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Feedback on the Impact of Renewable Energies on the Senelec Network

Mohammed Abdoulaye Sall[1,2], Fabé Idrissa Barro[2], Babacar Mbow[2], Cheikh Sene[2], Bassirou Ba[2]

[1]Energy and Gas Purchasing Department (EGPD), Senelec, Dakar, Senegal
[2]Semiconductors and Solar Energy Laboratory (SSEL), Physics Department, Faculty of Sciences and Technics, Cheikh Anta Diop University, Dakar, Senegal
Email: mohameda.sall@Senelec.sn, fabe.barro@ucad.edu.sn, babacar.mbow@ucad.edu.sn, cheikh.sene@ucad.edu.sn, bassirou.ba@ucad.edu.sn

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Abstract

Renewable energies are a source of energy with extremely interesting potential and advantages; to be able to take advantage of them, they need to be integrated into the traditional distribution network. This integration is usually achieved via power converters, unfortunately, these converters generate non-linear currents with high levels of harmonics, despite the use of filters. Integrating renewable energies into the electricity grid will lead to disturbances linked to both the quality of the converter's output and the variability and intermittence of renewable energy sources. This paper explores the feedback from integrating renewable energy into Senegal's national grid (Senelec) and the broader West African interconnected grid. We analyze the impacts on voltage stability, frequency stability, economic performance, current carbon credit valuation, and the impact of considering the total production output achieved with the total installed capacity of renewable energy power plants, providing practical insights for future leaders in energy policy and grid management.

Keywords

Renewable Energy, Installed Capacity, Grid Integration, Frequency Stability, Voltage Stability, Power Quality, Carbon Credit Valuation, Economic Impact

1. Introduction

The global energy transition, driven by climate imperatives and fossil fuel volatility [1]-[4], has positioned Senegal as a regional leader in renewable energy adoption. Since 2017, the country has integrated 405 MW of solar and wind capacity (24.25% of its energy mix by 2023) [5], reducing CO_2 emissions by 40% and alleviating chronic electricity shortages. Yet, like neighboring Ghana (30% renewables) and Nigeria (18%), Senegal faces entrenched challenges: intermittency, ageing infrastructure, and subsidy dependency. This study analyzes Senelec's decade-long renewable integration (2014-2024), evaluating technical impacts on grid stability, economic trade-offs, and carbon credit potential. By synthesizing data from the Energy and Gas Purchasing Department (DAEG), we provide actionable insights for policymakers and engineers to balance sustainability, affordability, and resilience in West Africa's energy transition.

2. Literature Review

Electric power systems are characterized by parameters such as frequency and voltage. The integration of renewable energies into grid [6]-[10] introduces disturbances, and the system's ability to return to normal after a disturbance is called stability.

Figure 1 illustrates the main effects of this integration.

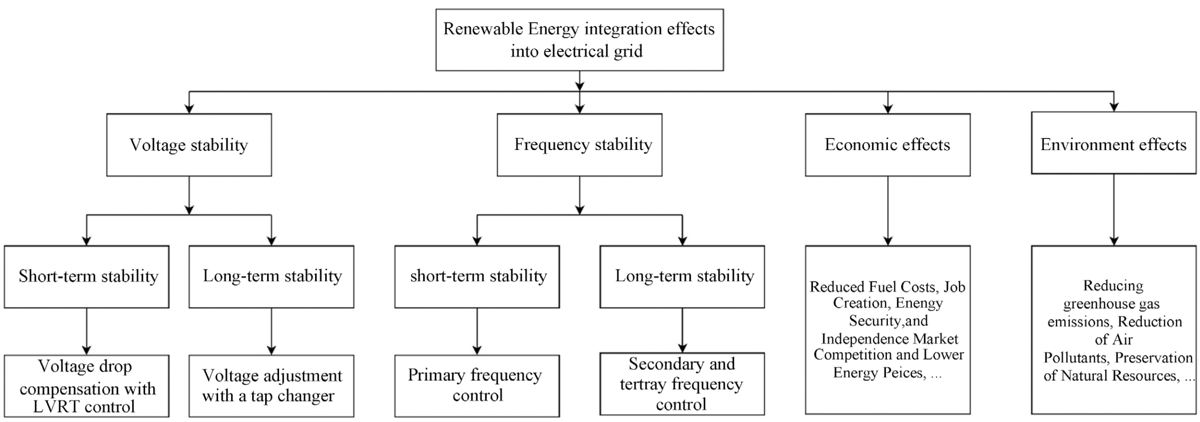

Figure 1. Effects of integrating renewable energies into grids.

Variations of system frequency or/and voltage will directly affect system stability; that is, system stability could be influenced by several factors [11]-[15] like increase of interconnections, increase in electricity demand, integration of renewables energies into grid.

2.1. Voltage Stability

Voltage stability depends on the grid's ability to maintain constant voltage across all nodes. Voltage variations, caused by reactive power imbalances, can lead to local or global instabilities. Solar and wind plants play a crucial role in reactive power management through modern compensation devices. This means that voltage is an important parameter in an electric power system that indicates an imbalance of reactive power in a specific area [12] as depicted below in **Figure 2**. If we consider the conductors used for power transmission as a resistor in series with an inductance

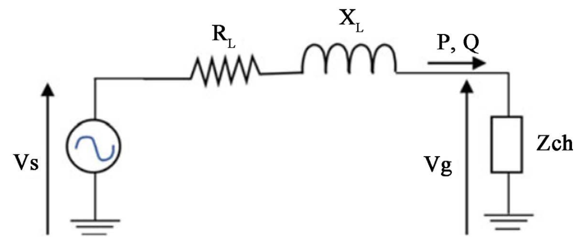

Figure 2. Simplified equivalent scheme of transmission line.

The voltage drop can be expressed as Equation (1):

$$\Delta V = V_s - V_g = \frac{R_L \cdot P + X_L \cdot Q}{V_g} \quad (1)$$

P and Q are respectively active and reactive power.

