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A COMPARATIVE STUDY ON INFLUENCE OF CLIMATE ON OPTIMAL DIMENSIONING OF A HYDROGEN-BASED MICROGRID

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Abstract- In a global context marked by climate variability and in the fight against global warming, Morocco has adopted an energy strategy focused on the development of renewable energies, specifically wind and solar. However, these renewable energies are known for their intermittent nature, which can be offset by the addition of a practical energy storage system. Hydrogen storage systems have gained popularity in recent years, particularly in microgrids, as they offer flexible and long-term storage capabilities compared to battery storage. In this study, the techno-economic feasibility of three energy storage system scenarios for an autonomous microgrid based on solar and wind energy is evaluated in three distinct climate regions of Morocco, namely Laayoune, Tanger, and Oued-Zem. The HOMER software is used to evaluate and examine the techno-economic and ecological impacts. The NASA platform was utilized to generate the meteorological data for these three regions. The aim of this investigation is to address the subsequent inquiries: 1) In these three climatic regions of Morocco, which renewable energy production system can meet the community's demand while also providing economic benefits? 2) In these three regions, which energy storage system offers the highest level of flexibility and cost-effectiveness? 3) Under specific climatic conditions, how is the hybrid storage system deployed to obtain the most cost-effective scenario? 4) What would be the impact of the uncertainties of the climate on the energy plans of the different climate regions in the future?

Keywords: HRES, HESS, MICRO-Grid, Community Load, Hydrogen, P2H2P, Climate Influence, HOMER.

1. INTRODUCTION

Until 2023, climate change shows no signs of slowing down. Indeed, some phenomena are already threatening the environment, such as (Floods, Submersion, Cyclones, Heatwaves, Droughts, Fires, Biodiversity, Economy); according to the latest IPCC report, which advocates that in every one of the last three decades, since 1850, the Earth's surface has been successively hotter than all the previous decades [1]. It confirms this time that the influence of humans on this climate disruption is unequivocal. Consequently, national governments still need to rise to the challenge of reducing their emissions of greenhouse gases, one way of which is to increase the penetration of renewable energies (RE).

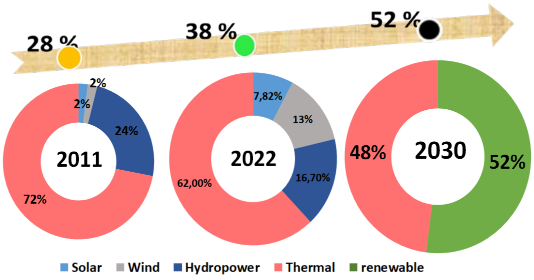

Figure 1. Evolution of the Moroccan energy mix in 2011-2030

In this regard, Morocco's strategy is based on the development of wind, solar, and hydraulic energies as well as on the reduction of subsidies for fossil fuels [2]. The Moroccan Green Plan envisages raising the share of RE in the energy mix to more than 52% by 2030, compared to 4% (PV and WIND only) in 2011. In 2021, Morocco adopted a New Development Model (NDM) with the aim of accelerating its energy transition process and enabling it to better meet its needs in terms of economic competitiveness and sustainability. This NDM includes the production of decentralized electricity and the widespread access to energy at competitive prices.

Currently, the production capacity continues to increase. In fact, the installed capacity of renewable energies is 4031 MW, which represents 38% of the total installed capacity. Out of this, 16.7% comes from hydroelectric energy, 13.48% from wind energy, and solar energy accounts for 7.86%, as shown in the Figure 1. Morocco, once again, confirms its dynamism in the field of renewable energy in Africa, ranking second on the continent in the production of electricity from wind and solar energy. This was revealed in the latest report "Global Electricity Review 2023" by the British Think Tank Ember Climate.

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However, photovoltaic and wind production is by nature intermittent, which limits the availability of electricity produced by these sources when and where it is needed and leads to network instability. To address this issue, several solutions have been proposed [3]. However, these contributions are limited by their climatic and geographical characteristics. Hybrid renewable energy sources (HRES) overcome this drawback by combining conventional electricity with one or more [4-5]. From a resource perspective, coupling wind turbines with photovoltaic panels significantly reduces the impacts of intermittence and is generally cheaper than a single-resource system [6-8]. To achieve a highly reliable energy system and overcome the intermittent nature of solar and wind resources, the addition of energy storage systems (ESS) is essential and has attracted a great deal of attention over the last few years because it allows the electric energy produced to be shifted over different time scales [9]. In this context, batteries, supercapacitors, hydrogen, and flywheels are the main technologies used in microgrid systems [10-11]. However, their integration raises questions about the choice of the most suitable technology for the needs.

