Generation capacity expansion planning with spatially-resolved electricity demand and increasing variable renewable energy supply: Perspectives from power pooling in West Africa

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Abstract

Power pooling has emerged as a regional strategy for accelerating generation capacity expansion in West Africa with the aim of leveraging vast domestic energy resources and promoting investment in regional power infrastructure. As part of their climate action pledges, most West African countries have committed to increasing the shares of variable renewable energy (VRE), particularly solar photovoltaics and wind power, in their generation mix. It, however, appears that approaches to grid-scale capacity expansion planning tend to overlook the inherent time intermittency and spatial variability of VRE-based generation. Moreover, despite influencing the techno-economic rationale for grid expansion and off-grid electrification, as well as the trade-offs between high renewable supply areas and grid expansion, the spatial distribution of demand has been overlooked in planning approaches, leading to conservative and weak prospects for the contribution of grid-scale VRE. Such inconsistencies with the region-wide potentials and policy ambitions highlight that it is paramount for West Africa to design its power pooling such that spatial and temporal fluctuations of VRE supply are duly considered in capacity expansion planning while taking advantage of complementarities between VRE supply and national electricity demand profiles. To address this, the present paper applies a long-term generation capacity expansion model, OptGen, soft-linked with a least-cost operation module, the SDDP tool, which is enhanced by geospatial electrification analysis using the OpeN Source Spatial Electrification Tool (OnSSET), to a subset of four member countries of the West African Power Pool – Burkina Faso, Cote d'Ivoire, Ghana, and Mali – for the 2023-2040 time horizon. The results highlight that current frameworks lead to missed opportunities for bridging the supply-demand gap in all countries, not only in terms of VRE generation capacity, but also of transmission capacity.

Keywords: Variable renewable energy; Spatial granularity; Time granularity; Stochastic Dual Dynamic Programming; Investment modelling; West Africa.

1. Introduction

The West African Power Pool (WAPP) which was created in 2000 as a specialized agency of the Economic Community of West African States (ECOWAS), essentially gathers power utilities from fourteen (14) countries with national electrification rates ranging from 19.3% to 85.9% [1]. The region has a relatively long history of bilateral imports/exports between neighboring countries with contrasting generation mixes, costs, and demand levels. Power pooling has emerged to create economies of scale in countries with relatively small power systems to integrate them into a non-discriminatory competitive market to reduce generation costs and electricity tariffs [2]. Moreover, the current political agenda for sustainable development has recently culminated in region-wide recognition of the urgency of tapping into the huge endowment of variable renewable energy (VRE), such as solar photovoltaics (PV) and wind power to expand generation capacity [3], [4]. Notwithstanding, only a handful of VRE projects are considered in the approved list of WAPP priority projects to be implemented by 2033 [4]. Additionally, the technical analysis for their selection relies on conservative assumptions (annual VRE generation capacity limited to a maximum of 10% of peak demand in each country) besides their final selection process being carried out by high-level decision-makers in collaboration with the Donor Coordination Committee [5]. This goes to support the remarks by [6]–[8] revealing that besides financial constraints, a severe challenge to scaling up electrification levels in West Africa remains poor planning processes stemming from the lack of resources and unsound methodology and objectives, especially with regards to VRE.

Hence, the ambitions for higher VRE shares appear to translate in practice into weak prospects for the contribution of grid-scale VRE which are inconsistent with countries' endowment, with power systems expected to remain dominated by hydro-thermal generation. This stems from the time and spatial dimensions of VRE supply and electricity demand being overlooked by conservative assumptions based on the widespread consideration that VRE fluctuations render their contribution to capacity and peak demand marginal. A study by [9] brought forth the limitations of considering average wind speeds for VRE deployment and demonstrated through hourly time steps analysis that quality wind energy resources are not limited to the Northern part of West Africa but can rather potentially be harnessed across an extended geographical area, stretching from Senegal to Nigeria. It also shows that higher wind speeds at night-time, particularly over the dry season, offer an exploitable potential for complementing PV plants thus suggesting that the idea of VRE plants being unsuitable for contributing to meeting baseload demand, used as an argument to conservatively limit their share in the power supply mix, becomes irrelevant as argued in [10]. Indeed, baseload is an inherent characteristic of (variable) demand rather than supply which should be contemplated considering the future.

Planning for higher shares of grid-scale VRE in expanding generation capacity, therefore, ought to consider both the spatial and temporal variabilities of these resources. Doing so provides insights not only into the techno-economic rationale for either expanding the grid or implementing off-grid solutions, but into the necessary trade-offs between high renewable supply areas and capacity expansion. Very few ECOWAS countries have individually been considered in the power systems literature with most countries featured in only one study [11], [12]. However, WAPP has slowly been attracting growing interest in the literature. The most relevant studies include [13]–[16] with limitations on either the time granularity or the spatial resolution of the models. The study by [16] improved the spatial resolution of their least-cost dispatch model but remained limited to the existing and planned interconnection nodes. The same authors later developed, for the first time, a bottom-up model for electricity demand forecasts in West Africa ([17]) which, among others, contributed to addressing the data availability limitation of [13] whereby demand profiles were not country-specific. However, even in [17], the spatial distribution of demand was overlooked.

The present study aims to contribute to filling this gap by answering the following questions: (i) to which extent can the conservative 10% limit to VRE shares in generation capacity be optimally challenged? (ii) can increasing VRE penetration disrupt the traditional characterization of importing versus exporting countries and effectively catalyze power pooling? This is done by modelling a two-scenario least-cost investment plan for generation capacity expansion considering the spatial and time operational constraints of increasing VRE supply, using the SDDP tool [18], [19] enhanced by the results of a previous study by the same authors [11] which applied the OpeN Source Spatial Electrification Tool (OnSSET) to Burkina Faso and Côte d'Ivoire. The present study is extended to two additional WAPP member countries: Ghana, and Mali. The four countries display the three enabling factors for power pooling described by [20], namely different consumption profiles, different peak load periods and different climatic conditions. The remainder of the paper is organised as follows: Section 2 describes the methods and data. Section 3 presents the modelling results. Section **Error! Reference source not found.** discusses the results and Section **Error! Reference source not found.** concludes the paper, emphasizing its main conclusions.

