Renewable energy impact integration in Moroccan grid-load flow analysis

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ABSTRACT

This paper analyzes the behavior of a Moroccan electric transportation system in the presence of an integration of renewable energy sources, which represents a significant challenge due to their intermittent nature. The aim is to evaluate the performance of the transportation system in various situations and possible configurations. The current study enables the calculation of power flow in the network using the Newton-Raphson method under the MATLAB/Simulink software. To achieve this, a series of power flow simulations were conducted on a 5-bus Moroccan electrical network, examining four distinct scenarios. In addition, this article offers an evaluation of the power flow performance of the same electric transportation system with varying percentages of renewable energy penetration. In order to provide a complete critical analysis, many simulations were conducted to obtain the voltage and active power profile generated at different bus locations, as well as an evaluation of the losses in the studied network.

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1. INTRODUCTION

Climate change is a highly concerning problem that humanity is now grappling with [1]. Undoubtedly, the notable increase in worldwide temperature, as shown by the HadCRUT4 global temperature data, necessitates an immediate shift towards sustainable energy sources. Consequently, there is a need for updated climate models that can incorporate the effects of climate change into energy strategies [2]. The main cause of global warming is greenhouse gas emissions, but deforestation accounts for over 24% [3], to the extent that East Africa, for example, has integrated climate change into its school programs [4], a strategy that could help promote climate-resilient sustainable development. Research emphasizes the detrimental consequences of air pollution caused by fossil fuels and underscores the critical significance of transitioning to renewable energy sources to alleviate these effects. It predicts a substantial decrease in air pollution emissions and the expenses related to air pollution by 2050, while also providing advantages for public health and the global economy [5], [6]. İnal *et al.* [7] has demonstrated a very close relationship between renewable energies, CO_2 emissions and economic growth in African oil-producing countries, making the energy transition to renewable sources paramount in order to mitigate global warming and stimulate economic growth. On the other hand, recent literature [8] has clearly presented the impact of globalization, technological innovation and economic growth on air quality in 60 of the world's most open countries between 1960 and 2020, making renewable energy policies crucial to ensuring a healthy and sustainable global environment.

The transition to renewable energies, dominated by wind and solar power, requires electricity storage to manage the existential variability of production, which calls for in-depth research and appropriate energy policies [9]. In addition, the intergovernmental panel on climate change (IPCC) report highlights the challenges that Morocco faces in its choice to integrate renewable technologies, underlining the need for a coherent approach and increased awareness to meet these major and promising challenges [10]. For this reason, since 2008, Morocco has embarked on a strategy of regional energy integration to meet the challenges of energy dependency and climate imperatives, with an emphasis on the development of renewable energies. This transition aims to transform the energy sector in depth and exploit interconnections with neighboring countries to achieve energy independence, despite the obstacles encountered, particularly in regions such as Dakhla Oued-Eddahab, which play a strategic role in this transformation [11], [12].

Integrating intermittent renewable energy sources into power grids presents significant technical challenges, necessitating extensive research to guarantee the reliability and stability of the system, especially when dealing with intermittency rates of up to 100% [13]. The geographical distribution of renewable energy facilities helps to alleviate the issue of intermittent power generation by minimizing the influence of climatic conditions on their generation. Additionally, the utilization of diverse technologies helps to lower the expenses associated with integrating these renewable energy sources [14]. The variation of renewable energy sources, such as wind or solar, poses obstacles to their optimal integration into the power grid. Variations in wind speed and solar irradiance create reliability and stability issues, leading to overvoltages and imbalances in the distribution network [15], [16]. The main goal of a power system operator is to ensure the dependable balance between power generation and demand, while minimizing costs and losses. Nonetheless, the inescapable influence of the irregularity of wind and solar power on the electrical system relies on the scale and inherent adaptability of the grid, as well as the extent to which intermittent renewable energy sources are included into the grid [17]. Ugwuanyi *et al*. [18] suggested that using flexible alternating current transmission system (FACTS) devices can increase renewable energy penetration in Nigeria by 40%, allowing for the integration of an additional 152 MW of wind energy without compromising system stability. The paper [19] examines hybrid wind and photovoltaic (PV) integration in urban areas, focusing on consistent DC bus-bar voltage and battery connections. A MATLAB model is developed to simulate grid performance, highlighting the efficacy of hybrid wind and PV in meeting sustainable energy goals, contributing to policymaking and research. In paper [20] renewable energy sources like solar and wind are increasingly being used to meet global energy demands while reducing greenhouse gas emissions. However, their unpredictable nature poses challenges for grid operators. The combined use of these sources could improve grid operability and safety.

This study focuses on the Moroccan 5-bus power grid, analyzing its behavior and performance under varying scenarios of solar and wind energy integration. Using the Newton-Raphson method in the MATLAB/Simulink environment, the research examines voltage levels and active power flows across different nodes in the network. Four distinct scenarios of renewable energy penetration are explored, highlighting the grid's response to variability in renewable energy generation. The analysis provides valuable insights into the impact of renewable integration on voltage stability, active power distribution, and power losses, identifying technical challenges and areas for optimization. Based on these findings, the study offers recommendations to enhance grid stability, manage voltage fluctuations, and minimize power losses, supporting efficient integration of renewable energy sources.

The paper is structured as follows: in section 2 outlines the theoretical foundations of load flow analysis, detailing its objectives, the classification of nodes within the power grid, and the resolution methods, specifically the application of the Newton-Raphson method for power flow calculations. In section 3, we present the design of the Moroccan 5-bus network model, including data parameters for buses and lines, and describe various scenarios for renewable energy integration into the grid. Section 4 provides the results of the load flow analysis for four different scenarios, analyzing voltage profiles, active power generation, and power losses, followed by a comparative discussion to identify the optimal case. Also, we examine how variations in solar energy penetration impact the network's voltage profile, power generation, and losses. Finally, section 5 summarizes the findings, emphasizes the implications for future renewable energy integration, and provides recommendations for improving grid stability and efficiency in Morocco's power system.

Load flow analysis is an innovative technique used to predict and manage the decrease in voltage resulting from the integration of renewable energies into the power grid [21]. The study also determines power losses, bus voltages, generator active power, and load active power during a complete day in a test system by employing load flow analysis [22]. The utilization of load flow analysis methodology provides a comprehensive assessment of voltage imbalance, enabling operators to identify key nodes and scenarios in the power grid [23]. A novel iterative approach is suggested for computing power flow in radial distribution networks, considering a broad spectrum of resistance and reactance, as well as the attributes of solar (SO) producers. The effectiveness of this method is validated by simulations using MATLAB [24]. The Newton-Raphson approach is used for obtaining load flow solutions in electrical systems, with analyses executed in MATLAB to enhance the efficiency of the process [25], [26]. An approach for simulation and data compression is used to decrease the amount of time and memory needed for load flow calculations in electrical systems [27].

