Comoros's energy review for promoting renewable energy sources

Jean-Philippe Praene, Ali Hamada Fakra, Fiona Bénard-Sora, Leslie Ayagapin

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Jean Philippe Praene[a,*], Damien Fakra[a], Fiona Benard[a], Leslie Ayagapin[a]

[a]*PIMENT Laboratory - University of la Réunion, 117 Rue du General Ailleret - 97430 Le Tampon - Reunion*

Abstract

At present, energy represents a key element in the social and economic development of a territory. This is particularly true for fragile territories that are not interconnected, such as small island states. As is true for many of the Small Island Developing States (SIDS) worldwide, the energy situation of the Comoros is substantially based on fossil fuel imports. The socioeconomic development of this archipelago is overwhelmingly dependent on energy security from sustainability, availability and affordability perspectives. As a forward-looking response to energy vulnerability, the deployment of renewables to diversify the generation of electricity appears to be an essential prerequisite for guaranteeing a sustainable future. Nevertheless, despite a high potential for renewable energy, only 3.8% of the electricity supply in the Comoros is provided by hydropower. This paper provides a comprehensive overview of the energy situation throughout the Comoros and focuses on renewable energy opportunities to facilitate the supply of green power. This study ultimately shows that renewable energies are rarely exploited despite the powerful potential of different resources. Finally, this paper attempts to provide recommendations for the Comoros to pursue a more sustainable future.

Keywords: Comoros Islands, Electricity generation, Renewable energy, Policy

*Corresponding author
Email address: praene@univ-reunion.fr (Jean Philippe Praene)
URL: piment.univ-reunion.fr (Jean Philippe Praene)

Nomenclature

AFD	Agence Française de Développement
AIMS	Africa, Indian Ocean, Mediterranean and South China Sea
COP	Conference of the Parties
DGME	Direction Générale de l'Energie, des Mines et de l'Eau
EDA	Electricité d'Anjouan
GDP	Gross Domestic Product
GEMIS	Global Emissions Model for integrated Systems
GIS	Geographic Information System
GWP	Global Warming Potential
HDI	Human Development Index
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IINAS	International INstitute for sustainability Analysis and Strategy
INDCs	Intended Nationally Determined Contributions
LCA	Life Cycle Assessment
LDC	Least Developed Countries
MA-MWE	MAdji na MWEndje ya komori
PASEC	Programme d'Analyse des Systèmes Educatifs de la Confemen
PV	Photovoltaic
RES	Renewable Energy Sources
SIDS	Small Island Developing States
SONEDE	SOciété Nationale d'Exploitation et de Distribution des Eaux
SONELEC	SOciété Nationale d'ELECtricité
UNFCCC	United Nations Framework Convention on Climate Change

1. Introduction

According to the International Energy Agency (IEA) World Energy Outlook [1], 13.4% of the world's total primary energy supply in 2015 was produced from renewable energy sources (RES), while the generation of renewable electricity (excluding hydropower) is estimated to account for 8.4% of global electricity production. To decrease the anthropogenic causes of climate change, the UNFCCC[1] has emphasized the importance of reducing greenhouse gas emissions. In particular, energy needs are among the highest worldwide in the countries throughout Sub-Saharan Africa [2]. This region boasts an abundance of energy resources; paradoxically, however, the countries in this region have an astoundingly low energy supply percentage. The overall population in this region accounts for 14% of the world's population, but this region represents only 4.5% of the global primary energy demand (619 Mtoe) [3]. In this context, African island states like

[1] United Nations Framework Convention on Climate Change

the Union of the Comoros make them more vulnerable. Being an islands, energy and transport costs are higher than those encountered by land lock countries [4–6]. Indeed, the islands of the Comoros could be subjected to extreme events such as natural disasters, could be affected by the volatility of oil prices, and socioeconomic energy risks or geopolitical instability [7–10]. Energy is crucial for human life and economic development; for progressive islands such as the Comoros, it is important to secure energy through four perspectives: availability, accessibility, affordability and acceptability [11, 12]. Therefore, due to the remoteness and isolation of the Comoros, its market-based economy and its limited natural resources, switching to renewable energies clearly appears to be a key strategy for achieving sustainable development. In the transition towards sustainable islands, one suggested pathway highlighted by state-of-the-art studies is to focus on the opportunities for generating 100% of energy through renewable resources [13–15]. However, before defining any energy planning scenario, it is appropriate to establish an overview of the current situation. A recent article reviewed energy planning scientific articles that addressed the countries in Sub-Saharan Africa, but it did not consider Comoros which form part of this region [16].

Therefore, the main objective of this paper is to fill the knowledge gap regarding the energy landscape of the Comoros. The remainder of this paper is organized as follows:

- Section 1 introduces the paper and describes the overall context of the present study.
- Section 2 presents the geographical and socioeconomic situation of the Comoros.
- Section 4 describes the current energy situation and focuses on the methods with which electricity is currently generated.
- Section 5 explores the opportunities for the generation of electricity through the deployment of renewable energies. This aspect is also discussed in terms of energy policies and planning strategies.

2. Overview of the Comoros situation

2.1. Geography and climate

The Union of the Comoros is a small archipelago located in the Indian Ocean within the Mozambique channel between the eastern coast of African and the island of Madagascar. The geography of the archipelago is highly variable and consists essentially of the following:

- Ngazidja (i.e., Grande Comore) : The biggest island of the Comoros with an approximate area of 1,148 km^2. It contains vast plains and an active volcano that rises to approximately 2,500 m above sea level; consequently, Ngazidja is a volcanic island covered with pozzolanic ash. The economic and administrative activities of the Comoros are located mainly on this island.
- Ndzuani (i.e., Anjouan): The second largest island of the Comoros with an area of approximately 424 km^2. This island is very mountainous with numerous rivers and waterfalls.
- Mwali (i.e., Moheli): The smallest island of the Comoros with an approximate area of 112 km^2. This island is very argillaceous and is covered mainly by a subtropical forest.