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2. Methods and data

2.1. Overview of OptGen and SDDP

OptGen

OptGen is a computational tool for long-term power systems expansion planning which determines the least-cost investment schedule, over a planning horizon of one year to several decades for new generation plant capacity (hydropower, thermal and renewables), transmission infrastructure (national transmission and regional interconnections), and gas networks. The least-cost expansion plan can be solved using either one of two types of solution strategies chosen by the modeler, named OptGen 1 and OptGen 2 [21]–[24]. Through Benders decomposition, OptGen is capable of directly solving the expansion planning problem by integrating SDDP calculations in a strategy solution called "OptGen 1". All the inherent features of investment and operating problems, namely stochastic, multiple stages and binary variables are solved directly within a single optimization package to obtain the optimal global solution. It also allows for system reliability representation in each iteration of the expansion plan through Monte Carlo simulation. Another strategy solution is "OptGen 2", which uses an hourly operation model and solves both investment and operation problems in the same Mixed-Integer Linear Programming (MILP). While the former is most suitable for hydro-thermal dominated systems, the latter is more relevant in systems with high penetration of RE other than hydro. The hydro-thermal dominated feature of the study region makes OptGen 1 more suitable for application.

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SDDP

SDDP is a mid- to long-term dispatch model with the representation of a hydrothermal and RE system alongside the transmission network for operational decision-making. The objective function is to minimize the immediate costs of using available hydro and thermal resources, and the expected value of future costs arising from hydrological uncertainty, intermittent RE generation, and electricity demand, through a Stochastic Dual Dynamic Programming algorithm [[18], [19]], [25]. This scheduling process means that today's operating decisions can impact long-term operation, thus affecting future operating costs, which is vital for systems with storage devices. The decision periods also called stages, can be chosen to be weekly or monthly. For this case study, monthly stages were chosen considering the data availability of historical water inflows and computational requirements. Electricity demand may be represented by blocks of similar load levels in a non-chronological demand curve in descending order, the Load Duration Curve, as well as by a chronological hourly order, hence allowing better characterization of the time intermittency of VRE supply. Within the scope of this study, the innovation of enhanced spatial granularity of the power system operation model was introduced at two levels:

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(i) Electricity demands in grid suitable areas by the time horizon were characterized and their spatial distributions were identified using the spatial electrification tool OnSSET, following the methodology in [11].
(ii) VRE generation profiles were complemented by VRE suitability zones mapping aided by existing mappings performed in [26]–[28] which were complemented by OnSSET outputs and results in [29] on solar PV and wind complementarities.

Fig. 1 presents the flowchart of the study.

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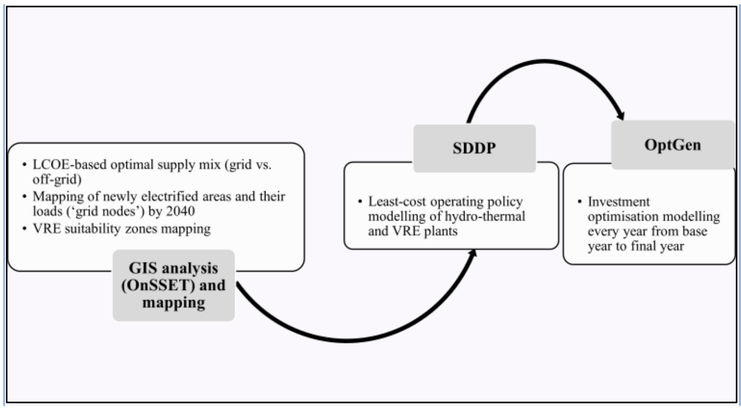


Fig. 1 Flowchart of the study

2.2. Data and assumptions

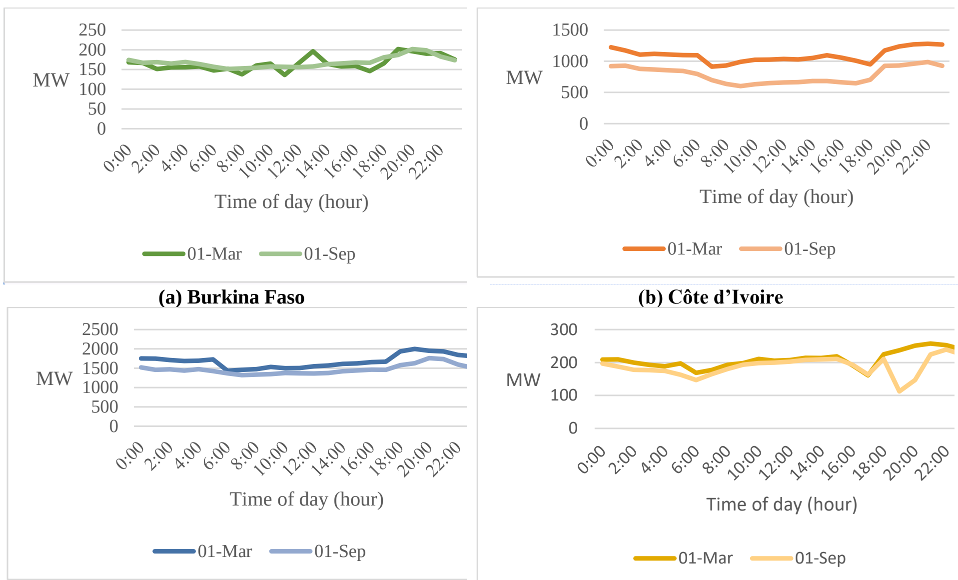
OptGen optimizes the trade-off between investment costs for new projects and operation costs (including the costs of unserved energy), using project financial data (investment costs, payment schedules, lifetime, construction time, etc.), as well as project specific data including minimum and maximum entrance dates, decision type (obligatory or optional) for future power plants (whether mere candidate/assumed or committed future plants). The complex characteristics of investment and operation problems combining continuous variables, binary variables, and uncertainty factors (RE generation, river flows, equipment availability, etc.) make such expansion planning problems both integer and multi-stage stochastic optimization problems. The difference between decided and candidate projects is reflected as follows: decided power plants are assumed to be operational by the final year of the modelling (2030, 2040), hence "existing". "Future" plants are candidate plants for which the least-cost optimization model will determine whether they are viable for investment. Future power plants include both planned (thermal, hydro, and RE) plants as per the latest WAPP Master Plan and assumed VRE plants as proposed by the characterization of REZs in the context of this research. Most power systems data was obtained from Tractebel Engineering (now Tractebel Engie), which led the consultancy work for the 2018 (and latest) update of the WAPP Master Plan.

