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Energy Planning for West African Power Pool with Geographical Explicit Representation of Variable Renewable Potential Sites

Nicolo' Stevanato*, Leonardo Dalla Riva, Valeria Baiocco, Emanuela Colombo

Department of Energy, Politecnico di Milano, Milano 20156, Italy

Corresponding Author Email: nicolo.stevanato@polimi.it

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ABSTRACT

This study investigates energy planning pathways for the West African Power Pool (WAPP) to 2040, using the Calliope energy system model to explore how renewable energy integration, storage deployment, and transmission strategies impact energy security, cost, and sustainability. Scenarios vary from national autarky to full regional interconnection, incorporating variable renewable energy sources (VRES), storage technologies, and open-cycle gas turbines (OCGTs). A key innovation is the spatial clustering of solar and wind supply regions—based on IRENA's all-Africa dataset—considering not only resource availability but also infrastructure proximity and economic viability. This approach enables realistic modeling of renewable siting constraints. Results highlight the economic and technical challenges of integrating VRES, underscoring the necessity of storage solutions such as pumped hydro and batteries. Regional interconnection scenarios outperform autarkic ones in both cost and reliability, enabling electricity trade and reducing storage needs. Countries like Mali and Niger could benefit as net exporters, although political developments challenge this potential. Policy insights suggest that a hybrid strategy—balancing national generation with interconnections—offers a more cost-effective and resilient energy future. The study calls for coordinated regional planning to enhance renewable integration and recommends further research on hydropower, market design, and investment mechanisms.

1. INTRODUCTION

Sub-Saharan Africa continues to face significant challenges in achieving universal electricity access, with energy demand projected to grow substantially in the coming decades [1]. Meeting this rising demand necessitates not only scaling up generation capacity but also reconfiguring the structure of the existing power systems. The integration of variable renewable energy sources (VRES) adds complexity to this process due to the intermittent nature of their output and the spatial variability of resources such as solar and wind [2]. In this context, effective energy planning becomes vital to ensure that the deployment of VRES is both economically sound and technically viable, enabling efficient resource use while keeping costs under control.

This study identifies three fundamental pillars for supporting renewable integration: natural gas-based generation, transmission infrastructure, and energy storage. Open Cycle Gas Turbines (OCGTs) are highlighted as a key source of system flexibility, capable of rapidly dispatching electricity during periods of low renewable output. Unlike conventional baseload plants, OCGTs can respond within minutes, making them particularly valuable in scenarios with limited storage capacity [3].

Enhancing transmission networks is equally critical. A modernized and expanded grid facilitates the transfer of electricity over long distances, reducing congestion and limiting the curtailment of surplus renewable generation [4]. Strengthened regional interconnections through power pooling mechanisms enable countries with abundant renewables to export excess energy, supporting both system reliability and decarbonization efforts.

Energy storage technologies also play an essential role in addressing temporal mismatches between supply and demand. Battery Energy Storage Systems (BESS), offering fast-response capabilities, are particularly relevant for solar-dominant systems and are expected to become central to the energy strategies of countries targeting high solar shares [5]. In contrast, Pumped Hydro Energy Storage (PHES) offers large-scale, long-duration storage, which is especially beneficial in regions with significant seasonal fluctuations in renewable generation. Together, these storage options provide the operational flexibility required to enable deeper integration of renewables into the energy mix.

2. METHODOLOGY

This study introduces an energy planning model for the West African Power Pool (WAPP), developed using the Calliope framework [6], to assess the integration of VRES under a variety of strategic configurations. The modeling explores different combinations of supply technologies, transmission network development, and storage systems. On the supply side, two alternative pathways are examined: one assumes a fully renewable build-out, while the other supplements VRES with OCGTs to provide additional system flexibility. Transmission development is explored through three scenarios: a national autarky setup with no cross-border exchanges; a configuration reflecting existing and planned regional interconnectors; and an enhanced interconnection scenario considering further expansion possibilities. The impact of storage is studied through three setups, no storage, inclusion of PHES, and integration of BESS.