The Comoros archipelago is subject to warm tropical and humid climate conditions. The climatic condition is divided into two seasons. Between middle November and middle April, the islands endure a warm and rainy season with an average temperature equal to 27 °C, a maximum temperature of approximately 31-35°C and a minimum temperature of approximately 23°C. Between June and the end of September, the Comoros are in a cold season with an average temperature of approximately 23-24°C, a maximum temperature of 28°C and a minimum temperature of approximately 18-19°C. The average annual rainfall of the three islands exceeds 1000 mm (between 1,398 and 5,888 mm in Ngazidja; between 1,371 and 3,000 mm in Ndzuani; and between 1,187 and 3,063 mm in Mwali).

2.2. Demography

The population in 2017 was estimated at approximately 800,000 citizens [17]. The inhabitants of the Comoros are characterized mainly by a young and rapidly growing population; approximately 60% of the population is less than 25 years old, while only 5% represent people greater than 65 years of age. The geographical distribution of the population according to each island is given as follows: 52% of the inhabitants live in Ngazidja, 42% live in Ndzuwani, and only 6% live in Mwali. Of the overall population, 70% of people live in rural zones, but considerable rural exodus (38.6% of rural zones) to urban zones (principal cities) has been observed since 2016. Therefore, among all the African nations, the Comoro Islands have a relatively high population density per square meter of living space, as described in [18].

2.3. Socioeconomic situation

The Comoros represent one of the poorest countries in Africa with a Human Development Index (HDI) value of 0.497 in 2015, ranking 160 out of 188 African

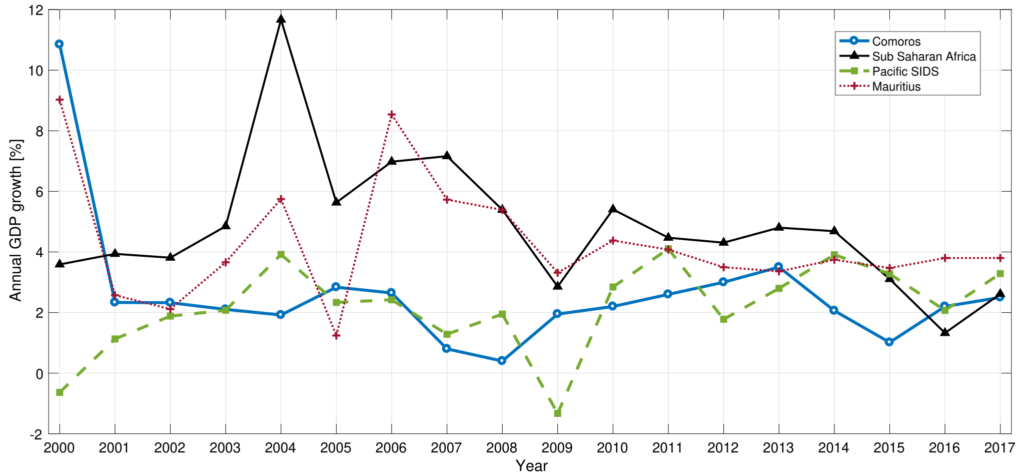

Figure 1: Annual Gross Domestic Product (GDP) growth during the 2000-2017 period.

nations. The poverty headcount ratio at \$1.90 a day has increased from 13.5% in 2004 to 18.1% to 2013. According to the World Bank's poverty assessment report [19], living conditions have improved significantly over the last two years due to structural reforms engaged through a recently stable political climate. Nevertheless, the Gross Domestic Product (GDP) per capita was still low in 2016 with a value of \$698. Thus, the funds transferred from expatriates, which represent more than 20% of the total GDP, are essential and fundamental to the balance of the Comoran economy.

Due to the ongoing electricity supply crisis, economic growth reached 2.1% in 2016 and 2.5% in 2017. As shown in Figure 1, the upswing that began in 2015 continued in 2017, and the annual GDP growth reached 2.2%. This dynamic was driven by the government issuing relatively strong incentive policies [20]. Since 2016, Comoros has been led from a political and economic context that is more favorable to growth. The Government is seeking to stimulate the economy through an ambitious investment plan targeting infrastructure. The Agence Française de Développement (AFD)[2] has defined a program to support the financing of the productive sector in Comoros since 2017, [21]. This program aims to boost economic activity by setting up a financial offer and support adapted to the needs of small businesses. It is thus crucial to ensure electricity production in order to support the development of the economic activity. Indeed, the frequent electricity shortages in previous years had been one of the main obstacles to investment. Three new thermal power plants were constructed to end both the alarming electricity generation shortages and the activities associated with

[2]French public institution fighting against poverty in developing countries

the implementation of a heavy fuel oil power plant. Compared with the Pacific SIDS, the Comoros seems to generate more stability. Nevertheless, the growth of the Union of the Comoros is lower than that of other islands in the Indian Ocean, such as Mauritius, but its trend is nearly similar to that of countries in Sub-Saharan Africa countries. The trade balance of the Comoros exhibits a structural deficit with exports originating mainly from agriculture (vanilla, clove and ylang-ylang) and imports, which represent approximately 40% of the GDP.

3. Methodology

3.1. Data collection

There is no study yet on renewable energy potential of Comoros. The main difficulty is the lack of past reliable data in energy. Thus, socio-economic data are taken from the World Bank database. Most of the data used were either collected from meetings and interviews with the various energy stakeholders in Comoros or gathered through publications. The potential of solar or wind energy production was carried out using online Geographic Information System (GIS) tools or widely used open-source software.

