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Dynamic Optimization of Electricity Tariffs in Senegal: A Pyomo-Based Model for a Resilient Renewable Energy Mix Toward 2050

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Abstract: This study develops a *Pyomo-based Mixed Integer Linear Programming (MILP)* model to optimize electricity tariffs in Senegal, aiming to design a framework that is economically efficient, socially equitable, and environmentally sustainable. The model integrates generation, storage, and dynamic pricing mechanisms into a unified optimization structure covering the period 2022–2050. Five tariff scenarios are simulated - Reference, Progressive, Feed-in Tariff, Static Hybrid, and Dynamic Hybrid - allowing a comparative assessment of their technical and financial performance. Results demonstrate that the *Dynamic Hybrid* scenario achieves the most favorable outcomes. By 2050, renewable energy reaches *80% of the total generation mix*, while the *average cost of electricity decreases by 18%* (from 83.8 to 68.9 FCFA/kWh). Public subsidies fall dramatically, from *27.5% to 6.8%* of sector revenues. Dynamic hourly pricing reduces peak demand by *12–15%*, limits reliance on thermal generation, and improves system flexibility through expanded energy storage (10% of the mix by 2050). Moreover, the social lifeline tariff (65 FCFA/kWh for the first 50 kWh/month) remains fiscally sustainable, ensuring protection for low-income households. Overall, the study highlights that *dynamic tariff optimization*, enabled by open-source algorithmic tools such as Pyomo, can serve as a strategic instrument for *predictive regulation* and *sustainable energy governance*. Policy recommendations are proposed for institutional strengthening, data-driven tariff setting, and regional integration within ECOWAS, positioning Senegal as a potential model for resilient energy transition in West Africa.

Keywords: Pyomo, Dynamic Pricing, Energy Optimization, Renewable Energy, Senegal

1. Introduction

Access to reliable, affordable, and sustainable electricity remains a major challenge for many emerging economies, particularly in Sub-Saharan Africa. In Senegal, despite the progress achieved through the *Plan Sénégal Émergent* and *Vision Senegal 2050*, electricity prices remain among the highest in West Africa averaging 83.8 FCFA/kWh in 2022[1], while public subsidies still represent nearly 27.5% of total sector revenues[2]. This heavy fiscal burden undermines the financial sustainability of the power sector and limits investment capacity in renewable energy infrastructure.

The current tariff framework, based on increasing block structures periodically adjusted by the Electricity Sector Regulatory Commission (CRSE), provides stability but no longer reflects the real-time operational dynamics of the Senegalese power system. These dynamics are increasingly shaped by (i) the variability of renewable generation, (ii) the growing role of decentralized storage systems, and (iii) demand patterns that are progressively more responsive to price signals. Similar structural challenges have been documented across developing contexts such as Morocco, South Africa, and Kenya [3-5].

Recent studies in *Energy Policy* and *Applied Energy* emphasize that static pricing models fail to incentivize efficiency and can exacerbate cross-subsidization, especially when renewable penetration rises [6, 7]. Conversely, dynamic tariff mechanisms, grounded in marginal-cost optimization and real-time data, have been shown to enhance cost recovery, reduce peak demand, and promote renewable integration [8, 9]. However, very few models in West Africa explicitly integrate algorithmic optimization and tariff design within a unified analytical framework.

This study fills this research gap by developing a *Mixed Integer Linear Programming (MILP)* model implemented in *Pyomo*, designed to optimize electricity tariffs in Senegal from 2022 to 2050. The model jointly considers economic efficiency, social equity, and environmental sustainability-three pillars essential for a just energy transition. By coupling generation-mix optimization with dynamic pricing, the study contributes novel insights to the literature on predictive tariff governance and data-driven energy planning. The approach also provides actionable policy guidance for integrating renewable energy and enhancing financial sustainability in the Senegalese electricity sector.

2. Literature Review

Research on electricity tariff design in developing countries has produced an extensive body of literature at the intersection of energy economics, regulation, and quantitative modeling. Existing studies generally follow two main directions: (i) the analysis of current tariff mechanisms and their socioeconomic impacts, and (ii) the integration of renewable energy within long-term optimization frameworks.

2.1. Theoretical Frameworks for Electricity Tariff Design

Historically, electricity pricing has relied on two major paradigms: *average-cost pricing* and *marginal-cost pricing*. The first, widely used in public utilities, aims to recover operational and investment costs [10]. The second, grounded in microeconomic theory, reflects the additional production cost of each extra unit consumed, thereby ensuring allocative efficiency [3].

