Optimization of Hybrid Power Systems in Moroccan Coastal Cities: Economic and Environmental Benefits

Original Scientific Paper

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Abstract *– Taking into consideration the numerous complex challenges that our planet is facing, particularly climate changes and the rising of energy costs, there is an urgent need to develop electrical architectures that are more resilient, intelligent, and environmentally friendly. Numerous case studies have demonstrated the economic as well as the environmental benefits of implementing such innovative electrical systems. Multiple micro-grid (MG) systems that use renewable energy as a primary resource will be essential to the city of the future. This study explores the viability of a hybrid power generation system that integrates multiple energy sources to meet the electricity needs of a residential area. Using Homer Grid software, we have conducted simulations to assess the economic and environmental benefits of sizing hybrid electrical architectures in Moroccan coastal cities along the Atlantic region. Our analysis identified the best system architecture among the three sites, offering optimal cost-effectiveness, a rapid payback period of 3.2 years, and an impressive internal rate of return of 31%. Furthermore, a sensitivity analysis incorporating a carbon emissions limit has revealed a significant annual reduction of at least 1,300 kg in CO_2 emissions. This research underscores the potential of hybrid energy systems to mitigate climate impact while providing tangible economic benefits, thereby paving the way for sustainable development*

Keywords: *electrical systems, renewable energy, Homer grid, economic and environmental benefits, CO_2 emission*

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1. INTRODUCTION

The urgency of global environmental challenges, combined with rising electricity demand and the growing adoption of electric mobility, calls for the modernization of power systems. Hybrid energy systems and micro-grids (MGs) have emerged as promising solutions by integrating renewable resources with active prosumer participation, thereby enhancing sustainability, efficiency, and resilience [1]. Even with advancements in technology, traditional grids still have recurring problems. These include continued reliance on fossil fuels, a significant contributor to greenhouse gas emissions; growing strain from population expansion and aging infrastructure; and susceptibility to disruptions including voltage sags, oscillations, blackouts, and overloads [2]. Adopting cleaner, more adaptable, and locally relevant energy frameworks is necessary to address these issues.

Extensive research has demonstrated the benefits of hybrid energy systems in both grid-connected and off-grid contexts. For instance, Olomiyesan [3] highlighted their role in supporting economic and educational activities in remote villages, while Mukherjee [4] exam-

ined their techno-economic feasibility in developing economies. In Morocco, several studies have evaluated hybrid photovoltaic (PV)–wind systems under local climatic conditions, including their application to public facilities [5], optimal design and carbon footprint reduction for residential areas in Oualidia [6], and autonomous systems for standalone houses in Marrakech [7].

More recent reviews have reinforced the importance of hybrid systems in future energy transitions. A comprehensive study by [8] analyzed hybrid energy systems across diverse applications—from micro-grids to healthcare and maritime systems—highlighting optimization strategies to improve sustainability and resilience. Similarly, [9] examined hybrid renewable energy systems for rural electrification in developing countries, emphasizing the role of spatially explicit modeling tools in supporting deployment strategies.

Building on this body of work, the present study focuses on Moroccan coastal cities along the Atlantic Coast, investigating how hybrid energy systems can strengthen energy security, reduce carbon emissions, and accelerate the transition toward a sustainable energy future.

2. HYBRID ENERGY SYSTEM AND MICRO GRIDS

2.1. ENERGY TRANSITION AND EVOLUTION

The evolution of the energy transition, described in Fig. 1, has been greatly influenced by technological advancements, economic dynamics, and environmental concerns. The current trend today is the integration of advanced digital technologies, and the use of decentralized, and intelligent systems based on local renewable energies [10].

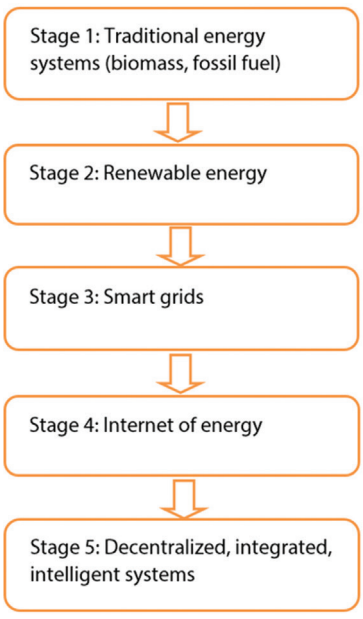


Fig. 1. Stages of the Energy Transition

The energy revolution, as it relates to sustainable smart cities and the IoE, is driving the advancement of infrastructure and technology, accelerating the transition to efficient and sustainable energy systems [11]. The transformation of energy systems unfolds in five stages, starting with conventional fossil-fuel-based power generation, which is marked by inefficiencies and high emissions. The second stage introduces renewable energy sources like wind and solar, though their integration is hindered by intermittency, necessitating policy support. In the third stage, smart grids emerge, improving energy efficiency through advanced technologies but requiring substantial investment. The fourth stage, the IoE leverages the Internet of Thing (IoT) technologies for real-time energy management, yet faces challenges such as data security and system interoperability. Ultimately, the fifth stage brings the development of fully integrated sustainable smart cities, where IoE, renewable energy, and smart grids work together to optimize energy consumption and minimize environmental impact, demanding continuous innovation and equitable access to technology.