At the community level, Li-ion battery is the most commonly used technology for short- and medium-term storage (from a few minutes to a few hours), whilst for long-term storage (days and weeks) hydrogen is the most recommended [12]. Furthermore, to compensate for the individual weaknesses of each energy storage system (autonomy, excess energy, stability, reliability), several research results show the interest in using the hybrid energy storage system HESS [13-14]. However, in spite of the benefits of HESS, each case study is limited to a very specific climatic zone [15-16]. Moreover, the discounted cost of hybrid systems, which integrates both RES and ESS technologies, has so far been used only marginally. Therefore, it is crucial to also evaluate their techno-economic costs.

To the extent that we are currently aware of, the question of at what point the conclusions obtained from previous reviews can be applied to completely different climatic zones, particularly in Morocco, remains unanswered. Consequently, this study focuses on comparing three distinct climatic regions in Morocco, namely Laayoune (case A), Tanger (case B), and Oued-Zem (case C). It also aims to address the following questions:

1) In these three climatic regions of Morocco, which renewable energy production system can meet the community's demand while also provide economic benefits?

2)In these three regions, which energy storage system offers the highest level of flexibility and cost-effectiveness?

3) Under specific climatic conditions, how is the hybrid storage system deployed to obtain the most cost-effective scenario?

4) What would be the impact of the uncertainties of the climate on the energy plans of the different climate regions in the future?

2. METHODOLOGY

2.1. Materials and Methods

In this study, the software HOMER-PRO (V 3.14) was used for the design and economic performance evaluation of three hybrid system scenarios, namely: Wind/PV/Battery, Wind/PV/FC/HT/EZ, and Wind/PV/Battery/FC/HT/EZ. This software includes numerous energy components. Simulation, optimization, and sensitivity analysis can be performed. Figure 2 illustrates a flowchart of the methodology.

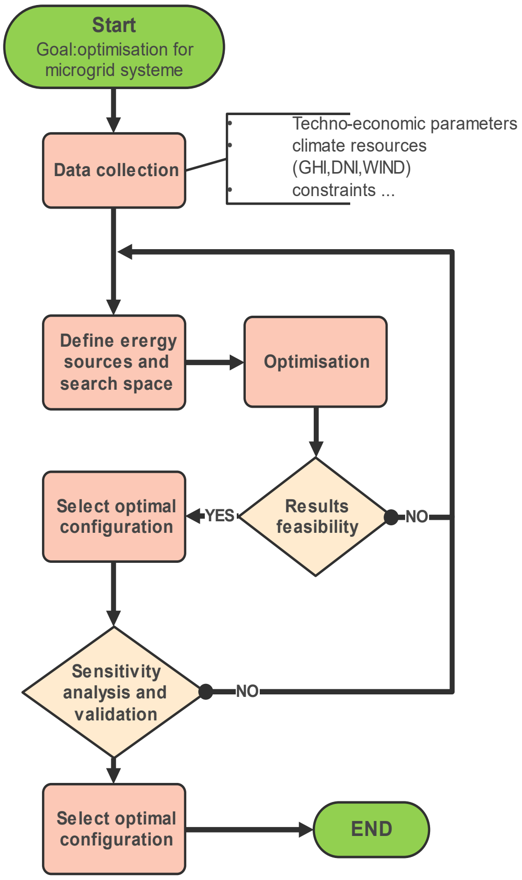


Figure 2. Proposed methodology

From the load profile, energy resources, technical and economic specifications of different components, as well as other constraints, HOMER examines the microgrid in three steps: simulation, optimization, and sensitivity analysis. During the simulation phase, which lasts a few tens of seconds, HOMER-PRO performs energy balance calculations for each time step (1 hour) over a one-year period. Then it eliminates all configurations that are not feasible and not compatible with specific constraints. Subsequently, HOMER-PRO proceeds to the optimization phase where feasible hybrid microgrid systems are ranked according to the net present cost (NPC), starting with the optimum solution. For the optimization of the hybrid system, the NPC and the levelized cost of energy (LCOE) are used as evaluation criteria. For feasible systems, an evaluation is conducted to estimate the installation and operation costs over the project's lifespan is carried out.

2.2. Site Description

In this research work, the design of the hybrid microgrid is proposed for three cities in Morocco, Laayoune (case A), Tanger (case B), and Oued-Zem (case C). These cities are located respectively in the south of the country, at the northwest end of the country on the Strait of Gibraltar, and in the center of Morocco. Consequently, the three cities have their specific climatic characteristics. Oued-Zem has hot and temperate continental characteristics (hot summer and humid winter). Tanger's climate is Mediterranean, tempered by the oceanic influence (mild autumn, winter and spring, dry summer), while the climate of Laayoune is arid-mild (BSn) type, almost mild desert (BWn) due to the low amount of precipitation, as shown in Figure 3.