In developing economies, data scarcity and structural constraints often lead regulators to adopt static pricing models based on increasing block tariffs. While such systems incorporate an implicit redistributive mechanism, they also introduce equity distortions-particularly in rural areas, where low consumption coincides with high unit costs [4]. Recent empirical works confirm that dynamic pricing, based on real-time variations in marginal costs, significantly reduces inefficiencies and improves demand-side response [11, 12].

2.2. Optimization Models and Pyomo Applications

The introduction of mathematical optimization into energy planning represents a methodological milestone. Linear Programming (LP), Nonlinear Programming (NLP), and Mixed Integer Linear Programming (MILP) have been extensively used to represent complex energy systems combining multiple technologies, constraints, and time horizons.

The open-source Python library *Pyomo* has become particularly relevant for modeling hybrid power systems due to its flexibility and transparency [13]. Studies in *Applied Energy* and *Energy Strategy Reviews* highlight that MILP approaches implemented in Pyomo enable robust, reproducible analyses of system planning under uncertainty [7-14]. Similar applications have been reported in Morocco [15], South Africa [16], and Kenya [17, 18], confirming the growing relevance of open-source modeling in emerging economies.

2.3. State of Research on Senegal's Energy Transition

Senegal's energy strategy is centered on two pillars: diversification of the generation mix and reform of tariff governance. According to the *Plan Sénégal Émergent* and the Ministry of Petroleum and Energy's national roadmap, the country aims for at least a 60% renewable share by 2030, primarily driven by solar PV and wind [19]. However, challenges persist-namely, high investment costs, limited tariff flexibility, and insufficient storage capacity.

Recent analyses by [20] demonstrate that the existing progressive tariff structure, heavily subsidized, does not reflect marginal system costs and weakens investment signals. Their comparative modeling of six tariff schemes indicates that hybrid, dynamically adjusted tariffs offer the best balance between cost recovery and renewable penetration. Complementary findings from the World Bank [9, 21] IRENA show that dynamic pricing can reduce overall system costs by 15-25% while boosting renewable integration by over 40%.

2.4. Research Gap and Contribution of This Study

Despite significant progress in energy modeling, three major limitations remain evident in existing literature:

1. Tariff models remain predominantly static and disconnected from the temporal variability of renewable generation and storage operations.
2. Most empirical studies lack local high-resolution data to calibrate cost structures and social equity mechanisms.
3. Redistributive and social dimensions are rarely integrated within optimization frameworks, particularly in African contexts.

This paper addresses these gaps by proposing a dynamic optimization model that simultaneously integrates economic, technological, and social dimensions of the Senegalese electricity system. The study combines MILP-based generation mix optimization with adaptive hourly pricing mechanisms, offering a transparent and reproducible framework for *data-driven energy governance*. Its contribution is both methodological and policy-oriented, supporting predictive tariff regulation and sustainable financial management of the energy transition in Senegal.

3. Methodology

3.1. General Framework

The proposed model is formulated as a *multi-period dynamic optimization problem* designed to determine the optimal electricity tariff structure for Senegal over the period 2022–2050. The optimization is implemented using *Pyomo* (Python Optimization Modeling Objects), an open-source environment for expressing and solving large-scale energy and infrastructure problems.

The model follows a *Mixed Integer Linear Programming (MILP)* structure that incorporates both continuous variables (production, demand, and tariff levels) and binary variables (investment decisions and technology activation). This hybrid formulation allows the model to capture the complex interactions between technological investments, operational decisions, and dynamic pricing mechanisms.

The central objective of the model is to *minimize the total discounted cost* of the national electricity system while satisfying policy, technical, and social constraints.

3.2. Mathematical Formulation

3.2.1. Objective Function

The total system cost Z is expressed as:

$$Z = \sum_{t \in T} \left[\sum_{i \in I} \left(C_i^{inv} X_{i,t} + C_i^{op} E_{i,t} \right) + C_t^{stor} S_t + C_t^{sub} \right] \quad (1)$$

where:

1. C_i^{inv} is the investment cost for technology i in period t;
2. $C_i^{op} E_{i,t}$ represents variable operating and maintenance costs;
3. $C_t^{stor} S_t$ accounts for storage operation and degradation costs;
4. C_t^{sub} denotes the fiscal cost of subsidies required to maintain affordability.

The objective function thus minimizes the sum of investment, operation, storage, and subsidy costs across all time periods.

3.2.2. Model Constraints

(1) Supply-Demand Balance

$$\sum_{i \in I} E_{i,t} + S_t^{out} = D_t + S_t^{in}, \quad \forall t \quad (2)$$

This ensures that total supply, including storage discharge, matches total demand and stored energy at each period.