2.2. ENERGY ACCESS IN AFRICA THROUGH MINI-GRIDS

The electrical sector in the African continent knows various issues in terms of electricity access and weak use of hybrid system that enhance economic and eco-friendly architecture. Around 600 million people in sub-Saharan Africa lack access to electricity according to Africa Energy Outlook 2022 report [12], with only 25% of those in rural areas having electricity available to them. However, the declining costs of PV panels have made solar off-grid systems increasingly affordable for these underserved areas, making them a competitive alternative to extending the main electricity grid [13-15].

Various international programs, such as the Green Mini-Grid Program, Sustainable Energy for All, and Power Africa, aim to achieve the UN's seventh Sustainable Development Goal (SDG). The International Energy Agency (IEA) predicts that off-grid MGs will be the most viable solution to electrify over 200 million people in Africa by 2030 [16]. Mini-grids play a crucial role in improving energy access across Africa. According to the Africa Mini-grid Developers Association (AMDA) [17], the World Bank [18], and the Africa Energy Portal [12], mini-grids could sustainably power around 380 million people by 2030, on the condition that decisive actions are taken now. The IEA's Africa Energy Outlook 2022 report emphasizes their importance in meeting sustainable development goals [12].

The African mini-grid market has seen significant growth, with the number of private sector mini-grids rising by 39% from 288 in 2019 to 400 in 2021, largely driven by donor funding and private investments. Regional dynamics have also shaped mini-grid development. East Africa, having started earlier, has seen more progress, demonstrating the impact of supportive political and financial environments.

Despite this progress, challenges still persist, because reliable data, political support, and consistent

investment are essential to fully unlocking mini-grids' potential in Africa. Overcoming regulatory, financial, and technical barriers is key to achieving sustainable, inclusive energy access. Continued investment, supportive policies, and community engagement are vital for realizing mini-grids' full potential.

This awareness has spurred governments in both industrialized and emerging economies to promote cleaner energy production methods. Renewable technologies, including wind, solar, and modern biomass, offer practical solutions, making electricity indispensable for socio-economic development, especially in developed countries.

2.3. ARCHITECTURE OF MICROGRID SYSTEMS

The concept of smart MG has already emerged. The smart MG is a new organization form of smart distribution network. The simplified model of the energy distribution architecture is illustrated in Fig. 2, which presents a typical smart MG model.

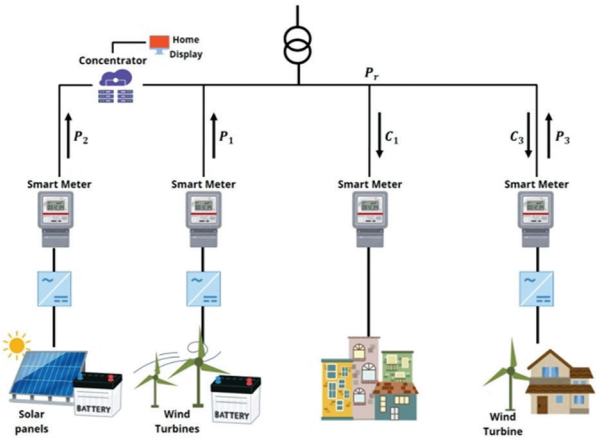


Fig. 2. Electrical energy allocation architecture in a smart MG including renewable energy producers

The architecture includes:

- Supply: storage and distributed generation (renewable and non-renewable sources).
- Demand: energy consumption devices including residential households.
- IT Management platform: An intelligent system that optimizes supply and demand based on management objectives and influencing factors.

This trend toward smart MGs refers to the adoption of information and communication technology (ICT) and the emergence of supervisory control and data acquisition SCADA-EMS systems since the early 1990s [19]. Today, the concept of smart cities is gaining momentum to address the rapid urbanization of the global population. Smart cities aim at meeting the economic and environmental needs of urban areas while ultimately enhancing the quality of life for their citizens.

Smart MGs contribute too to the implementation of demand management by providing accurate information on the energy flow, which will monitor and optimize energy consumption [20].

The use of smart meters, which are called the first brick of smart MGs, enables detailed monitoring of energy flows, allowing prosumers to track both consumption and generation patterns throughout the day.

2.4. BENEFITS OF HYBRID ENERGY SYSTEMS

A hybrid energy framework that combines multiple energy sources and storage technologies offers numerous advantages, including enhanced sustainability, reliability, and efficiency in energy production and consumption [21]. One key benefit is improved reliability and stability. By diversifying energy sources, hybrid systems mitigate the intermittency of renewable energy, ensuring a continuous power supply even when one source faces fluctuations or disruptions.

Another advantage is the increased energy availability. Integrating complementary sources like solar and wind boosts overall energy supply by leveraging their different production patterns [22]. Energy storage systems (ESS) act as reliable reservoirs, ensuring steady power during periods of low production, providing a consistent energy output despite natural variations in renewable energy generation [23].