2.2.1. Characterization of electricity demand

The characterization of electricity demand was performed at two levels to provide insights into the hourly profiles and the spatial distribution of loads in each country.

Hourly demand data

Fig. 2 illustrates hourly demand data in 2017 for selected weekdays of the dry and wet seasons. It appears that hourly load profiles are complementary between two groups of countries. On the one hand, baseload demand in Côte d'Ivoire and Ghana mainly occurs between 9 am and 5 pm, with peak loads before 9 am and after 5 pm. Hence, demand levels appear to be at their lowest levels during the typical peak solar PV production time, assuming a bell-shaped production profile, and potentially at their highest levels during times with higher wind power outputs (which are typically late evenings, especially during the dry season in West Africa) [9]. On the other hand, higher and peak loads in Burkina Faso and Mali typically occur between 10 am and 3 pm, particularly over the dry season, therefore coinciding with a bell-shaped PV production profile.



(a) Burkina Faso **(b) Côte d'Ivoire**

(c) Ghana **(d) Mali**

Fig. 2 Hourly electricity demand in the study countries for selected months in 2017

Spatial distribution of demand

OnSSET was applied to determine the optimal supply path between grid extension and off-grid systems for Burkina Faso, Côte d'Ivoire, and Ghana. In-depth interpretation and discussion of the OnSSET modelling results for Burkina Faso and Côte d'Ivoire are available in [11]. The analysis for Ghana was performed following the same methodology as in [11]. Mali was not included in this spatial analysis as its surface area is estimated at over 1.24 million km² (4.5 times that of Burkina Faso, 3.8 times that of Côte d'Ivoire, and 5.2 times that of Ghana [30]), and would require a very high computational effort and memory to process high spatial resolution data, even at a 10 km x 10 km resolution (1 km x 1 km spatial resolution for the other countries). For the sake of allowing for a similar comparative base, it was deemed appropriate not to seek analyzing the cost-optimal electrification pathways of Mali. For the remaining three countries, a two-level validation approach was carried out to measure the accuracy level of the OnSSET model in representing the

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state of electrification in the base year, as well as its coherence with electricity demand projections performed by relevant studies considering socio-economic factors potentially affecting future trends. The first level pertains to the spatial distribution of loads and the second level to the bottom-up approach to residential demand modelling. The detailed validation process is provided in Appendix A (also including the spatial load distributions of each country). Disaggregated demand data for the selected "grid nodes" with their hourly profiles served as inputs to the optimization model as elucidated by Fig. 1.

Fig. 3 maps the electrical areas modelled in each country. Color codes represent electrical areas in each country. Color coding was performed in such a way that neighbor areas can be differentiated from each other within and between systems. Hence, no specific meaning is attached to electrical areas with the same color code. The black dots represent the buses within each electrical area with the highest load values.

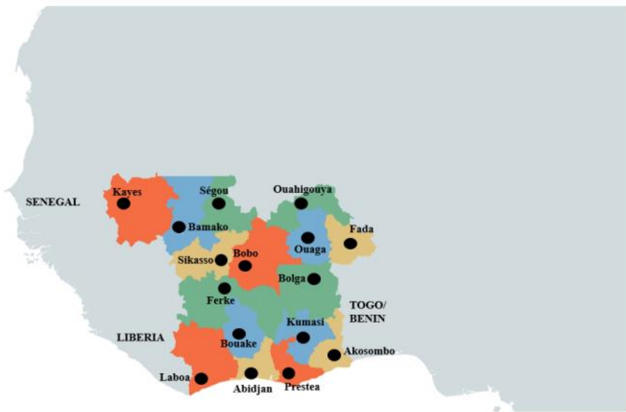

Fig. 3 Mapping of electrical areas for SDDP modeling

2.2.2. Characterization of variable renewable energy supply

Characterization of VRE supply in the study area was processed in two phases. The first phase consisted in identifying Renewable Energy Zones (REZs) from existing assessments which were overlayed with the results from the study by [29] on the complementarities of solar PV and wind power in West Africa. This allowed constructing assumed VRE power plants to be tested in the power system optimization modelling. Within the scope of this study, the REZs in [26]–[28] were used to propose candidate utility PV and wind plants which were included in the optimization model. These plants augmented future plants with full or partial funding clearance, as well as candidate plants as per national and regional Master Plans. Given that REZs spread across widespread areas, particularly in high resource countries, such as Burkina Faso and Mali, the proposed candidate plants were selected according to the solar PV-wind complementarities on diurnal timescales between 2019 and 2017 demonstrated in the first-ever high time and spatially resolved study for West Africa using ERA5 reanalysis data (see [29]). Table 1 summarizes SDDP input data features, assumptions, and sources.

Table 1 Descriptive summary of SDDP input data features, assumptions, and sources

Input data	Spatial granularity	Time resolution	Descriptive summary	Source
Historical and forecast electricity demand				
	National	Hourly	Demand levels in the base year. For Côte d'Ivoire and Ghana, historical hourly demand data were provided by the national utilities. For Burkina Faso and Mali, the modelling results of [17] were leveraged upon, as it was the first study of its kind to apply a bottom-up approach to model residential demand for individual West African countries.	Utility data and own processing
	National	Hourly	Demand forecasts to 2040 based on validated OnSSET modelling results. Hourly demand values in 2030 were obtained using the same coefficients of the base year (actual values). Demand levels in 2040 were estimated using the average annual growth rate from OnSSET analysis (between 2020 and 2030). Hourly values were obtained using the same coefficients for the year 2030.	Own processing from OnSSET results with residential shares of demand obtained in [31] and [32].
Existing and future generation infrastructure				
Fuels and thermal plants	Individual power plant	-	• Fuel prices (including transportation costs) and emission factors. • Thermal plant configuration: installed capacity, minimum and maximum generation, type (must-run or standard), forced (due to maintenance schedule) and composite (equipment maintenance and outage) outage rates.	Tractebel Database [33]
Hydrology and hydropower plants	Individual power plant 0.1° x 0.1° (ca. 10 km x 10 km) for hydrological inflows	Monthly	Historical water inflows between 1980 and 2017 were obtained for each gauging station. Observed inflows of rivers in West Africa are generally poorly measured in space (number of gauging stations) and time (timesteps and continuity). To compensate for missing inflow data, particularly in Burkina Faso, Ghana, and Mali, the CMIP6 models of the Hydrological Modelling Framework for West Africa [34] were used.	Own processing from [34]

