

Modeling and Simulation of a Renewable Energy-Integrated Distribution Network in Boujdour

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Article Info	ABSTRACT
Article history: Received May 18, 2026 Revised Aug 29, 2026 Accepted Sep 14, 2026 Keywords: Modeling Simulation Distribution Network Renewable Energy Intermittency	This paper presents a system-level modeling and simulation study of the 22 kV distribution network of Boujdour, southern Morocco, integrating photovoltaic (PV) and wind energy. The PV and wind models are validated using real operational SCADA data. Two operating conditions are analyzed: grid-connected operation with PV injection and a main-grid-loss condition with combined PV–wind generation. The results show how renewable intermittency affects power balance and medium-voltage voltage behavior and identify infrastructure constraints that limit further renewable penetration. The study provides a validated operational baseline for future smart-grid extensions involving dynamic inverter models, energy storage, advanced monitoring, and data-driven forecasting. Copyright © 2026 Institute of Advanced Engineering and Science. All rights reserved.
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1. INTRODUCTION

Within the framework of its energy transition, Morocco has set ambitious targets, including strengthening the share of renewable energy in the electricity mix to reach 52% by 2030, reducing energy consumption by 20% by 2030 and creating added value in energy-intensive economic activities [1], [2].

The National Electricity Regulatory Authority (ANRE), an independent public-law legal entity established under Law No. 48-15 and entrusted with the regulation of the electricity sector in Morocco, has published in its annual report the key figures of the energy sector for 2024 (Table 1) [3].

Table 1. 2024 data on the electricity sector in Morocco				
Data type	Wind	Solar	RES	Total
Installed Capacity	2.39 GW	0.928 GW	5.43 GW	12.01 GW
Energy generation	9.36 TWh	1.61 TWh	11.66 TWh	43.71 TWh

The development of renewables is helping to improve energy security as well as deliver on Morocco's clean energy and climate change commitments. Morocco is making progress towards affordable, reliable, sustainable and modern energy in line with the United Nations Sustainable Development Goals [4], [5].

The power system considered in the province of Boujdour, in southern Morocco, was managed by the National Office of Electricity and Drinking Water (ONEE) until October 2025 and currently by Laayoune Sakia El Hamra Regional Multiservices Company (SRM-LS S.A.), established under Law No. 83.21.

Historically, the system supply was ensured by local diesel generation. In 2007, it was interconnected with the national grid via a 60 kV radial line to enhance security and meet the growing demand. To reduce technical losses and operating costs, lower CO₂ emissions and improve service quality, the authorities have promoted the deployment of generation facilities based on RES in the province of Boujdour.

Accordingly, a 15 MWp PV system was commissioned in 2018. In 2023, wind generation of 10 MVA was integrated from a wind farm with a total installed capacity of 300 MW to enhance supply reliability.

The objective of this paper is to analyze the current electricity supply conditions in Boujdour and to examine the behavior of generation sources and load over selected periods, with particular emphasis on renewable intermittency, power balance, voltage behavior, and system-level operational performance.

The study identifies the operational, technical, and economic constraints that limit the benefits of photovoltaic and wind integration. It also discusses a future smart-grid roadmap involving advanced monitoring and control, energy storage, communication infrastructure, and data-driven forecasting; these technologies are presented as future extensions and are not implemented in the present MATLAB/Simulink model [6]–[8].

The main contribution of this work is the development of a system-level model of an actual 22 kV regional distribution network in Boujdour, Morocco, rather than a generic benchmark feeder. The PV and wind models are calibrated and validated against real operational SCADA measurements, and the validated network is evaluated under both grid-connected operation and a main-grid-loss operating condition using historical renewable and load profiles. This combination of a real MV network, field operating data, and scenario-based analysis provides a practical baseline for assessing renewable integration constraints and identifying requirements for subsequent smart-grid and dynamic studies.

Recent distribution-system studies emphasize hosting capacity, voltage deviation, power quality, and inverter-based resource interaction with network controls, while islanded microgrids increasingly use hierarchical control, storage, and grid-forming inverters [9]–[14]. These studies provide the state-of-the-art context for interpreting the present system-level analysis.

Finally, economic deployment is also affected by remuneration and contractual risk. Feed-in tariffs influence investment incentives and system costs, while renewable PPAs can reduce revenue uncertainty but introduce price and counterparty risks [15]–[17]. These issues are discussed as future techno-economic extensions.

2. METHODOLOGY

The following sub-sections present the methodology adopted for system description, modeling, simulation, validation, and analysis of the obtained results.

2.1. Description of the Electrical Power System

The main power supply of Boujdour Province is provided by the national transmission network via a 60/22 kV substation. This substation is equipped with two 20 MVA power transformers. It supplies the city through three medium-voltage (MV) feeders, namely HOPITAL, CORNICHE, and AL AMANE I, as well as a fishing village via the MV feeder SIDI ELGHAZI. The substation is also interconnected with the step-up substation of a 3.92 MW diesel power plant through two additional MV feeders, namely CENTRE VILLE and PROVINCE as shown in Figure 1(a).