Energy optimization is also achieved, as storage systems accumulate excess energy during peak production times and release it during low-production periods, promoting efficient energy use. This enables flexible load management and distribution, aligning energy supply with demand. Hybrid frameworks also improve energy efficiency by combining various sources to optimize conversion efficiencies, reducing energy losses during transmission and distribution, and contributing to a more efficient infrastructure [24].

Additionally, hybrid systems bolster grid resilience. They provide ancillary services such as frequency regulation and voltage control, enhancing grid stability. In case of grid disruptions, systems with energy storage can operate independently, ensuring continuous energy delivery and supporting infrastructure resilience.

At the economic level, hybrid systems offer cost savings by reducing dependence on expensive, polluting energy sources. They promote long-term savings and foster energy security by utilizing locally available renewable resources, thus reducing reliance on centralized power generation and creating a more self-sufficient energy model [25, 26]. At the environmental level, hybrid systems contribute to sustainability by integrating renewable energy sources, significantly lowering GHG emissions and supporting the transition to a low-carbon economy [27-29].

Overall, the integration of multiple energy sources and storage systems in hybrid frameworks provides a comprehensive approach to energy production, fostering a more sustainable, reliable, and efficient energy landscape for the future.

3. MODELING PLATFORM

3.1. METHODOLOGY

This work develops an energy architecture based on collected and requested data (power sensing and energy on demand) and the optimal allocation of this energy. Furthermore, we evaluate the environmental impact in terms of CO_2 emissions. To optimize the management of electrical energy in an electric grid, various decision-making methods can be employed. Solving the objective function with constraints involves three essential stages: (i) identification of variables, (ii) formulation of constraints, and (iii) definition of the objective function. One of the most powerful tools for optimizing energy systems is HOMER. It is commonly used to balance cost-effectiveness, environmental impact, and technical feasibility. Businesses, utilities, and researchers seeking to optimize grid-connected MGs and distributed energy resources rely on HOMER for its comprehensive analysis and decision-making support. HOMER Grid utilizes a combination of linear and heuristic optimization methods to determine the optimal configuration of MG systems [30-32]. More recent studies [33, 34] have also employed HOMER to address similar energy system design challenges, demonstrating its continued relevance and effectiveness in solving the proposed problem. These methods ensure cost-effectiveness, reliability, and efficiency in integrating renewable energy sources with traditional power generation. The two primary optimization approaches used in HOMER Grid are on the one hand Linear Optimization, and the other hand Heuristic (Derivative-Free) Optimization.

3.2. OVERVIEW OF OPTIMIZATION METHODS USED IN HOMER GRID

Some examples used in Homer grid are given in the Table 1 below.

Table 1. Optimization Methods Used in HOMER Grid: Types and Applications

Method	Type	Example Use in HOMER Grid
Linear Programming (LP)	Linear	Economic dispatch (each time step's selection of the least expensive power source)
Mixed-Integer Linear Programming (MILP)	Linear/ Discrete	Optimal scheduling of battery/ generator/grid
Genetic Algorithm (GA)	Heuristic (DFO)	Finding best combination of renewable energy & storage
Particle Swarm Optimization (PSO)	Heuristic (DFO)	Optimizing MG system sizing and cost
Simulated Annealing (SA)	Heuristic (DFO)	Avoiding local minima while optimizing a system
Grid search	Heuristic (DFO)	Looking through various system sizes (e.g., PV, battery)

HOMER Grid effectively integrates linear programming for short-term dispatch optimization and heuristic, derivative-free methods for long-term system design optimization. Linear methods such as LP and MILP ensure economic operation, while heuristic approaches like Grid Search, GA, PSO, and SA enable the identification of optimal system configurations in complex, nonlinear energy systems. These methodologies help HOMER Grid efficiently design and manage MGs, balancing cost, reliability, and sustainability.

3.3. LINEAR OPTIMIZATION IN HOMER GRID

Linear optimization is employed in HOMER Grid for dispatch optimization, ensuring that generators, batteries, and grid interactions operate at the lowest possible cost while meeting energy demand. This approach involves solving linear programming (LP) problems, which are particularly effective for short-term decision-making.

Mathematical Model:

The objective function for cost minimization in dispatch optimization is given by

$$min\, C = \sum (C_{fuel,t} G_t + C_{grid,t} P_{grid,t} + C_{battery,t} P_{battery,t}) \quad (1)$$

Where:

- G_t= generator output at time t
- $P_{grid,\,t}$ = power bought from the grid at time t
  $P_{battery,\,t}$ = battery charge/discharge power at time t.
- $C_{fuel,\,t}$, $C_{grid,\,t}$, $C_{battery,\,t}$ represent their respective cost coefficients.

In brief, linear programming ensures that the energy supply meets demand while minimizing operational costs.

3.4. HEURISTIC TECHNIQUES

3.4.1. Derivative-Free Optimization Algorithm

In complicated energy systems where the objective function is non-differentiable or computationally costly, HOMER Grid uses Derivative-Free Optimization (DFO) approaches, which are essential. These techniques are ideal for issues involving nonlinear constraints and discrete choice variables because they explore the search space without the need for gradient computations.

DFO's ability to strike a compromise between computational economy and solution quality makes it popular in engineering and energy system optimization.