These dimensions, summarized in Table 1, are combined to define 18 distinct scenarios, enabling a detailed assessment of how different strategies affect renewable energy integration across the region. Furthermore, the model adopts a sequential approach: installed capacities resulting from the 2030 scenarios are carried forward into the 2035 runs, and subsequently into 2040, allowing for a progressive and realistic build-up of capacity over time. The first line of each paragraph shall be indented by one character, approximately the length occupied by two lower-case letters here.

Table 1. Scenarios composition

Technology		Power Pool		Storage
VRES		Autarky		No Storage
	+	Existing Transmission	+	BESS
VRES and OCGTs		Transmission Expansion		PHES

The model builds upon the existing infrastructure and technology landscape of the WAPP, enabling the addition of new VRES capacity in geographically defined areas. Recognizing the strong spatial dependence of renewable resource availability, this study relies on the geospatial dataset by Sterl et al. [7], which was specifically developed to support site selection for solar PV and onshore wind deployment across Africa. Rather than identifying locations based solely on resource potential, the dataset defines so-called Model Supply Regions (MSRs) by incorporating multiple siting criteria, such as proximity to existing grid lines and road networks, while excluding areas that are either densely populated or environmentally protected.

Each MSR is characterized by detailed parameters, including maximum potential capacity, infrastructure accessibility, connection costs, and hourly generation profiles. Although these MSRs could be directly used in the capacity expansion modeling as candidate locations for new power generation assets, their sheer number would make the model computationally burdensome. To address this, a two-stage processing approach was applied: screening and clustering.

In the screening phase, an upper limit of 5% of each country's land area was imposed for new renewable installations. MSRs were ranked by their projected levelized cost of electricity (LCOE), and only the most cost-effective ones within this threshold were retained for further analysis.

Even after applying the initial screening criteria, the number of viable MSRs within the WAPP remained high, totaling 1,311 for solar PV and 1,104 for onshore wind. To ensure computational feasibility, a clustering method was employed to group MSRs with similar generation profiles and cost characteristics. This was achieved through k-means clustering, which aggregates geographically distinct but technically similar MSRs into representative clusters. Each cluster then serves as a single investment option within the energy model, significantly reducing its complexity while retaining the key variability in renewable generation potential.

An example of the spatial distribution and clustering of solar MSRs is shown in Figure 1. To verify that this simplification did not distort the modeling results, outputs from simulations using both the full (unclustered) and the reduced (clustered) MSR sets were compared. Across all scenarios analyzed, differences in key indicators such as total installed capacity and LCOE were marginal. These findings validated the use of clustered MSRs in the remaining analysis, enabling a more efficient modeling process without compromising result accuracy.

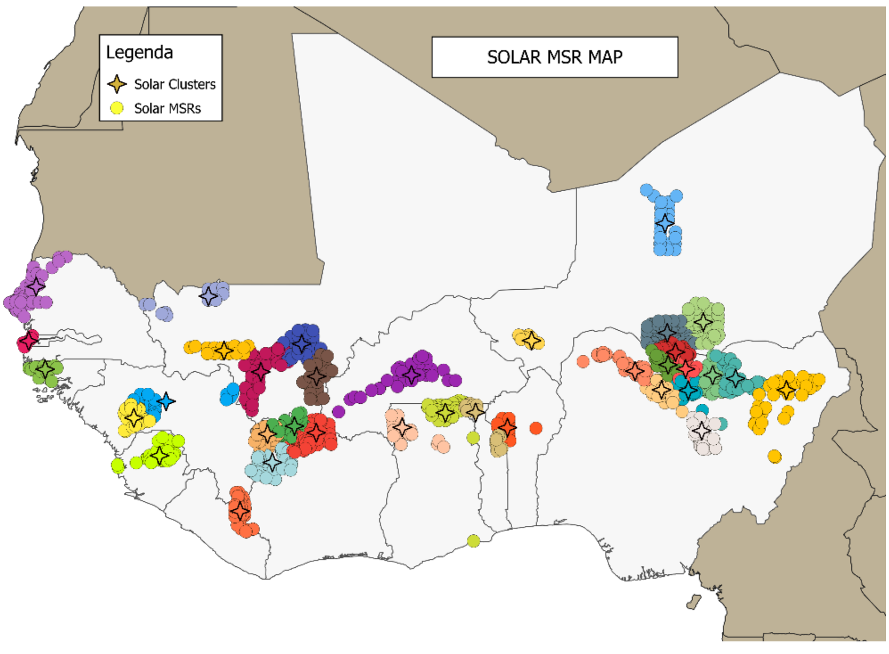

Figure 1. Solar MSRs and clusters

Each cluster is then spatially mapped to its corresponding region in the model and characterized by a total capital expenditure (CAPEX), which includes both the investment cost of the generation technology and the estimated cost of grid connection. In addition, operation and maintenance (O&M) costs are incorporated for each power plant installation.