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Input data	Spatial granularity	Time resolution	Descriptive summary	Source
			• Reservoir storage limits and initial condition at the beginning of the study, reservoir spillage type (controllable or not) • Monthly evaporation coefficients • Hydro plant configuration defining the technical characteristics of the generators and reservoirs, topology, storage, and flow tables.	Tractebel database [33]
VRE plants	1 km x 1 km for both PV and wind	Hourly	Solar PV and wind power plants, both existing and future. ‘Candidate’ future plants are drawn from the geospatial analysis, in addition to ‘decided’ future plants. Satellite imagery used in the Global Solar Atlas which has been validated against actual measurements on the ground with an accuracy range of ±4% to ±8. The 1 km x 1 km resolution has been shown to allow capturing small-scale spatial fluctuations of wind speeds.	**VRE Zoning:** Own processing from OnSSET, and [27], [28], [35], and [29]. **Generation profiles**: [36] for PV and [37], [38] for wind.
			Transmission infrastructure	
Electric network	MV-HV transmission line		The electric network is represented through bus, circuit, and area configurations. For the sake of reducing the complexity of the model, the multi-nodal approach was applied, whereby each node is a composite of multiple buses within a geographical space.	Utility reports and own processing based on OnSSET outputs and GIS analysis
Extents of electric areas			They are delimited according to the geographical locations of their associated nodes. One electric area may thus cover multiple nodes, provided that the transmission line has a voltage greater than 90 kV.	Own processing from OnSSET modelling and Tractebel database.
Load per bus			Loads associated with each bus were provided for each year of the study horizon. It was assumed that for each bus, the load value remains constant throughout the year. Such values were calculated as the product of the total load of the system by the associated weight of a given node as per the OnSSET modelling. The weights of each bus load were assumed to remain constant during the entire study horizon.	Own processing using bus load values from power utility data in 2017 (latest available).

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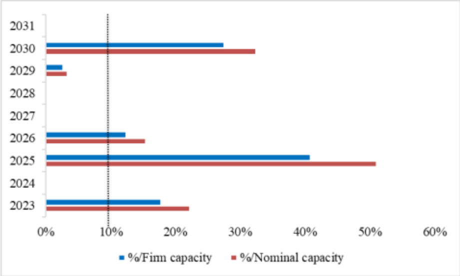
3. Results

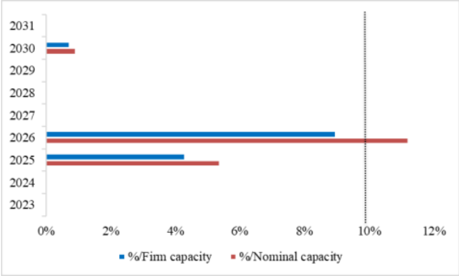
In both the base case scenario and the relaxed transmission scenario, only transmission lines greater than 90 kV were modelled. The modelling results are presented for different operating decisions per output class, and parameter as described in Table 2. In Fig. 4, each bar illustrates the share of new VRE capacity added each year either in terms of installed capacity or firm capacity compared to the annual peak demand for the same year in each country. This allows comparison against the conservative 10% limit on new VRE capacity compared to annual country peak demand used in the latest WAPP Master Plan (represented in Fig. 4 by a vertical black dotted line). In all countries, it appears optimal that all additional VRE power plants come online by 2030. It is important to note that no new VRE capacity is not added every year in any country, considering both their expected commissioning dates from official sources and the optimization results based on supply/demand requirements. It is worth emphasizing, however, that although the 10% conservative value used in the WAPP Master Plan is given as a share of the total installed capacity, representing renewable penetration targets as a share % of served demand provides more information to the planning process than the former. This is because renewable generation presents variability and intermittency, and therefore, their future dispatch factors are uncertain.

Table 2 Summary of outputs extracted from the set of modelling results

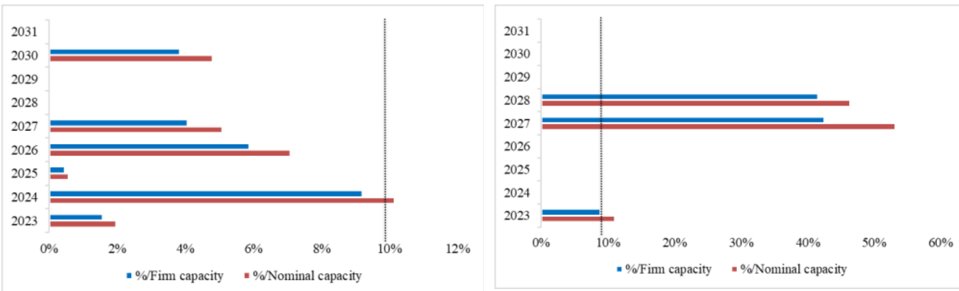
Class	Parameter	Description	Unit
Area	Export by area	Energy exports between electric areas, which in turn, are given by a set of nodes	GWh
	Import by area	Energy imports between electric areas, which in turn, are given by a set of nodes	GWh
Hydro plant	Hydro dispatch factor	Percentage of hydro utilization	%
Thermal plant	Thermal dispatch factor	Percentage of thermal utilization	%
Renewable source	Renewable source generation	Renewable source generation	GWh
	Renewable dispatch factor	Percentage of renewable utilization	%
	Renewable generation spillage	Renewable generation spillage	GWh
Interconnection	Interconnection flow	Interconnection flow between systems	GWh
Cost	Total investment cost	Total investment cost per system	k$