3.2. Barriers analysis

An overall analysis of all the barriers to the deployment of renewable energies in a territory was carried out in Painuly's work [22]. Seven categories of barriers were identified from more than forty barriers. The case of Comoros is particular since it is a small island state and other studies have already demonstrated the existence of these barriers in island territories and their specificities [23, 24]. This study is based on the list of barriers established in Painuly's work and identifies one by one of the practical obstacles on the territory. This identification was made through meetings with energy stakeholders in Comoros (electricity supplier, politicians, engineering consultants, etc.).

3.3. Life cycle assessment methodology

Life Cycle Assessment (LCA) is a methodology for the global evaluation of a product's environmental impact throughout its life cycle [25]. This systemic method presents a holistic approach for a comprehensive environmental assessment, following a standardized method that guarantees the reproducibility of results [25, 26]. The results can be used in different ways. As stated previously, one of the main objectives of the study is to focus on the possibilities of generating 100% of energy through renewable resources. For this purpose, emission factors for each technology for all Indian Ocean islands were defined and evaluated. A comparison between Comoros and other Indian Ocean islands was carried out to highlight the energy vulnerability of these territories. The assessment focuses on the various environmental impacts resulting from the production of electricity. The steps took into account the acquisition of raw materials, the transportation of these materials to the production site, and the cradle-to-grave operation of electricity generation. For electricity production, we observe the emissions generated from 1 kWh of electricity produced and ready for distribution on the entire Comoros electricity grid. Inventory flows is based on a regional raw materials account for electricity generation. Since this study focused on the production of the Comoros grid mix, Global Emissions Model for Integrated Systems (GEMIS) software was used for the life cycle inventory and life cycle impact assessment. One of the advantages of GEMIS is that it integrates energy and material flows, transport, and the database, developed by Oko-Institut in 1989 and distributed by the International INstitute for sustainability Analysis and Strategy (IINAS) platform [27], see Figure 2. Thus, each territory's technologies were considered

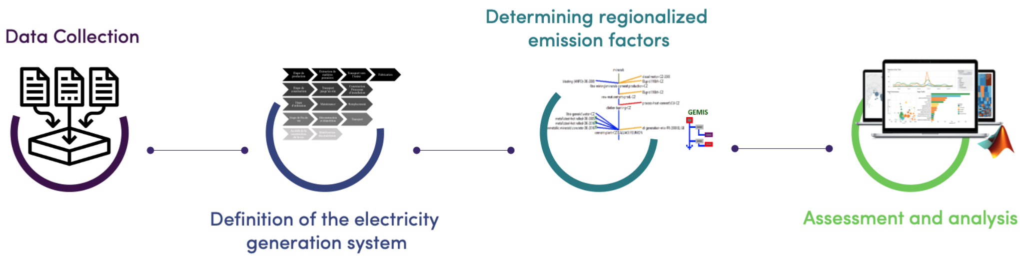

Figure 2: Impact calculation flowchart to perform LCA of electricity generation.

from the extraction of raw materials to the distribution site. According to Morales et al.[28], it is essential to regionalize the local data of island territories in the field of construction. His works has demonstrated the importance of integrating regionalized inventory data into local practices, since environmental impacts vary considerably compared to non-regionalized data. Generic data, or data calculated for a continental country, cannot be used for an island territory without adaptation. Construction methods and climatic conditions for certain territories must be considered on a case-to-case basis. A LCA tool was developed by Rakotoson and Praene to evaluate the environmental impact of an electricity mix in insular context [29, 30]. Additionally, the impact factor was defined using the GEMIS based on data expressed in terms of total production in 2015 and 2016 [31]. However, this approach focuses only on the cradle-to-gate life cycle. Thus, the impact is calculated from resource extraction to power plant production.

4. Current energy status

With an insular situation heavily characterized by spatial inequalities among the three islands in terms of energy security and economic development, the sustainable electricity issue remains an important issue for the Union of the Comoros.

4.1. Energy sector in the Comoros

In the coming years, the greatest challenge that the Comoros will face is reconciling the quality electric supply with the generation of low carbon emissions. The electricity sector of the Comoros must develop critical strategies to address issues in financing, management and governance that continue to hinder the development of renewable energies in spite of their high potential, particularly with regard to the rural electricity supply. Compared with other islands throughout in the Indian Ocean, such as Mauritius [32], Madagascar [33] and Reunion [24], the proportion of renewable energy in the Comoros is nearly non-existent (see Table 1).

Table 1: Energy use by source in 2016 [34].

Resources	**Energy (toe)**	**Share (%)**
LPG [1]	831	0,56
Diesel	29759	20,07
Gasoline	11274	7,60
Oil/Jet fuel	16416	11,07
Dry wood	89816	60,58
Renewable energy	155	0,10
Coal	6338	4,28

[1] *Liquified petroleum gas.*

As shown in Figure 3, the energy balance in the Comoros highlights that these islands are subjected to a vulnerable energy supply situation. Indeed, 100% of fossil fuel resources are imported from Saudi Arabia; thus, the territory particularly suffers from the volatility in fuel oil prices. Petroleum products are used mainly for transportation and electricity generation, where the former accounts for nearly 60% of all fossil fuel imports, and the remainder is shared by the industrial, residential and tertiary sectors. As in many other developing countries throughout Sub-Saharan Africa [33, 35], solid biomass remains a dominant energy resource for cooking in the Comoros. On the other side, house construction increases the demand for wood as a resource during the construction phases. Furthermore, the production of gasoline is an aggravating factor in deforestation. Since gasoline's price is high, people favor the use of wood from forests for households, particularly for cooking. Moreover 80% of the wood used each year is destined for ylang-ylang distilleries (about 837,000 m^3). Due to the pressure of anthropogenic activity, with a 5.8% rate [36], the country has the 4th highest deforestation rate in the world. For example, dry wood is not considered a sustainable resource because of its heavy environmental impact. The 2017 Energy