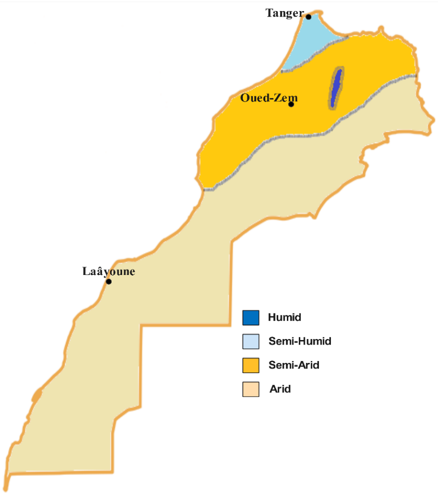


Figure 3. Morocco natural climate zones

Renewable resources have been collected from the NASA energy database and surface meteorology. The three regions, consequently, present a certain degree of divergences and similarities. Laayoune has an average annual wind speed 25% higher than that of Tanger and 42% higher than that of Oued-Zem, as shown in Figure 4b, while there is not a great divergence in terms of solar resources. The monthly solar radiation in Laayoune (kWh/m^2/day) is around 5% higher than in Oued-Zem and 11% higher than in Tanger, as shown in Figure 4a. For the three sites, solar resources show a stronger seasonal variation, while there is a certain regularity in wind resources. There is also complementarity between wind and solar resources in Tanger and Oued-Zem. Figure 4a shows that solar resources peak in summer and reach a minimum in winter, whereas wind resources peak in winter and decrease to a minimum in spring and summer, as shown in Figure 4b.

2.3. Estimated Load Profile

In this study, the AC load profile chosen remains independent of the geographic area. This assumption is made in order to emphasize the influence of climate on the configuration of the storage system. The average annual consumption per capita in Morocco in 2021 was 974.5 kWh, only 32% of the global average (3045.3 kWh) and 93% of the African average (1047.85 kWh). In the context of this research, the load profile is synthesized from the year 2020 using a resolution of 60 minutes, corresponding to the electricity demand of 1000 inhabitants next to each other, so it is assuming to be the load profile of a community. Figure 5a shows the approximation of the daily load profile, which is marked by lower demand at night and higher demand in the evening. Additionally, Figure 5b shows that electricity consumption in winter months is higher than that in summer months. It can also be observed that the seasonal variation in electricity demand in Figure 5b is inversely correlated with solar resources in Figure 4a.

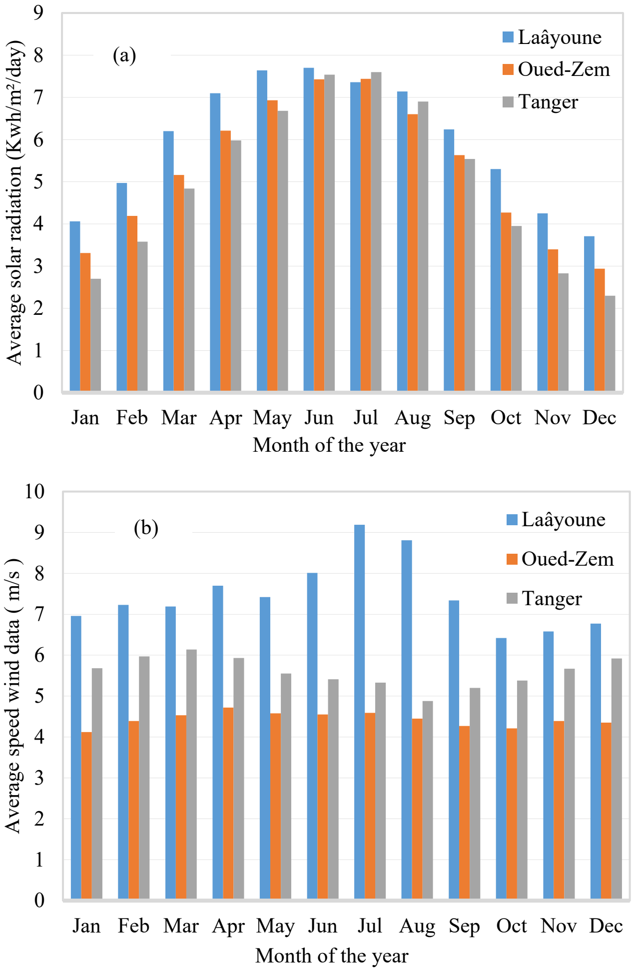


Figure 4. Comparison of solar and wind energy potential in Laayoune, Tanger and Oued-Zem: a) Mean monthly wind speed, b) Monthly average solar radiation

2.4. Modeling

In this article, three energy storage system scenarios have been proposed for the community: Battery, FC/HT/EZ, and hybrid (Battery; FC/HT/EZ). Each scenario is modeled, simulated, and analyzed using the HOMER-PRO software. The proposed hybrid microgrid system model for the three study locations is illustrated in Figure 6. For each scenario, the percentage of wind and solar energy production, as well as the size of the battery, is not defined but is rather computed by the algorithm in a derivative-free manner. However, the capacity of the hydrogen cycle is initially varied in a large search space.