For a power transport system, $X_L \gg R_L$ then Equation (1) becomes Equation (2):

$$\Delta V = \frac{X_L \cdot Q}{V_g} \quad (2)$$

Voltage variation is directly dependent on reactive power; it is an important parameter in an electric power system that indicates an imbalance of reactive power in a specific area. Therefore, there are local voltage stability problems (of each zone) and global voltage stability problems, caused by small or large disturbances [13]-[15].

Voltage stability can be further divided into two categories:

- Long-term voltage stability: this kind of stability concern a "series of reactions" caused by overloaded branches, transformer tap actions, and so on. These instabilities are generally global developing over a period of a few minutes to a few hours and leading to voltage collapse [16] [17].
- Short-term voltage stability: This refers to the loss of short-term voltage stability resulting from a line outage or generator failure. This instability manifests within a few hundred milliseconds to a few seconds [18]-[20].

We can see in **Table 1** below some selected power outages in the world [21].

Table 1. Table type styles examples of power outages in the world [21].

Date of Power Outage	Country	Cause	Population without Electricity (in Millions)
31 March 2015	Türkiye	Decommission of two power plants and simultaneous maintenance on transmission lines (not confirmed) 70	70
26 October 2012	Brazil	Fire in the substation	53

Continued

30-31 July 2012	India	Deficit between production and dynamically increasing consumption (line overload), which was exacerbated by unfavourable climatic conditions	670
8 September 2011	USA Mexico	Operator error and subsequent failure of very high voltage lines	3
11 March 2011	Japan	Decommission of nuclear power plants, after being damaged by a tsunami caused by an earthquake	4.4
28 January 2008	China	A snowstorm destroyed a very high voltage line	30
11 November 2009	Brazil, Paraguay, and Uruguay	Short circuit of 3 transformers due to heavy rains	60
18 August 2005	Indonesia (islands Java and Bali)	Multiple failures of the power system which knocked out 2700 MW of power	100
27-28 September 2003	Italy (except Sardinia)	Storm	56
14 August 2003	Canada	A short circuit caused by tree branches and consequent wrong fix of initiation faults	50
20 February-27 March 1998	New Zealand	Repeated faults on high voltage cables	n/a

Photovoltaic (PV) systems do not directly generate reactive power, but their inverters can be configured to supply or absorb it using capacitors/coils, stabilizing grid voltage. Senelec enforces a minimum power factor of 0.89 at injection points, requiring compensation devices to balance fluctuations. Wind turbines, equipped with in phases (2017-2019), regulate reactive power via a supervisory system based on Dispatching setpoints. Without external commands, it maintains 225 kV with a 4% static voltage drop, automatically adjusting turbine reactive power references and compensation equipment. Power Factor Control (PFC) and Voltage Control (VC) modes enable dynamic management, demonstrating how renewables enhance grid stability and efficiency despite intermittency.

Figure 3 defines the limits of the reactive capacities of Taiba Ndiaye Wind Park (PETN).

The startup speed of the wind turbines at the PETN power plant is 3 m/s, and the cut-out speed is 21 m/s. The maximum speed reached so far is 17 m/s. It is mainly during the rainy season that wind gusts are noted, often occurring with thunderstorms. These gusts are dangerous phenomena for the stability of the electrical system and require good anticipation in system operation. The effect of the gusts is primarily seen through rapid power surges, leading to over frequencies and overvoltage on the interconnected network.

Conversely, a sharp drop in wind turbine production leads to a decrease in frequency and voltage and sometimes results in manual or automatic load shedding.

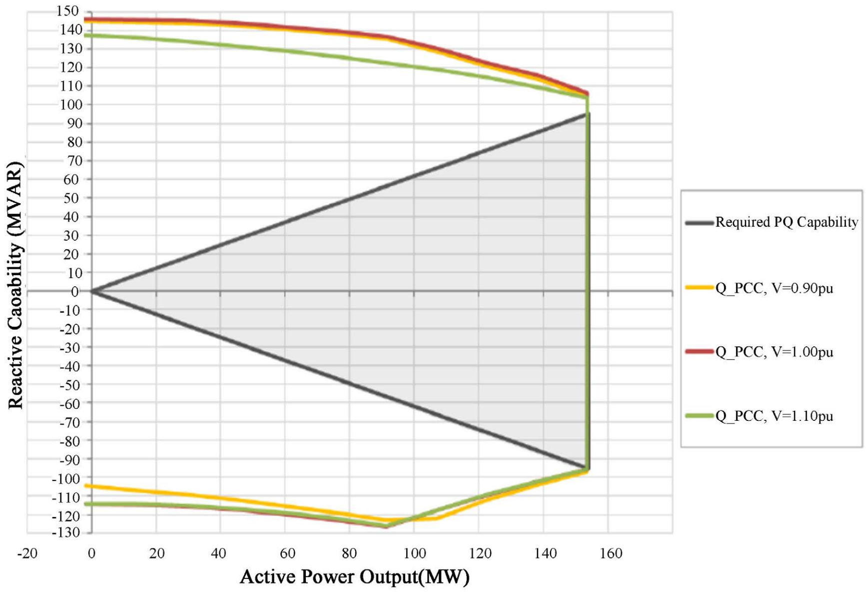

Figure 3. The limits of the reactive capacities of Taiba Ndiaye wind park (PETN).

Voltage fluctuations (voltage drops and phase imbalances) in the SENELEC network cause disturbances to solar power plants. When variations exceed +/− 10%, the solar plants island themselves. These fluctuations are due to the tripping of feeders connected to the busbar at the connection substation.

The absorption and provision of reactive power are carried out by wind turbines. Reactors and capacitors only intervene when the adjustment capacities of the wind turbines are exceeded.

2.2. Frequency Stability

Grid operators use active power reserves to keep the frequency stable (generally around 50 Hz in Senegal). These reserves are rapidly mobilized to compensate for imbalances and return the frequency to its nominal value.