A comparative analysis is conducted to evaluate the performance of several flexible AC transmission system (FACTS) devices. This analysis is done using a Newton-Raphson load flow method and conventional IEEE 5-bus and 30-bus systems [28]. The integration of wind power into the Nigerian grid is studied, examining the impacts on active power flow via load buses and the progressive replacement of conventional generators by wind turbines [29]. Gianto and Purwoharjono [30] proposed a method to incorporate wind turbine generating systems (WTGS) in three-phase load flow analysis of unbalanced electric power systems, based on a modified single-phase two-port network model, validated using 12-node and 19-node distribution systems. The work in [31] analyzes load flow for a 5-Bus system and the IEEE 14-bus distribution network using the Newton Raphson method and ETAP short circuit analysis software. It evaluates faults and load profiles, providing valuable insights for future load flow analysis in distribution network systems. Gianto [32] proposed a new steady state model for load flow analysis of DFIG-based wind power plants (WPPs), derived from DFIG power formulas, allowing easy representation in sub-synchronous and super-synchronous conditions and considering constant power factor. Hiwarkar *et al.* [33] presented a load flow analysis of an IEEE14 BUS system using the Newton-Raphson method, using MATLAB for electrical performance and power flows under steady state conditions. This research [34] focuses on uncertainty modeling techniques in probabilistic load flow analysis for distributed energy resources. The authors recommend this review for engineers, scientists, and researchers in this field. Bin *et al*. [35] proposed an adaptive bandwidth kernel density estimation with Latin hypercube sampling for accurate probabilistic load flow (PLF) analysis of power injections from sustainable energy sources like solar and wind, reducing errors and computational burden, and offering a potential solution for sustainable energy solutions. Small-scale generators are essential to the electrical market as power systems shift from traditional to competitive architecture, according to Zabihi and Parhamfar [36]. Table 1 provides a comprehensive enumeration of each reference cited in the study. It distinctly emphasizes the particular contributions of each reference to the research. The table also delineates the methodology utilized in these contributions, offering a thorough summary of their significance to the study.

Table 1. Contributions and methodologies in power system analysis

Reference	Contribution	Methodology
[21]	Predicts and manages voltage decreases caused by renewable energy integration.	Load flow analysis
[22]	Assesses power losses, bus voltages, generator active power, and load active power over daily cycles in test systems.	General load flow analysis
[23]	Provides a comprehensive assessment of voltage imbalance, identifying key nodes in the power grid.	Load flow analysis
[24]	Proposes a novel iterative approach for radial distribution networks considering resistance, reactance, and solar producer attributes.	MATLAB simulations
[25], [26]	Uses Newton-Raphson method for efficient load flow solutions, improving computational performance.	MATLAB
[27]	Employs data compression techniques to reduce computation time and memory in load flow calculations.	Simulation and data compression
[28]	Conducts performance evaluation of FACTS devices on IEEE 5-Bus and 30-Bus systems using Newton-Raphson load flow methods.	Newton-Raphson method
[29]	Examines the effects of wind turbine integration on active power flow in the Nigerian grid, highlighting generator replacement.	Load bus analysis
[30]	Proposes integration of wind turbine generating systems (WTGS) in unbalanced three-phase load flow models using a modified single-phase two-port network model.	Two-port network model
[31]	Analyzes IEEE 5-Bus and 14-Bus systems for faults and load profiles using Newton-Raphson and ETAP short-circuit analysis.	ETAP software and Newton-Raphson method
[32]	Develops a new steady-state model for DFIG-based Wind Power Plants (WPPs) considering sub-/super-synchronous conditions and constant power factors.	Steady-state modeling
[33]	Performs load flow analysis on IEEE 14-Bus systems to evaluate steady-state electrical performance and power flows using MATLAB.	Newton-Raphson method
[34]	Reviews uncertainty modeling techniques in probabilistic load flow (PLF), including stochastic and probabilistic methods.	Probabilistic load flow analysis
[35]	Introduces adaptive bandwidth kernel density estimation with Latin hypercube sampling for accurate PLF analysis of solar and wind power injections.	Probabilistic load flow with kernel density
[36]	Demonstrates the benefits of transformer-less inverters in photovoltaic (PV) systems, reducing costs and improving efficiency for grid connections.	Analysis of PV grid integration

2. METHODOLOGY
2.1. Theoretical study
2.1.1. The objectives of load flow analysis

Load flow analysis is a terminology that represents a set of numerical analyses and procedures performed on a computer to determine the power distribution in a given system in order to control this power distribution. The determination of reactive and active power in the transmission line is based on predefined considerations related to the receiver or generator. This includes calculating the potential differences at each node or set of buses and ensuring that no line is overloaded. Continuous monitoring is also required, especially in the event of reclosing. Additionally, the specific power flow is determined to achieve optimal dispatch by calculating the network's state (P, Q, V, and φ) under specified production and consumption assumptions. Every set of bars (node) is associated with 4 defined parameters: the active power injected or extracted (P), the reactive power injected or extracted (Q), the voltage module (V), voltage phase shift (φ).

Load flow is therefore the resolution of a system of non-linear equations, which eliminates the possibility of an analytical solution in most cases. Numerical solutions are computer-aided. Load Flow analysis of a distribution network containing a hundred busbars and transmission lines appears to be a complex process. For a highly simplified network, Figure 1 shows a simpler network with two busbars. The transmission line will be considered lossless; the linear resistance is negligible and the admittance: $\underline{Z} = jlw$.

Figure 1. A simpler network with two buses

2.1.2. Determination of generator and receptor active and reactive power

Phase shift φ between $\underline{V_1}$and $\underline{V_2}$ such that:

$$\varphi = \angle V_2 - \angle V_1 \tag{1}$$

The complex power at the generator and receiver will be:

$$\begin{cases} \underline{S_1} = \underline{P_1} + j\underline{Q_1} = \underline{V_1}\underline{I^*} \\ \underline{S_2} = \underline{P_2} + j\underline{Q_2} = \underline{V_2}\underline{I^*} \end{cases} \tag{2}$$

$\underline{V_2}$ is taken as the phase origin.