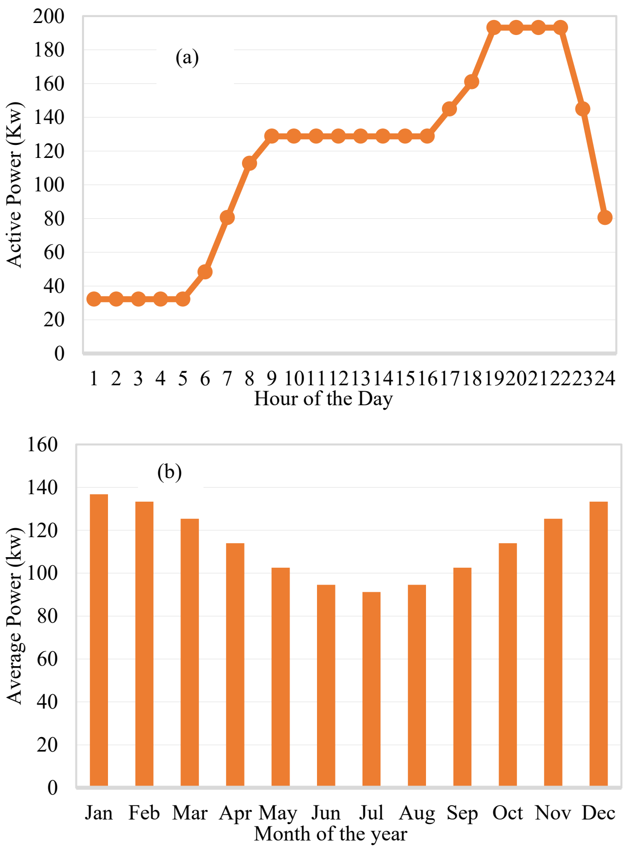


Figure 5. Community load profile: (a) daily AC load profile; (b) Monthly average AC load profile

Table 1 displays the input parameters for all three scenarios. The table shows the techno-economic input data for all components of the system, including investment and operating costs (CAPEX and OPEX), which were imported from the HOMER library and adjusted to the current quasi-real cost based on the basis of a literature analysis [17-18]. To get the optimum configuration possible, a search space has to be created for each component using an allocation strategy and the size of each component. The possible size of each component is defined by : Photovoltaic solar power capacity ($P_{\min} = 0$ and $P_{\max} = 1200$ kw), Wind power capacity ($P_{\min} = 0$ and $P_{\max} = 1200$ kw), Battery capacity ($C_{\min} = 0$ and $C_{\max} = 5000$ kWh), Converter ($P_{\min} = 0$ and $P_{\max} = 800$ kw), Fuel cell output capacity (0, 200, 250, 300, 330, 350 kW) Electrolyzer power capacity (0, 200, 250, 300, 350, 400, 440, 500 kW) and Hydrogen tank capacity (0, 600, 700, 800, 900, 1000, 1050, 1100, 1150, 1200 kg).

Here, two allocation strategies have been modeled in HOMER Pro, namely cycle charging (CC) and load following (LF). Under the CC strategy, the FC will be operated at its full power in order to satisfy the load demand and any excess of energy will be used to operate the EZ to produce hydrogen. Under the LF strategy, the aim is primarily to satisfy the load demand (RE is only used to power the principal load), If the RE system cannot satisfy the load demand, the FC operates at a rate which provides just enough energy to cover that demand. The two control strategies, LF and CC, differ in the way the fuel cells operate.