Objective Function:

The general objective function for system design optimization in HOMER Grid is:

$$minf(B, P, W, G)=Total\ Net\ Present\ Cost@\ (NPC) \quad (2)$$

Where:

- B = battery size
- P = solar panel size
- W = wind turbine size

- G = generator size

The goal is to minimize the lifecycle cost while satisfying energy demand and operational constraints.

3.4.2. Grid Search Algorithm

The Grid Search Algorithm is an exhaustive optimization method that methodically tests a set of predefined parameter values to find the optimal configuration. It finds widespread application in:

- Machine learning
- Optimization of energy systems
- Solving engineering design challenges

Unlike gradient-based approaches, Grid Search exhaustively examines the entire solution space by testing all possible combinations of parameters. The process of Grid Search involves:

- Defining a range of candidate values for each parameter.
- Evaluating the objective function f(x) for every combination of parameters.
- Choosing the optimal combination based on the desired optimization criterion (either minimization or maximization).

Mathematical Formulation:

$X1, X2,..., Xn$ are the parameters to optimize.

$S1, S2,..., Sn$ are the discrete sets of candidate values for each parameter.

$f(x)$ is the objective function to minimize or maximize.

The optimization problem is formulated as:

$$x^*=arg\ min\ f(x) \quad x \in S \tag{3}$$

$$\text{Or} \quad x^*=arg\ max\ f(x) \quad x \in S \tag{4}$$

Where: $S=S1.\ S2.\cdots.Sn$, meaning that the function $f(x)$ is evaluated for all possible combinations within the search space.

In HOMER Grid, Grid Search is used to optimize: Battery capacity (B), Solar panel size (P), wind turbine (W), Generator size (G)

The optimization problem can be expressed as:

$$min\ f(B, P, W, G) \quad (B, P, W, G) \in S$$

Where f (B, P, W, G) is the total cost or energy efficiency metric.

3.5. HOMER PROCESS

HOMER Grid is used to model and optimize hybrid energy systems for the selected cities. The software considers factors such as energy demand, resource availability, and economic viability. The process entails locating the site and gathering the information required for the suggested system, where the inputs are profile load, components of the system, price, environmental parameter, and weather information. Fig. 3 illustrates the procedure adopted.

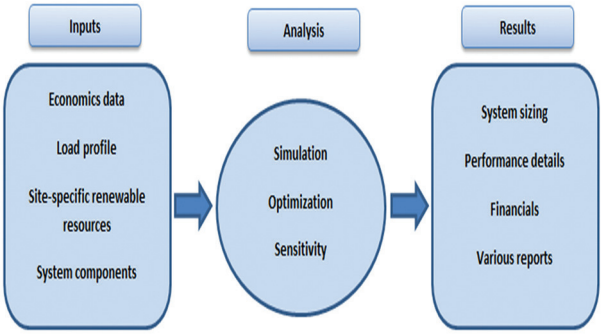


Fig. 3. Homer's design process

3.6. HOMER OPTIMIZER

HOMER Grid employs a proprietary optimization algorithm known as the HOMER Optimizer™. This algorithm is designed to efficiently identify the least-cost configurations for MGs and distributed energy systems. It is a "derivative-free" optimization method, meaning it does not rely on gradient information, which makes it well-suited for complex, non-linear problems often encountered in energy system modeling

Objective function:

To calculate the optimized produced power using the Homer software, the following objective function is defined as:

$$F_{obj}=min\ (total\ NPC) \tag{5}$$

Where NPC represents the total net present cost of the project.

A system's total net present cost ($TNPC$) is calculated by subtracting the present value of all of its revenue over its lifetime from the present value of all of its expenses [35]. The formula for it is:

$$TNPC=CT_{ann}/CRF \tag{6}$$

The total annualized cost (CT_{ann}) is the sum of the annualized costs of all system components. And CRF refers to the capital recovery factor.

The Capital Recovery Factor (CRF) is a formula used to convert a total investment cost into equal annual payments over the life of a project, considering a fixed interest rate.

The average cost of one kWh of electricity produced by the system is known as cost of energy (COE) [36]. COE is calculated by dividing the total served electric load (E_{served}) by the yearly cost of energy generation.

$$COE=CT_{ann}/E_{served} \tag{7}$$

In HOMER Grid, the financial metrics below are commonly used to evaluate the economic feasibility of energy systems.

- Levelized cost of energy (LCOE):

$$LCOE=Total\ Annualized\ Cost/\ Total\ Electric\ Load\ Served\ per\ year\ (kWh) \tag{8}$$

Total Annualized Cost includes capital, replacement, O&M, fuel, and grid interactions (purchases/sales)

- Internal Rate of Return

$$0=\sum_0^T Ct/(1+IRR)^t \quad (9)$$

Ct : Net cash flow in year t (savings-costs)
T: Project lifetime in years
IRR is the discount rate that makes the Net Present Value (NPV) = 0

- Net Present Cost

$$NPC= annualized\ cost\ (1-(1+r)^T)/r \quad (10)$$

r : Real discount rate (interest rate-inflation)

T: Lifetime (years)

NPC is the total present value of all costs over the system's lifetime.