The current in the line:

$$\underline{I} = \frac{\underline{V_1} - \underline{V_2}}{\underline{Z}} \tag{3}$$

$\underline{S_1}$ is the complex apparent power at bus 1

$$\underline{S_1} = \underline{V_1}\underline{I^*} = \underline{V_1}\left[\frac{(\underline{V_1^*} - \underline{V_2^*})}{\underline{Z^*}}\right] = \frac{(V_1^2 - V_1 V_2 e^{j\varphi})}{(-jX)} \tag{4}$$

Then:

$$P_1 = \left(\frac{V_1 V_2}{X}\right) \sin\varphi \quad (W) \tag{5}$$

$$Q_1 = \left(\frac{V_1^2 - V_1 V_2 \cos\varphi}{X}\right) \quad (Var) \tag{6}$$

For bus 2:

$$\underline{S_2} = \underline{V_2}\underline{I^*} = \underline{V_2}\left[\frac{\underline{V_1^*} - \underline{V_2^*}}{\underline{Z^*}}\right] = \frac{(V_1 V_2 e^{j\varphi} - V_2^2)}{(-jX)} \tag{7}$$

So:

$$P_2 = \left(\frac{V_1 V_2}{X}\right) \sin\varphi \quad (W) \tag{8}$$

$$Q_2 = \left(\frac{V_1 V_2 \cos\varphi - V_2^2}{X}\right) \quad (Var) \tag{9}$$

Assuming this line has one resistance R per phase, the Joule Effect losses are:

$$P_{ligne} = R|I|^2 \quad (W) \tag{10}$$

$$\underline{S} = P + jQ = \underline{VI^*} \tag{11}$$

Then:

$$\underline{II^*} = |I|^2 = \frac{(P^2+Q^2)}{|V|^2} \tag{12}$$

So

$$P_{ligne} = R\left(\frac{P^2+Q^2}{|V|^2}\right) \quad (W) \tag{13}$$

In real systems, an explicit analytical expression will be unfeasible due to fluctuating busbar loads on the one hand, and the inability to predetermine the voltage at the receiver on the other. In this case, numerical methods must be used to determine the unknowns, generally through iterative procedures.

The current entering node K is given by:

$$P_{ligne} = R\left(\frac{P^2+Q^2}{|V|^2}\right) \quad (W) \tag{14}$$

With Y_{Kn}, transfer admittance associated with nodes 'K' and 'n', V_n,voltage at node 'n' and N, total number of nodes. Which can be rewritten as (15):

$$I_K = Y_{KK}V_k + \sum_{\substack{n=1 \\ n\neq k}}^{N} Y_{Kn}V_n \tag{15}$$

V_K, We obtain:

$$V_K = \frac{I_K}{Y_{KK}} = \frac{1}{Y_{KK}}\sum_{\substack{n=1 \\ n\neq k}}^{N} Y_{Kn}V_n \tag{16}$$

$$S_K = V_K I_K^* \qquad So: \qquad S_K^* = V_K^* I_K \tag{17}$$

$$S_K^* = V_K^* I_K = P_K - jQ_K \tag{18}$$

Hence:

$$I_K = \frac{P_K - jQ_K}{V_K^*} \tag{19}$$

$$V_K = \frac{1}{Y_{Kn}}\left(\frac{P_K - jQ_K}{V_K^*} - \sum_{\substack{n=1 \\ n\neq k}}^{N} Y_{Kn}V_n\right)$$
$$for\ K = 1,2,\ldots,N \tag{20}$$

The set of N in (20) constitutes the load flow equations.

2.1.3. Classification of nodes

Nodes can be classified into three categories: Consumer node (load bus): it is a set of bars for which P and Q are known, while V and φ are to be determined. Producer node (generator bus): this is a set of bars for which the amplitude of the generated voltage V and the corresponding power P are known, while Q and φ are to be determined. Balance node (Swing bus): it is a generator bar for which V and φ are specified, P and Q are to be determined. This is usually the most powerful generator node. It is taken as a reference. Given the large number of voltage levels on a meshed network, Load Flow problems will be solved using reduced quantities: $V\angle\varphi = 1\angle 0°$ per unit.

2.1.4. Resolution methods

Numerous methods have been used (Gauss, Gauss Seidel, Newton-Raphson, Relaxation, and Residuals) of which the best known are the following [37], [38]: Gauss-Seidel and Newton-Raphson. The most commonly used methods today are variants of the Newton-Raphson (NR) method, to apply it to a Load Flow problem, for node K:

$$\begin{cases} V_K = |V_K| \angle \varphi_K \\ V_n = |V_n| \angle \varphi_n \\ Y_{Kn} = |Y_{Kn}| \angle \theta_{Kn} \end{cases} \quad (21)$$

The utilization of the Newton-Raphson approach presents numerous notable benefits when applied to the analysis of electrical systems. It is notable for its capacity to reach a solution with a reduced number of iterations, leading to a more efficient computing time. In addition, its improved precision makes it a strong choice, less affected by factors like the selection of the Slack bus or tweaks to transformer management. An especially remarkable feature of this method is that the number of iterations needed remains nearly constant, regardless of the complexity of the system being analyzed. This highlights its reliability and applicability in diverse and complex situations. From (21):

$$P_K - jQ_K = \sum_{n=1}^{N} | V_K V_n Y_{Kn} | \angle(\theta_{Kn} + \varphi_n - \varphi_K) \quad (22)$$

This leads us to deduce:

$$P_K = \sum_{n=1}^{N} | V_K V_n Y_{Kn} | \cos(\theta_{Kn} + \varphi_n - \varphi_K) \quad (23)$$

$$Q_K = \sum_{n=1}^{N} | V_K V_n Y_{Kn} | \sin(\theta_{Kn} + \varphi_n - \varphi_K) \quad (24)$$

2.2. Simulation models

The single-line simplified diagram of Morocco's 225 kV, 5-bus power system is shown in Figure 2, and comprises two stations, a solar plant in Tinghir II (from the Noor Ouarzazate station) and a wind park (WP) in Midelt (Parc Eolien Midelt), and 4 loads. Each line has a series impedance RL. Modeling parameters are presented in Tables 2 and 3.

In this study, we established several scenarios to simulate the production and integration of solar and wind energy into the electrical grid. Each scenario models energy output based on variations in solar irradiation and wind speed that directly impact electricity generation from renewable sources. By adjusting these parameters, we can simulate how renewable energy systems respond to different environmental conditions. For solar energy, scenarios consider fluctuations in solar irradiation due to factors like time of day, weather conditions, and seasonal changes. This allows us to assess the variability in solar power generation and its effects on grid stability. For wind energy, we simulate different wind speed profiles, accounting for changes caused by weather patterns and geographical influences. These profiles help us understand the reliability of wind power under various conditions. By integrating these simulations, we can evaluate the performance of the grid when subjected to the intermittent nature of renewable energy sources. The scenarios help identify potential challenges, such as periods of low generation during calm or cloudy days, and allow us to explore solutions like energy storage or demand response strategies. The data presented in Table 3 is sourced from the National Office of Electricity and Drinking Water (ONEE).