(a) Burkina Faso



(b) Côte d'Ivoire

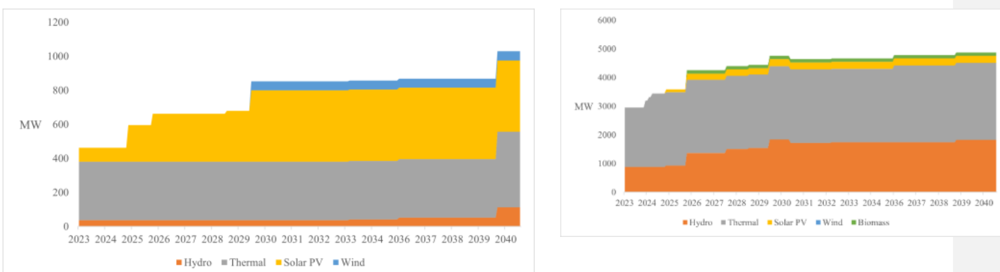


(c) Ghana (d) Mali

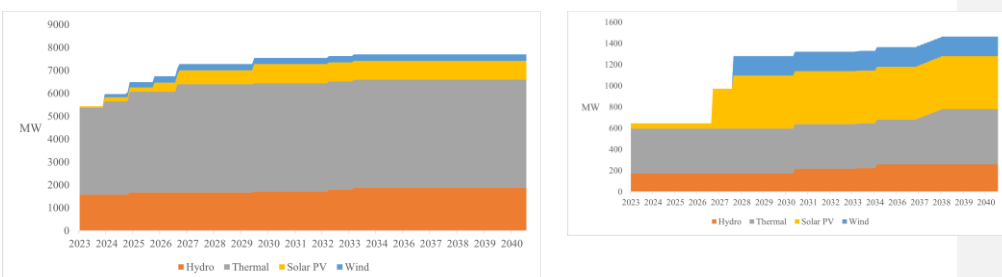
Fig. 4 Annual peak demand versus installed and firm capacity by source in each country (base case scenario)

Base case scenario: Generation capacity expansion with transmission constraints

The system capacity expansion throughout the study horizon is illustrated by Fig. 5.



(a) Burkina Faso (b) Côte d'Ivoire



(c) Ghana (d) Mali

Fig. 5 System capacity expansion between 2023 and 2040 (base case scenario)

As per the current configuration in the WAPP Master Plan, all cross-border interconnectors are single-circuits, which impose unidirectional power flows from one bus to another. In the case of cross-border interconnectors, such technical constraints mean that countries that are traditionally importers (Burkina Faso and Mali) are bound to remain so. The same applies to traditional exporting countries (Cote d'Ivoire and Ghana). Interconnection flows are detailed in Fig. 6. The dispatch factors of thermal, hydro, and renewable power plants, as well as the renewable generation spillage levels for selected power plants, are illustrated in Fig. 7. The selected power plants are located in electrical areas associated with cross-border interconnectors.

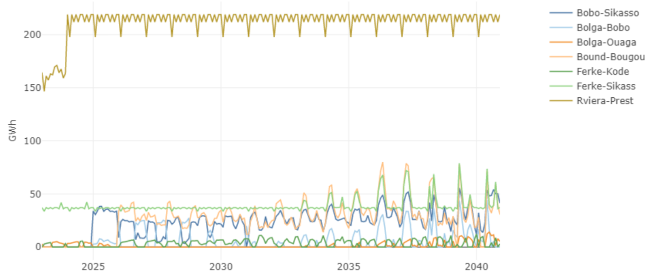
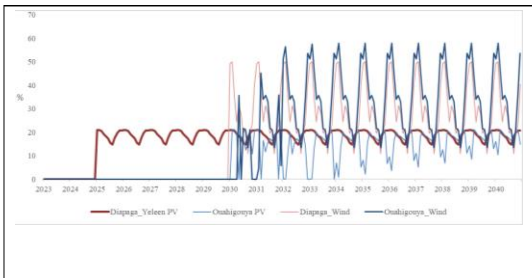
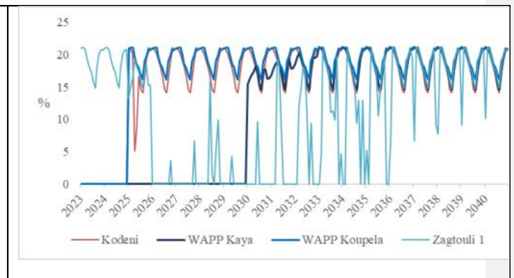


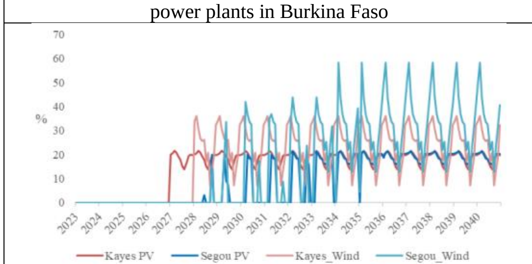
Fig. 6 Interconnection flows between Burkina Faso, Côte d'Ivoire, Ghana, and Mali (base case scenario)



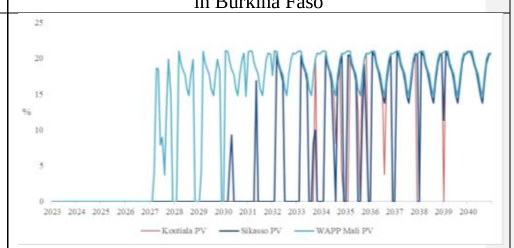
(a1) Renewable dispatch factor (%) for selected solar-wind power plants in Burkina Faso