4. CASE STUDIES AND RESULTS

4.1. THE STUDIED SITES

Morocco has achieved significant milestones in electricity access, reaching 100% coverage in 2021. However, the country's energy needs are expected to achieve more than triple by 2030, according to the Ministry of Energy Transition. In response to this growing demand, renewable energy technologies have gained increased attention due to their positive environmental impact and ability to meet rising energy requirements. With growing environmental concerns, hybrid power systems remain in high demand. Based on the results of [5], we will perform simulation tests using Homer software for three coastal cities in Morocco to calculate the avoided amount of CO2 and improve affordable energy architecture. The three cities selected are Tangier, known for its strong and consistent winds due to its coastal location near the Strait of Gibraltar; Dakhla, recognized for its abundant renewable energy potential due to its coastal desert climate; and Safi, a city with growing renewable energy potential, particularly in wind and solar power. In all of these cities, several renewable energy projects have been implemented, particularly wind power plant projects. Table 2 below presents the coordinates of the selected sites.

Table 2. Sites information

Data\site	DAKHLA	SAFI	TANGIER
Latitude	23 degrees 41.8 minutes N	35 degrees 43 minutes N	32 degrees 39.8 minutes N
Longitude	15 degrees 57.7 minutes W	9 degrees 3 minutes W	5 degrees 58.1 minutes W

4.2. GENERAL ARCHITECTURE

Our architecture consists of using different renewable energy sources in addition to the state grid. The rated energy to meet of the hybrid system is: 11.26 kWh/d. The value of the non-critical load is: 6.40kWh/d. Fig. 4 represents the system architecture developed in Homer grid.

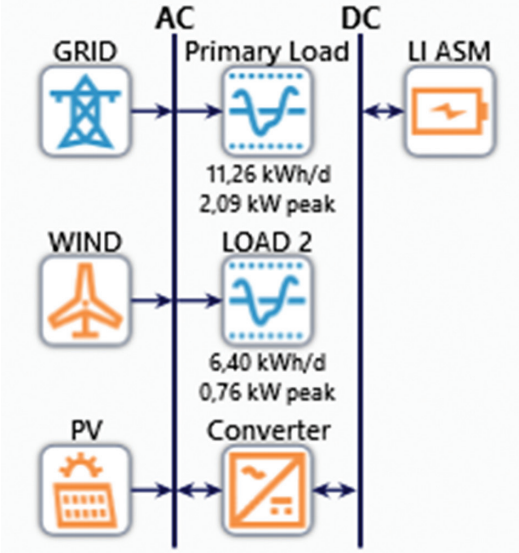


Fig. 4. System architecture

Basic assumptions of the Homer software

Photovoltaic (PV) : Solar power is among the most economical renewable energy sources (RES). For this hybrid system, a 1 kW PV panel was selected. It costs $3220.00, a 25-year lifespan, and annual maintenance expenses of $100.00

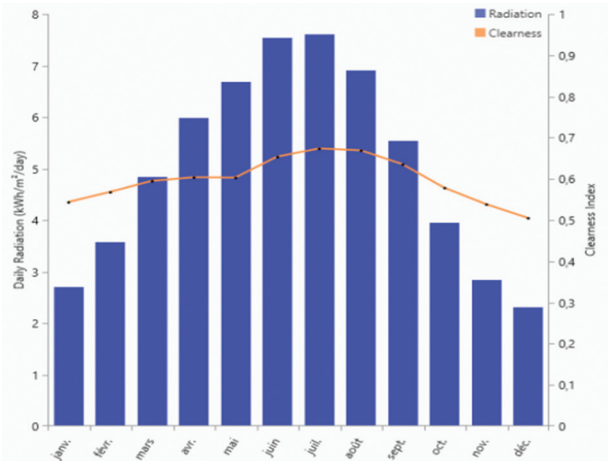
Wind Turbine: Wind turbines (WT) transform wind's kinetic energy into mechanical energy, then into electricity. Because of their relatively high cost, choosing the right model is critical. Several turbine types were tested during system design, and a Generic 1 kW WT was chosen. It costs $1400.00 initially and to replace, has a 20-year lifespan, and requires $70.00 in annual maintenance. The turbine's hub height is set at 17 meters.

Battery Storage: The battery storage system stores excess electricity as chemical energy and converts it back to electricity when needed. This ensures a stable energy supply when renewable sources fluctuate. Due to their high cost, selecting the right number and type of batteries is important. After evaluating options, a generic 1-kWh lithium-ion battery was chosen. Each battery costs $700.00, with a matching replacement cost and a lifespan of 15 years.

System Converter: The inverter (Inv) manages power conversion between AC and DC. AC power is needed for most uses, while DC is used to charge the batteries. Both types of current are essential for the hybrid renewable energy system (HRES) to function efficiently. The inverter selected costs $300.00, with the same replacement cost, no yearly maintenance, a lifespan of 15 years, and operates at 95% efficiency.

4.3. SOLAR IRRADIATION PROFILES

The irradiation data were obtained from NASA's Prediction of Worldwide Energy Resource database. The Figs. 5 and 6 below show the average monthly sunlight profile for the three sites covered in this study.