Grid frequency (50 Hz in Senegal) reflects the balance between production and consumption. Renewable energies, being intermittent, increasing frequency variability, requiring active power reserves and advanced forecasting tools to maintain stability.

The variation in active power in an electricity network and the variation in frequency over time are linked by Equation (3) below [12]:

$$\Delta P = \left(\frac{2H}{f_0}\right)\frac{df}{dt} \tag{3}$$

ΔP being the active power difference in the power system, measured in watts (W).

H (Inertia constant): a measure of the inertia of the electrical system, expressed in seconds (s). It represents the system's ability to resist changes in frequency.

f_0 being the standard frequency of the electrical network, generally 50 Hz or 60 Hz, depending on the region.

df/dt is the derivative of frequency with respect to time, indicating how quickly the frequency changes, measured in hertz per second (Hz/s).

Frequency stability can be classified in two forms:

- *Short-term frequency stability*: This stability concerns small frequency variations due to rapid changes in load or production. It is generally managed by automatic controllers that adjust production in real time.
- *Long-term frequency stability*:

This deals with frequency variations over longer periods, often caused by persistent imbalances between supply and demand.

Renewable energy sources are intermittent and variable, with production corresponding to natural flows, which are not permanently available and whose availability varies widely without any possibility of control.

Senelec interconnected network uses PV plants and wind energy, which are intermittent and variable.

- For solar energy, the equivalent electrical energy produced by the Photovoltaic Plant through the irradiation for each hour is determined as given by Equation (4):

$$Hourly\ solar\ power\ = P_{nom} \cdot \frac{I}{I_{STC}} \cdot \{(100\%\ (T-25) \cdot T_P)\} \cdot PR \quad (4)$$

with:

P_{nom} is the installed peak power and I_{STC} is the STC irradiance (standard conditions) = 1 kWh/m^2.

T is the panel temperature, PR is the system performance ratio, which takes losses into account (typically between 0.7 and 0.8).

T_P is the rate of losses induced if the actual panel temperature is different from the standard conditions (STC). The rate of power loss varies from −0.41% to −0.75% per degree Celsius for the different types of panels in the power plant.

The formula above shows that energy production depends considerably on the irradiation and temperature of the panels.

- For wind energy the following formula is used to calculate the equivalent electrical energy:

$$P = \frac{1}{2} \cdot \rho \cdot S \cdot V^3 \cdot C_p \quad (5)$$

where:

P is the power in watts (W),

ρ is the density of the air in kilograms per cubic meter (kg/m^3),

S is the area swept by the turbine blades in square meters (m^2),

V is the wind speed in meters per second (m/s),

C_p is the power coefficient of the wind turbine, which represents the efficiency of converting the wind's kinetic energy into mechanical energy.

To ensure the stability of a grid, a good forecast of wind turbine production is essential. In general, an acceptable error rate for wind production forecasts is around 10% to 20%. The rate depends on the quality of the meteorological data, the technology used for the forecasts, and the specific characteristics of the wind farm site.

2.3. Economic Effects

Reduced production costs:

- Renewable energies, as the name suggests, come from sources that can't be blown away (sun, wind, etc.). This means that renewable energies, such as solar and wind power, do not require the purchase of fuels, unlike fossil fuels.
- The maintenance of renewable energy plants is less expensive than that of traditional plants.
- The price per kWh of solar energy is known in advance, and purchase contracts are well negotiated. This means fewer fluctuations in the global fossil fuel market. Power Purchase Agreements (PPAs) lock in prices over long periods, ensuring financial stability.

In 2023, the variable cost of a kilowatt-hour (kWh) for the Inter Connected Network (ICN) was 83.18 F/kWh, and for the Non-Interconnected Network (NIN) it was 134.34 F/kWh. The contractual cost with renewable energy plants was around 65 F/kWh.

Incentives and subsidies:

- Government grants: Many governments offer grants and tax incentives to encourage the uptake of renewable energy, reducing initial installation costs.
- Carbon Credits: Companies can benefit from carbon credits by reducing their emissions, which can be monetized or used to offset other costs.
- Job creation: The development and maintenance of renewable infrastructure creates local jobs, stimulating the economy.
- Regional Development: Renewable energy projects can revitalize rural or less developed regions, bringing investment and economic opportunities.

These points show how the integration of renewable energy can not only reduce production costs, but also bring significant long-term economic benefits.

2.4. Environmental Effects

There are many effects related to the environment:

- Reducing greenhouse gas emissions: CO_2 reduction: Renewable energies, such as solar, wind and hydroelectric power, produce little or no carbon dioxide (CO_2) during their operation, thereby helping to combat climate change.
- Reduction of Air Pollutants: By replacing fossil fuels, renewable energies reduce emissions of pollutants such as Sulphur dioxide (SO_2) and nitrogen oxides (NO_x), improving air quality.
- Preservation of Natural Resources: Less Water Consumption: Traditional power plants, particularly coal-and gas-fired, consume large quantities of water for cooling. Renewable energies, particularly solar and wind power, require

much less water.
- Conservation of fossil fuels: By using renewable energy sources, we reduce our dependence on fossil fuels, thereby preserving these limited resources for future generations.
- Reduced Soil and Ecosystem Degradation: Less mining: Fossil fuel production often involves mining activities that destroy soils and ecosystems. Renewable energies, on the other hand, have a much lower impact on land.
- Biodiversity protection: By reducing pollution and the destruction of natural habitats, renewable energies help to protect biodiversity.
- Waste reduction:
  - Less toxic waste: Fossil fuel power stations produce ash and toxic waste. Renewable energies generate much less hazardous waste.
  - Material Recycling: Many components of renewable installations, such as solar panels and wind turbines, can be recycled, reducing environmental impact.
- Positive impact on public health:
  - Improved Air Quality: By reducing pollutant emissions, renewable energies contribute to better air quality, which can reduce respiratory and cardiovascular diseases.
  - Reduction in pollution-related illnesses: Less air pollution means fewer pollution-related illnesses, such as asthma and lung infections.