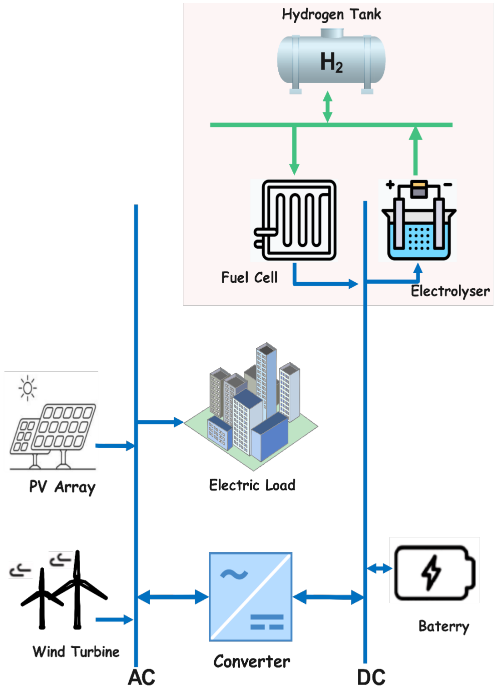


Figure 6. Schematic diagram of the studied electrification system

The feasibility of the proposed system is limited by the conditions set out below:
1) meeting the load demand at over 99.99%.
2) able to handle a 5% rise in annual peak load and a surge of 10% in load at each time step.
3) able to serve the load even if the output of the photovoltaic generator and the wind turbine suddenly drops by around 25% and 50% respectively at each time step.
4) in S1, the battery must have an autonomy of at least 12 hours and, in S2, the fuel cell must cover the peak load of 320 kW and the hydrogen tank must have at least two days of autonomy.
5) The effects of ambient temperature on the photovoltaic and wind fields were included in this study, with a degradation rate of 80% for PV and wind turbines.

Table 1. Overview of the technical-economic input variables used for the components. Legend: capital expenditure (CAPEX), operating expenditure (OPEX), photovoltaic panels (PV), wind turbines (WT), battery banks (BB), Electrolyser (EZ), hydrogen tanks (HT)

Component	CAPEX	Replacement Cost	OPEX	Lifecycle
WT 10 KW, 24m	13 250 $	13 250 $	20 $/year	20 years
PV	1200 $/kW	1200 $/kW	5 $/kW/year	25 years
BB	335 $/kWh	316 $/kWh	9 $/kWh year	15 years
EZ	2254 $/kW	-	72 $/year	15 years
HT	500 $/kg	100 $/kg	5 $/kg/year	25 years
FC	2254 $/kW	150 $/kW	0.01 $/op. hr.	50000 op. hr.
Converter	300 $/kW	300 $/kW	-	15 years

3. RESULTS AND DISCUSSION

The results of the modeling, simulation, and performance of the different scenarios for each community are presented in this section. Figure 7 shows the optimal NPC simulation results of the three scenarios for the three cities. For each scenario, the system is respectively simulated with renewable energy sources (PV; Wind; hybrid PV and Wind). The results show that the NPC of the HRES system (Hybrid PV and Wind) is the lowest in the three climatic zones and for the different scenarios.

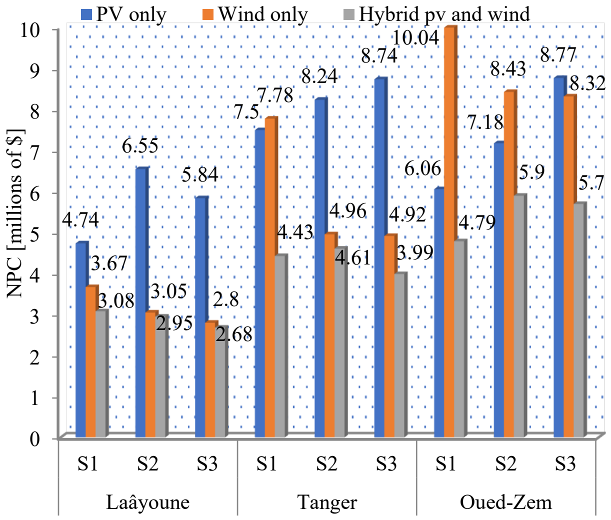


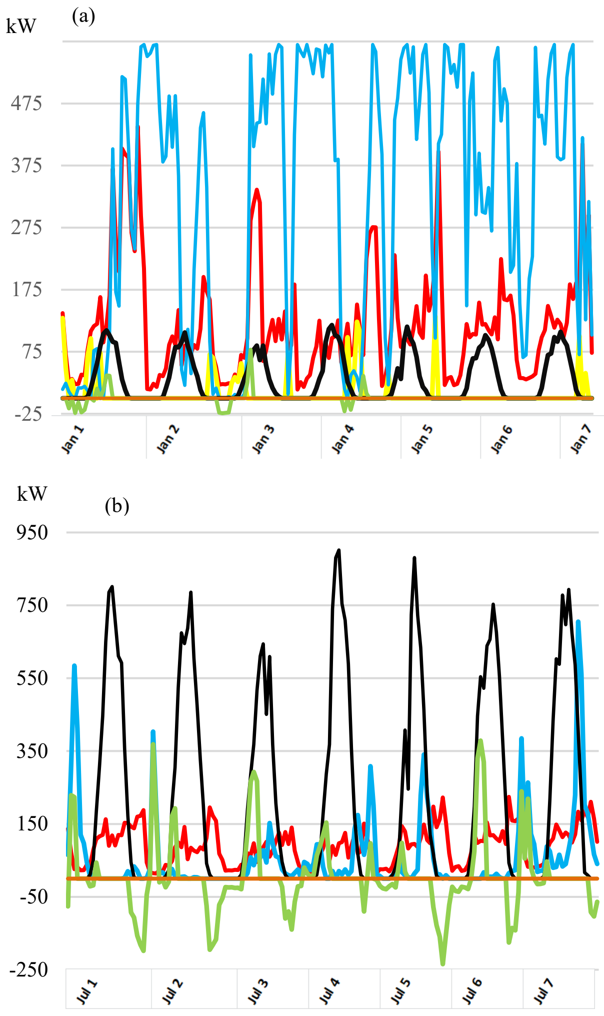
Figure 7. Comparison of NPC, optimal simulation results of the three scenarios for three cities