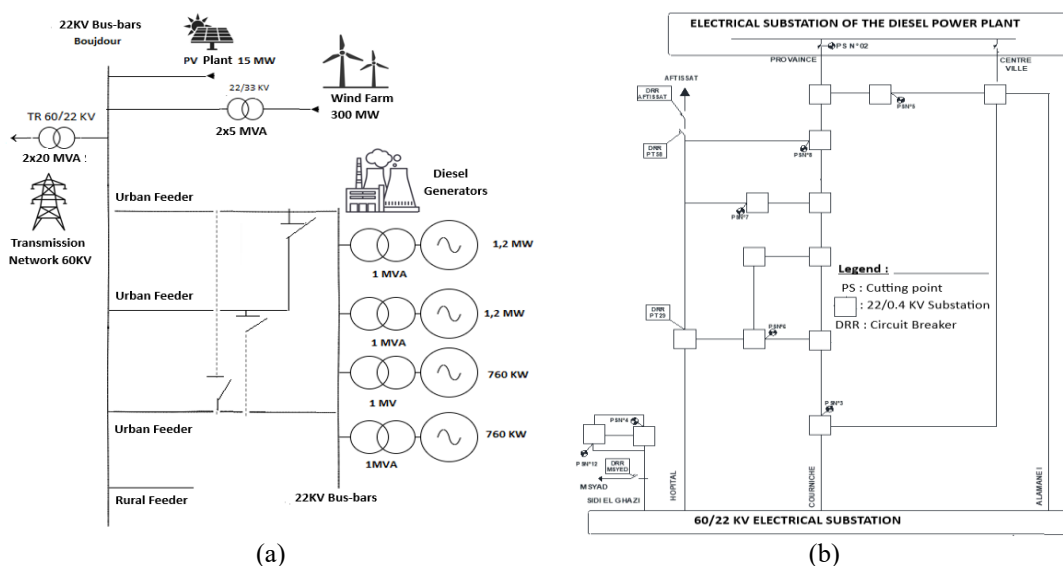


Figure 1. Electricity supply of Boujdour (a) Energy sources (b) Diagram of the MV grid

A second power supply is provided by a 15 MWp photovoltaic (PV) Solar Plant. This power plant injects electricity into the 22 kV distribution network during daytime operation, up to the level of the provincial load demand. Any surplus generation is exported to the national transmission network via the aforementioned 60/22 kV substation, which operates in this case as a 22/60 kV step-up substation.

A backup power supply is ensured by a Wind Farm. With an installed capacity of 300 MW, this farm primarily injects power into the national transmission network at 400 kV. It also provides a backup supply to the city of Boujdour, delivering up to 10 MVA through a 33/22 kV transformer substation. The 33 kV level corresponds to the wind turbine output voltage, while 22 kV is the voltage level used in distribution.

As illustrated in Figure 1(b), the 60/22 kV Boujdour substation supplies the city of Boujdour through three medium-voltage (MV) feeders interconnected in a loop configuration via sectionalizing points PSN°3, PSN°5, PSN°9 and PS N°2. The fourth feeder operates in a radial configuration and supplies a rural area.

2.2. System Modeling

2.2.1. PV System Modeling

To develop a photovoltaic system model for power-flow analysis, renewable-generation profiling, and 24-hour power-balance studies, a model based on irradiance, PV field area, and efficiency is adopted. The model is then extended to represent the conversion of generated power into injected three-phase current.

Direct Current (DC) Power Generated by the PV Field

DC power is given by [18]:

$$P_{PV,dc}^{th}(t) = \eta_{PV} A G(t) \quad (1)$$

Where:

$G(t)$: irradiance (W/m²).

A : PV field area PV (m²).

η_{PV} : PV Field efficiency.

In practice, the power is limited given the nominal maximum capacity P_{rated} (W) [19]:

$$P_{PV,dc}(t) = \min(P_{PV,dc}^{th}(t), P_{rated}) \quad (2)$$

Inverter Efficiency and DC to AC Conversion

The inverter converts $P_{PV,dc}$ into injected AC power. In an average model [20]:

$$P_{AC}(t) = \eta_{inv}(P_{PV,dc}(t)) P_{PV,dc}(t) \quad (3)$$

Where η_{inv} is the inverter efficiency.

Active and Reactive Power References

Power reference is defined to calculate the currents required to inject the requested power.

The controller defines:

$P_{ref}(t)$ as the active power injected into the grid ($P_{AC}(t)$).

$Q_{ref}(t)$ as the reactive power reference (zero as no reactive power setpoint).

Phase Currents Injected by the Inverter

Instantaneous Power:

$$p(t) = v_a i_a + v_b i_b + v_c i_c \quad (4)$$

Where:

$v_a(t), v_b(t), v_c(t)$ are the instantaneous phase voltages at the point of connection (V).

$i_a(t), i_b(t), i_c(t)$ are the injected phase currents (A).

A normalization is then introduced:

$$\Sigma_v(t) = v_a^2 + v_b^2 + v_c^2 \quad (5)$$

A gain is defined as:

$$\kappa_P = \frac{P_{ref}}{\Sigma_v(t)} \quad (6)$$

$$i_k(t) = \frac{P_{ref}(t)}{\Sigma_v(t)} v_k(t), k = a, b, c \quad (7)$$

If reactive power is considered, a quadrature component is added to injected phase currents:

$$i_k(t) = \frac{P_{ref}}{\Sigma_v(t)} v_k(t) + \frac{Q_{ref}}{\Sigma_v(t)} v_k^{90}(t) \quad (8)$$

Park Representation in dq

To convert the three-phase AC system into DC signals and simplify control, Clarke and Park transformations are used [21]:

Clarke ($abc \rightarrow \alpha\beta$):

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (9)$$

Park ($\alpha\beta \rightarrow dq$):

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \quad (10)$$

Power in dq:

$$P = \frac{3}{2} (v_d i_d + v_q i_q), Q = \frac{3}{2} (v_q i_d - v_d i_q) \quad (11)$$

$$\frac{3}{2} \begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3} \frac{1}{v_d^2 + v_q^2} \begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix} \begin{bmatrix} P_{ref} \\ Q_{ref} \end{bmatrix} \quad (13)$$

The inverse Park and Clarke transformations are then applied to obtain i_a, i_b, i_c .

2.2.2. Wind Farm Modeling

To model the wind farm for the same system-level objectives as the PV system, a wind-speed-based model is adopted. Wind energy is converted into electrical power and then into injected three-phase currents. This representation is suitable for the operational analysis of the hybrid PV–wind system.

Wind Speed

Wind speed $v_{wind}(t)$ is an input variable measured in m/s using wind farm sensors. A normalized wind speed is defined using a rated reference V_{ref} (V_{rated}) speed:

$$v_{norm}(t) = \frac{v_{wind}(t)}{V_{ref}} \quad (14)$$

Calculated Power

The calculated wind power in (W) is expressed as [22]:

$$P_{th}(t) = K_w \cdot v_{wind}(t)^3 \quad (15)$$

Where K_w is the conversion coefficient.