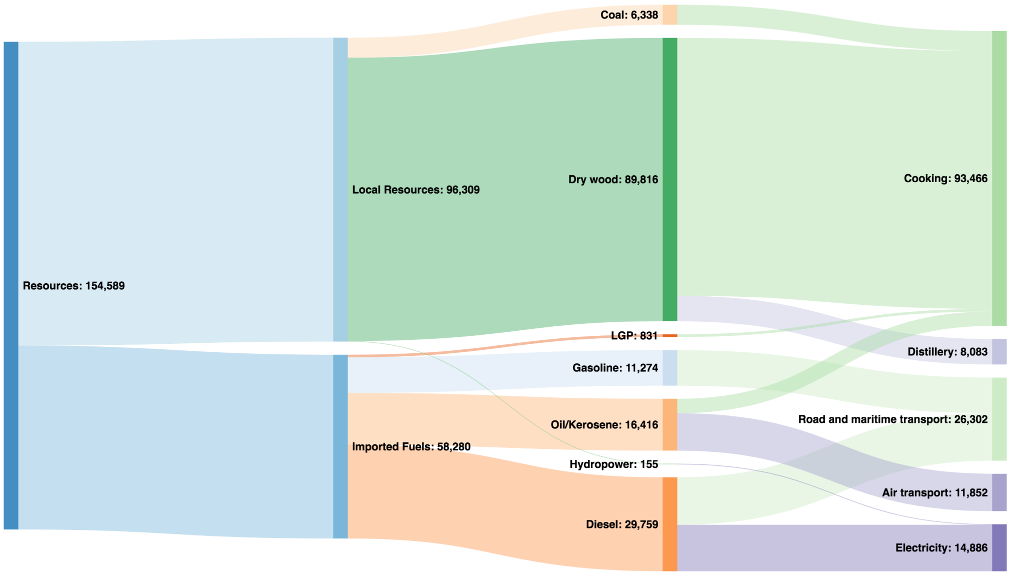

Figure 3: Sankey diagram depicting the overall energy supply and demand in the Comoros (in toe).

Access Outlook report [3] indicated that nearly 90% of households rely on either wood or charcoal. Therefore, neither imports nor local resources will be sustainable over the long term, except for hydropower electricity generation, which represents less than 0.1% of all primary energy in the Comoros.

4.2. Electricity situation

Access to electricity is problematic in most regions within the Union of the Comoros and represents a significant barrier to socioeconomic development. According to the Direction Générale de l'Energie, des Mines et de l'Eau (DGME)[3], in 2016, the mean value of electricity access was 48.50%. This rate, which represents the actual situation on the ground, is radically different from the rate of 77.8% indicated by the World Bank Open Data in 2016 [37]. Moreover, there is a considerable disparity in electricity access among Mwali (10%), Ngazidja (60%) and Ndzuwani (50%). This difference is particularly notable because failures could range from 2-6 hours in urban areas to 12 hours in rural areas.

To date, the electricity market in the Comoros has not been liberalized. Electricity production was historically operated by two public companies, namely,

[3]National energy, mining and water management organization

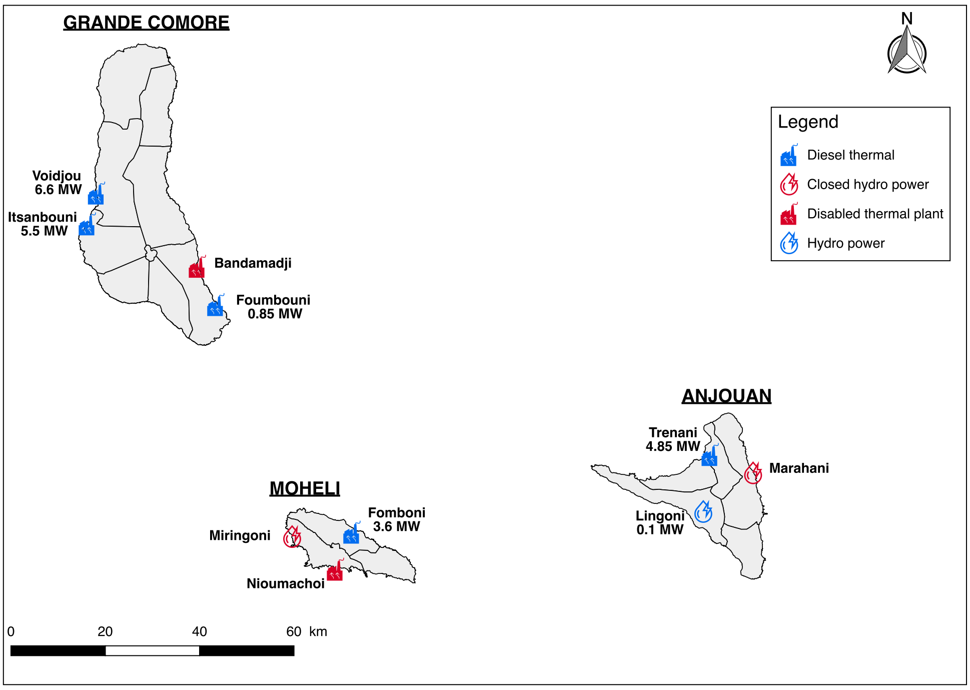

Figure 4: Electricity power plants in the Comoros.

Madji na MWEndje ya komori (MA-MWE)[4] for Ngazidja and Mwali and Electricité d'Anjouan (EDA)[5] for Ndzuani. In September 2018, these two companies were merged, but they subsequently split in 2019 into two new national companies called SONELEC (SOciété Nationale d'ELECtricité)[6] and SONEDE (SOciété Nationale d'Exploitation et de Distribution des Eaux)[7]. The missions of these companies remain the same: to produce, distribute and market their services throughout the national territory. The Comoros power system consists of one subsystem for each island without any interconnection between them. The actual situation of the electricity grid is shown in Figure 4. A large portion of the existing equipment is composed of ageing installations, some of which are disabled. In addition, transmission and distribution losses reaching an extreme of 48% represent a major source of inefficiency in the Comorian power system. The available capacity decreased from 25 MW in 2013 to 21.5 MW in 2016. This difference between the installed capacity (~36 MW) and available capacity is described in Table 2. The difference between the installed and available capacity

[4]A public company for electricity and water production
[5]Electricité d'Anjouan: Anjouan Electricity provider
[6]National Electricity Company
[7]National Water Operation and Distribution Company

is due to the installation and not to the rainfall in the islands. Indeed, the installations have lacked maintenance over time. This explains a significant decrease in production over time. As shown by these data, the effective production is very low according to whether half of the diesel-fueled generator facilities are being serviced.