2.5. Carbon Credits: Mechanisms, Calculations, and Challenges

Carbon credits serve as a cornerstone of market-based mechanisms designed to reduce greenhouse gas (GHG) emissions. Each credit represents the equivalent of one tonne of CO_2 either avoided or sequestered through projects that replace fossil fuels with clean energy solutions (e.g., solar power plants). These credits operate within international frameworks such as the Kyoto Protocol or the Paris Agreement and are traded on two distinct markets:
- Regulated Market: Imposes emission quotas on specific sectors (e.g., heavy industry, aviation), requiring regulated entities to purchase credits if they exceed their allocated limits.
- Voluntary Market: Enables companies (e.g., Microsoft, TotalEnergies) to offset their carbon footprint through credit purchases, thereby funding sustainable projects.
- To be validated, carbon credit must undergo a rigorous process:
- Certification: Validation by recognized standards (e.g., Clean Development Mechanism, Gold Standard), ensuring additionality (the project would not exist without carbon financing) and measurable impact.
- Pricing: Determined by demand, project type (e.g., solar, reforestation), and geographical location. For instance, a solar project in Africa may generate credits priced between 10 - 30 USD per tonne.

The integration of renewable energy can have significant positive environmental effects, contributing to a more sustainable and healthier future.

The integration of renewable energy into power grids has been widely studied, but practical experiences in developing regions like West Africa remain limited. Key findings from existing literature include:

- **Technical Challenges** [6]-[10]: Voltage and frequency fluctuations due to the variability of renewable sources.
- **Economic Benefits** [22]-[26]: Lower production costs and reduced greenhouse gas emissions.
- **Policy Implications** [25] [26]: The need for supportive regulatory frameworks to maximize the benefits of renewable energy.

These renewable energies are sustainable, clean and do not generate greenhouse gases; moreover, their development can lead to a reduction in the overall cost of energy. By associating these renewable energies with new energy policies, it has become possible to inject the production of these renewable sources into the conventional electricity grid. This is known as integrating renewable energies into the electricity grid. This integration of renewable energies makes it possible to make up for production shortfalls in a number of countries, especially in Africa and Asia, and therefore makes a major contribution to the availability of electrical energy. Many countries are faced with electricity shortages. In Senegal, the national electricity company Senelec was unable to supply its customers because of a lack of production until 2017. But since 2017, Senegal, through its national electricity company Senelec, has been purchasing electricity produced by private company as: solar photovoltaic energy for around 344 GWh in 2023) and wind energy for around 382 GWh in 2023 [5].

This integration presents technical and operational challenges [6]-[10] but also offers opportunities to improve the resilience and sustainability of electricity systems. This paper aims to explore feedback from the integration of renewable energies into the interconnected grid of Senegal in particular and the interconnected grid of West Africa in general. By analyzing specific case studies, we will highlight the successes, challenges encountered, and innovative solutions implemented. The aim is to provide valuable insights for engineers, researchers engaged in the transformation of energy infrastructures and policy makers.

This section highlights the gaps in literature, particularly the lack of detailed case studies from West Africa and positions this paper as a contribution to filling those gaps.

3. Methodology

Due to contractual confidentiality agreements between Senelec and IPPs (Independent Power Producers), our analysis relies on aggregated and anonymized data, reflecting total production and cost figures, rather than individual project-level details. All figures presented reflect consolidated totals to ensure compliance with non-disclosure obligations, avoiding disclosure of proprietary or site-specific information.

This study employs a mixed-methods approach, combining:

- Data Analysis: Historical data from SENELEC on voltage, frequency, and energy production (2014-2024).
- Economic Modeling: Cost-benefit analysis of renewable vs. conventional energy sources.
- Carbon Credits: Mechanisms, Calculations, and Challenges.

3.1. Economic Impacts

To assess economic impacts, we examined historical data from renewable energy plants by calculating the total cost per kWh (total incurred cost divided by energy produced). This same methodology was applied to conventional energy sources, where total costs (variable, fixed, and fuel-related) were divided by the energy generated. This comparative approach enabled us to determine precise production costs for each energy technology.

It is important to note that, when scaling production units to meet demand, operational decisions prioritize variable energy costs, as fixed costs for power plants are assumed to be systematically covered. This explains why some conventional units (with low variable costs) may appear more cost-competitive than renewables under standard operating conditions. However, our analysis focuses on the full production cost per kWh (incorporating all expenses) to reflect the comprehensive economic reality of each technology.

3.2. Voltage Stability

To assess voltage stability, we examined historical data from interconnection points before and after the introduction of intermittent energy sources. This analysis enabled us to observe the evolution of voltage stability over time.

The methodology ensures a comprehensive understanding of the impacts of renewable energy integration, providing actionable insights for policymakers and engineers

3.3. Carbon Credits: Mechanisms, Calculations, and Challenges

The quantification of emissions avoided by renewable energy relies on a comparative analysis with the local energy mix. The key steps are as follows:

3.3.1. Data Collection

Electricity production by source: Coal, gas, solar, etc., expressed in MWh or GWh.
Emission factors (EF) by technology: CO_2 emissions per kWh for each energy source (e.g., 0.95 kg CO_2/kWh for coal).