Figure 3 illustrates the block diagram of a section of the Moroccan national electrical network, modeled in MATLAB/Simulink. This section comprises five key buses: the national network, Tinghir II, Errachidia, PE Midelt, and Mibladen. The global diagram of the entire Moroccan network was also developed in MATLAB/Simulink to provide a comprehensive representation of its structure and components.

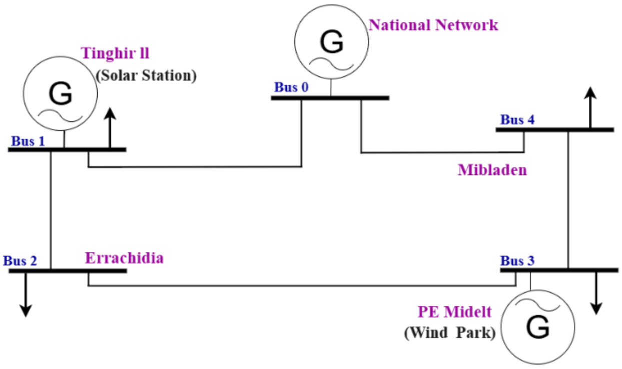

Figure 2. Simplified diagram of Morocco's 5-bus network

Table 2. Line DATA of 5-bus Moroccan power system

Line from	Line To	Line Impedance R(Ω)	X(Ω)
0	1	R=7.2433	X=40.8730
1	2	R=9.6896	X=54.6770
2	3	R=7.2433	X=40.8730
3	4	R=0.7930	X=4.4749
4	0	R=7.2433	X=40.8730

Table 3. Bus DATA of 5-bus Moroccan power system

Bus N°	Name	Bus code	Voltage (p.u)	Generation MW	Generation Mvar	Load MW	Load Mvar
0	National Network	Swing	1.05+0j	0	0	0	0
1	Tinghir II	PV	1+0j	140	226.17	20	32.3
2	Errachidia	PQ	1+0j	0	0	68	110
3	PE Midelt	PV	1+0j	180	290.8	1	1.61
4	Mibladen	PQ	1+0j	0	0	30	48.46

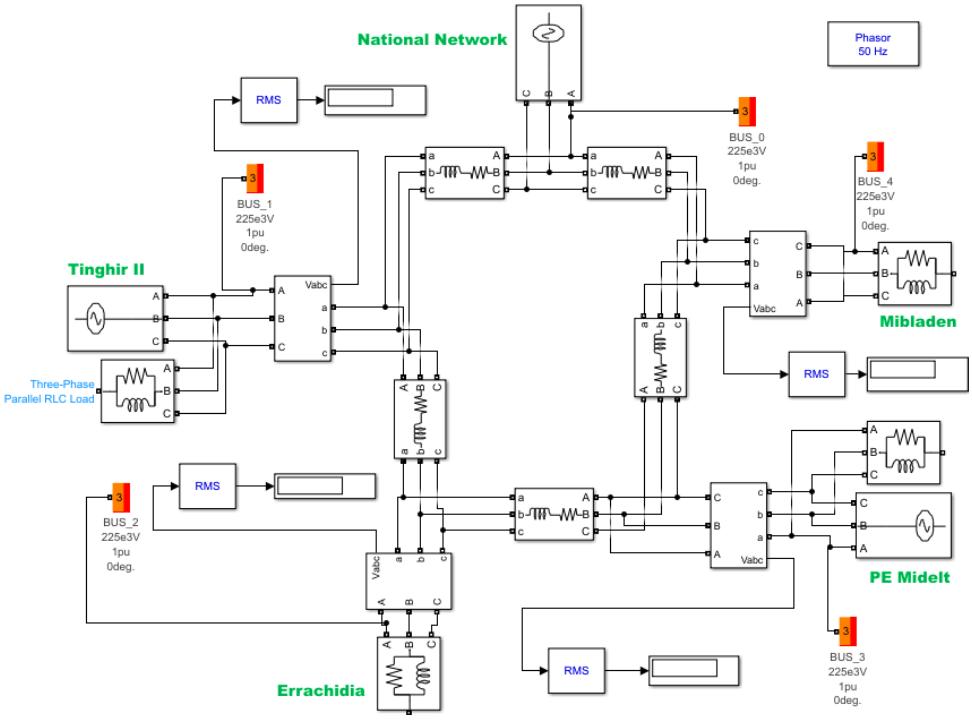

Figure 3. Simplified modeling of the 5-bus Moroccan network in MATLAB/Simulink

3. SIMULATION RESULTS AND INTERPRETATIONS

3.1. Results of load flow analysis for 4 scenarios

In this study, a Moroccan 5-bus power grid including different energy sources, such as the national grid, solar and wind power, is used to supply a consumer area. Most of the electricity will be supplied by the national grid, during the course of the day, solar energy production increases progressively, while wind energy begins to operate when the region is windy, thus reducing dependence on the national grid. Four cases will be treated:

- Case R1 (WP=0 & SO=0): At any time of day, the national network is activated if neither solar nor wind energy is available to supply the power grid.
- Case R2 (WP=0 & SO=1): When the sun is shining brightly, electricity is supplied solely by solar power, without recourse to the national grid.
- Case R3 (WP=1 & SO=0): In the presence of favorable winds, wind power operates autonomously to supply the electrical grid, independently of the national grid.
- Case R4 (WP=1 & SO=1): When the sun is shining and the wind is blowing at the same time, both solar and wind energy contribute to the power supply without having to rely on the national grid.

3.2. Case R1 (WP=0 & SO=0)

In this hypothesis, both the wind park and the solar park do not contribute to power generation, and only the national grid is responsible for producing electricity. Figure 4 illustrates the proportional voltages (per unit) at different buses in the network, indicating a little rise in voltage at bus 0, which serves as the primary power supply. Buses 1, 3, and 4 exhibit a little decline in voltage, which may be tolerable for regular network operation. However, the voltage on bus 2 is much below its designated value, resulting in imminent stability and quality issues that demand immediate attention.

Figure 5 represents the active power generated at different buses in the analyzed network. It demonstrates the assumptions made in this case study, where only the national grid (Bus 0) serves as the only power source. It is crucial to take into account the particular context of the power system, since an excessive concentration of active generation on a single bus could provide difficulties in terms of network balancing and stability. Power losses are calculated using the following equation:

$$PowerLosses = (\sum P_{PV} + P_{SWING}) - (\sum P_{PQ})$$

In this case, power losses are equal to 6.2949 MW.