(a2) Renewable dispatch factor (%) for selected PV plants in Burkina Faso

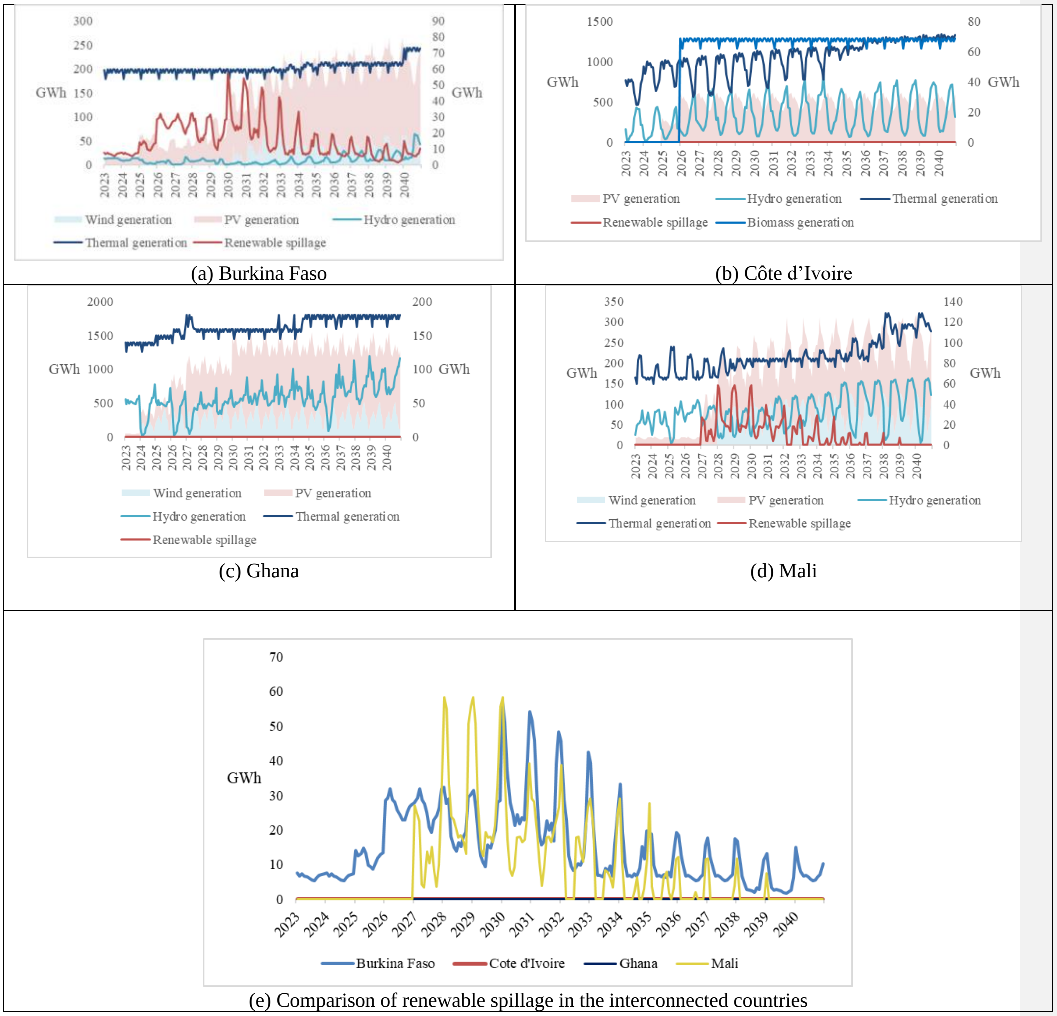


(d1) Renewable dispatch factor (%) for selected solar-wind power plants in Mali



(d2) Renewable dispatch factor (%) for selected PV plants in Mali

Fig. 7 Renewable dispatch factor (%) of selected plants in the study countries for the base case scenario



(a) Burkina Faso

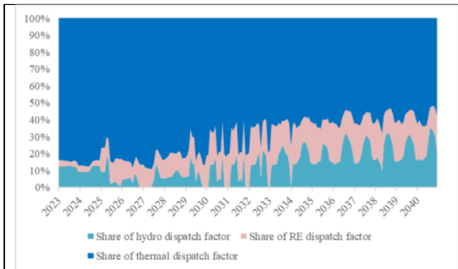
(b) Côte d'Ivoire

(c) Ghana

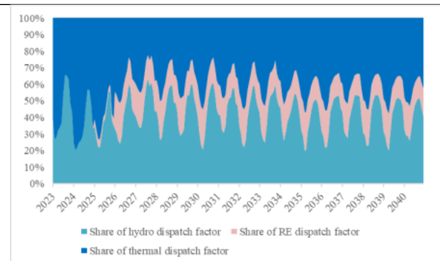
(d) Mali

(e) Comparison of renewable spillage in the interconnected countries

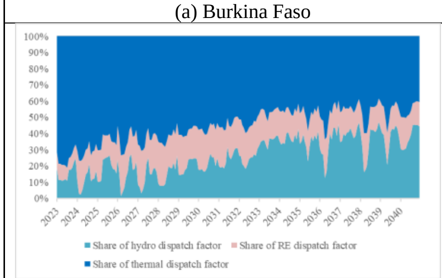
Fig. 8 Electricity generation by source (GWh) and generation spillage (GWh) in the interconnected countries for the base case scenario (left axis for thermal and hydropower generation; right axis for renewable generation and spillage)



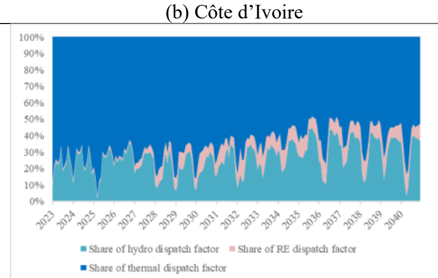
(a) Burkina Faso



(b) Côte d'Ivoire



(c) Ghana



(d) Mali

Fig. 9 Comparison of hydro and renewable dispatch factors based on thermal dispatch factors in the interconnected countries (base case scenario)

Relaxed transmission scenario: Generation capacity expansion with relaxed transmission constraints

In this scenario, all existing single tie-lines between countries are assumed to be converted to double circuit lines; by doing so, bidirectional power flows would be allowed between countries by the dispatch centers. Fig. 10 and

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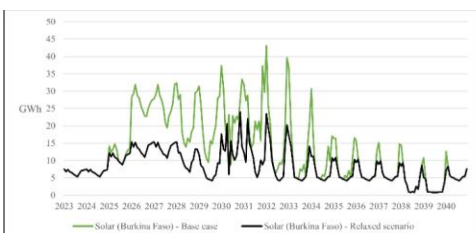
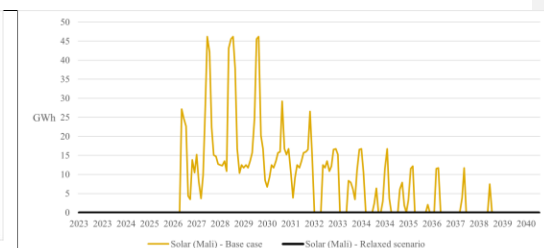
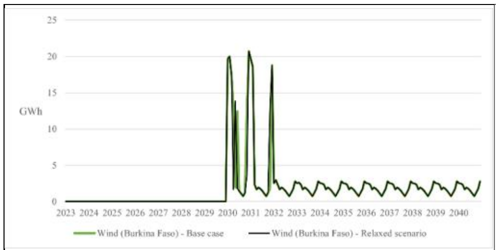