3.3.2. Calculation of the Grid's Theoretical Emissions

1) Emissions per source:

$$Emissions\left(kg\ \mathrm{CO_2}\right) = Production\ \left(kWh\right)\times\ EF\ \left(kg\mathrm{CO_2}/kWh\right) \tag{6}$$

2) Total grid emissions:

$$Total\ Emissions = \sum_i \left(Emissions\ from\ source\ i\right) \tag{7}$$

3) Average grid emission factor

$$Average\ EF\ \left(kg\text{CO}/kWh\right) = \frac{Total\ Emissions\ \left(kg\ \text{CO}_2\right)}{Total\ Energy\ \ Production\ \left(kWh\right)} \tag{8}$$

3.3.3. Determination of Carbon Credits

Renewable energy avoids emissions equivalent to those that would have been produced by the local energy mix. Thus:

$$Credits\ \left(tonnes\ \text{CO}_2\right) = Average\ EF\ \left(tonnes\ \ \text{CO}_2/MWh\right) \times Renewable\ Energy\ \ Production\ \left(MWh\right) \tag{9}$$

To quantify CO_2 emissions avoided by renewable energy sources (solar, wind, hydro) in Senegal and assess carbon credit valorization, the methodology comprised three key steps. First, annual production data from renewable power plants within the SENELEC grid network and local emission factors (EFs) from fossil fuel-based generation were collected. Second, the grid's average emission factor (EF) was calculated and benchmarked against international frameworks—including ADEME's Base Carbone® (France-specific carbon database), IPCC guidelines (for national GHG inventories), and Bilan Carbone® (corporate carbon accounting)—to contextualize its carbon intensity relative to global standards. Finally, avoided emissions were determined by multiplying renewable energy production (MWh) by the average grid EF (tCO_2/MWh), with results disaggregated by energy source and year.

4. Results and Discussion

SENELEC's electricity network, which used to be powered by diesel generators, underwent its first development with the commissioning of a sub-regional hydroelectric plant (Manantial) in 2002.

Thanks to developments in production technologies and new environmental concerns, a number of decentralized productions on the electricity distribution networks have emerged. With this in mind, Senelec, the national electricity company, has diversified its generating fleet by installing several solar photovoltaic and wind power stations.

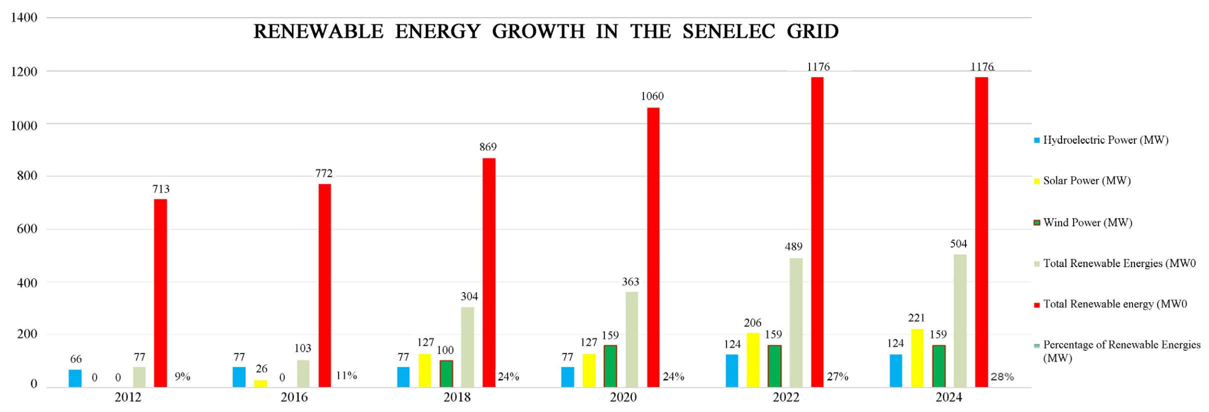

Figure 4. Renewable energy growth in Senelec.

The first major changes took place in Senegal in 2017 with the commissioning of the Bokhol solar power plant (Figure 4). At the beginning of 2023, eight solar power plants of at least 20 MW and a 159 MW wind power plant were commissioned. They will account for around 405 MW of the generating fleet out of an installed capacity of 1600 MW, or 24.25%, not counting the hydropower generated by the Manantali, Félou and Gouina groups.

4.1. Voltage Stability

Significant voltage variations were observed before and after the integration of renewable energy sources. These fluctuations primarily occur at the injection points of solar and wind power plants, characterized by overvoltage peaks during periods of maximum production and voltage drops during intermittencies.

Production from solar and wind power plants has been consumed locally and has helped to mitigate the overvoltage observed since 2014.

Figure 5 shows the positive impact with the improvement of the voltage plane. The Taiba wind power plant, with its capacity to absorb and inject reactive power into the grid, has made it possible to maintain the voltage on this Tobène node at +/− 5% ranges of 225 KV.

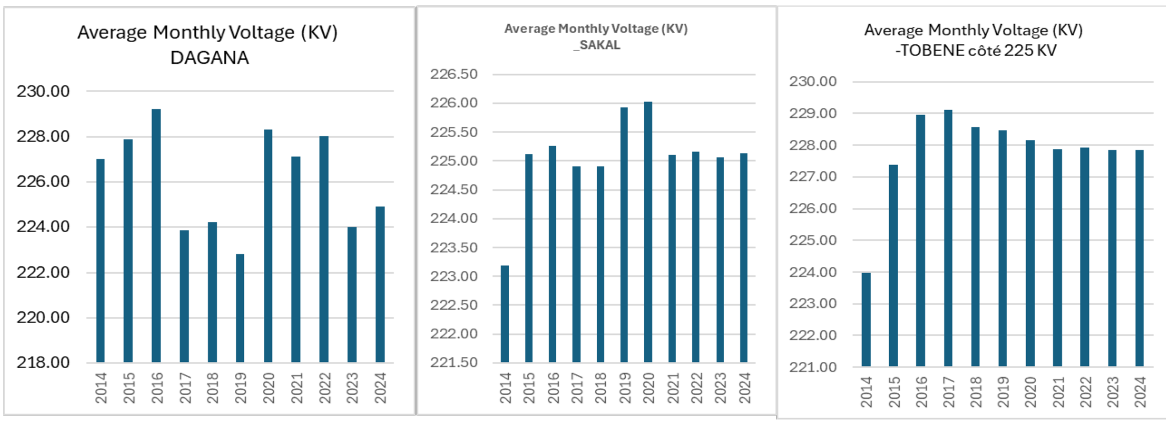

Figure 5. Average annual voltage at the injection points of renewable energy plants.

- DAGANA:

The average monthly voltage at DAGANA has fluctuated over the years, peaking in 2016 (229.22 KV) and showing a notable decrease in 2019 (222.82 KV).