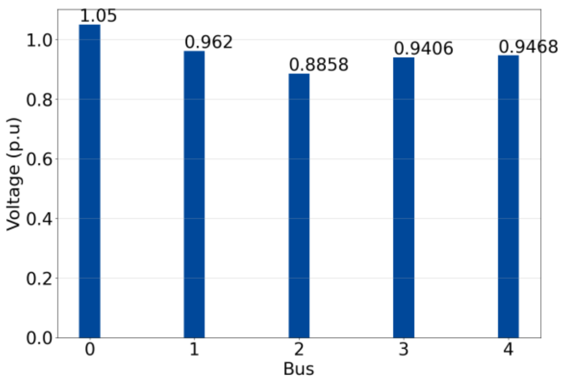

Figure 4. Voltage profile of the 5-bus Moroccan network system with PE=0 & SO=0 on the buses

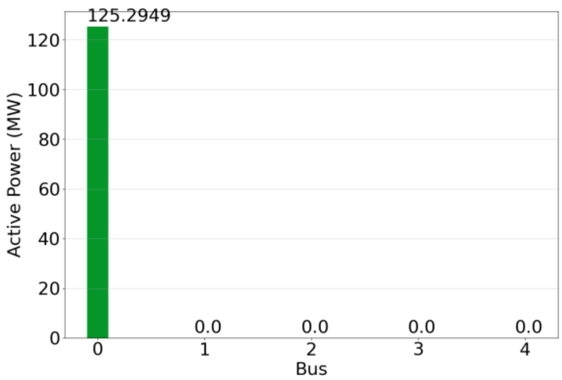

Figure 5. Active power generated of the 5-bus Moroccan network system with PE=0 & SO=0 on the buses

3.3. Case R2 (WP=0 & SO=1)

In this hypothesis, the solar park is productive, while the wind park is out of service. Figure 6 illustrates the relative voltage values, expressed in per unit (p.u.), at various buses within the electrical network. At Bus 0, the voltage is 1.05 p.u., slightly above the nominal value, indicating a minor voltage excess that may be acceptable depending on network specifications. Basically, this situation results in fluctuations in voltage levels at various locations within the network. It seems that buses 1, 2, 3 and 4 are experiencing voltage deviations that need to be analyzed and potentially adjusted in order to ensure the stability of the power system. Bus 0 seems to be slightly higher than usual, but it is still within an acceptable range.

Figure 7 depicting the distribution of active power in the electrical network showcases the relationship between active power and buses. Simply put, active power is primarily generated by bus 1, while bus 0 consumes active power. It seems that buses 2, 3, and 4 are not currently playing a role in power generation. This distribution of active power suggests a specific arrangement of the electrical network, with active sources and loads unique to each bus. Understanding the unique circumstances surrounding each bus is crucial. Considering the specific context of the system is crucial when evaluating network balance and stability. In this case, power losses are equal to 4.5126 MW.

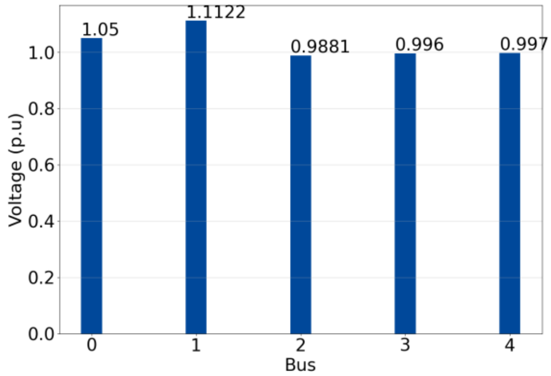

Figure 6. Voltage profile of the 5-bus Moroccan network system with PE=0 & SO=1 on the buses

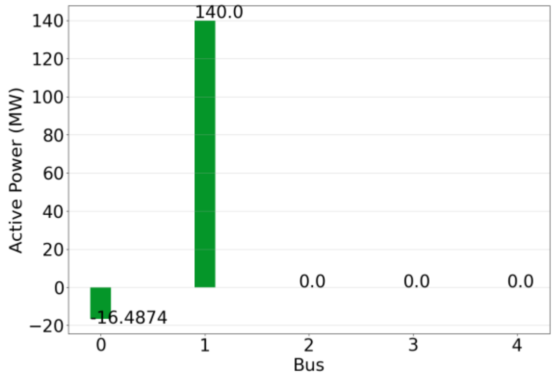

Figure 7. Active power generated of the 5-bus Moroccan network system with PE=0 & SO=1 on the buses

3.4. Case R3 (WP=1 & SO=0)

In this case, the wind park is productive, while the solar park is out of service, Figure 8 shows voltage profile of the 5-bus Moroccan network system on the buses. Buses 0, 1 and 2 exhibit a voltage that is slightly above the standard voltage level, necessitating specific monitoring. Bus 3 and 4 are displaying elevated voltages, suggesting the possibility of requiring regulation to ensure stability.

The active power for each bus shown in Figure 9 illustrates the distribution of power in the electrical network. To summarize, active power is primarily generated by bus 3, while bus 0 consumes active power. It seems that the other buses are not actively participating in power generation. This distribution of active power suggests a particular arrangement of the electrical network, with active sources and loads unique to each bus. Considering the specific context of the system is crucial when evaluating network balance and stability. In this case, power losses are equal to 4.9213 MW.

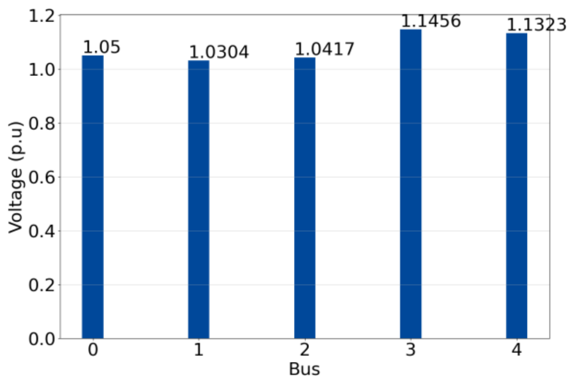

Figure 8. Voltage profile of the 5-bus Moroccan network system with PE=1 & SO=0 on the buses

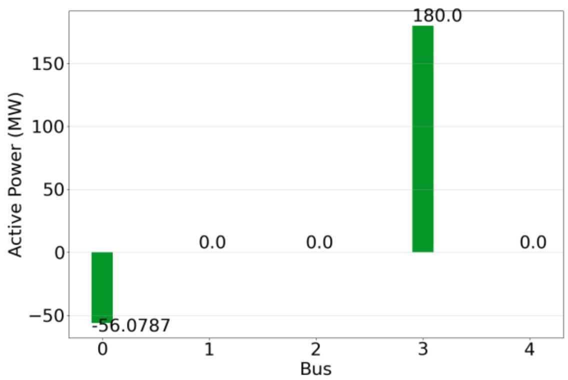

Figure 9. Active power generated of the 5-bus Moroccan network system with PE=1 & SO=0 on the buses

3.5. Case R4 (WP=1 & SO=1)

Both the wind park and the solar park are highly productive in this scenario. The voltage values provided for the different buses in Figure 10 represent the relative voltage (expressed in per unit, p.u.) at those specific locations in the electrical network. The voltage at Bus 0 is 1.05 per unit (p.u.), matching the nominal value and indicating relative stability at this point. Buses 1, 2, 3, and 4 exhibit notably elevated voltages, suggesting a possible requirement for voltage management to ensure the stability of the system, while ongoing monitoring remains advisable.

