green hydrogen storage. It discusses Mozambique's potential for renewable energy, particularly solar and wind, and the country's efforts to implement clean energy sources to meet growing energy demands and reduce reliance on fossil fuels. The transition presents opportunities for sustainable development, job creation, and improved quality of life, but it must be managed to avoid socio-economic disparities. Mozambique aims to become a significant player in renewable energy transition, with a focus on inclusivity and collaboration. The paper also reviews various international programs and initiatives that promote clean energy and energy efficiency, highlighting Mozambique's participation in these efforts. It provides detailed technical insights into the design and implementation of solar and wind energy systems, including energy storage solutions like green hydrogen, to support the country's transition to a low-carbon energy future. Mozambique is actively transitioning towards renewable energy sources, focusing on integrating hybrid solar and wind energy systems with green hydrogen storage. The country's potential for solar and wind energy generation is being tapped through various projects to meet domestic and industrial energy demands. Green hydrogen serves as a key storage solution, with applications across different industries. The transition involves the implementation of photovoltaic systems and wind turbines, considering aspects like efficiency, storage, and grid integration. Community engagement and education are vital for the success of the energy transition. Although the renewable energy industry in Mozambique is expanding, it still requires further exploration and investment to overcome current limitations and to support new research. The government seeks national and international partnerships to support sustainable development and to achieve its ambitious goal of a 100% national electrification rate by 2030, with a significant portion coming from renewable sources. Challenges related to investment, infrastructure, technology, and regulation must be addressed to ensure the success of renewable energy initiatives.

Future studies should be carried out to assess the satisfaction of the communities benefiting from the “Energy for All” program should be carried out to assess the degree of satisfaction of the communities and their involvement in this project. In order not to incur the risk of vandalization of the plants and misinformation of the communities by the new technologies. Another no less important point are studies that must be carried out continuously for the stipulation of energy tariffs so that rural communities feel benefited from these renewable resources.

Another future study suggested is the use of the Economic Input-Output Life Cycle Assessment (EIO-LCA), a methodology mentioned by Ferrão and Nhambiu (2009), using official data to assess the satisfaction of rural communities about the benefits of implementing energy auction strategies. This fact may reveal the real situation of the economic viability of the phases of the energy transition in Mozambique.

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