Furthermore, the NPC is strongly influenced by the availability of individual renewable resources in each city. In fact, the NPC in Laayoune is the lowest due to the richness of climatic resources in this city compared to the other two. Thus, the synergy effect between two different sources of renewable energy production, as mentioned in Section I, is validated. The following results are simulated with the HRES system, which includes both photovoltaic solar panels and wind turbines. The techno-economic comparison of the different scenarios is presented in Table 2; it is noted that the NPC, COE, and installed power of renewable energies in Laayoune are the lowest compared to those of the other two cities. Indeed, this is due to the availability of renewable resources in this city throughout year, which directly influences optimal sizing of installed renewable energy power and consequently the cost.

In S1, about 60% of excess energy is observed in Oued-Zem and Tanger compared to 71% in Laayoune. This excess energy in S1 is the largest compared to S2 and S3, respectively, this is due to the fact that their optimal configuration relies solely on a short-term energy storage system (batteries), while in S3 the excess energy is the smallest compared to the other two scenarios. The effect of the synergy of the two storage systems has, therefore, been validated. The battery park is used to ensure the stability of the system in the short term, while the FC/HT/EZ system manages energy transfer over the long-term, ensuring the reliable operation of the 100% renewable system.

- Case 1 (Laayoune): By storing the energy produced as hydrogen, S2 proves to be more cost-effective and provides greater autonomy compared to S1. The installed power of HRE has also been reduced by about 34%, and the energy surplus is reduced by about 50% as a result of the long-term hydrogen storage capacity. Compared to S2, the S3 scenario with the hybrid energy storage system is the most cost-effective system with better performance in terms of energy surplus, autonomy, and installed power.
- Case 2 (Tanger): In this climatic zone, the wind energy resources are slightly higher than those in the climatic zone around Oued-Zem. A comparison of NPC and COE between S1 and S2 shows that the battery storage system is more profitable than the hydrogen-based one; this is because of the low potential of wind energy resources in this area compared to the Laayoune zone, Whereas the optimal configuration is obtained in S3 with a HESS, which is due to the synergy of the two storage systems.
- Case 3 (Oued-Zem): Due to the low potential of wind energy resources in this climatic zone, the optimal configuration relies on a battery-based storage system only. In fact, the LCOE in S1 is about 18% lower than the other two scenarios.

Figure 8 shows two samples of the optimal energy distribution of the system for each climatic zone; the first sample is taken during a winter week and the second during a summer week. Most of the load is satisfied by the hybrid wind energy source (blue curve) and solar (black curve), wind production is predominant in the first two sites, while photovoltaic production is dominant throughout the year in the third site. Each proposed system meets the energy demand of the load community with almost no capacity shortage (brown curve).