Table 2: Existing power plants and available capacity in 2016.

Island	Power plant	Number of generators	Energy source	Installed capacity (MW)	Available capacity (MW)
Ngazidja	Voidjou	10	HFO	16	6.6
	Itsambouni	5	HFO	6.2	5.5
	Foumbouni	2	HFO	1.2	0.85
	Bandamaji	1	HFO	0.12	0
Mwali	Fomboni	5	HFO	5.38	3.6
	Nioumachoi	1	HFO	0.14	0
	Miringoni	2	Hydro	0.22	0
Ndzuani	Trenani	7	HFO	6.3	4.85
	Lingoni	1	Hydro	0.3	0.1
	Tratinga	1	Hydro	0.3	0

Unfortunately, the abovementioned problem goes much deeper. In fact, the public companies suffer from operational and financial governance problems, which is due to a lack of investments and frequent commercial and technical losses. The subsidies that are assigned to these companies amount to 10% of the state budget. The price of electricity in the Comoros is among the highest in Africa. The cost to produce electricity is approximately 595 USD/MWh, and the sale price to the consumer is 298 USD/MWh. Despite the high cost of energy, the population is ready to pay for access to electricity. At the same time, it has become increasingly common for individuals to bypass electricity meters illegally to obtain access to the power grid. Since then, the Comoran government has taken necessary actions to stop such unlawful practices. However, no audit was carried out to assess the scale of these actions.

4.3. Environmental impact assessment

The electricity consumption per capita is currently 279.83 kWh, which is below the average value of 483 kWh/capita[8] in Sub-Saharan Africa. As shown in Table 2, the generation of electricity is highly depended on Heavy Fuel Oil (HFO) plant which results significant environmental impact. The LCA technique is a well-recognized method that is widely used to evaluate potential environmental impacts such as Global Warming Potential (GWP). Here, a comparative analysis

[8] Excluding high-income countries.

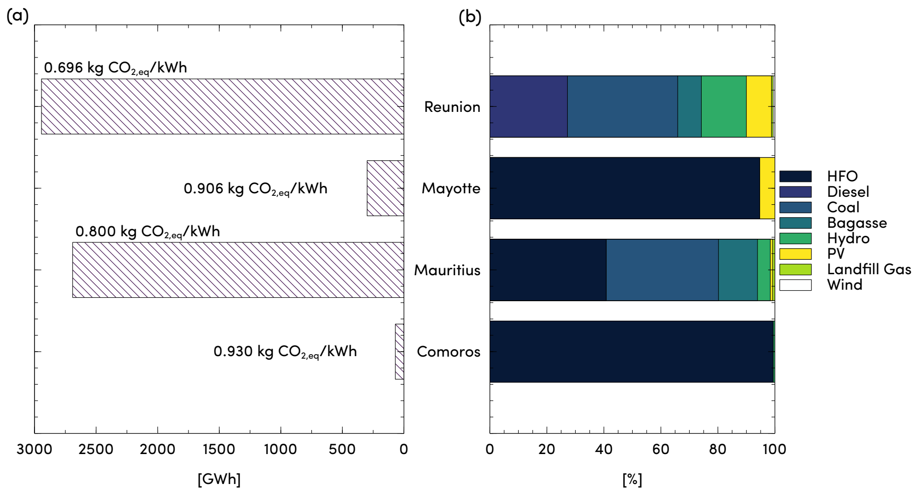

Figure 5: Comparing the electricity production of Indian Ocean small islands: a)- GWP and electricity producted, b)- Electricity generation by fuel sources.

is performed among four small islands in the Indian Ocean; for detailed information on all islands, see the supplementary data. The electricity mix of each territory is depicted in Figure 5. At present, the level of production in the Comoros is small overall but has a high environmental impact. The GWP, which is used to qualify greenhouse gas emissions, is evaluated at 0.930 kg CO_2eq/kWh. This result results that the Comoros is locked into a fossil fuel-dependent electricity situation, which creates a more vulnerable energy position in the near future. As it is the case for many of the SIDS worldwide, the Comoros Islands rely heavily on fossil fuels to meet their energy demand. As shown in Figure 5, the other islands in the Indian Ocean also have a high carbon mix. Unlike Comoros, most of these islands are already engaged in energy planning to achieve their territory's energy autonomy. Thus, the economy of the Comoros is dependent on a high energy requirement for all goods and services produced in the territory. This constraint also results in long supply distances for resources (energy, food, etc.) due to the lack of economies of scale and the island geography (which increases the distance to the main markets). This remoteness, which can be observed in other small islands in the Indian Ocean, leads to additional environmental costs due to the transported of raw materials for electricity production. Besides, electricity, apart from being highly carbonized in Comoros, does not penetrate households very much. Thus, the most widespread use for cooking remains wood because of its marginal cost. However, the impact on forests is more and mor dramatic.