Taking P_{rated} as wind farm power (W). The coefficient is adjusted such that:

$$P_{th}(V_{rated}) = P_{rated} \quad (16)$$

$$K_w = \frac{P_{rated}}{V_{rated}^3} \quad (17)$$

$$P_{ref}(t) = \min(P_{th}(t), P_{rated}) \quad (18)$$

Conversion of Power to Current

Similar to the PV system model, the phase currents are obtained as follows:

$$\kappa(t) = \frac{P_{ref}(t)}{\Sigma v(t)} \quad (19)$$

$$i_k^{ref}(t) = \kappa(t) v_k(t) (k = a, b, c) \quad (20)$$

If reactive power is included:

$$i_k = \frac{P_{ref}}{\Sigma v} v_k + \frac{Q_{ref}}{\Sigma v} v_k^{90^\circ} \quad (21)$$

2.2.3. Upstream Transmission Network Modeling

The upstream transmission system is modeled as an ideal three-phase voltage source in series with an equivalent impedance of R and X. It corresponds to the Thévenin equivalent of the upstream grid as seen from the point of common coupling (PCC). The short-circuit power S_{cc} and the X/R ratio at the PCC are provided by the national transmission system operator.

2.2.4. Modeling Scope and Limitations

The PV and wind conversion systems are represented by average-value models intended for system-level analysis and operational behavior. The models do not explicitly represent switching devices, phase-locked loops (PLLs), inner current-control loops, DC-link dynamics, current-limiting functions, protection logic, or detailed fault ride-through (FRT) controls. Consequently, the present model is not intended to reproduce sub-cycle electromagnetic transients or to verify inverter-level FRT performance. The 5-second simulation step is appropriate for operational profiles and renewable intermittency but does not resolve electromagnetic phenomena occurring at millisecond or sub-cycle time scales.

2.3. Model Validation

To ensure the accuracy of the results, the developed PV and wind system models were validated before being deployed in the simulations.

Methodology

Model validation was carried out using historical data measured and recorded by SCADA systems from both the generation units and the distribution system operator. System input variables (solar irradiance and wind speed) were injected into MATLAB/Simulink models developed and previously defined.

Simulation outputs were then compared with actual power injection data recorded by SCADA systems. Deviations between simulated and measured values were used to assess the reliability of the developed models.

SCADA systems Data

For the PV and Wind systems, irradiance (W/m²) and wind speed (m/s) data measured by on-site sensors were obtained from the SCADA systems of the plant operator.

Active power data (kW) injected into the grid by solar and wind generation were measured at the 22 kV feeders and recorded by the distribution system operator's SCADA, since both renewable sources are directly connected to the distribution network via 22 kV feeders.

The historical data sets used correspond to the year 2023. Measured irradiance and wind speed from 15/09/2023 and 04/01/2023 (Figure 2) were used for the validation of PV and wind farm systems respectively.

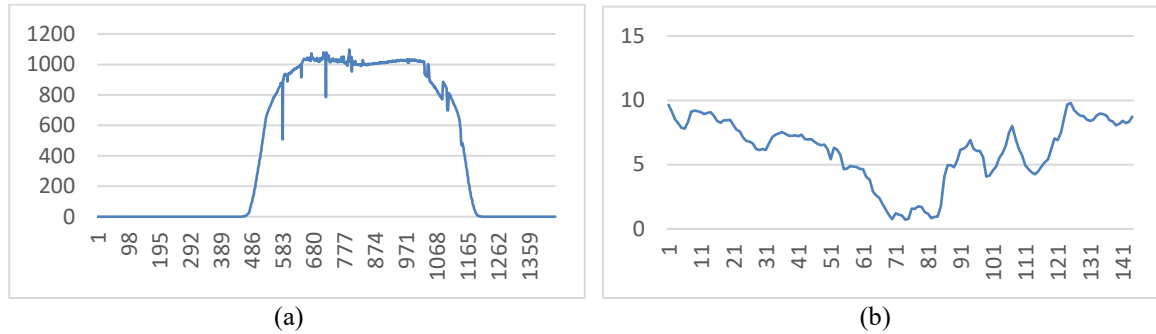


Figure 2. SCADA measurements (a) Irradiance (W/m^2) on 15/09/2023 (b) Wind speed on 04/01/2023 (m/s)

Results comparison

Figure 3 below shows the simulation results compared with measured power data, for both solar and wind generation:

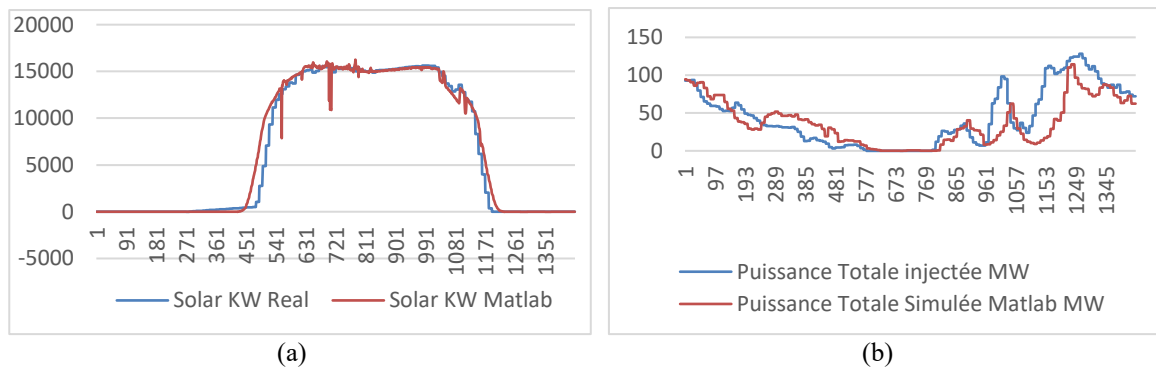


Figure 3. Comparison of simulated and measured power (a) Solar injection (b) Wind injection

The simulated and measured PV-wind power profiles showed close agreement, and daily energy production was similar. The observed discrepancies were mainly due to time-synchronization differences between SCADA measurements and MATLAB simulations, sampling-resolution differences (1 or 10-minute SCADA data versus a 5-second simulation step), and the assumption of spatially uniform irradiance and wind over the entire field in the model, whereas irradiance and wind speed were measured at a single point within a large-scale plant.

When wind speed dropped below a certain threshold, the wind farm stopped injecting power into the grid.