The active power curve generated for each bus in Figure 11 illustrates the allocation of active power within the electrical network. Bus 0 has an active power of -191.9499 MW, indicating it absorbs active power instead of generating it, highlighting significant network traffic. Bus 1 generates 140 MW, functioning as a source and contributing to overall power generation. Buses 2 and 4, with no active power generation (0 MW), do not contribute to the system's active power. Meanwhile, Bus 3 produces 180 MW of active power, serving as a key source and making a substantial contribution to the network's total generation. Buses 1 and 3 are the primary sources of active power generation, while bus 0 consumes a considerable quantity of active power. The other buses do not seem to be actively participating in power generating. In this case, power losses are equal to 9.0501 MW.

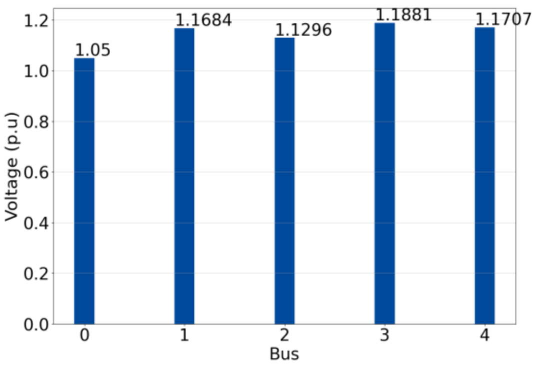

Figure 10. Voltage profile of the 5-bus Moroccan network system with PE=1 & SO=1 on the buses

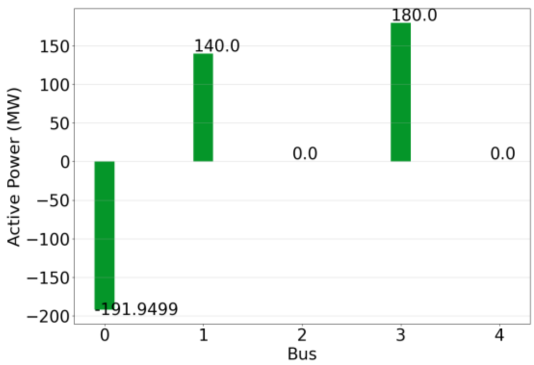

Figure 11. Active power generated of the 5-bus Moroccan network system with PE=1 & SO=1 on the buses

4. DISCUSSION

4.1. Numerical and statistical comparisons

Important insights can be gained from the analysis of voltage profiles, power losses, and energy contributions across examples R1, R2, R3, and R4 shown in Figure 4. With low power losses (4.51 MW, 3.61%) and a steady voltage at Bus 1 (1.1122 p.u.), Case R2 (solar-only) showed the maximum energy efficiency, but with a little danger of undervoltage at Bus 2. With minimal power losses and better voltage distribution, Case R3 (wind-only) offered more operating freedom. On the other hand, Case R4 (solar+wind) put more strain on the system due to the largest power losses (9.05 MW, 7.17%) and over voltages. Because of this, R2 and R3 are more effective in the existing grid environment, whereas R4 would necessitate the use of sophisticated grid management techniques. Table 4 present a statistical comparison between cases R1, R2, R3 and R4.

Table 4. Statistical comparison between the 4 cases

Metric	Case R1 (No Solar/Wind)	Case R2 (Solar Only)	Case R3 (Wind Only)	Case R4 (Solar + Wind)
Voltage at Bus 0 (p.u.)	1.05	1.05	1.05	1.05
Voltage at Bus 1 (p.u.)	1.0	1.1122	1.05	1.1684
Voltage at Bus 2 (p.u.)	0.922	0.9881	1.05	1.055
Voltage at Bus 3 (p.u.)	1.0	0.996	1.105	1.08
Voltage at Bus 4 (p.u.)	1.0	0.997	1.105	1.08
Active power losses (MW)	6.2949	4.5126	4.9213	9.0501
Bus 0 Active Power (MW)	126.52 (supply)	-16.48 (absorbing)	-56.08 (absorbing)	-191.94 (absorbing)
Bus 1 Active Power (MW)	0	140	0	140
Bus 3 Active Power (MW)	0	0	180	180
Power loss percentage (%)	**4.98%**	**3.61%**	**3.93%**	**7.17%**

4.2. Comparison between the 4 cases
4.2.1. Voltage profiles of the four cases

Each of the four scenarios exhibits unique voltage profiles that come with individual benefits and drawbacks. Figure 12 shows voltage profile for the four cases of the Moroccan 5 bus network system. Case R1 ensures stability at the specified voltage level, however there is a small possibility of seeing a tiny decrease in voltage at bus 2. Case R2 effectively regulates the voltage at bus 0, with a reduced voltage fluctuation across buses. However, it also poses a potential risk of undervoltage at bus 2. Case R3 provides adaptability to moderate voltage fluctuations, although it does carry the potential for overvoltage on bus 3. Case R4 ensures that the voltage at bus 0 remains at its intended level, but it also poses a potential risk of overvoltage at bus 3. Additional study suggests that Case R2 and Case R3 seem to be marginally more advantageous.

However, the best selection is contingent upon the specific goals of the network. To achieve a more impartial comparison between R2 and R3, we listed in Table 5 the advantages and drawbacks of each and we compared the two cases in terms of stability and voltage variations between the buses. The network operator's priorities will choose which of Cas R2 and Cas R3 to use. While Cas R3 provides a more flexible solution when flexibility to manage moderate changes and small tolerance of voltage variation is required, Cas R2 is preferred when stability at nominal voltage and accurate regulation are critical. However, the best decision depends on the specific requirements of the network, taking into account the balance between maintaining voltage stability and avoiding power losses. Additional assessment is necessary in order to make a well-informed conclusion taking into account the specific attributes of the power system.