5. Renewable energy development perspectives

5.1. Renewable energy potential

5.1.1. Solar energy

Despite the considerable amount of solar radiation in this part of world, the Comoros archipelago does not exploit this form of renewable energy in abundance. Moreover, there is no information about the exact quantity of photovoltaic (PV) or/and heat panels actually installed on all three islands. These materials (i.e., solar panels) are exempted from customs duties, but there is no policy or regulation on net metering. PV for electricity generation is gradually entering the market but remains negligible compared to other sources. There are already examples of individual PV systems at households, but no PV farms yet. The theoretical energy potential for the entire archipelago is estimated at 78.72 MW. The estimated electrical requirement of an average family in the Comoros (composed of between four and five persons) can be evaluated with TECSOL software. The parameters for the simulations are as follows: The daily consumption of an average household is equal to 2,820 Wh/year, which approximately represents a daily electricity demand of 7.7 kWh. The solar panels are manufactured by a TENESOL company, and the meteorological data used are from Pamandzi. The inclination of the panels corresponds to the average inclination of the roofs of Comorian houses, i.e., 12°. In addition, all the solar panels are considered to be oriented towards geographically towards north. Given these assumptions, it is possible that a photovoltaic panel generates approximately 4.5 kWh/kWp per day. This would make it possible to meet the energy needs of some villages that are slightly more isolated. Thus, the Comoros possesses huge potential with regard to the development of photovoltaic energy. However, such an investment would require a rapid return given the country's economic situation.

Very recently, a French company signed a contract with SONELEC to purchase electricity from solar energy for 26 years. With this contract, the construction of a 3 MW solar park [38] located in the town of Foumbouni, southeastern Ngazidja, can begin. This park will contribute an increase of 13.5% in the overall electricity production of the Union of the Comoros. This project of the Innovent company should be delivered during the year 2020. In Anjouan, a 3.15 MW solar power plant is currently under construction in Pomoni by Engie [39], covering about 85% of daytime demand. A second project of the same scale is planned on the same island within the next two years, making it feasible to cover all the population's current needs. The Commission de l'Océan Indien (COI)[9] Energie project has stimulated the development of the solar sector. COI has implemented a support plan for the deployment of renewable energies in the Indian Ocean islands.

[9] Intergovernmental organization of Indian Ocean countries

5.1.2. Geothermal

The island of Ngazidja is characterized by an active volcano called "Karthala", which rises to an altitude of 2,361 m. This volcano currently produces no geothermal energy despite its estimated energy potential of 10 MW. Indeed, the cost for investing in geothermal energy is very high, and thus, the Comorian government continues to explore more profitable financial solutions.

5.1.3. Biomass

Like other SIDS, waste management is one of the many problems facing the Comoros. Currently, no plantation is dedicated to the cultivation of bioenergy resources. Additionally, information on the quantity of agricultural products in the Comoros is very limited. However, some studies produced a theoretical estimation of approximately 4.01 MW of potential energy for the entire Comoros archipelago. In 2015, the study by Mohee et al. [40] estimated a municipal solid waste generation rate of 1.56 kg/capita day for the Africa, Indian Ocean, Mediterranean and South China Sea (AIMS) SIDS. In 2013, a solar energy equipment supplier in South Africa named Mikrosolar proposed the gasification of 22,000 tons/year of mixed wastes. Unfortunately, this project has been discontinued for the time being.

According to the work of Issihaka et al. [41], the fermentable fraction of the municipal and assimilated waste produced in the Comoros is 60%; half of this waste is organic, and 10% is wood waste. Thus, the implementation of an anaerobic digestion process appears to be an appropriate choice for the recovery of municipal waste.

5.1.4. Wind energy

Like the other islands throughout in the Indian Ocean, the Comoros is also exposed to cyclones. The Indian Ocean is a very active zone of tropical cycloes. However, the probability of being struck by to a cyclone in the Comoros is relatively low because a combination of factors favorable to a very particular trajectory is required [42]. For this reason, the development of wind energy seems an excellent opportunity. Indeed, wind energy is one of the cheapest and easiest renewable resources to use. Nevertheless, the number of wind turbines installed throughout the Comoros is unknown. Historically, two wind turbines were installed on Ngazidja in 1987. These facilities were used to supply underground pumping systems. However, the expected volume of water was not achieved. As a result, the tests were not conclusive. Only a recent theoretical study conducted by the government has suggested the allocation of land area for the development of wind farms. The mean annual value of wind speed is very low (rarely above 3 m/s). Furthermore, based on the map proposed by the Global Wind Atlas [43], the Comoros has a relatively low wind power density distributed mainly between

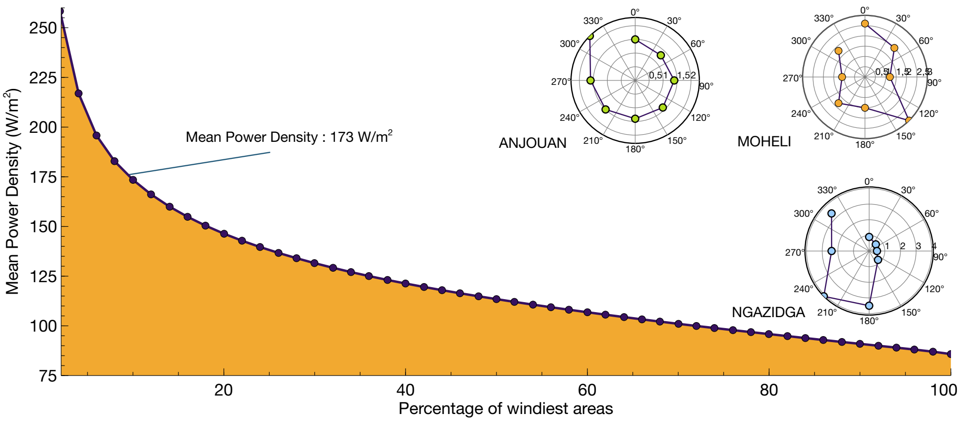

Figure 6: Wind energy profiles of the Comoros.