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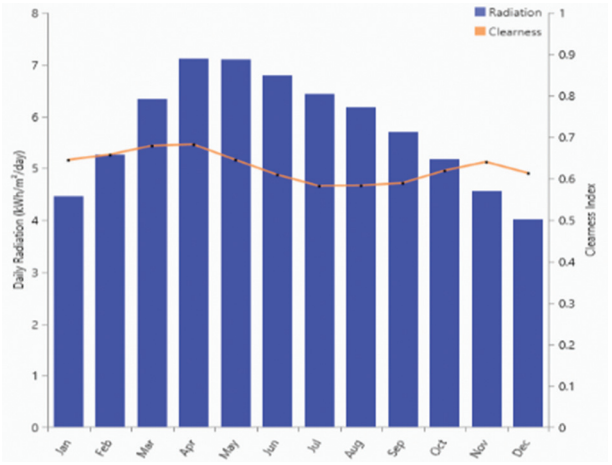

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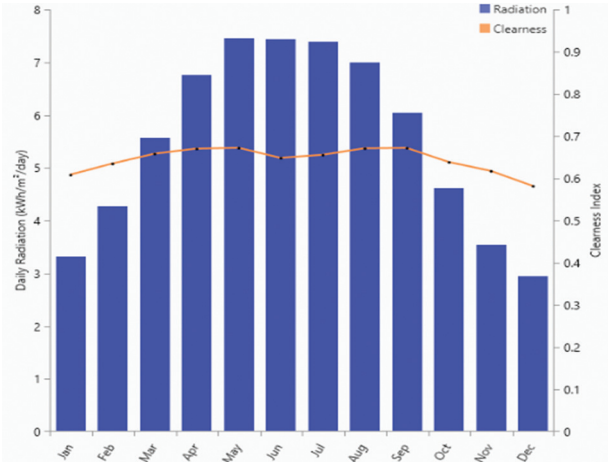


(c)

Fig. 5. Monthly radiation and clearness index during the year: (a) Tangier city, (b) Dakhla city, (c) Safi city

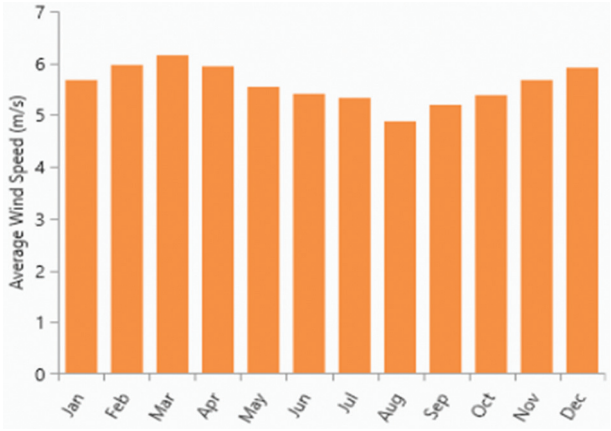
The annual average of the selected site in Tangier city is: 5.04 kWh/m^2/day

The annual average of the selected site in Dakhla city is: 5.76 kWh/m^2/day

The annual average of the selected site in Safi city is: 5.53 kWh/m^2/day

4.4. WIND PROFILES

The Figures below show the average monthly wind speed profile for the three sites. The data were obtained from NASA's Prediction of Worldwide Energy Resource database.



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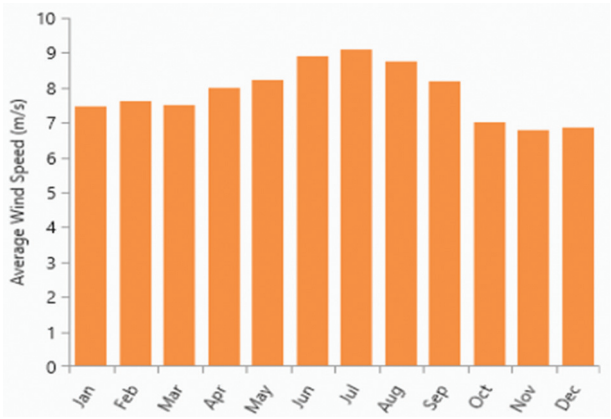

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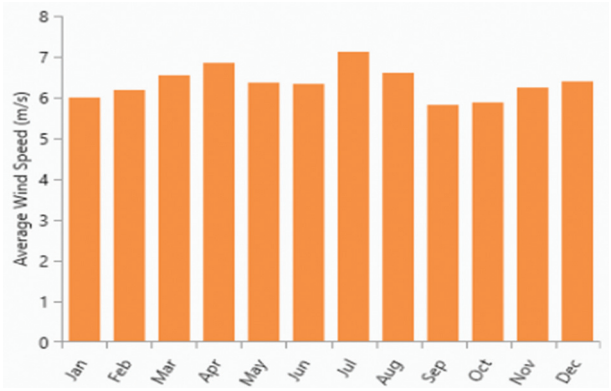

(c)

Fig. 6. Wind speed profile in the located sites: (a) Wind speed profile in Tangier region, (b) Wind speed profile in Dakhla region, (c) Wind speed profile in Safi region

The bar chart displayed above shows that the monthly average wind speed exceeds 7 m/s in Dakhla City, while in Safi City and Tangier City, the monthly average wind speed is 6.37 m/s and 5.59 m/s, respectively.