Regarding electricity demand projections, the model uses 2019 hourly consumption profiles from the Joint Research Centre (JRC) as a baseline for each WAPP country. Demand is scaled over time using a compound annual growth rate (CAGR) of 6%, in line with recent IRENA forecasts [8]. This growth trajectory also results in a 2030 demand level that closely mirrors estimates from the IEA's Sustainable Africa Scenario [9].

To finalize the model setup, the deployable technologies, namely OCGTs and storage systems, are defined. OCGTs are characterized by fixed investment and O&M costs, as well as fuel costs tied to natural gas. The gas price is modeled to rise gradually over time, reflecting anticipated increases in Nigeria's gas break-even prices. Both OCGTs and BESS are modeled as non-location-specific, meaning they can be installed in any country in any quantity.

In contrast, suitable sites for PHES are derived from the Australian National University's Global Pumped Hydro Atlas [10], which identifies greenfield sites worldwide. This study selects only closed-loop PHES installations with a 2 GWh capacity and 6-hour duration to minimize environmental impact. Meanwhile, BESS are modeled with a 4-hour discharge duration.

3. RESULTS

The three core scenarios, autarky, existing transmission, and transmission expansion, offer contrasting pathways for the evolution of West Africa's energy system, each with significant implications for investment strategies and policy design. In the autarky scenario, countries are modeled as operating independently, relying exclusively on domestic energy resources to satisfy demand. This approach exposes limitations in balancing supply and demand, particularly in configurations where only VRES are permitted and no storage is available. Under such conditions, unmet demand emerges, especially in the VRES-only No Storage and VRES-only PHES scenarios.

Integrating OCGTs into the system introduces operational flexibility, helping mitigate demand variability. However, their presence limits the penetration of VRES: by 2040, renewables account for just 20% of generation in scenarios where OCGTs are included. Without OCGTs, the VRES share rises substantially, reaching 55%. As shown in Figure 2, storage systems, particularly battery and pumped hydro, enable higher solar PV deployment, while wind capacity remains relatively stable across all configurations.

Nonetheless, adopting a fully renewable and storage-dependent strategy under autarky conditions entails significantly higher capital investments. As depicted in Figure 3, the VRES-only scenarios with storage options (BESS and PHES) are several times more costly than those that include OCGTs. The PHES scenario is especially costly: of the $23.4 billion allocated to energy storage across the region by 2040, $13.7 billion is concentrated in Togo alone, which leverages PHES for seasonal storage to meet national demand. This outcome underscores the limited financial viability of a purely autarkic, storage-intensive approach.

The existing transmission scenario incorporates regional interconnections, enabling cross-border electricity exchange based on real-time supply and demand conditions. This represents a fundamental transformation in system design, easing the burden of domestic capacity expansion and enhancing overall operational efficiency. The analysis reveals that regional trading facilitates greater integration of VRES, particularly wind, as surplus electricity from high-resource countries can be exported rather than curtailed due to local demand limitations.

As illustrated in Figure 4, wind capacity installations increase under this scenario compared to the autarky cases, while solar PV deployment slightly declines. This reflects a regional optimization of renewable resources, where wind, owing to its higher capacity factor, becomes more economically favourable in a connected system. Notably, countries like Niger and Mali emerge as net exporters of electricity, capitalizing on their competitive renewable generation costs. In contrast, Côte d'Ivoire and Nigeria become significant importers, benefiting from access to more affordable power from neighbouring states.