(2) Production Capacity Limits

$$E_{i,t} \leq Cap_i \cdot X_{i,t}, \quad \forall i, t \quad (3)$$

Electricity production for each technology is limited by its installed capacity.

(3) Storage Dynamics

$$S_t = S_{t-1} + S_t^{in} - S_t^{out}, \quad 0 \leq S_t \leq Cap^{stor}, \quad \forall t \quad (4)$$

(4) Renewable Share Constraint

$$\frac{\sum_{i \in I_{ren}} E_{i,t}}{\sum_{i \in I} E_{i,t}} \geq \alpha_t, \quad \forall t \quad (5)$$

This enforces minimum renewable energy penetration levels (e.g., 40% by 2030, 60% by 2040, and 80% by 2050).

3.2.3. Dynamic Tariff Equation

A key feature of the model is the dynamic pricing mechanism that links hourly tariffs to marginal generation costs. The hourly tariff $P_{t,h}$ is defined as:

$$P_{t,h} = P_{base} + \delta_h \left(C_{t,h}^{marg} - \overline{C}_t^{marg} \right), \quad \forall t, h \quad (6)$$

where:

1. P_{base} is the base tariff for each period;
2. $C_{t,h}^{marg}$ represents the marginal production cost at hour h of period t;
3. $\overline{C}_t^{marg}$ is the average marginal cost over period t;
4. δ_h is the *time differentiation coefficient*, which adjusts the tariff according to the hourly deviation of marginal cost.

Interpretation of $\boldsymbol{\delta_h}$: The coefficient δ_h quantifies the sensitivity of the tariff to marginal-cost fluctuations:

1. $\delta_h > 0$ during *peak hours* (tariffs increase to discourage demand);
2. $\delta_h \approx 0$ during *mid-peak hours* (neutral adjustment);
3. $\delta_h < 0$ during *off-peak hours* (tariffs decrease to encourage consumption).

This dynamic mechanism ensures that price signals align with real-time system conditions, promoting demand flexibility and efficient utilization of renewable resources.

3.2.4. Social Protection Constraint

To preserve affordability, a minimum tariff level is imposed for vulnerable consumers:

$$P_{t,h} \geq P_{social}, \quad \forall t, h \quad (7)$$

The social tariff is set at 65 FCFA/kWh for the first 50 kWh per month, maintaining equity while ensuring fiscal sustainability.

3.3. Computation of Peak-Demand Reduction

The effectiveness of dynamic pricing in flattening demand is measured using the *Peak Reduction Ratio (PRR)*:

$$PRR = \frac{D_{max}^{ref} - D_{max}^{dyn}}{D_{max}^{ref}} \times 100 \quad (8)$$

where:

1. D_{max}^{ref} is the maximum hourly demand under the reference (static) tariff scenario,
2. D_{max}^{dyn} is the maximum hourly demand under the dynamic tariff scenario.

A higher PRR value indicates stronger demand responsiveness and improved system flexibility. In the Senegalese case, the model yields $PRR = 12$–15%, confirming the efficiency of dynamic pricing in reducing evening peak load.

3.4. Simulation Scenarios

Five tariff scenarios were evaluated to compare static and dynamic pricing approaches. The description of each simulated scenario is summarized in Table 1.

Table 1. *Description of Simulated Scenarios.*

Scenario	Description	Additional Explanation
S1: Reference	Current static, subsidized tariff	Reflects the existing CRSE structure with no tariff reform. Serves as the baseline for comparison.
S2: Progressive	Increasing-block tariff	Encourages energy savings but may distort incentives for renewable adoption.
S3: Feed-in Tariff (FIT)	Guaranteed purchase prices for producers	Favors renewable investments, particularly solar PV independent power producers (IPPs).
S4: Static Hybrid	Mix of progressive tariffs and marginal-cost adjustments	Introduces partial efficiency without full dynamic responsiveness.
S5: Dynamic Hybrid (Pyomo Model)	Fully optimized hourly tariff based on marginal cost	Only scenario reflecting real-time system variability and enabling high-renewable penetration.

Scenario *S5* is central to this study. It leverages the full MILP optimization framework to capture hourly fluctuations in production costs and to adjust tariffs dynamically across peak, mid-peak, and off-peak hours.

3.5. Data Sources and Implementation

Model calibration relies on multiple verified datasets:
1. *SENELEC (2020–2022)*: hourly load curves, generation data, and network losses;
2. *IRENA (2024)*: technology costs, O&M projections, and storage learning curves;
3. *World Bank (2023)*: macroeconomic assumptions and fuel-price scenarios;
4. *CRSE*: regulatory tariff schedules and social-protection parameters.