Energy Assessment

Using the power profile, the energy is given as [23]:

$$E = P\Delta t \quad (22)$$

Table 2 presents a comparison of simulated and measured power used in validation:

Table 2. Simulated and measured power comparison			
Source	Measured Energy	Simulated Energy	Error
Solar	156.7 MWh	162.2 MWh	+3.5%
Wind	2.11 GWh	1.84 GWh	-12.7%

To evaluate the agreement between simulation results and SCADA measurements, the Mean Absolute Percentage Error (MAPE) was used. A lower MAPE value indicated a better fit between data.

For the PV system, the model exhibited a MAPE of 3.5%. Compared with similar studies [24], which reported MAPE values of 1.24%, 5.14%, 9.16%, and 9.24% for TRNSYS, Archelios, PVSyst, and PVGIS respectively, the developed MATLAB/Simulink model demonstrated good accuracy.

For the wind system, the MAPE was 12.7%, while the average of a proposed model of a multi-layer deep neural network for wind power forecasting established based on Stacked Auto Encoders had a value of

15.96% [25]. Other models reported errors of 47.33% and 27.88% as averages. In practice, wind variability remains the dominant source of error in predictions [26], [27]. The model demonstrated satisfactory accuracy.

2.4. Simulation Scenarios

2.4.1. Methodology

After validating the PV and wind models, simulations were conducted to analyze the behavior of the Boujdour electrical network under normal supply operation by the national transmission grid with PV injection and under a main-grid-loss operating condition with combined PV and wind generation. The analysis focuses on renewable intermittency, active-power balance, and medium-voltage behavior.

Historical SCADA data for irradiance, wind, and load were used as inputs to the MATLAB models. Simulation results were then used to analyze each delivery point and the effects of renewable intermittency on power balance and voltage behavior.

For the SCADA system data, and in addition to the electrical parameters used in model validation, namely irradiance and wind speed, 22 kV feeder load curves were extracted from the distribution system operator's SCADA system.

2.4.2. Scenario 1: Normal Operation

In this scenario, the Boujdour network was supplied by the national transmission system via the 60 kV line. The simulations were conducted using data collected from 02/02/2024 and 17/02/2024, which exhibited a variety of weather conditions. Figure 4 shows data from 02/02/2024:

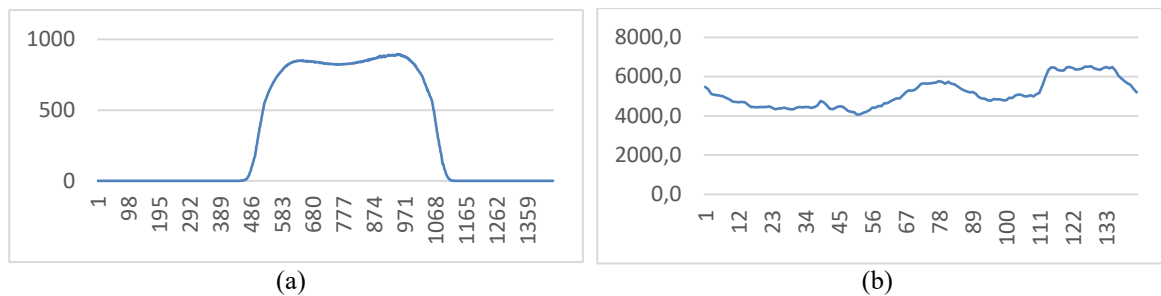


Figure 4. Clear sky day data from 02/02/2024 (a) Irradiance (W/m^2) (b) Load profile (KW)

The solar irradiance profile showed no intermittency. Irradiance increased rapidly around 08h, reached optimal levels, remained stable until 17h, and then decreased. The daily profile of load was typical and exhibited two peaks: day peak recorded between 12h and 13h, and night peak recorded between 19h and 20h.

Figure 5 shows the simulation data from 17/02/2024, namely irradiance and Load profile:

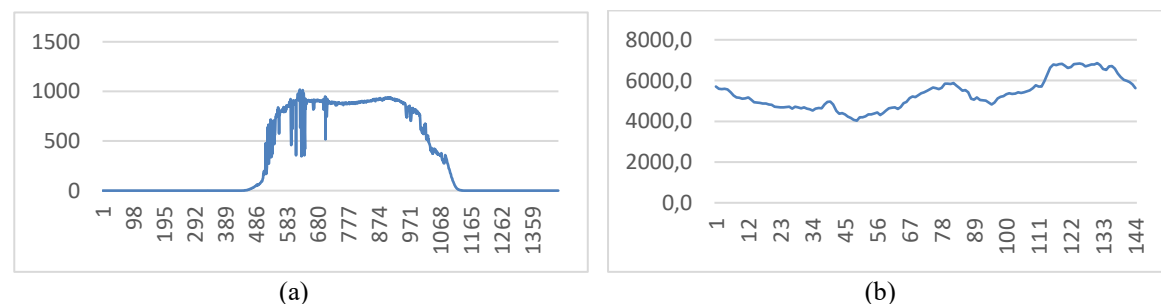


Figure 5. Cloudy with intermittency data from 17/02/2024 (a) Irradiance (W/m^2) (b) Load profile (KW)

The irradiance profile exhibited significant fluctuations between 09h and 11h. Additional fluctuations were observed between 16h and 18h later in the day, causing distortion of the typical irradiance profile. The profile of load remained similar to the one from 02/02/2024.