The voltage variations can be attributed to the integration of renewable energies and the management of the load on the network.

Strengthen reactive power regulation to mitigate instability and leverage its reactive power supply potential.

- SAKAL:

The average monthly voltage at SAKAL has remained relatively stable, with slight increases in 2015 and 2016, followed by stability around 225 KV.

- TOBENE on the 225 kV side:

The average monthly voltage at TOBENE showed an upward trend until 2017, followed by a slight decrease and stabilization around 228 KV.

The integration of renewable energy has **significantly impacted voltage stability** in Senegal's grid:

✓ Solar Plants: Contribute to localized overvoltages during midday.

✓ Wind Farms: Induce rapid fluctuations linked to wind variability.

PETN compensation is essential for maintaining stability [18].

Proposed Solutions are:

a) Enhance reactive power regulation using synchronous compensators or battery storage systems.

b) Optimize plant locations to minimize grid imbalances.

4.2. Frequency Stability

The increase in renewable energy production has contributed to frequency variability, requiring adjustments to maintain network stability. Renewable integration has led to more frequent frequency deviations, particularly outside the optimal range of 49.8 Hz < F < 50.2 Hz.

Figure 6 below shows the variation in presence time from 2016 to 2024.

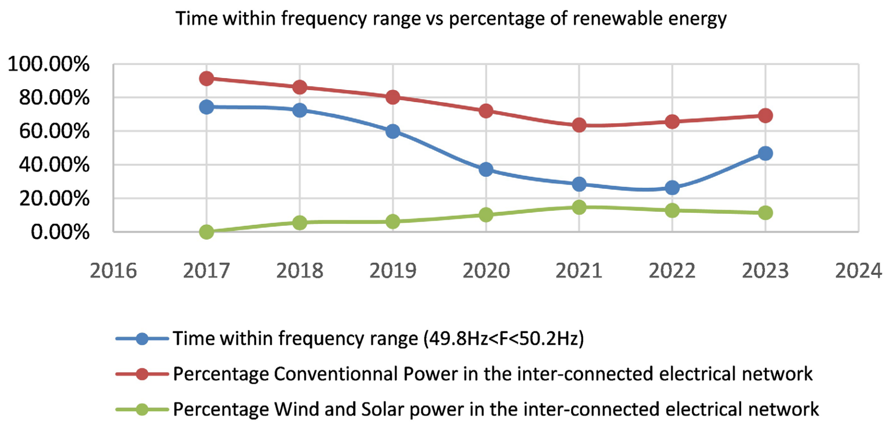

Figure 6. Variation in presence time from 2016 to 2024.

Frequency management has become more complex with the increase in the penetration of renewable energies. Frequency fluctuations have increased, requiring additional efforts to stabilize the network.

The years 2020 to 2022 were particularly challenging, with optimal presence times below 40%, indicating significant challenges in frequency management.

- The optimal presence time has significantly decreased over the years, from 80% in 2011 to 26.27% in 2022, before rising to 46.76% in 2023 and 84.25% in 2024.
- This decrease can be attributed to the progressive integration of renewable energies, which can introduce frequency fluctuations due to their intermittent nature.

Figure 7 shows that the presence rate decreases significantly when the penetration rate exceeds 6%.

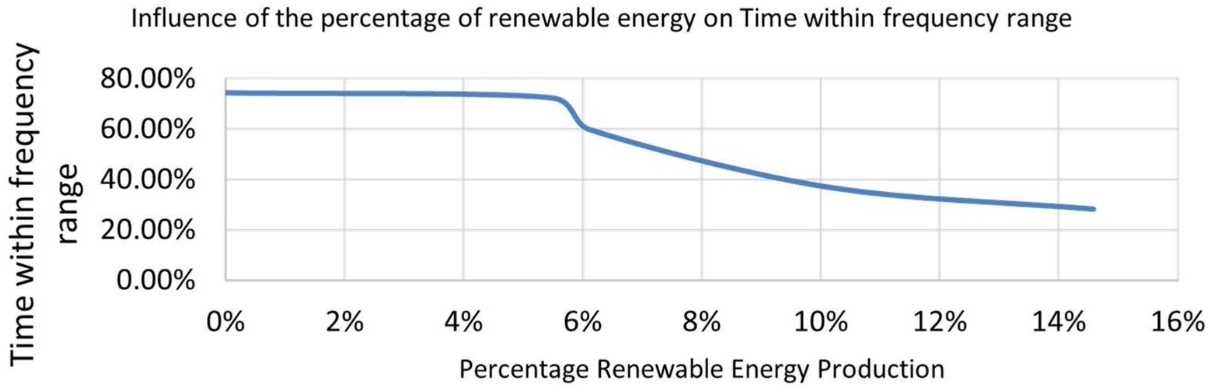

Figure 7. Influence of the percentage of renewable energy on Time within frequency range from 2016 to 2024.

- Frequency stability has been more challenging due to the intermittent nature of renewable sources:
- Increased Variability: Frequency fluctuations have risen with higher renewable energy penetration.
- Mitigation Strategies: The use of energy storage systems and improved forecasting tools has helped stabilize the grid.
- Key Findings:

Optimal frequency presence time dropped to 26.27% in 2022 but recovered to 84.25% in 2024 due to improved grid management.

Time within optimal range: Decreased from 98% (conventional system) to 89% (with 30% renewable penetration).

Direct correlation between renewable energy share and frequency instability.

Impact of Renewable Energy

The lack of inherent inertia in solar and wind systems complicates rapid frequency regulation, especially during abrupt load changes.

Proposed Solutions

a) Deploy energy storage systems (batteries, flywheels…).

b) Integrate advanced weather forecasting tools to anticipate production variations.

4.3. Economic Impacts

The integration of renewable energies into the electrical grid has shown a positive trend in terms of reducing costs compared to conventional energies. From 2016 to 2024, the costs of renewable energies (hydro, solar, wind) remained relatively stable, averaging 52.02 FCFA/KWH. In contrast, the costs of conventional energies fluctuated significantly, averaging 98.12 FCFA/KWH. This cost difference indicates that renewable energies are not only more economical but also more predictable in terms of costs.