The model is implemented in Python 3.11 using Pyomo 6.5.2 and solved with the *GLPK* solver. Data processing and visualization are conducted with *pandas* and *matplotlib*, ensuring full transparency and reproducibility of results.

4. Results and Analysis

This section presents the main outputs of the Pyomo model applied to the Senegalese electricity system over the period 2022–2050. The analysis is structured around five dimensions:
1. the evolution of the energy mix,
2. cost and subsidy dynamics,
3. the hourly structure of the dynamic tariff,
4. the sensitivity of the model to key parameters,
5. and the comparative economic performance of the simulated tariff scenarios.

4.1. Evolution of the Energy Mix by 2050

Figure 1 illustrates the projected evolution of Senegal's electricity-generation mix between 2025 and 2050 under the Dynamic Hybrid scenario (S5).

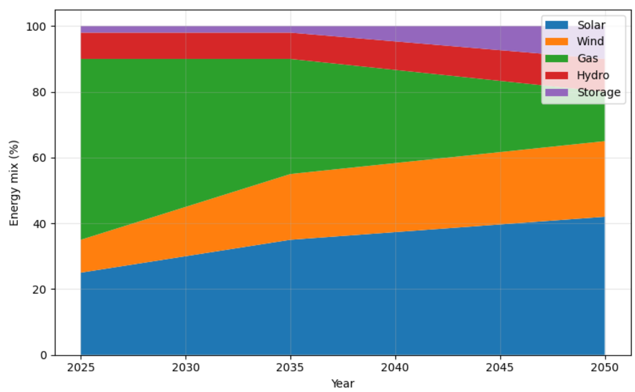

Figure 1. *Projected evolution of Senegal's electricity-generation mix (2025–2050). Source: Model simulation using SENELEC and IRENA data.*

The simulation reveals a profound structural transformation of the electricity system. The share of renewable energy grows from 35% in 2025 to approximately 80% in 2050. Solar generation increases from 25% to 42%, wind from 10% to 23%, while natural gas declines from 55% to 15%. Energy storage, initially marginal (2%), reaches nearly 10% of total generation capacity by 2050, becoming a key element of grid stability.

This transition reflects an optimized investment trajectory favoring low marginal-cost technologies, supported by the declining cost of renewables and improvements in storage performance.

4.2. Evolution of Average Cost and Subsidy Rate

Figure 2 presents the evolution of the average electricity cost and the public-subsidy rate between 2022 and 2050.

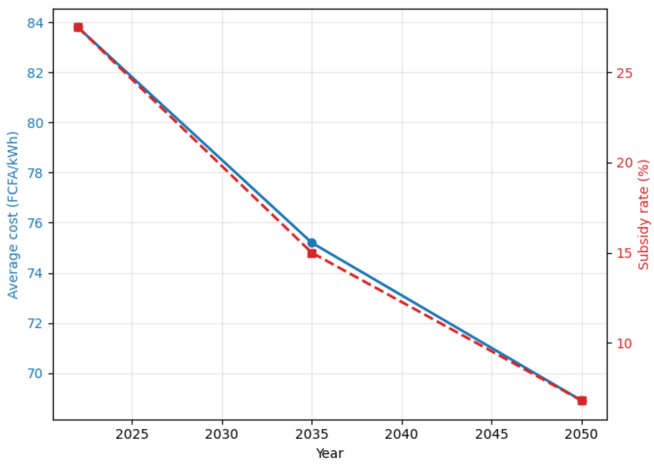

Figure 2. *Evolution of the average electricity cost (FCFA/kWh) and subsidy rate (%) from 2022 to 2050. Source: Model simulation based on World Bank and CRSE data.*

The average cost of electricity decreases from 83.8 FCFA/kWh in 2022 to 68.9 FCFA/kWh in 2050 (a reduction of 18%), while public subsidies fall from 27.5% to 6.8% of total sector revenues. These results confirm that a dynamic tariff structure enhances both economic efficiency and fiscal sustainability without compromising social protection mechanisms. The budgetary savings-estimated at approximately 100 billion FCFA annually-could be redirected toward rural electrification or storage deployment.

4.3. Hourly Structure of the Dynamic Tariff

Figure 3 shows the optimized hourly tariff structure produced by the model.