4.5. TECHNICAL & ECONOMIC METRICS

Tables 3, 4, and 5 below summarize the simulation results from Homer software, comparing key economic indicators across the selected locations in the studied cities. Each possible solution is analyzed to determine the most cost-effective energy option. The economic indicators used are: LCOE, IRR, NPC and simple payback.

Table 3. Economic results for different architectures of Dakhla city

Indicator \ config	Wind Storage: LI ASM + GRID	Solar + Wind + Storage: LI ASM + GRID	Wind + GRID	Solar + Wind + GRID	Solar + Storage: LI ASM + GRID
LCOE (€/kWh):	0.146	0.146	0.142	0.141	0.401
IRR %	30.59	30.48	41.72	39.56	16.19
Net Present Cost (€)	22,962	22,970	24,161	24,211	34,335
Simple payback time (yrs)	3.2	3.2	2.4	2.5	5.8

Table 4. Economic results for different architectures of Safi city

Indicator \ config	Wind Storage: LI ASM + GRID	Solar + Wind + Storage: LI ASM + GRID	Wind + GRID	Solar + Wind + GRID	Solar + Storage: LI ASM + GRID
LCOE (€/kWh):	0.179	0.207	0.210	0.198	0.403
IRR %	21.77	21.58	32.50	26.38	16.21
Net Present Cost (€)	27,957	27,728	29,095	28,796	34,431
Simple payback time (yrs)	4.4	4.5	3.1	3.8	5.8

Table 5. Economic results for different architectures of Tangier city

Indicator \ config	Wind Storage: LI ASM + GRID	Solar + Wind + Storage: LI ASM + GRID	Wind + GRID	Solar + Wind + GRID	Solar + Storage: LI ASM + GRID
LCOE (€/kWh):	0.246	0.264	0.231	0.251	0.410
IRR %	17.71	16.77	21.10	20.46	17.70
Net Present Cost (€)	31,805	31,258	32,729	32,120	35,505
Simple payback time (yrs)	5.3	5.6	4.6	4.8	5.5

Based on these results, it is clear that the best economic architecture is:

- Wind + Storage + GRID with 22,962€ of NPC for Dakhla city.
- Solar + Wind + Storage + GRID with 27,728 € and of 31,258€ of NPC for Safi and Tangier cities, respectively.
- The payback period is 3.2 years for Dakhla city, 4.5 years for Safi city and 5.6 years for Tangier city.

The table 6 below gave the installation size.

Table 6. Installation size for each component for the winning architecture

Installation size\ area	PV kW	Wind kW	Battery 1kWh Li-Ion
Tangier	0.875	3	4
Safi	0.535	3	4
Dakhla	0	3	4

The optimal architecture identified for Dakhla city, compared to the other sites, relies solely on wind turbines without the need for photovoltaic panels. This is attributed to the city's consistently high wind speeds.

4.6 ENVIRONMENTAL IMPACT

Since the Rio Earth Summit in 1992, the world has become increasingly aware of the risks posed by climate disruption due to the growing consumption of fossil fuels such as oil, gas, and coal [37]. Indeed, renewable energy sources are a cornerstone in the global fight against climate change, offering sustainable alternatives to fossil fuels and significantly reducing GHG emissions.

Carbon dioxide (CO2) is a gas that is released naturally into the environment from the exchange of CO2 between sea and land, humans and animals breathing, and organisms that cause the decomposition of plants and animals.

Net-zero will bring wide social benefits including benefits to human health with improved air quality and to the natural environment, of which human beings should be custodians, not destroyers.

The reference [38] provided the quantity of CO2 emission for each energy source.

The Fig. 7 below show the total CO2 emission per year for each configuration.

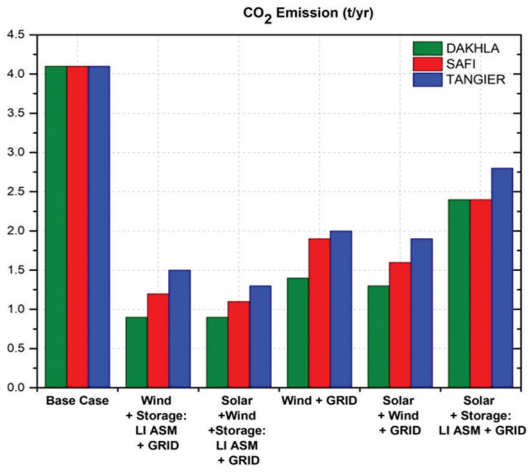

Fig. 7. CO_2 gas emissions for the different architectures

The highest CO2 emission was observed with the Solar + Storage + GRID configuration in Tangier, amounting to 2.8 t/year.