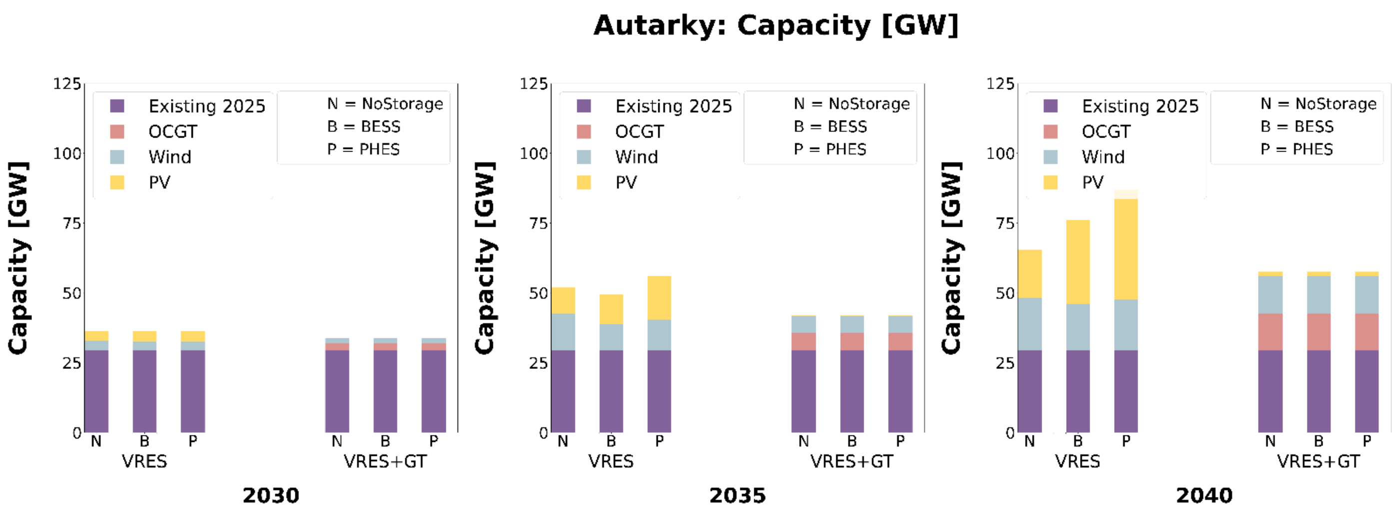

Figure 2. Installed capacity autarky scenarios

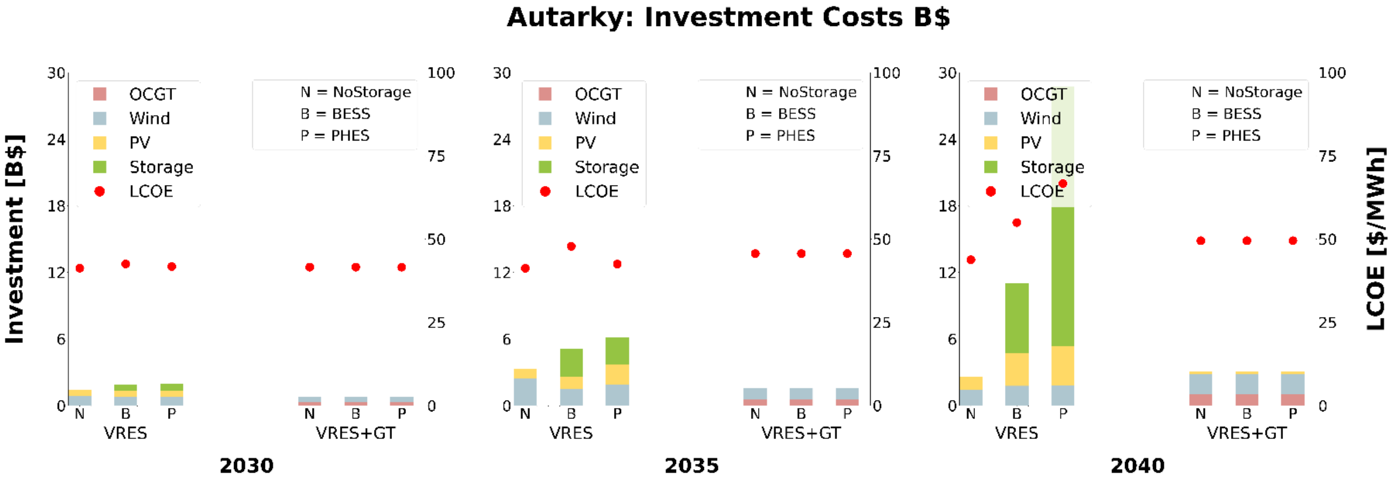

Figure 3. Investment costs autarky scenarios

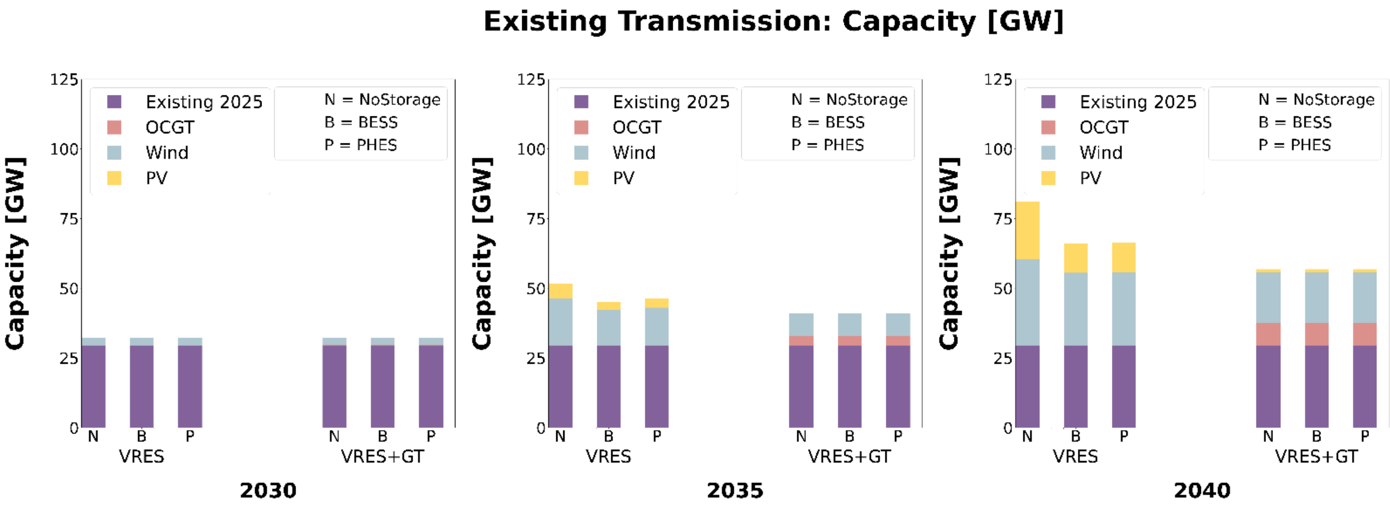

Figure 4. Installed capacity existing transmission scenarios

The resulting trade dynamics are visualized in Figure 5, which shows the trade balance for the *VRES-only with BESS* scenario. This interconnection-driven redistribution of energy flows also shifts investment patterns, reducing dependence on OCGTs and further supporting the deployment of high-capacity-factor renewables such as wind.