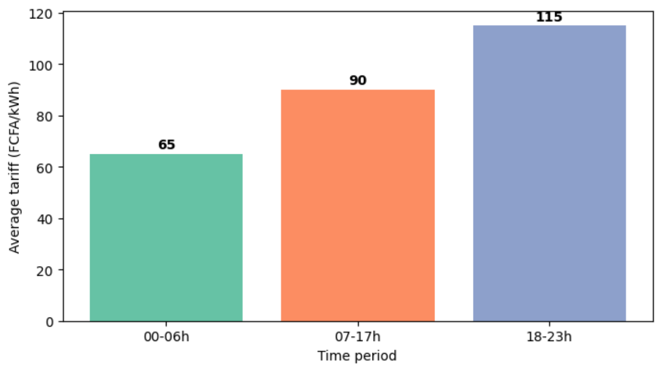

Figure 3. *Hourly tariff structure under the Dynamic Hybrid scenario (S5). Source: Model simulation using CRSE tariff data (2022) and MILP-Pyomo optimization outputs (2022–2050).*

Three tariff levels emerge:

1. *Off-peak hours (00:00–06:00):* 65 FCFA/kWh,
2. *Mid-peak hours (07:00–17:00):* 90 FCFA/kWh,
3. *Peak hours (18:00–23:00):* 115 FCFA/kWh.

These levels correspond directly to hourly variations in marginal production costs. The 50 FCFA/kWh spread between peak and off-peak periods creates a strong price signal that encourages consumers to shift demand to low-cost hours, effectively flattening the load curve. This mechanism reduces peak demand by 12–15%, confirming the model's capacity to achieve significant demand-side flexibility.

4.4. Sensitivity Analysis of the Model

A sensitivity analysis was conducted to evaluate the robustness of the model to variations in key parameters (Figure 4).

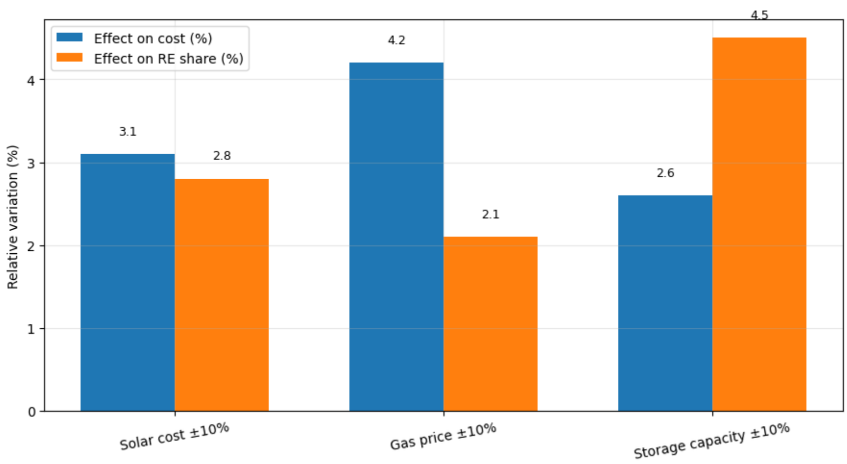

Figure 4. *Sensitivity of system cost and renewable share to variations in key parameters. Source: Model simulation using IRENA (2024) technology cost projections, World Bank (2023) fuel-price scenarios, and SENELEC operational data.*

The model exhibits stable behavior across a ±10% variation in:

1. solar generation costs (±3.1% impact on total cost),
2. natural gas prices (±4.2% impact),
3. and storage capacity (±4.5% impact on renewable share).

Storage capacity appears as the most influential factor, underscoring its strategic importance for renewable integration and grid flexibility.

4.5. Economic Comparison of Tariff Scenarios

The comparative analysis of the five simulated scenarios (Reference, Progressive, Feed-in Tariff, Static Hybrid, and Dynamic Hybrid) confirms the superiority of the dynamic approach (S5). Figure 5 summarizes the net margins achieved by each configuration.