80 and 270 W/m^2. This low potential is also due to the minor variability of the topography throughout the three islands of the archipelago. As shown in Figure 6, the wind profiles of the three islands are very different, and the mean power density for the top 10% windiest areas is 173 W/m^2 with a mean wind speed of 1.81 m/s, which is lower than that of other areas in the region such as Mauritius (471 W/m^2 and 8 m/s, respectively) [32, 44]. Thus, wind energy should be a supplementary resource and not an important investment for the diversification of electricity sources.

5.1.5. Hydropower

The first installations dates back to the French colonial period, 1930. However, most of the plants were installed between 1970s and 1980s. The lack of regular maintenance has led to an accelerated deterioration of the infrastructure. This explains the gradual depletion of hydropower in the electricity mix. The archipelago has an under-exploited hydroelectric potential, particularly on the islands of Anjouan and Mohéli. From a topological and hydrological stance, these two islands are endowed with hydropower resources. The power generation potential is calculated according to Eq. 1.

$$P_{gen} = \eta \cdot \rho \cdot g \cdot H_{net} \cdot q_v \tag{1}$$

where η is the hydraulic efficiency (-), ρ is the water density (kg/m^3), g is the acceleration due to gravity (m/s^2), H_{net} is the net head available at the turbine (m), q_v is the water flow (m^3/s)
The results of the assessment of the four potential sites are detailed in Table 3. As can be seen, Anjouan has the highest potential for Comoros. Thus, based on the average energy consumption, these facilities could meet the electricity

demand of more than 32,500 households. The financing of these installations is currently done within the PASEC[10] project framework financed by the African Development Bank Group. The total amount invested is more than 5.7 million euros.

Table 3: Hydropower potential in Anjouan an Moheli islands.

	Anjouan			Moheli
	Marahani	Lingoni	Tatinga	Miringoni
η		0.6		
H_{net}	30.9	32.8	19.7	17.5
q_v	1.4	0.8	1.2	0.1
Pgen (kW)	253.10	153.5	138.31	10.24
Egen (GWh)	2.22	1.34	1.21	0.09

5.2. Barriers to the deployment of RES

The deployment of renewable energies on remote island territories represents an important economic challenge. These fragile territories, including the Comoros, are often underdeveloped, and therefore, the issue of such deployment is a major development issue, and the barriers to this development are significant. In a study on SIDS, Weisser identified three main development obstacles focused on the territories' capacities: human and institutional capacities, financial capacities and knowledge of technologies [45]. Such obstacles can be barriers to the development of renewable energy, barriers specific to energy and technology, and barriers specific to the territory [22]. In 2001, Painuly reviewed all the barriers to the deployment of renewable energy in a territory and identified seven main categories. The first two types of barriers are directly related to the market, namely, the failure and imperfection of the market and its distortions. There are many examples associated with these types of barriers: lack of infrastructure, lack of competition on the market (in particular, a monopoly situation), controlled energy sectors, taxes on new technologies, etc. [22]. This analysis of the Comoros archipelago allows us to quickly see the lack or rather the complete absence of competition throughout the territory. The energy sector and, in particular, energy production has been highly controlled by the state since 1976. Only two companies exist in the territory, and they are both owned by the state: MA-MWE for Ngazidja and Moheli and EDA for Anjouan [46]. These two companies regulate the energy market.

This control distorts a market that already suffers from economic and financial flaws (the third category of barriers identified in Painuly's work). The Comoros

[10] Comoros Energy Sector Support Project

archipelago is composed of three islands that cover an area of 2,236 km^2 with a population of more than 800,000 inhabitants. As a result, the archipelago offers a small economic market that not only hinders the possibility of implementing economies of scale but also restricts the diversification of producers and therefore competition. Furthermore, the size of the market makes it impossible to encourage external investors on the basis of a simple economic argument. Nevertheless, with another argument, the Comoros succeeds in attracting investors: indeed, being a member of the League of Arab States, the archipelago benefits from significant investments through this channel. These investments could support a renewable energy market that is not profitable from a purely economic perspective.

The fourth barrier is institutional. Developing renewable energies in any region requires a favorable institutional framework. This constitutes a barrier that is present in the case of the Comoros. The electricity sector suffers from several shortcomings: weak governance and limited political reforms, a lack of transparency regarding the budget dedicated to the sector, and a lack of responsibility and autonomy for companies [47]. Nevertheless, in recent years, a political commitment to renewable energies has been declared. Since 2012, the Union of the Comoros has been reforming the energy sector with the National Energy Sector Strategy of 2012 [46]. Strong policy measures have already been taken to encourage companies to adopt renewable energies. The Intended Nationally Determined Contributions (INDCs) of 2015 identified key measures for the deployment of renewable energy. With the overall objective of contributing to reducing poverty and providing sustainable development, the Union of the Comoros seeks to provide adequate solutions to the challenges of global warming [48] [46]. The state is also a signatory of twenty-first session of the Conference of the Parties (COP 21), which established this commitment to renewable energies. Nevertheless, the country suffers from short- and medium-term management problems that do not allow for stable development within the sector. In addition, the abundance of funds from external sources (via the Comorian diaspora or the country's membership to economic alliance groups such as the League of Arab States or the Indian Ocean Commission), although necessary for the country's development, leads to a situation of strong dependence on the state and hinders the adoption of long-term plans.

The fifth category of barriers includes all technical barriers ranging from lack of infrastructure to lack of skilled labour [22]. The Comoros archipelago has been classified as a least developed country (LDC) since 1977 [49]. Moreover, there is huge disparities in the island: the territory is under significant demographic pressure, and the population is settling on the little land that is still available. Some regions, such as Nyumakele (Anjouan), reach 1,000 inhabitants/km^2 [50]. The population has settled in areas according to historical trends and geographical opportunities. In 2015, 60% of the population lived in rural areas [51]. This situation creates technical difficulties for the transmission of electricity. In 2016, only 77.84% of the population was connected to electricity[11]. In other words, electicity is not available to the entire population, yet the existing facilities are not sufficient to meet the demand of the population connected to the grid. Indeed, there are periods of electricity shortages due to an insufficient storage capacity for fuel supplying the power plants.