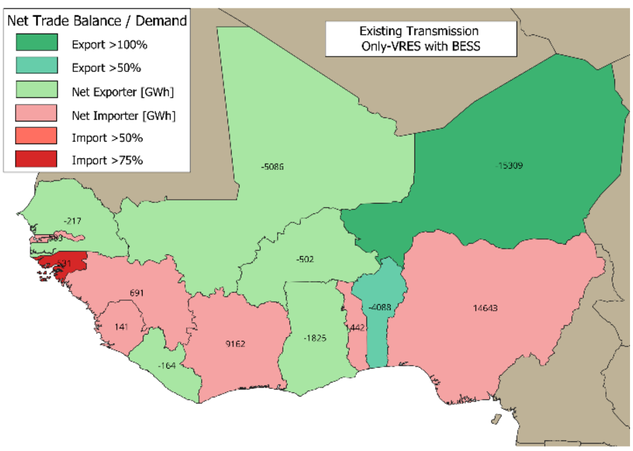

Figure 5. 2040 cross-border energy trading map - Existing transmission only-VRES BESS scenario

One of the most significant outcomes under the existing transmission scenario is the strategic reallocation of storage capacity. In contrast to the autarky setup, where each country must independently invest in its own storage infrastructure, interconnectivity enables a more centralized and efficient deployment of storage technologies. This regional coordination not only allows storage to be installed in optimal locations but also substantially reduces the overall storage requirement across the system.