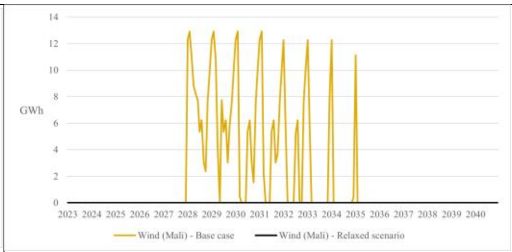
(a) Solar PV spillage - Burkina Faso



(b) Solar PV spillage - Mali

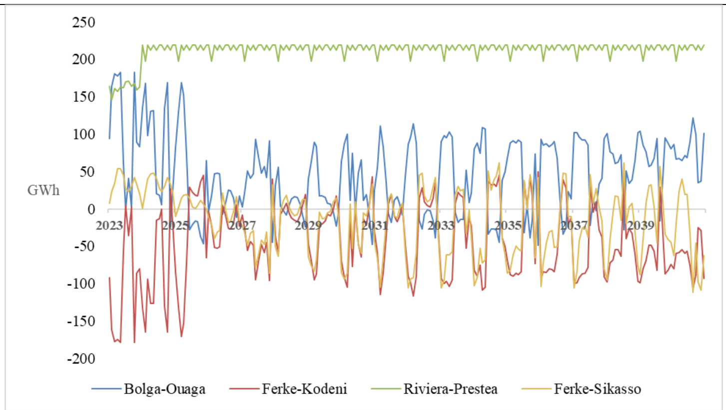


(c) Wind spillage – Burkina Faso

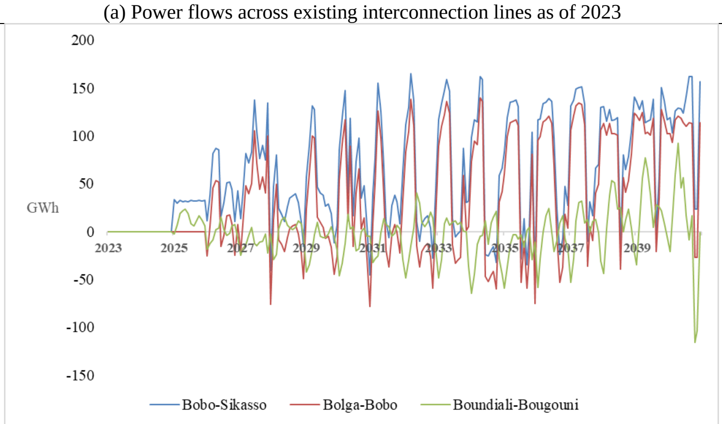


(d) Wind spillage - Mali

Fig. 11. respectively illustrate interconnection flows, renewable dispatch factors, renewable generation spillage for selected plants, imports/exports by area, and the generation mix of electricity imported/exported by electrical area in the study countries.



(a) Power flows across existing interconnection lines as of 2023



(b) Power flows across planned interconnection lines as of 2023

Fig. 10 Interconnection flows between Burkina Faso, Côte d'Ivoire, Ghana, and Mali (relaxed scenario)

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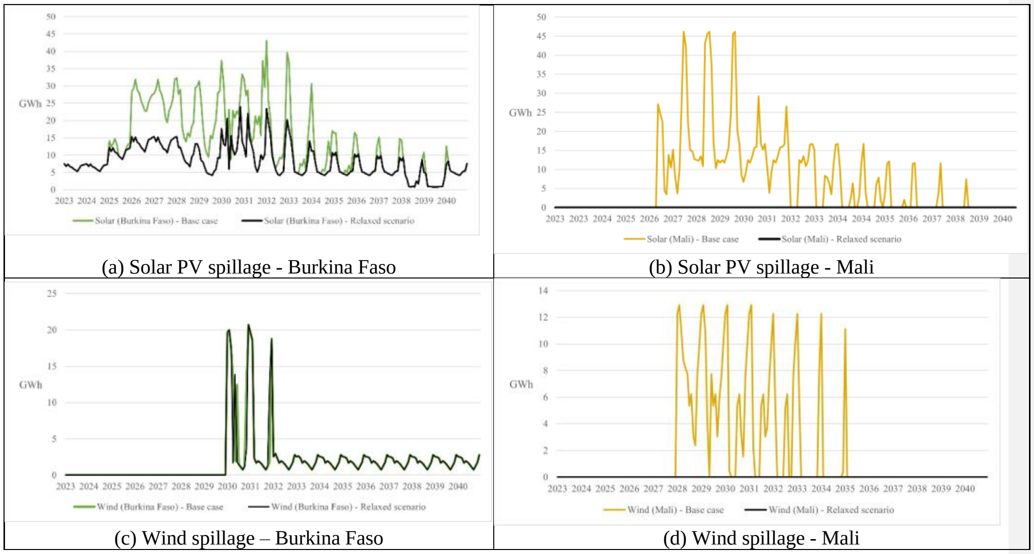

(a) Solar PV spillage - Burkina Faso

(b) Solar PV spillage - Mali

(c) Wind spillage – Burkina Faso

(d) Wind spillage - Mali

Fig. 11 Comparison of renewable generation spillage (GWh) in the relaxed scenario compared to the base case scenario in Burkina Faso and Mali

4. Discussion of results

To which extent can the conservative 10% limit to VRE shares in generation capacity be optimally challenged?

Fig. 4 shows that the 10% conservative limit applied in the 2019 (and latest) WAPP Master Plan is not optimal for Burkina Faso and Mali. For Cote d'Ivoire and Ghana, it is not optimal around the years 2025/2026 considering nominal capacities rather than firm capacities (such a difference was not specified in the Master Plan). Comparing the annual investment in new firm VRE capacity with the national peak demand, it appears that additional VRE capacity can optimally reach between 12.4% and 40.9% of annual peak demand in years when such generation capacity comes online in Burkina Faso. These shares are higher when considering installed capacity. The only exception is for the year 2029 where the share of firm VRE capacity invested represents only 2.7% of peak demand. This can be explained by the expected higher generation of hydropower during 2029, which would be curbed the following year (in 2030) allowing a drastic increase in the share of VRE compared to peak demand, as described by Fig. 8. As for Côte d'Ivoire and Ghana, the shares of additional VRE capacity compared to national peak demand are generally consistent with the 10% limit although exceptions occur around 2026/2027 when the systems become energy-constrained as hydropower generation reach exceptionally low levels with no sufficient thermal generation to compensate.