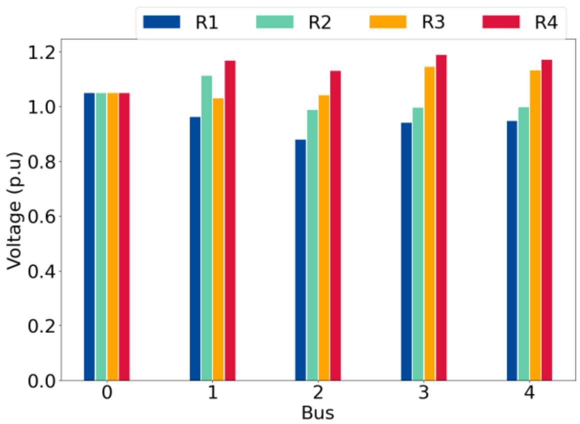

Figure 12. Voltage profile of the four cases of the Moroccan 5-bus network system

Table 5. Comparison between R2 and R3

Aspect	Case R2	Case R3	Comparison
Advantages	- Ensures constant voltage level at bus 0, contributing to network stability. - Exhibits minimal deviation among buses, indicating precise voltage regulation.	- Despite significant variance, all voltages remain within an acceptable range. - Provides flexibility to manage moderate voltage fluctuations.	-
Drawbacks	- Bus 2 has the lowest voltage, posing a risk of undervoltage.	- Bus 3 has the highest voltage, posing a risk of overvoltage.	-
Stability at nominal voltage	Maintains voltage at its nominal value at bus 0.	Shows greater variation at bus 0.	Case R2 is more favorable for stability at nominal voltage.
Voltage Variation	Smallest variation between bus voltages, indicating precise regulation.	Larger variation between bus voltages.	Case R2 is better for voltage variation.
Flexibility	Maintains stable voltage levels with minimal variation.	Allows moderate voltage variations.	Case R3 is more flexible for managing voltage fluctuations.
Undervoltage or Overvoltage	Potential risk of undervoltage at bus 2.	Potential risk of overvoltage at bus 3.	Case R2 has undervoltage risk; Case R3 has overvoltage risk.

4.2.2. Power losses in the four cases

Figure 13 indicates the variation of active power losses under four distinct network situations. When evaluating the four scenarios, power losses emerge as a critical indicator of both energy efficiency and system stability. Case R2 is notable for its minimal losses, indicating an optimal network architecture or special tweaks that enhance energy efficiency. Comparably, Case R3 displays minimal losses as well, suggesting a rather high level of active power management efficiency. Case R4 exhibits notably elevated losses, indicating significant inefficiencies or peculiar network characteristics that necessitate attention. Case R1, despite being intermediate, emphasizes the significance of thorough analysis in comprehending the factors that cause losses. This comparison emphasizes the necessity of optimizing network configuration in order to decrease losses and enhance overall power system efficiency. This optimization process may entail making technical adjustments or implementing improvements in operational management.

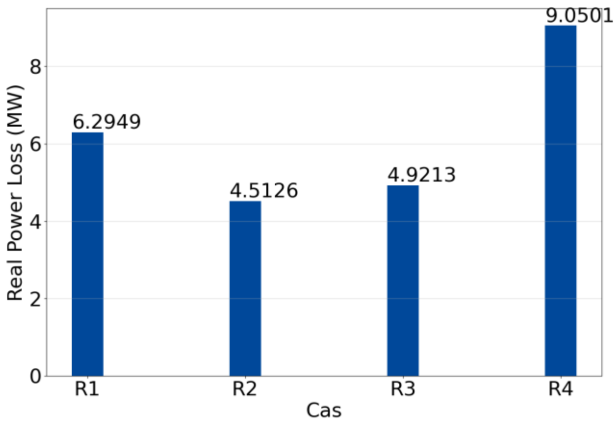

Figure 13. Real power loss of the four cases of the Moroccan 5-bus network system

4.2.3. Comparative analysis

When taking into account power losses as well as voltage profiles, it is crucial to find an equilibrium between network stability and decreasing power losses. Analyzing the voltage stability and power losses of each case. In terms of power losses, Case R2 demonstrates slightly lower losses compared to Case R3, highlighting its efficiency. Regarding voltage stability, Case R3 provides greater flexibility to accommodate moderate voltage variations; however, it carries a potential risk of excessively high voltage levels. Case R2 offers a possibility to minimize losses in the event of undervoltage tolerance.

4.3. Assessing the impact of solar energy variations

This section analyzes the effects of variations in solar energy on different levels of utilization. It explores how these variations influence the system's ability to meet energy demands reliably across different conditions. Additionally, it identifies the critical threshold beyond which integrating an additional energy source becomes necessary to reduce dependence on the main power grid and ensure energy stability.

4.3.1. Voltage profile

Figure 14 depicts the correlation between voltage and the proportion of solar energy used, emphasizing the variations in voltage at different points in the system based on the quantity of solar energy generated. The data illustrates a correlation between the decline in solar power use and a corresponding fall in bus voltages. This suggests a growing reliance on alternative energy sources inside the network. At high levels of solar power usage, the voltages at different points in the power system remain steady and close to the expected voltage. However, at decreasing levels of solar power usage, the voltages tend to decline, indicating a possible disruption in the power system. This emphasizes the significance of maintaining an appropriate equilibrium in the utilization of diverse energy sources to guarantee the stability of the power system.

In this interpretation, bus 0 symbolizes the national grid, while bus 1 symbolizes the solar power source. Furthermore, a supplementary wind source is incorporated to diminish reliance on the primary power grid supply. When the solar power utilization reaches a high percentage (90%), the voltage at bus 0 (national grid) remains consistently stable at 1.05 per unit, suggesting a dependable supply from the primary power grid. However, the voltage at bus 1 (solar source) experiences a decline. Nevertheless, the incorporation of wind energy can offset this decline, so preserving grid stability without relying on the primary power source. In general, a rise in the proportion of solar power utilization results in a reduction in voltage across all buses in the network, with more noticeable fluctuations observed specifically on bus 1. However, bus 0 has a higher level of voltage stability compared to the other buses, which experience more significant voltage drops due to their larger reliance on solar electricity. This analysis emphasizes the significance of closely monitoring voltage fluctuations to guarantee the stability of the power grid, especially as renewable energy sources are being integrated more and more.