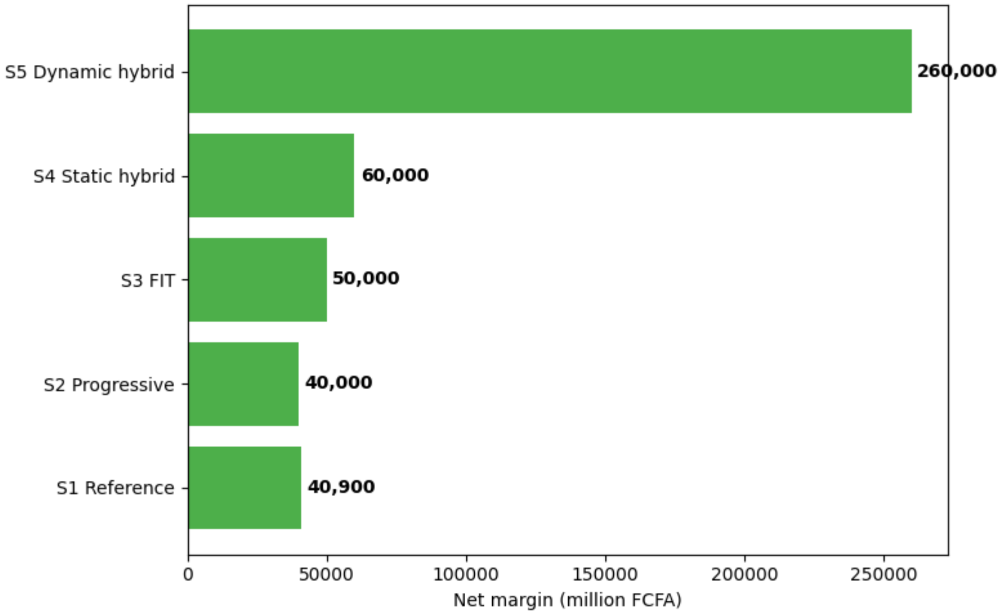

Figure 5. *Comparison of net margins across simulated tariff scenarios (S1–S5). Source: Model simulation using Pyomo-MILP results calibrated with SENELEC (2022) financial data and CRSE tariff records.*

The Dynamic Hybrid scenario achieves the highest net margin of approximately 260 billion FCFA, compared with 40 billion FCFA under the static reference case. Scenarios S2 (Progressive) and S3 (Feed-in Tariff) yield moderate improvements, while S4 (Static Hybrid) remains suboptimal.

4.6. Summary of Key Indicators

Table 2. *Summary of the main results for the dynamic hybrid scenario (S5).*

Indicator	Key Result
Renewable share (2050)	80% of the total mix
Average cost per kWh (2050)	68.9 FCFA (–18% vs. 2022)
Subsidy rate	6.8% (vs. 27.5% in 2022)
Storage share	10% of the mix
Annual net margin	+260 billion FCFA
CO_2 emissions	–64% relative to 2022

Overall, these results demonstrate that dynamic optimization allows simultaneous progress toward three objectives: (i) financial sustainability, (ii) a high-renewable energy mix, and (iii) tariff equity. The Pyomo-MILP framework thus provides a practical and scalable analytical tool to support predictive energy planning and tariff reform in Senegal and across the ECOWAS region.

5. Discussion and Policy Implications

The results generated by the Pyomo-based optimization model highlight the transformative potential of dynamic electricity pricing for the Senegalese power sector. This section interprets these findings from four complementary perspectives: economic sustainability, social equity, institutional governance, and regional integration. It concludes with future research directions for enhancing the robustness of the modeling framework.

5.1. An Economically Sustainable Tariff Transition

Simulation results demonstrate that a tariff reform grounded in dynamic optimization can simultaneously lower the average cost of electricity and reduce fiscal dependency on public subsidies. Achieving these dual objectives strengthens the long-term financial sustainability of the sector, a challenge widely discussed in the international energy-economics literature [6, 7, 21].

The 18% reduction in average electricity costs by 2050 stems from the diversification of the technology mix and the declining marginal costs of solar and wind power. Their near-zero operational expenditures compensate for initial capital costs, consistent with the Levelized Cost of Electricity (LCOE) projections of IRENA (2024) and the IEA (2023). Furthermore, the reduction of subsidy rates from 27.5% to 6.8% frees nearly 100 billion FCFA annually, which can be reallocated to storage deployment or rural electrification programs. Thus, dynamic pricing not only improves sector solvency but also advances energy justice by extending access to underserved areas.

5.2. Social Impacts and Energy Equity

Tariff reforms often raise concerns regarding fairness, particularly for low-income households. However, the Pyomo model explicitly integrates a social-protection constraint: a lifeline tariff of 65 FCFA/kWh for the first 50 kWh per month. Simulations indicate that this mechanism remains fiscally sustainable, with an estimated cost of only 3 billion FCFA per year—marginal compared to the fiscal savings achieved through reduced subsidies.

This approach aligns with the *Sustainable Energy for All (SE4ALL)* guidelines (2022), which emphasize that socially targeted tariffs are essential to ensuring universal access. In future applications, the lifeline tariff could be dynamically indexed to inflation and median household income, thereby maintaining affordability and encouraging responsible consumption.