Figure 6 presents the view of Matlab Simulation Model of scenario 1, established to assess the PV and Grid Interaction:

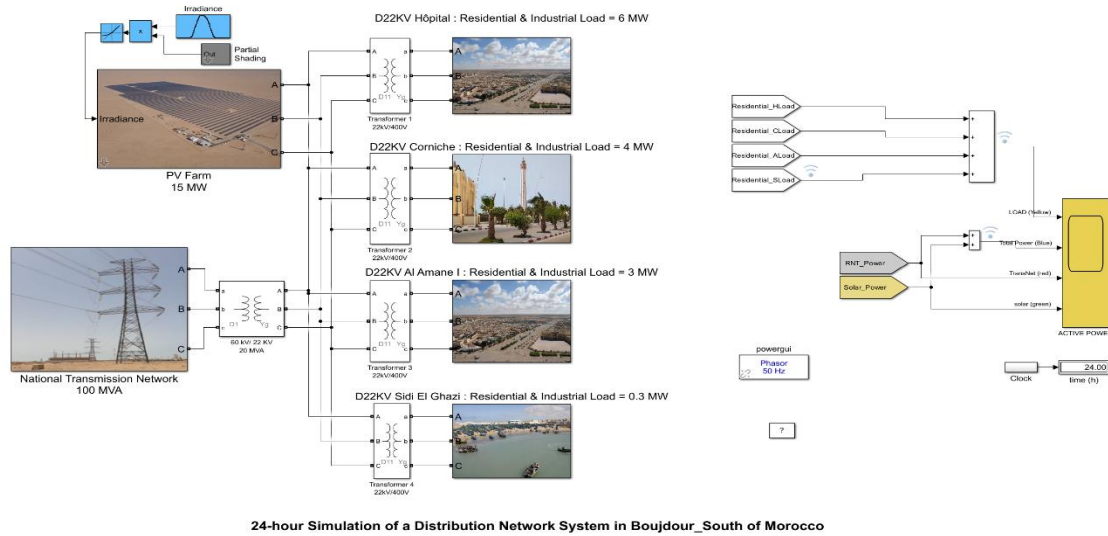


Figure 6. MATLAB/Simulink Simulation Model for scenario 1 of normal operation

2.4.3. Scenario 2: Loss of the Main Grid

This scenario considered the outage of the 60 kV transmission line and the operation of the Boujdour system under combined PV–wind supply in a simulated quasi-autonomous operating condition. The 300 MW wind farm is also connected through a 33/400 kV transformation to the national 400 kV transmission network. This connection provides an alternative transmission path for evacuating surplus wind generation and, when the 60 kV connection is unavailable, can provide the network reference required for frequency regulation at Boujdour. For comparative purposes, the wind farm was scaled to 30 MW (300/10), consistent with the PV plant scale (15 MWp). The simulations were conducted using data collected between 22/02/2025 and 24/02/2025. Scenario 2 is then a system-level sensitivity study.

Figure 7 shows the simulation data from the period, specifically load, irradiance, and wind speed:

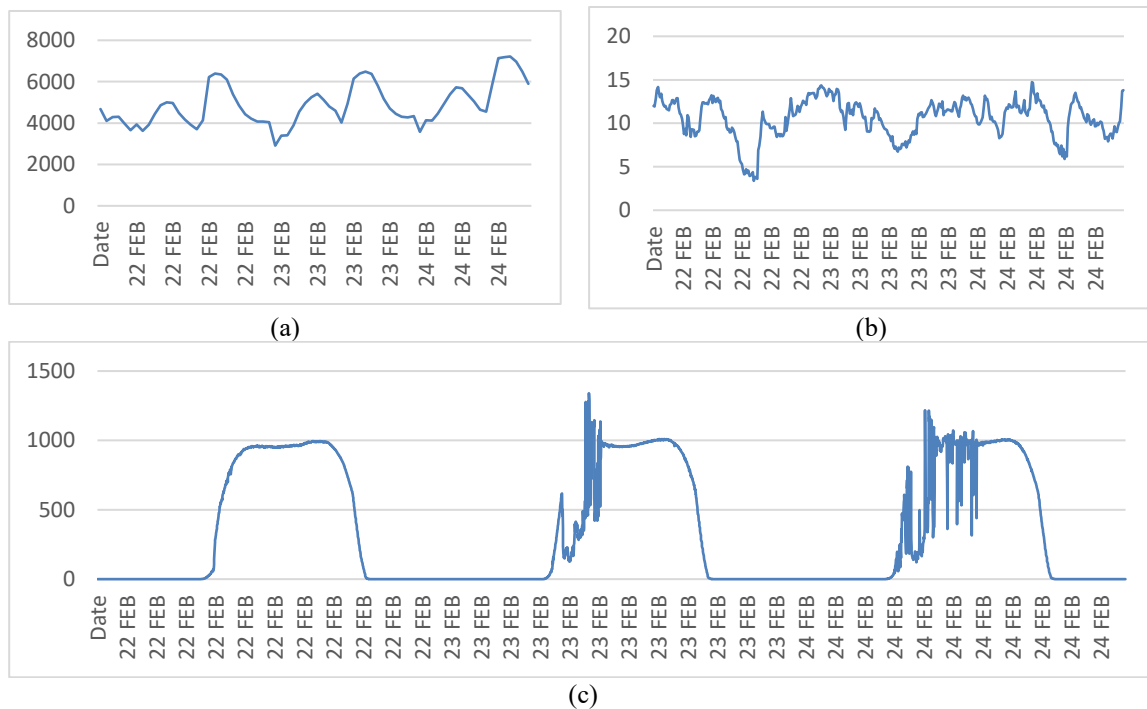


Figure 7. Simulation data from 22-24/02/2025 (a) Load (KW) (b) Irradiance (W/m²) (c) Wind speed (m/s)

The daily load profile showed day and night peaks. The solar irradiance exhibited significant intermittency on 23 and 24 February between 08h and 14h, leading to distortion of the typical irradiance profile,

while wind speed varied naturally between 3,3 m/s and 14,7 m/s, indicating high volatility. Figure 8 presents the view of Matlab/Simulink simulation Model of scenario 2 of operation:

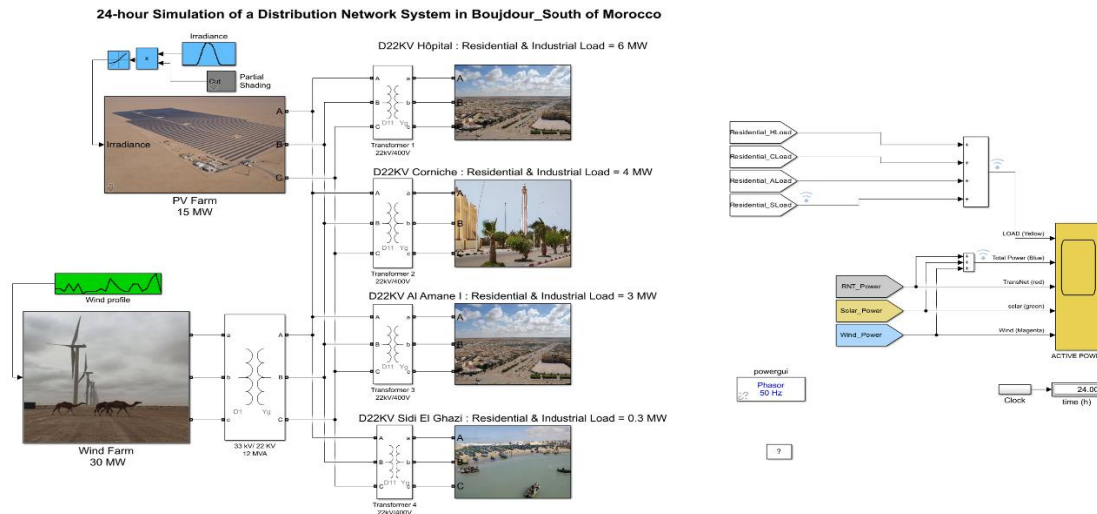


Figure 8. MATLAB/Simulink Simulation Model for scenario 2 of Loss of the Main Grid operation

3. RESULTS AND DISCUSSION

In this section, the simulation results were analyzed using power curves and voltage profile.

3.1. Simulation results of Scenario 1: Normal Operation

Figure 9 shows the simulation results from 02/02/2024, namely power curves and voltage profile:

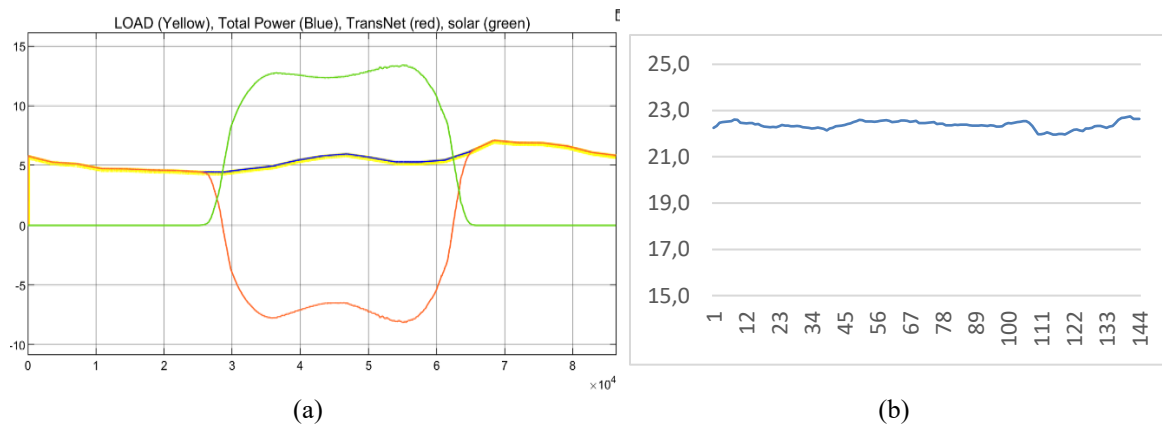


Figure 9. Simulation results from 02/02/2024 (a) Active power curves (MW) (b) Voltage profile (KV)

Before 08h, the PV plant doesn't inject power into the 22 kV grid. The entire demand was supplied by the national transmission system through the 60 kV line. In this case, the 60/22 kV transformers at the Boujdour substation operated in step-down mode. When PV generation started, the plant supplied part of the demand, which increased with irradiance. During this transition period, the transmission grid supplied the remaining power demanded. When PV generation exceeded the local demand, the surplus power was injected into the transmission grid via the 60 kV line. In this case, the 60/22 kV transformers operated in step-up mode.

Figure 10 shows the simulation results from 17/02/2024, namely power curves and voltage profile:

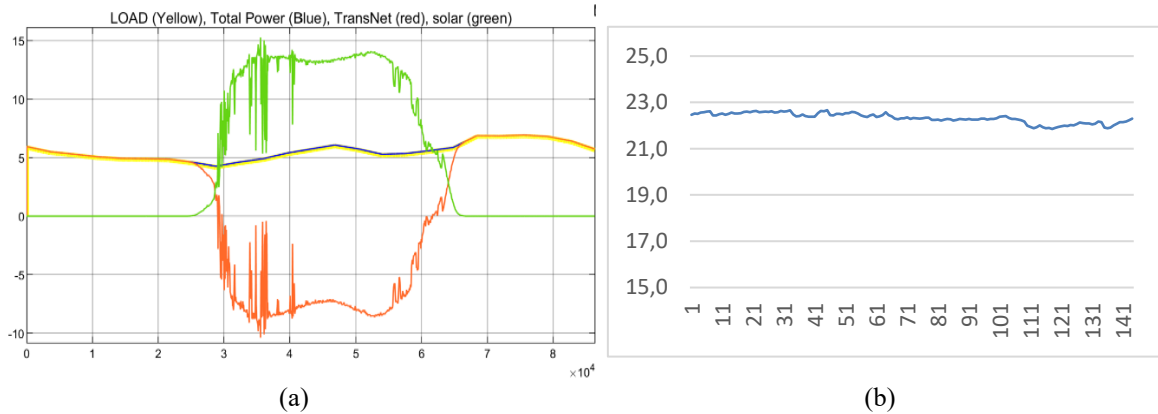


Figure 10. Simulation results from 17/02/2024 (a) Active power curves (MW) (b) Voltage profile (KV)

In addition to previous observations, fluctuations in injected PV power due to irradiance variability were also reflected in the exported power to the transmission grid.