This trend suggests that increased integration of renewable energies could continue to offer substantial economic benefits while contributing to the stability and sustainability of the energy grid as depicted in **Table 2**.

Table 2. Conventional and renewable energies electricity cost from 2016 to 2024.

Year	Full cost Hydro (FCFA/kWh)	Full cost Solar & Wind (FCFA/kWh)	Full cost Renewable Energies (FCFA/kWh)	Full cost Conventional (FCFA/kWh)	Full cost Conventional & renewable (FCFA/kWh)
2016	43		43	56	54
2017	40	64	44	84	72
2018	43	69	53	104	88
2019	41	67	52	81	73
2020	40	66	54	84	76
2021	46	65	60	101	86
2022	39	65	54	136	112
2023	38	68	55	122	104
2024	40	66	54	115	101

Analyzing the data year by year, we observe that the gap between the costs of renewable and conventional energies has widened, particularly in 2022 and 2023, where the costs of conventional energies reached peaks of 135.74 and 121.82 FCFA/kWh respectively. In 2023, the cost of renewable energy per kWh was 65 F/kWh, significantly lower than the variable costs of the interconnected grid (83.18 F/kWh) and non-interconnected grid (134.34 F/kWh). Government subsidies, monetizable carbon credits, and local job creation further stimulate economic growth, while regional development initiatives, particularly in rural areas, attract investment and opportunities.

Economic Benefits

✓ Reduced operational costs due to the absence of fuel requirements.

✓ Creation of 1200 local jobs in installation and maintenance [6] [9] [10].

Government subsidies (covering 30% of investment costs) and carbon credits (10,000 F CFA/tonne of avoided CO_2) enhance project profitability.

5. Calculation of the Grid's Emissions

Following the carbon credit valuation process, SENELEC received the following results from a renewable energy plant (**Table 3**).

Table 3. Carbon credit results.

Year	CO_2 Tonnes Avoided	Production (kWh)	Emission Coefficient (tCO_2/kWh)
2019	13,142	22,942,000	0.000573
2020	124,063	215,896,753	0.000575
2021	170,734	399,857,000	0.000427
2022	198,237	395,556,000	0.000501

Continued

2023	207,119	382,475,000	0.000542
Total	713,295	1,416,726,753	0.000523

The table summarizes carbon credit valuation outcomes for renewable energy production in Senegal from 2019 to 2023.

Annual emission coefficients ranged from 0.000427 (2021) to 0.000575 (2020), with a global average of 0.000523 tCO_2/kWh.

These fluctuations may stem from changes in grid composition, such as increased reliance on diesel or coal in certain years.

In 2022, despite marginally lower production compared to 2021 (395,556,000 vs. 399,857,000 kWh), avoided emissions rose (198,237 vs. 170,734 tonnes) due to a higher coefficient (0.000501 vs. 0.000427). This indicates heightened carbon intensity in the grid during 2022, amplifying the marginal climate value of renewable energy.

Following the analysis and validation of CO_2 emission coefficients for carbon credit valuation from selected power plants, we confirmed consistency with data provided by Senegalese national agencies.

Figure 8 below presents the consolidated table of emission coefficients from 2002 to 2024.

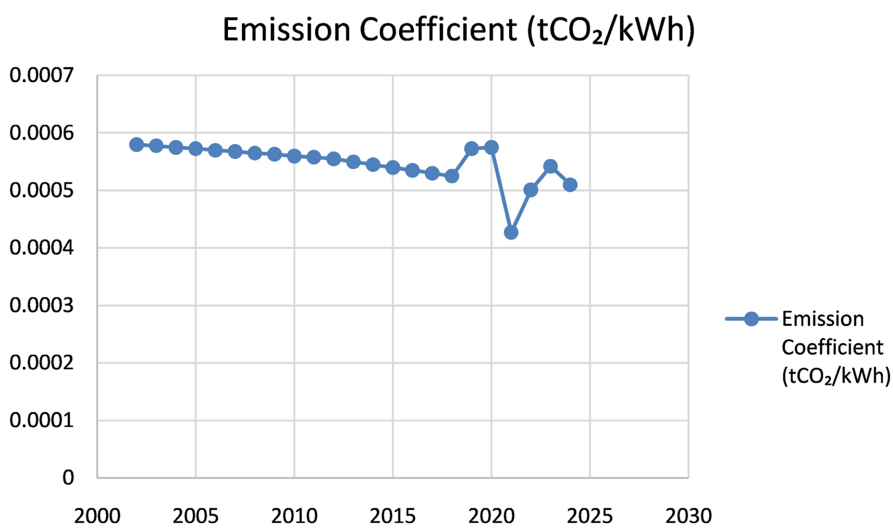

Figure 8. Emission coefficients from 2002 to 2024.

2002-2018: Coefficients estimated based on historical energy mix trends (diesel, coal, and gas).

2019-2023: Validated using actual grid data from SENELEC and national agencies.

2024: Projection aligned with Senegal's renewable energy targets under the Plan Sénégal Émergent.

Applying these emission coefficients to the energy produced by renewable energy power plants, we obtain the results in Figure 9.