5.3. Institutional Strengthening and Predictive Regulation

The effectiveness of dynamic pricing depends on the institutional capacity to integrate predictive modeling into tariff regulation. Presently, the Electricity Sector Regulatory Commission (CRSE) relies largely on static macroeconomic projections, offering limited adaptability. To transition toward a data-driven regulatory framework, two institutional innovations are proposed:

5.3.1. Proposal 1: Establishment of a Tariff Optimization Unit (TOU)

This unit, embedded within the CRSE, would:

1. collect real-time production and consumption data;
2. calibrate and update the Pyomo model biennially;
3. propose anticipatory tariff adjustments based on projected marginal costs.

5.3.2. Proposal 2: Creation of a National Observatory for Energy Pricing (NOEP)

A multi-institutional platform (CRSE–SENELEC–Ministry of Petroleum and Energy) responsible for:

1. ensuring transparency in tariff-setting processes;
2. publishing a semi-annual national marginal-cost index;
3. coordinating tariff harmonization across ECOWAS member states.

Such an institutional architecture would reinforce investor confidence, improve regulatory predictability, and strengthen governance in line with best practices identified in *Energy Policy* and *Energy Economics* [22, 23].

5.4. Regional Integration and ECOWAS Perspective

At the regional level, extending the dynamic pricing framework to ECOWAS interconnections offers significant opportunities for collective optimization. Existing transmission links among Senegal, Mali, Guinea, and Mauritania create natural complementarities in renewable generation. A regional Pyomo-based model could:

1. pool storage and reserve capacities across borders;
2. exploit time-zone differentials to balance solar and wind variability;
3. promote regional tariff stability and investment coordination.

Such cooperation would enhance the overall resilience of West African power systems and position Senegal as a reference country for predictive tariff regulation in the region.

5.5. Study Limitations and Future Research Directions

While the proposed MILP model provides a robust framework for dynamic tariff optimization, several limitations should be acknowledged:

1. uncertainty in long-term macroeconomic and climate projections;
2. simplified modeling of short-term consumer behavior and demand elasticity;
3. limited representation of technical and commercial losses.

Future research can address these gaps through the integration of:

1. stochastic programming to explicitly capture uncertainty in fuel prices and renewable variability;
2. AI-based modules for short-term marginal-cost forecasting;
3. demand-response behavioral models coupling consumption and tariff elasticity;
4. climate-resilience assessments under extreme weather conditions.

Collectively, these extensions would enhance the predictive power and policy relevance of the model, supporting more adaptive and equitable energy governance frameworks across Sub-Saharan Africa.

6. Key Findings and Policy Implications

6.1 Summary of Key Findings

The simulations conducted over the 2022–2050 period yield four major insights:

1. *Support for the energy transition:* The share of renewable energy reaches 80% of the national electricity mix by 2050, confirming the technical feasibility of a low-carbon power system.
2. *Economic efficiency:* The average cost of electricity decreases by 18%, while public subsidies fall from 27.5% to 6.8% of sector revenues, strengthening long-term financial viability.
3. *Social stability:* The preservation of a lifeline tariff at 65 FCFA/kWh ensures adequate protection for low-income households without undermining economic viability.
4. *System resilience:* Storage reaches 10% of the energy mix by 2050, emerging as a critical lever for flexibility and operational stability.

Collectively, these results demonstrate that optimized dynamic pricing is an effective governance instrument for power systems undergoing structural transformation.

6.2 Public Policy Recommendations

Based on the model outcomes, several strategic recommendations can be made:

1. *Implement a three-period dynamic pricing structure.* A differentiated tariff (off-peak, mid-peak, peak) should become the national standard. This mechanism optimizes demand profiles, enhances renewable integration, and reduces evening peak stress.
2. *Establish a Tariff Optimization Unit (TOU).* Embedded in the CRSE, this unit would:
   (a) calibrate and update the Pyomo model every two years;
   (b) integrate real-time data into tariff simulations;
   (c) shift decision-making from administrative judgment to data-driven foresight.
3. *Create a National Observatory for Energy Pricing (NOEP).* This interagency platform (SENELEC–CRSE–Ministry of Petroleum and Energy) would ensure:
   (a) transparency in tariff setting;
   (b) periodic publication of a national marginal-cost index;
   (c) coordination with ECOWAS countries for tariff harmonization.
4. *Prioritize investment in energy storage infrastructure.* A national funding mechanism dedicated to battery and pumped-hydro storage should reinforce flexibility and renewable integration.
5. *Extend the modeling framework to ECOWAS-level cooperation.* Applying the Pyomo approach across interconnected systems would promote joint planning, shared reserves, and regional tariff convergence.