3.2. Simulation results of Scenario 2: Loss of the Main Grid

Figure 11 shows the simulation results from 22/02/2025 to 24/02/2025, namely the power and voltage profiles:

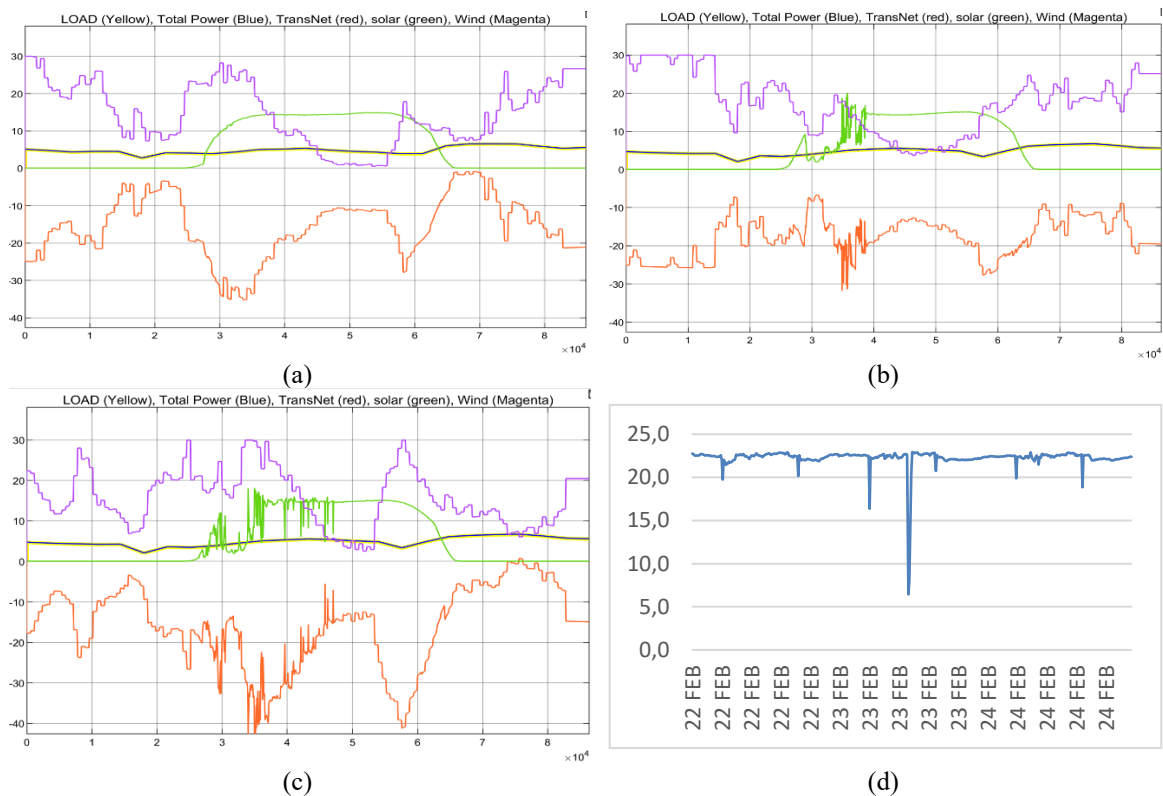


Figure 11. Simulated Active power (MW) (a) Day 22/02/2025 (b) Day 23/02/2025 (c) Day 24/02/2025 (d) Voltage profile (KV)

Before 08h, irradiance was very low and the PV plant no longer injected power into the 22 kV grid. The entire load demand was supplied by the wind farm through the 22 kV network after transformation at the 33/22 kV substation. In this case, the wind farm transformer operated in step-down mode.

When PV generation started, it supplied part of the load, increasing with irradiance, while wind generation covered the remaining demand.

When PV generation exceeded demand, the PV plant fully supplied the load, wind generation no longer injected power into the 22 KV grid, and surplus energy was injected into the transmission system via a 33/400 kV connection at the wind farm. In this case, the 33/22 kV transformers operated in step-up mode.

3.3. Discussion

This research investigated the positive impacts and operational challenges associated with supplying a distribution network using wind and solar energy sources. It evaluated the ability of the system operator to manage the volatility of RES despite their intermittency and variability, combined with load fluctuations.

Models of the PV solar plant, wind farm, and the Boujdour distribution network were developed under MATLAB/Simulink. The developed models were validated using real SCADA data measurements [28].

Then, two scenarios of operation were simulated to evaluate system behavior and intermittency management, under operational constraints in presence of renewable solar and wind sources.

The first scenario assessed the behavior of PV injection coupled with the national transmission grid over a 24-hour period. Results (Figure 9 and Figure 10) showed that PV generation was optimal between 08h and 17h. The production-consumption balance was maintained by the national grid, which either supplied or absorbed power to compensate for the mismatch between PV generation and 22 kV load demand. The intermittency observed at the beginning and the end of PV production (Figure 10(a)) doesn't affect system balance nor voltage quality (Figure 10(b)), which remained within the acceptable range of 21.9 kV to 22.7 kV.

The second scenario evaluated system behavior under combined PV and wind operation without the 60 kV main grid supply. Figures 11(a)–(c) show significant wind volatility over 24 hours, together with PV variability on 23–24 February, particularly during PV ramp-up periods. The hybrid PV–wind configuration improved renewable utilization and enabled the modeled generation to cover the power demand during the analyzed periods. The voltage profile in Figure 11(d) remained within the expected operating range for most of the simulation period, with values generally between 21.5 kV and 22.9 kV. However, some voltage excursions were predicted by the model, with minimum values of approximately 6.4 kV, 8 kV, and 14 kV on 23–24 February between 08h20 and 12h00. Relative to the 22 kV nominal level, these values correspond to voltage depressions of approximately 71%, 64%, and 36%, respectively. Such severe excursions should be regarded as critical system-level indicators even if they didn't cause service interruption or system collapse Figures 11(b)(c).

The hybridization therefore improves the modeled renewable supply complementarity, but the severe voltage excursions demonstrate that loss of the main grid can create critical voltage sensitivity. Increasing renewable penetration is also constrained by the power-transfer capacity of transmission lines and transformer ratings at evacuation substations. In fact, the wind-farm 33/22 kV substation is rated at 10 MVA, and the associated 22 kV feeder uses a 75.5 mm² All Aluminium Alloy Conductor. For the PV system, inverter and transformer capacity is limited to 15 MWp. Any further increase in renewable penetration requires detailed feasibility studies and infrastructure investment.