In addition to the preceding purely structural constraint, there is a cultural constraint, i.e., a certain conflict among the different islands, leading to occasional malfunctions in the power plants. This represents the sixth category of barrier identified by Painuly: social, cultural and behavioral barriers [22]. Indeed, the acceptance of new technologies by society and the population is important. In the case of the Comoros, the territory is not yet fully electrified, nor is there systematic access to drinking water. The country's level of development is very low with an HDI of 0.503 for the year 2017. For this type of development situation, the question of an ecological transition seems inappropriate in relation to the severe problems that this territory faces. In particular, the poverty level in the Comoros is rather high; the poverty gap at \$1.90[12] a day in 2016 reached a rate of 17.8% [51]. Nevertheless, the promotion of renewable energies could accelerate the development of the territory and could thus be considered an invaluable opportunity.

5.3. Discussion

In the Comoros, there is no specific policy that provides an incentive for the development of RES. This is explained by three main difficulties. First, the current economic situation of the country is dismal. Indeed, the country suffers from structural vulnerabilities, and the economic situation remains fragile, thereby limiting the territory's ability to invest in its development. Second, recurrent political instability hinders the investment of foreign capital and the sustainability of strategic political orientation, particularly in the energy sector. Third, the definition of a road map for the energy sector requires precise statistical data on the territory that are not currently available. Given all these handicaps, the Comoran government held its first national conference on energy in June 2017 [52]. At this event, the government affirmed its willingness to lift the country out of its precarious energy situation. To achieve its objectives, the government has mobilized energy stakeholders on its medium-term strategic vision called "Comoros Horizon 2030". The supply of electricity is currently driven by the Ministry of Energy. However, the country receives recurrent foreign funds to improve or renew these facilities. To date, the main problem has been addressing electricity

[11] https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=KM

[12] The \$1.90 line is set by the World Bank.

demands as a matter of urgency using fossil fuel plants. The implementation of a real energy policy is crucial for laying the foundations for long-term energy planning. Nevertheless, no laws or regulations govern the energy sector. Thus, it is essential to create an incentive and an attractive legal framework. This framework is particularly important for investors because of the importance of initial investments. As discussed by Surroop [23], a persistent problem among SIDS is the lack of political willingness to engage in radical change. The Comoros is no exception. In the short term, the emergence of a real political agenda combined with the restructuring of the electricity sector would constitute the first steps towards a decarbonized society. It also seems crucial to establish an independent regulatory environment that could freely evaluate the level of political choices and investment to define whether the defined objectives are being achieved. Thus, the definition of a new framework should provide an economic incentive for the harmonious and sustainable development of the energy sector. In addition to political intentions, in a vulnerable territory such as the Comoros, some economic support mechanisms are required to achieve electrically self-sufficient islands [53]. Unfortunately, despite the energy conference in 2017, the initial signs of such a transition are not yet visible, and the ambitions affirmed in 2017 have not yet been reflected in the national legislative framework. Thus Comoros, like many small islands, must abandon its monolithic energy governance. This approach has shown for many years a structural heaviness. Its territory has to adapt quickly to face the challenges of transition. The energy vulnerability of Comoros is threefold. On the one hand, the high cost (0.24€/kWh) of carbon-based electricity is due to a poorly performing distribution network. This deteriorated state leads to more than 40% of losses. This cost is currently the highest in the area. On the other hand, this strong dependence on fossil resources makes the area sensitive to price volatility on world markets. Finally, the government is financing more than 65% of electricity generation. This support is a barrier to the sustainable development of the territory. Indeed, other crucial issues, such as access to drinking water or maternal and child health, cannot be adequately supported because of the resources tied up for the energy sector.

Conclusion

Driven by global concerns, the islands throughout the Indian Ocean are becoming increasingly interested in energy security and sustainability issues. The Comoros, similar to Madagascar, Mauritius, and Reunion, has very recently focused their efforts on the transition to RES throughout its territory. This paper provides policymakers with a comprehensive overview of the energy situation in the Comoros. Another objective of this article is to highlight the potential of the Comoros archipelago to introduce renewable energies into its energy sector.

Fossil fuels and hydropower are currently the primary supplies of energy in the Comoros. Some conclusions can be drawn in the case of the Comoros. The first objective is to make a review of the data and potential for the development of renewable technologies in the Comoros Archipelago. This first step allowed us to characterize the territory and to build a reliable database that we are currently using to build scenarios for the electricity autonomy of Comoros by 2050. One of the major problems we identified in 2017 was the availability and reliability of online information about the archipelago. As highlighted by Dornan [54], external aid and national energy policies are the key elements that can shape energy transitions for SIDS. In addition to its exposure to the effects of climate change, the Comoros is particularly vulnerable to the volatility of global energy prices due to its fragile socio-economic situation. Moreover, the intertwining of energy and regional development issues is undeniable, especially in the case of noninterconnected areas such as the Comoros.

In many works, remoteness and a small population are regarded as barriers to development and energy transitions. A territory such as the Comoros represents a significant opportunity for the deployment of new energy policies that encourage the integration of RES. Unlike monolithic energy governance models, such as those in Europe, the consequences of urgent decisions that must be made in the Comoros will quickly affect the territory [55]. Thus, the Union of the Comoros urgently needs to diversify its energy mix with RES. This article shows that the three islands have a feasible potential to develop solar, biomass, wind and geothermal energy. However, this requires the implementation of regulatory tools and investment incentives in the energy sector. These changes first require the definition of a proactive energy policy, which will make it possible to set short- and medium-term objectives to be achieved within the energy planning framework. Further research will strengthen the development of this potential through the definition of energy scenarios. This work will make it possible to propose a gradual evolution of the energy mix by 2050.

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