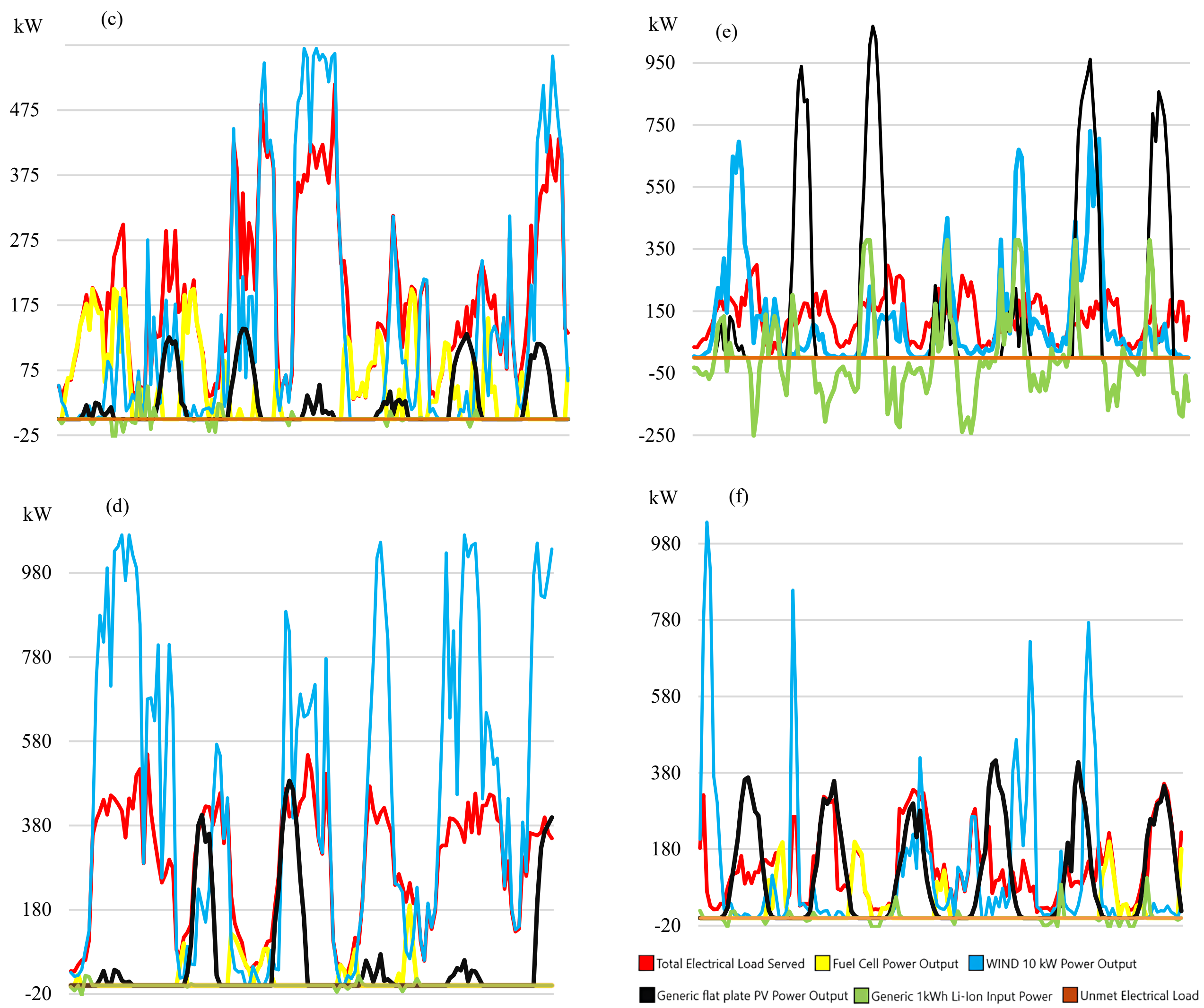


Figure 8. System power distribution: a) Laayoune, January; b) Laayoune, July; c) Oued-Zem, January; d) Oued-Zem, July; e) Tanger, January; f) Tanger, July

Table 2. Optimal simulation results for all scenarios under HRES

		LAAYOUNE			TANGER			OUED ZEM		
		S1	S2	S3	S1	S2	S3	S1	S2	S3
System Component	Fuel Cell [kW]	--	300	200	--	330	200	--	330	330
	Electrolyser [kW]	--	250	250	--	440	250	--	500	440
	Hydrogen Tank [kg]	--	600	600	--	900	1000	--	700	1150
	Battery [kWh]	2680	--	232	4 656	--	440	4 352	--	232
	Wind Turbine [kW]	740	580	570	730	1140	1070	730	1120	1200
	Solar PV [kW]	452	154	141	600	313	486	1069	1195	1044
	Converter [kW]	362	288	319	534	421	365	379	509	426
Autonomy	H2 Tank Autonomy [h]	--	175	175	--	263	292	--	205	336
	Battery Autonomy [h]	18.8	--	1.63	32.7	--	3.09	30.5	--	1.63
RE	Excess Energy [MWh/ year]	2 531	959	913	1 504	1 438	1 628	1 600	1 710	1 598
	Excess Energy [%]	70.9	36.1	35.3	58.7	44.4	44	59.9	46.8	46
Economics	NPC [millions of $]	3.08	2.95	2.68	4.43	4.61	3.99	4.79	5.9	5.7
	COE [$/kWh]	0.239	0.228	0.208	0.344	0.357	0.309	0.371	0.45	0.442
	CAPEX [millions of $]	2.29	2.39	2.23	3.17	3.78	3.42	3.58	4.93	4.92
	OPEX [$/year]	61 276	42 912	35 276	208 714	63 967	50 444	93 496	75 345	60 356