As shown in Figure 6, this shift leads to a marked reduction in the capital investments needed for the energy transition. The most notable savings occur in the PHES scenario, where total investment drops from $36.8 billion in the autarkic case to just $10 billion under the interconnected system. Similarly, in the BESS scenario, investment costs are nearly halved, from $18 billion to $9.5 billion. These findings highlight how regional cooperation can unlock significant economic efficiencies by optimizing both the siting and scale of storage technologies.

The transmission expansion scenario investigates the impact of going beyond the current and planned interconnection infrastructure to unlock additional benefits of regional energy integration. The analysis reveals that while moderate grid development improves system-wide energy distribution, overreliance on extensive transmission buildout introduces both financial strain and strategic vulnerabilities. In the absence of storage technologies, the demand for cross-border capacity grows sharply, requiring over 60 GW of new transmission lines by 2040. This reshapes regional electricity flows, with northern countries emerging as major exporters, while southern nations, particularly Ghana, Côte d'Ivoire, and Nigeria, increasingly depend on imports.

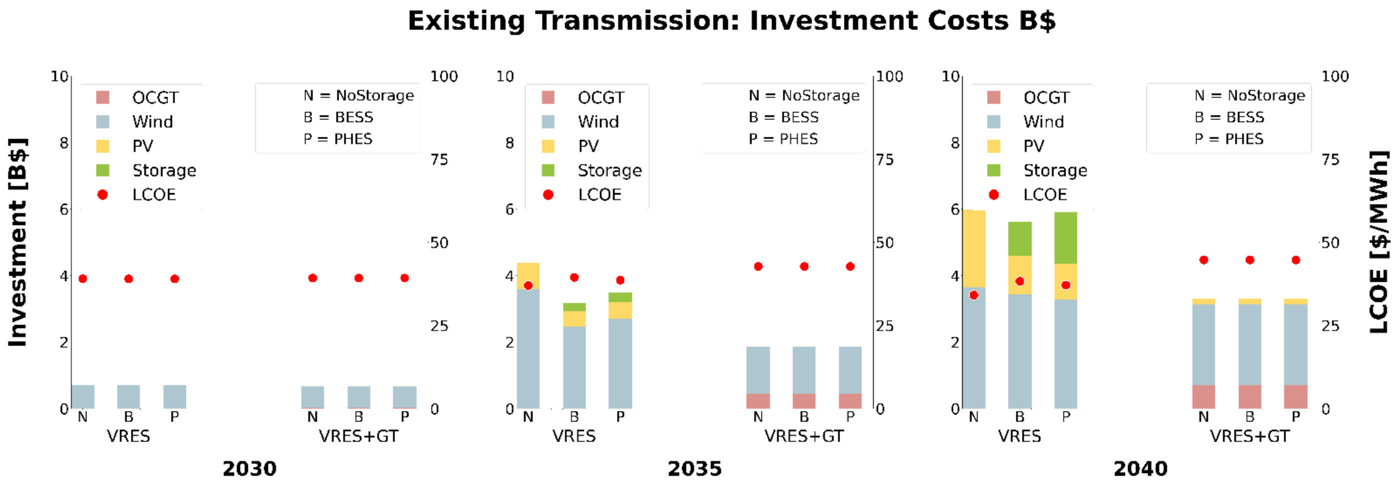

Figure 6. Investment costs existing transmission scenarios

Although this configuration enables the highest share of renewables, exceeding 80% by 2040, it also poses significant challenges. The investment required for such a massive expansion is likely to exceed the fiscal capacity of many WAPP member states. Moreover, a high degree of import dependency may raise energy sovereignty concerns, especially for large demand centers like Ghana and Nigeria, which risk becoming reliant on foreign generation despite their untapped domestic renewable potential.