4.7. DISCUSSION

Economic indicator: The analysis reveals that the most cost-effective configuration is the Wind + Storage + Grid system in Dakhla, with a Net Present Cost (NPC) of €22,962. In comparison, the optimal architecture for Safi and Tangier are Solar + Wind + Storage + Grid systems, with NPCs of €27,728 and €31,258, respectively. The financial payback periods are 3.2 years for Dakhla, 4.5 years for Safi, and 5.6 years for Tangier, highlighting Dakhla's superior economic performance

Baseline Emissions (Base Case): The Base Case represents the current CO2 emissions in each city without any renewable energy integration. Across all three cities, the baseline emission rate is 4.1 tons per year.

Integrating wind energy: particularly when combined with storage solutions (Wind + Storage: LI ASM + GRID), shows significant reductions in CO2 emissions across all cities. The most substantial reduction is observed in Dakhla and Safi, with emissions falling to 0.9 tons per year (for Dakhla) when wind energy is combined with storage.

Influence of Solar Energy Integration: The integration of solar energy alongside wind and storage solutions (Solar + Wind + Storage: LI ASM + GRID) also contributes to lowering CO2 emissions in all cities. Tangier shows the highest emission with this configuration, achieving 1.3 tons per year.

Effect of Grid Integration: Integrating renewable energy sources with the grid (Wind + GRID, Solar + Wind + GRID) generally reduces emissions compared to the Base Case but not as significantly as when combined with storage solutions. Safi demonstrates notable emission reductions with grid-integrated configurations.

Combined Impact of Solar and Wind Integration: Combining solar and wind energy with or without grid integration leads to further reductions in CO2 emissions compared to individual renewable sources. Tangier and Dakhla exhibit considerable emission reductions with combined solar and wind setups.

Storage Solutions and Their Role: The inclusion of storage solutions alongside renewable energy sources plays a crucial role in stabilizing energy supply and further reducing emissions. Cities like Dakhla and Safi experience significant emission reductions when storage is integrated with renewable energy sources.

5. CONCLUSION

The aim of this study was to perform economic and environmental analysis and promote the use of optimized and sized hybrid energy systems in different locations. This research delved into the simulation of hybrid energy systems utilizing Homer grid software across three Atlantic cities. The results showed that the optimal architecture for Dakhla city is Wind + Storage: LI ASM + GRID. As for Safi and Tangier, the optimal architecture is Solar + Wind + Storage (LI ASM) + Grid. Our analysis revealed that the most cost-effective architecture system was that in Dakhla city. It boasted a payback period of 3.2 years and an internal rate of return (IRR) of 31%. Additionally, a carbon limit constraint was incorporated as a sensitivity analysis, resulting in a reduction of at least 1,300 kg of CO2 emissions per year.

The analysis done for the Atlantic areas in Morocco gave insights about suitable renewables energies to use and calculations of environmental impact that each system architecture will have. This study contributes by offering data information about reliability and decarbonisation aspects in hybrid system based on renewable energies in Moroccan cities. Tangier generally showed higher emissions across various configurations compared to Dakhla and Safi, indicating potential areas for targeted emissions reduction efforts. Safi demonstrated relatively lower emissions in configurations involving wind or solar integration.

This underscores the importance of transitioning towards renewable energy sources and integrating storage solutions to achieve significant reductions in CO2 emissions. Policymakers could utilize this information to develop tailored strategies for each city, considering their unique characteristics and potential for renewable energy adoption. Continued investment in renewable energy infrastructure, storage technologies, and grid modernization is crucial for sustainable emission reduction efforts.

In conclusion, the findings emphasize the transformative potential of integrating renewable energy systems, particularly when paired with storage solutions, to reduce CO2 emissions. To fully realize this potential and achieve long-term sustainability goals, tailored strategies and sustained investments are essential. This study primarily aimed to demonstrate the feasibility of diverse hybrid energy architectures by evaluating their environmental impacts through a comprehensive techno-economic analysis using HOMER software. Known that fossil fuels remain the leading contributors to pollution, addressing energy and environmental challenges is a critical priority for policymakers and analysts. Implementing carbon taxes represents a promising approach to incentivize greater investment in renewable energy projects and accelerate the transition to cleaner energy systems.

As future work, we suggest exploring the improvement of these architectures by encouraging electricity trading, both selling and purchasing, in Moroccan cities, and integrating carbon pricing policies to account for environmental impact.

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NOMENCLATURE

AMDA: Africa Minigrid Developers Association
MG: Micro-grid
CO2: Carbon dioxide
SCADA: supervisory control and data acquisition
GHG: Greenhouse Gas
Homer: Hybrid Optimization of Multiple Energy Resources
IEA: International Energy Agency
IoE: Internet of Energy
IoT: Internet of Things
IRR: Internal rate of return
CRF: Capital recovery factor
CTann: total annualized cost
LCOE: levelized cost of energy
NASA: National Aeronautics and Space Administration
NREL: national renewable energy laboratory
NPC: net present cost
PV: photovoltaic
SDG: Sustainable Development Goal
ESS: energy storage systems
LP: Linear programming
PSO: Particle swarm optimization
GA: Genetic algorithm
DFO: Derivative-Free Optimization
TNPC: total net present cost

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DATA AVAILABILITY STATEMENT

Data is based on open literature resources such as reports and articles, and Homer simulation program.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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