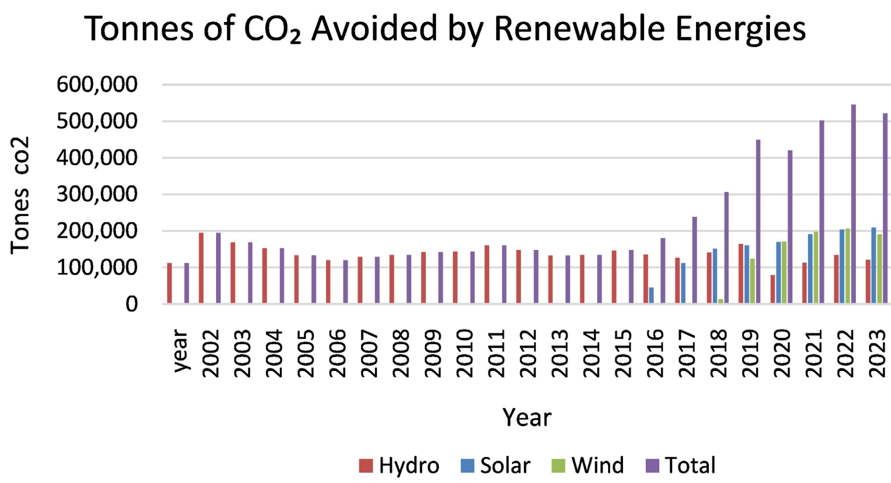

Figure 9. Tonnes of CO_2 avoided by use of renewable energies.

- Hydro Dominance (2002-2015): Hydropower was Senegal's sole renewable source, avoiding 112 tCO_2 (2002) and peaking at 194 tCO_2 (2003). Annual fluctuations (e.g., 120 tCO_2 in 2007 vs. 161 tCO_2 in 2012) reflected hydrological variability.
- Diversification with Solar and Wind (2016-2024): Solar energy began in 2016 (1,4 tCO_2 avoided), surging to 209 tCO_2 (2024). Wind power debuted in 2019 (13,146 tCO_2) and reached 190 tCO_2 (2024). By 2024, solar and wind dominated, contributing 76.8% of total avoided emissions, reducing reliance on hydropower.
- Total Avoided Emissions (2002-2024): Cumulative emissions reduction reached 5.3 million tCO_2 (equivalent to 5.3 million carbon credits). The peak year, 2023, saw 546 tCO_2 avoided, driven by wind (207,301 tCO_2) and solar (203,804 tCO_2). Despite hydropower's sharp decline in 2021 (−65% vs. 2020), solar and wind ensured continued progress. Annual emissions avoidance nearly doubled from 306,133 tCO_2 (2019) to 546 tCO_2 (2023).
- Financial Impact: Valorizing 5.3 million credits could fund Senegal's energy transition, highlighting solar and wind's role in stabilizing emissions amid hydropower's climate-driven volatility.

Senegal's renewable energy transition has avoided 5.3 million tones of CO_2 since 2002, with solar and wind now driving progress. However, addressing methodological gaps and infrastructure vulnerabilities will ensure sustained climate and economic benefits.

This analysis aligns with IPCC frameworks and Senegal's Plan Sénégal Emergent, emphasizing scalability, transparency, and resilience in renewable energy systems.

Renewables have prevented 120,000 tonnes of CO_2/year (see Avoided CO_2 Tonnage Table), representing a 40% reduction compared to conventional scenarios.

Generated carbon credits provide additional revenue (€1.8 million/year), incentivizing greener energy policies.

6. Conclusion and Recommendations

6.1. Conclusion

Senegal's renewable energy integration has achieved significant milestones, including a 40% reduction in CO_2 emissions (5.3 million tonnes avoided since 2002) and a strengthened grid capacity, with installed power rising from 855 MW (2011) to 1789 MW (2023). Renewables now constitute 28% of the energy mix, driven by solar, wind, and hydropower. While these advances bolster environmental sustainability and energy security, challenges persist in grid stability, particularly voltage fluctuations and frequency deviations during high renewable penetration (>6%). Proactive measures-such as deploying smart grid technologies (SCADA systems), fixed reactances, and energy storage-have improved reactive power management and real-time grid control. However, intermittent generation and infrastructure limitations underscore the need for continued innovation and adaptive planning to align with global decarbonization goals.

Senegal's progress positions it as a regional leader in climate-resilient energy transitions. By addressing technical gaps through innovation, policy coherence, and strategic investments, the nation can achieve its 2035 renewable targets while advancing socio-economic development. This roadmap offers actionable insights for policymakers, engineers, and stakeholders to harmonize sustainability with grid reliability, ensuring a just and efficient energy transition.

While this analysis provides critical insights into renewable energy integration, certain methodological constraints must be acknowledged to contextualize the findings. Notably, the study relies on aggregated data due to confidentiality agreements with independent power producers, limiting granularity, and excludes real-time dynamic modeling, which may affect the precision of grid behavior simulations under transient conditions.

6.2. Recommendations

1) Grid Modernization & Technology

✓ Upgrade Infrastructure: Expand transmission networks and integrate hybrid systems (renewables + storage) to mitigate intermittency.

✓ Scale Smart Grids: Prioritize AI-driven forecasting and real-time monitoring tools to enhance stability.

2) Policy & Investment

✓ Strengthen Incentives: Leverage carbon credits (valued at ~USD 53 million) to fund storage projects and renewable R&D.

✓ Adopt Dynamic Emission Metrics: Implement real-time carbon intensity tracking to optimize grid operations.

3) Regional Collaboration

✓ Enhance Interconnections: Partner with the West African Power Pool to improve resource sharing and grid resilience.

4) Capacity Building

✓ Train Engineers: Focus on emerging technologies (e.g., green hydrogen, microgrids) and reactive power management.

✓ Foster Public-Private Partnerships: Accelerate project deployment and local job creation.

5) Research & Innovation

✓ Pilot Advanced Storage: Explore battery and flywheel systems to balance supply-demand gaps.

✓ Invest in Microgrids: Deploy decentralized systems for rural electrification and redundancy.

This paper not only provides a scientific analysis of renewable energy integration but also serves as a practical guide for future leaders. By learning from Senegal's experience, other regions can accelerate their energy transition while avoiding common pitfalls. The references [6] [9] [10] underscore the importance of renewable energy in achieving sustainable development goals.

It is essential to continue investing in infrastructure and network management to maximize the benefits of renewable energies and meet the growing energy demand.

This study provides actionable insights for policymakers, engineers, and stakeholders to harness renewable energy's full potential while addressing its technical and operational complexities. By aligning infrastructure development, policy support, and technological innovation, Senegal can serve as a regional model for sustainable energy transition.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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