Introducing storage systems such as BESS and PHES mitigates the need for excessive transmission buildout by providing local flexibility to absorb and release renewable energy as needed. The cost analysis supports this integrated approach, showing that a strategy combining moderate transmission upgrades with targeted storage deployment is the most cost-effective. Table 2 presents the investment savings achieved in the VRES-only with BESS scenario when comparing the current grid setup to the transmission expansion case.

Table 2. Cost reduction with transmission expansion

Costs	Existing [M$]	Expansion [M$]	Diff. [%]
PV	1594	1490	-6%
Wind	6635	6494	-2%
BESS	1269	1051	-17%
HVAC	0	87	-
Total	9497	9122	-4%

An important contextual factor addressed in this study is the evolving geopolitical situation involving Mali, Burkina Faso, and Niger, which have recently declared their withdrawal from the Economic Community of West African States (ECOWAS). This development poses potential risks to regional energy cooperation, as exiting ECOWAS could restrict these countries' participation in cross-border electricity trade and limit their access to international financing mechanisms for energy infrastructure. Despite this, model results highlight that these nations hold substantial potential to act as net energy exporters within the WAPP, particularly due to their competitive renewable energy resources.

If regional electricity trade frameworks continue to function independently of ECOWAS membership, these countries stand to gain economically through the export of affordable renewable power. However, should geopolitical tensions lead to increased isolation, it could stall or reverse progress on their renewable energy development, undermining both their national energy strategies and the broader regional transition.

The findings of this study underscore the critical value of coordinated regional energy planning. Interconnected systems are shown to significantly lower investment costs, enhance energy security, and facilitate greater integration of renewable energy compared to fragmented national approaches. Nevertheless, while grid expansion delivers substantial benefits, it must be carefully balanced with targeted investment in energy storage to secure long-term system resilience and sustainability.

4. CONCLUSIONS

This research has explored multiple energy planning strategies for the WAPP, delivering several actionable insights for policymakers. One of the key takeaways is the critical importance of regional cooperation. Strengthening cross-border electricity trade and integrating renewable resources at a regional level can significantly reduce overall investment needs, prevent supply shortfalls, and limit excessive reliance on costly storage solutions, as evidenced in the autarky scenarios. Interconnections are shown to be essential enablers of the energy transition; without them, phasing out OCGTs would require large-scale storage deployments, which are not financially viable for most countries.

Another central finding is the prominent role of wind energy in a pooled power system. In the interconnected scenarios, wind, primarily harnessed in the northern countries, becomes the backbone of regional exports, while the share of solar PV declines compared to the autarky case. This indicates a natural complementarity between the two technologies: solar should remain a cornerstone of national energy strategies, while wind power, with its favorable capacity factors and spatial concentration, is more suited to regional planning and export-oriented deployment.

At the same time, the study emphasizes the need to mitigate energy security risks for countries that might become overly dependent on imports. Planning should therefore include safeguards and flexibility to ensure resilience. Geopolitical instability, such as the recent withdrawal of Mali, Niger, and Burkina Faso from ECOWAS, must also be considered, as it may limit the feasibility of cross-border energy collaboration and financing.

From a technology perspective, BESS emerge as a cost-effective solution, offering lower investment requirements compared to other options. While PHES involves higher upfront costs, its ability to provide seasonal storage makes it a valuable strategic asset for long-term grid balancing.

In summary, this work demonstrates that a well-coordinated, regionally integrated energy system offers the most cost-effective and sustainable path forward for the WAPP. The optimal strategy combines targeted interconnection expansion, smart deployment of storage technologies, and a gradual shift away from fossil fuels. Together, these elements can support economic development, enhance energy access, and accelerate the transition to a resilient, low-carbon power system across West Africa.

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NOMENCLATURE

BESS	Battery Energy Storage System
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure, USD
HVAC	High Voltage Alternating Current
LCOE	Levelised Cost of Electricity
MSR	Model Supply Regions
O&M	Operation and Maintenance
OCGT	Open Cycle Gas Turbine
PHES	Pumped Hydro Energy Storage
PV	Photovoltaic
VRES	Variable Renewable Energy Sources
WAPP	Western African Power Pool