The present study should be viewed as a technical baseline for a future smart-grid architecture. The next stage should integrate: (i) a communication layer based on appropriate substation/distribution protocols such as IEC 61850; (ii) a BESS model with state-of-charge constraints and charge/discharge dispatch; (iii) forecasting modules for load, solar irradiance, and wind generation; and (iv) supervisory energy-management and grid-forming control strategies. IEC 61850-based communication can support automated monitoring and control, while BESS can mitigate renewable fluctuations and provide fast flexibility, [13], [14], [29]–[31]. AI-based forecasting and optimization can subsequently be evaluated using the SCADA database, but no AI forecasting or BESS dispatch is claimed in the present work.

The occurrence of voltage excursions during PV ramp-up can be attributed to the sensitivity of the relatively weak MV network to renewable and load variations. After 60 kV grid loss, upstream voltage support is removed, increasing this sensitivity, while the OLTC cannot compensate instantaneously. This interpretation is consistent with the effects of DER penetration, feeder impedance, and voltage-control mechanisms [10], [12]. The average-value model, however, does not resolve detailed converter or electromagnetic dynamics and does not calculate THD and dynamic power-factor behavior that require a detailed EMT or high-fidelity dynamic model [11], [12].

3.4. Energy study

Under grid-connected operation with PV injection (scenario 1), voltage regulation is ensured by on-load tap changers (OLTC) of the 60/22 kV transformer connected to the 60 kV transmission line. The PV plant internal voltage control system is deactivated. The voltage setpoint is 22 kV, with regulation triggered for $\pm 2\%$ deviation following an inverse time curve and the allowable voltage limits over 60 s are -25% and $+10\%$.

Since regulation is performed at the 60/22 kV transformer level and 60 kV voltage is not measured at the PV plant, reactive power control of the PV system is based on a power factor constraint and cannot be directly controlled with respect to 60 kV or 22 kV voltage levels. In practice, the PV plant did not comply with contractual power factor requirements when operating in consumer mode ($\cos \phi < 0.8$), leading to financial

penalties due to reactive power consumption during the period January–July 2019. These penalties amounted to approximately 2.5 million MAD.

To mitigate this issue, the PV operator enforced a unity power factor setpoint ($\cos \varphi = 1$) in its internal SCADA system. However, power factor degradation was still observed during communication failures.

In the case of combined PV and wind operation (scenario 2), voltage regulation is ensured by the OLTC of the 33/22 kV wind farm transformer, while PV voltage control remains inactive. When voltage deviations exceed $\pm 2\%$ of the 22 kV setpoint, regulation responds within 10 seconds.

For the present penetration level, the voltage profile indicates acceptable operation for most of the modeled period, but the extreme excursions identified in Scenario 2 prevent a general conclusion of voltage acceptability under main-grid loss. The results instead identify periods that require further investigation with detailed dynamic and power-quality models.

The distribution system, initially designed for unidirectional power flow from the 60 kV transmission system to consumers via the 60/22 kV substation, has become a bidirectional network system [32]. As a result, system design adaptation is required, including sizing, reinforcement, and protection system updates.

For example, in 2024 the PV plant delivered a total of 43.69 GWh to the 22 kV network of which 22.51 GWh was exported to the transmission grid during periods when generation exceeds demand.

The PV plant, with an investment cost of 302 million MAD and an expected annual production of 45 GWh, contributes to CO₂ emission reduction of approximately 23 855 tCO₂/year [33].

From a commercial perspective, PV energy sales are based on a revenue-sharing model between ONEE and the Moroccan Agency for Sustainable Energy (MASEN). In fact, the energy selling price is set at 0.75 MAD/kWh, of which 0.5 MAD/kWh is allocated to the plant operator (all-inclusive cost), and 0.25 MAD/kWh is shared equally between ONEE and MASEN. In comparison, the average purchase price of conventional energy from the national grid is 0.808 MAD/kWh, resulting in a net benefit of 0.183 MAD/kWh for the distributor when using solar energy. The estimated annual gain is 7.99 million MAD.

Wind energy contribution to the 22 kV network remained limited, as it was mainly used during outages of the 60 kV transmission line (case of maintenance or unexpected failures).

The average technical loss rate in the transmission system is 5.4%. Without the PV injection, annual energy losses amount to 2.36 GWh, corresponding to financial losses of around 1.9 million MAD.

4. CONCLUSION

This work focused on the development and simulation of a system-level model of the Boujdour distribution network in southern Morocco, including photovoltaic and wind renewable energy sources. The principal contribution is the use of an actual 22 kV regional network and real operational SCADA measurements for model validation, followed by scenario-based assessment of renewable intermittency, power balance, voltage behavior, and infrastructure constraints.

At the current RES penetration level, simulation results indicated that the system can accommodate intermittency with acceptable performance, although sensitivity increases under PV–wind hybridization.

PV integration maintained acceptable voltage behavior for most of the grid-connected operating period, reduced technical losses by 5.4%, and generated annual energy savings of 2.36 GWh, corresponding to 1.9 million MAD. Other benefits from PV energy trading were estimated at 7.99 million MAD per year. Penalties associated with reactive power consumption can be avoided by enforcing a unity power factor setpoint at inverter level instead of SCADA-based control.

The PV–wind combination improves the modeled temporal complementarity of renewable generation and can reduce dependence on the main grid during the analyzed operating periods. However, the results do not establish islanded frequency stability, inverter FRT capability, or converter-level transient stability. The severe voltage excursions predicted in Scenario 2 should therefore be treated as critical system-level indicators requiring further study.

Voltage levels remained acceptable despite occasional deviations. The system operator is encouraged to adopt similar voltage regulation schemes at the wind farm as those used at the main 60/22 kV substation.

However, technical constraints remain significant. When demand increases, the 33/22 kV substation capacity (10 MW) and the 22 kV feeder conductor section (75.5 mm²) limit power transfer capability. Therefore, reinforcement of network infrastructure is unavoidable.

The present work does not implement a complete smart-grid architecture, BESS dispatch, AI-based forecasting, IEC 61850 communication, or grid-forming control. These functions are future extensions. A next-generation study should combine the validated network with detailed inverter and diesel dynamics, frequency regulation, grid-forming controls, BESS energy management, communication models, and power-quality metrics such as THD and voltage unbalance [11]–[14], [34]–[36].

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