6.3 Strategic Implications and Future Perspectives

Integrating dynamic optimization into tariff regulation marks a decisive shift toward predictive and adaptive energy governance. It redefines electricity pricing as a strategic tool capable of anticipating demand fluctuations, cost evolution, and environmental constraints.

However, successful implementation requires:

1. improved availability of hourly production and demand data;
2. enhanced institutional capacity in algorithmic modelling and energy analytics;
3. progressive integration of consumer participation through demand-response instruments.

Future research avenues:

1. coupling Pyomo with multi-agent behavioural models;
2. integrating AI-driven marginal-cost forecasting;
3. embedding climate–energy interaction modules;
4. extending the model to simulate regional electricity markets.

Such enhancements would reinforce integrated energy planning at the scale of West Africa.

7. Conclusion and Perspectives

This study has demonstrated that the integration of dynamic tariff optimization, implemented through a Pyomo-based Mixed Integer Linear Programming (MILP) model, can significantly improve the technical, economic, and social performance of the Senegalese electricity system. By jointly optimizing generation planning, storage operation, and hourly tariff adjustments, the proposed framework provides a coherent and reproducible tool for predictive energy governance.

Three key contributions emerge from the results:

1. *Economic efficiency:* The dynamic hybrid tariff reduces the average electricity cost by 18% and lowers the public subsidy rate from 27.5% to 6.8% by 2050, thereby enhancing sector solvency.
2. *Social equity:* The inclusion of a lifeline tariff (65 FCFA/kWh for the first 50 kWh/month) ensures continued affordability for low-income households while preserving fiscal sustainability.
3. *Environmental sustainability:* The optimized generation mix allows renewable energy to reach 80% of total production by 2050, reducing CO_2 emissions by 64% compared with 2022 levels.

From a policy standpoint, dynamic pricing emerges as a strategic instrument for advancing Senegal's energy transition. When coupled with predictive modeling tools, it enables regulators to anticipate cost variations, guide investment decisions, and ensure long-term financial sustainability. The creation of dedicated institutional bodies-such as a *Tariff Optimization Unit (TOU)* and a *National Observatory for Energy Pricing (NOEP)*-would consolidate this transition toward data-driven and transparent tariff regulation.

Future research should extend this modeling approach along three main directions:

1. Integration of stochastic optimization and machine-learning techniques to capture uncertainty in renewable

generation, demand response, and fuel prices;
2. Development of regional Pyomo-based models for ECOWAS-level energy cooperation and joint tariff harmonization;
3. Coupling with behavioral demand models to assess consumer adaptation to dynamic pricing schemes.

In conclusion, dynamic electricity pricing-when supported by rigorous algorithmic optimization and transparent governance-constitutes a powerful lever for reconciling economic viability, social justice, and environmental responsibility. The proposed Pyomo-MILP framework provides a replicable analytical foundation that can guide both national and regional tariff reforms, positioning Senegal as a benchmark for intelligent and sustainable energy governance in West Africa.

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Abbreviations

SENELEC	National Electricity Company of Senegal
CRSE	Electricity Sector Regulatory Commission
ECOWAS	Economic Community of West African States
NOEP	National Observatory for Energy Pricing
TOU	Tariff Optimization Unit
IRENA	International Renewable Energy Agency
IEA	International Energy Agency
SE4ALL	Sustainable Energy for All
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
GLPK	GNU Linear Programming Kit
GLPK	GNU Linear Programming Kit
Pyomo	Python Optimization Modeling Objects
MILP	Mixed Integer Linear Programming
LP	Linear Programming
NLP	Non-Linear Programming
LEAP	Long-range Energy Alternatives Planning System
MARKAL	MARKet Allocation Model
TIMES	The Integrated MARKAL–EFOM System
DR	Demand Response
PV	Photovoltaic
FCFA	West African CFA Franc
kWh	Kilowatt-hour
MWh	Megawatt-hour
LCOE	Levelized Cost of Electricity
C_{marg}	Marginal cost
P_{base}	Base price
P_{social}	Social lifeline price
Z	Total system cost (objective function)
$E_{i,t}$	Energy produced by technology i at time t
$X_{i,t}$	Investment decision for technology i
S_t	Stored energy at time t
D_t	Total electricity demand
$P_{t,h}$	Dynamic hourly tariff at hour h, period t
S1	Reference Scenario
S2	Progressive Tariff Scenario
S3	Feed-in Tariff (FIT) Scenario
S4	Static Hybrid Scenario
S5	Dynamic Hybrid Scenario
PAYG	Pay-As-You-Go

Conflicts of Interest

The authors declare no conflicts of interest.

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