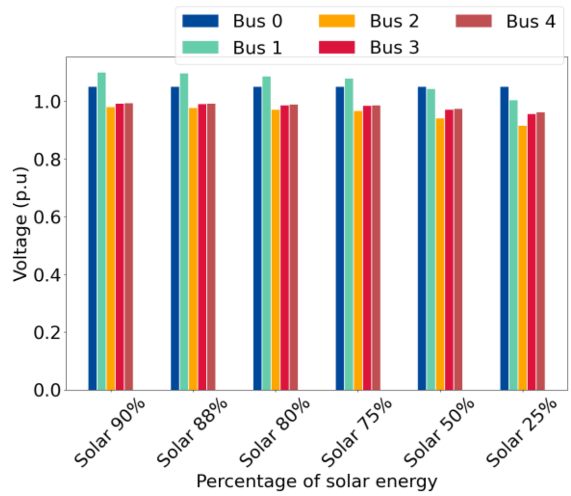

Figure 14. Voltage profile of the Moroccan 5-bus network with different percentages of solar energy

4.3.2. Evolution of power generated in the network

The distribution of energy production between the national network and the solar source changes at different degrees of solar energy utilization, as indicated by the active power curve in relation to the percentage of solar energy utilization. According to Figure 15, when solar energy utilization reaches 90%, the national grid power is -2.9194 MW, indicating that the grid is absorbing energy and injecting it into the system, while the solar source power is 126 MW. At 88% solar energy usage efficiency, the national grid power balances at 0 MW, reflecting a perfect equilibrium between grid demand and generation, with the solar source power at 123.2 MW. To maintain this balance and reduce dependency on the national grid, incorporating wind energy alongside the existing 88% solar contribution becomes crucial. However, as solar power utilization drops, the demand on the national grid significantly increases, rising from 10.757 MW at 80% utilization to 17.6383 MW at 75%, and further to 52.5206 MW at 50%, underscoring the grid's higher burden when solar contributions decline.

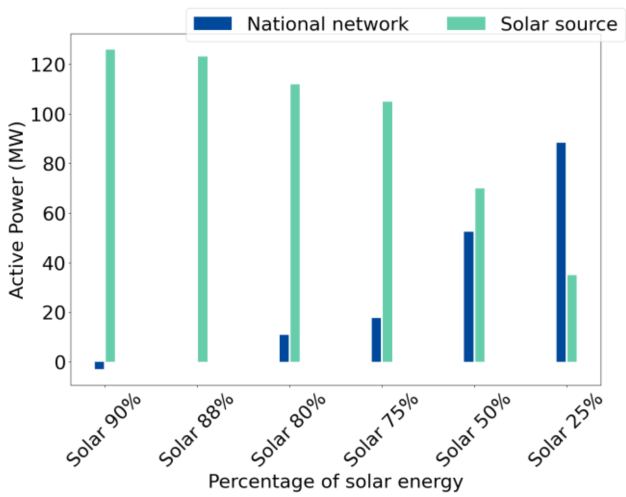

Figure 15. Active power generated of the Moroccan 5-bus network with different percentages of solar energy

This analysis emphasizes that when the proportion of solar energy utilization increases, the solar source makes a larger contribution to the overall power supply of the grid, resulting in a reduced reliance on the national grid. This underscores the significance of solar electricity in decreasing the strain on the national network. However, after solar energy use decreases beyond a certain level, the power of the national network steadily increases, signaling a rise in demand. Adding another renewable source, such wind power (PE Midelt), in this situation, might decrease dependence on the national grid for generating electricity. This would provide a solution for fulfilling energy demands while encouraging the use of sustainable resources.

4.3.3. Power losses

An examination of power losses in relation to the proportion of solar power use in Figure 16 demonstrates a connection between decreased utilization of solar energy and heightened power losses in the electrical grid. As the use of solar electricity diminishes, there is a steady increase in power losses. When the solar power usage reaches 90%, the power losses amount to 4.0806 MW. However, when the utilization drops to 5%, these losses increase to 5.7927 MW. This discovery emphasizes the significance of solar electricity in minimizing power losses in a network, while also highlighting the possible difficulties involved in decreasing its usage.

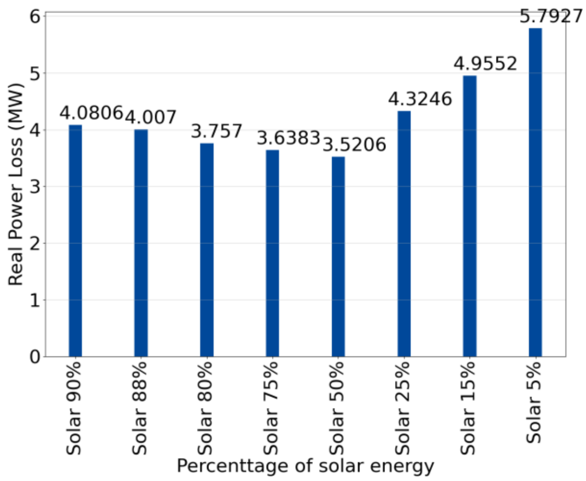

Figure 16. Real power loss of the Moroccan 5-bus network with different percentages of solar energy

The rise in power losses signifies an increasing reliance on the primary electrical system. Nevertheless, the inclusion of an additional sustainable energy source, such as wind power, alongside solar energy, can potentially diminish this need. Integrating wind power can offset power losses, allowing grid stability to be maintained independently from the main grid. This strategy demonstrates the significance of expanding the range of renewable energy sources in order to guarantee the dependability and long-term reliability and sustainability of the power grid.

5. CONCLUSION

In conclusion, this study proposes an in-depth analysis of the behavior of an electric transmission system in Morocco in the face of the increasing integration of renewable energy sources. The transition to sustainable sources is essential for mitigating the effects of climate change, and this research contributes to this perspective by assessing system performance in various situations and possible configurations. Extensive simulations have been performed to compute power flow using the Newton-Raphson approach, yielding a precise voltage and active power profile at various network nodes. In addition, analyzing power flow performance at different penetration rates of renewable energy provides important information for energy planning in the future. This paper focuses on the technological difficulties that arise when incorporating intermittent energy sources into power systems, emphasizing the significance of continuous research to guarantee the reliability and stability of the power system. To summarize, the present paper provides guidance for energy policy in achieving an effective and sustainable transition. It emphasizes the need of technological innovation and international cooperation in addressing the energy and climate challenges of the 21st century.

In our forthcoming research, we plan to expand the simulations to encompass more areas of the Moroccan electricity system, facilitating a more thorough evaluation of its overall performance and stability. This expansion will allow us to examine the interactions among various regions within the broader network, considering regional disparities in power generation and consumption. Additionally, we intend to use sophisticated machine learning and deep learning models to forecast the behavior of the analyzed areas of the grid. Utilizing these models, we want to augment the precision of load forecasting, detect potential system weaknesses, and boost the grid's responsiveness to fluctuations in supply and demand. These predictive capabilities will be essential for optimizing grid operations, improving grid stability, and facilitating future advancements in smart grid development.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, SE, upon reasonable request.

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