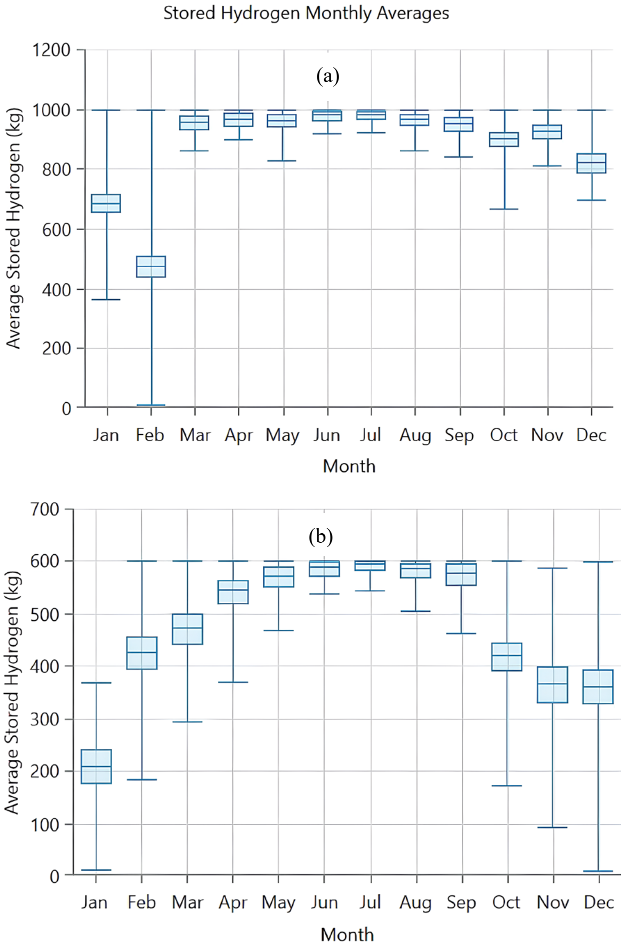


Figure 9. Hydrogen tank level: a) Tanger; b) Laayoune

It is noted that electricity production from fuel cells (yellow curve) mainly occurs during the night and early morning, where there is no solar radiation and a lack of wind resources. It is also noted that excess energy is used to operate the EZ and charge the batteries (green curve). The contribution of the batteries to electricity production only occurs when the electricity demand exceeds that produced by the FC (case 1 and case 2); this occurs at very short intervals.

The excess energy in all three cases is sufficiently high to support future expansion of energy needs. Furthermore, it can be used for electric heating with the advantage of reducing the cost of energy. A comparison between photovoltaic and wind power production at the three sites shows a strong dependence on wind resources in climate zone 1, especially during the summer months, and in climate zone 2 during the winter months. On the other hand, there is a strong dependence on photovoltaic resources in climatic zone 3.

Due to the strong wind and solar resources in zone 1, Figure ٩a, scenario S3 relies partly on the seasonal transfer of surplus renewable resources from summer to winter. The monthly level of the hydrogen reservoir in zone 1 follows similar seasonal cycles as the wind and solar resources Figure٩ b. On the other hand, the level of the hydrogen reservoir in scenario S3 of zone 2 behaves irregularly due to the variability of renewable resources.

4. CONCLUSIONS

In this techno-economic study, a renewable energy-based microgrid system is designed to meet the energy needs of a community of approximately 1000 people located in three different climatic regions of Morocco. The feasibility of the HRES has been thoroughly evaluated in the three regions. For each of the three regions, an analysis based on the design of an optimal storage system is studied through three different scenarios, viz. a storage system based on batteries, a storage system based on hydrogen, and a hybrid storage system. Two financial performance indicators, namely the Cost of Energy (COE) and the Net Present Cost (NPC), have been evaluated for the scenarios. NASA meteorological data has been used. All simulations of the different microgrid architectures have been carried out using HOMER Pro software. The project's lifespan is 25 years.

Of all the scenarios and for different climate zones, the HRES system is the most promising approach for a 100% renewable energy production system. The synergy between the two sources, wind and photovoltaic, not only allows for the COE and NPC, but also enhances the system's resilience. Furthermore, storing the electrical energy produced by the HRES system in the form of hydrogen significantly reduces excess energy and enables the conversion of surplus energy into other forms.

The climatic characteristics of the three cases studied have a significant effect on the design of the optimal system; the southern region of Morocco (Case A) has abundant wind resources throughout the year, and therefore, the installed capacity of the Renewable Energy Sources (HRES) as well as the Hybrid Energy Storage System (HESS) are smaller. However, in the northern region of Morocco (Case B) where, wind resources are insufficient and less available than in Case A, the size of the HRES and the hydrogen storage reservoir are much larger to meet the energy needs of the load throughout the year. In the central region of Morocco (Case C), wind resources are significantly insufficient. Consequently, the optimal size of the system, which relies on battery storage, is considerably larger than that of the other two cases.

The projects of this nature not only demonstrate a commitment to the environment, but also allow Morocco to become more energy independent by turning to renewable energy sources. In addition, the implementation of these systems in isolated sites can bring significant social and economic benefits.

NOMENCLATURES

Acronyms

RE	Renewable Energy
HRES	Hybrid Renewable Energy Sources
HESS	Hybrid Energy Storage System
COE	Cost of Energy
IPCC	Intergovernmental Panel on Climate Change
NPC	Net Present Cost

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