Within the scope of this study, historical hydro inflows have been used as future samples throughout the study horizon. Notwithstanding, there is a large body of evidence describing the historical disruptions of water inflows in the region, as well as forecasting further disruptions as a result of the adverse effects of climate change, topic which is out of the scope of this work. Hence, linkages between renewables and hydropower generation can result in hydro basins being used as virtual storage facilities for solar PV and wind power [39]. This topic is increasingly gaining interest in the Southern African scientific community for the integration of wind power in the region, with a particular focus on the adverse effects of climate change on the seasonality and magnitude of water inflows, hence on the long-term use of reservoirs for RE integration [39]. Therefore, it could be reasonably argued that for hydro-thermal power systems such as those under study, the conservative 10% limit may be further pushed in the context of more recurrent dry years.

Can increasing VRE penetration disrupt the traditional characterization of importing versus exporting countries and effectively catalyze power pooling?

The four interconnected countries display generation mixes dominated by thermal and hydropower plants, except for Burkina Faso where hydropower plays a marginal role (Fig. 8). This is also reflected by Fig. 8 showing for instance that in Burkina Faso, the dispatch factors of hydropower and RE generation only peak at 67% in September 2040 and 41% in February 2039 respectively, of the thermal dispatch factors for the same time periods. Overall, the base case scenario, which is reflective of the current constrained and single-circuit transmission system, inhibits power exchanges from VRE-rich and low demand countries (Burkina Faso and Mali, traditional importers) to less VRE-rich and high demand countries (Côte d’Ivoire and Ghana, traditional exporters). It is also worth noting that this occurs in a context where the latter group is experiencing an increasingly flexible generation fleet with combined-cycle gas turbines, as well as pumped hydro storage projects, thus highlighting missed opportunities for better accommodating intermittent VRE supply.

Base case scenario

The contribution of renewable generation from solar PV and wind plays an increasing role especially from as early as 2024/2025 in Burkina Faso and Ghana, and from 2027 in Côte d’Ivoire and Mali (Fig. 8). Solar PV holds the lion’s share of renewable generation in all countries except for Côte d’Ivoire where electricity generated from biomass outgrows that of PV from as early as 2026. Côte d’Ivoire is also the only country where wind generation plays no role in the country’s mix. In Ghana and Mali where some wind power plants are already planned, the least-cost investment plan shows that from 2026 (in Ghana) and 2028 (in Mali), they will start contributing to the mix, essentially complementing PV generation. Although Burkina Faso has currently no official investment plan for wind power plants, the OptGen model shows that from 2031, the two ‘assumed’ plants in the Northern and Eastern parts of the country would cost-effectively complement PV generation in those areas, thus ensuring higher and more reliable power supply.

However, as expected in this scenario, traditional importing countries such as Burkina Faso and Mali remain importers despite the excess generation of low marginal cost PV. Indeed, renewable generation spillage is prevalent in the studied countries and is particularly significant in countries with the highest potential and generation levels, Burkina Faso and Mali (Fig. 8). Ghana also experiences high spillage levels particularly between 2025 and 2037 with no possibility to export to high-demand areas in Côte d’Ivoire through the Côte d’Ivoire-Ghana one-directional transmission line. The PV dispatch factors oscillating around 20% in the interconnection areas in Burkina Faso and Mali even during peak times in these countries, highlight that the current single-circuit transmission system inhibits potential power exports to countries such as Côte d’Ivoire and Ghana at high demand periods (Fig. 2). Moreover, the renewable dispatch factors in these countries are higher for wind power plants than for PV plants, with solar-wind complementarities from the year 2030 (Fig. 7).

Relaxed transmission scenario

Moreover, Fig. 10a shows that on existing transmission lines, power flows could optimally occur from traditional importing countries (Burkina Faso and Mali) to Côte d’Ivoire and Ghana. This is particularly true for the Ferke-Kodeni line connecting Côte d’Ivoire to Burkina Faso where “to-from” flows largely outpower “from-to” flows, suggesting a significant opportunity for relieving the current “from-to” constraint. In that case, renewable generation spillage in Burkina Faso decreases by at least 20% from the commissioning of the double-circuit interconnection line in 2025 to nearly 80% between 2029 and 2032 and oscillates between 40% and 60% in the subsequent year, compared to the base case scenario. In both Burkina Faso and Mali, wind generation generally witnesses the most drastic reductions, reaching 100% less spillage for several years from the year 2027. In addition, imports from Côte d’Ivoire to Burkina Faso would be cut down by up to 63% compared to 2020 levels amounting to 488.9 GWh [40]. Most of such imports would occur in the rainy season (May-September) with some occurrences in the early dry season months in Burkina Faso (October and November). These periods generally correspond to high hydropower generation in Côte d’Ivoire and lower PV/wind generation in Burkina Faso during the rainy season, and marginal hydropower generation in the dry season in Burkina Faso. Power exchanges along the Bolga (Ghana)-Ouaga (Burkina Faso) line present opposite trends to those of the Ferke-Kodeni line with imports from Ghana mostly occurring during exports to Côte d’Ivoire, and exports to Ghana during imports to Côte d’Ivoire.

Additionally, Burkina Faso will continue to import electricity from Ghana almost all year long across the study horizon with peaks of up to 27% (compared to 2020 levels at 990.5 GWh [40]. This could be explained by the spatial load distribution in Burkina Faso where the electrical area “Ouaga” represents over 60% of the total load compared to only 20% for the “Bobo” area (including the “Kodeni” node). Notwithstanding, after 2030, imports from Ghana could be reduced by up to 48% compared to 2020 levels with the increasing penetration of PV and wind generation in Burkina Faso. The Ferke (Côte d'Ivoire)-Sikasso (Mali) interconnection line displays similar trends to the Ferke-Kodeni line, therefore the same interpretation applies. As for the Riviera (Côte d'Ivoire)-Prestea (Ghana) line, power flows do not differ from the base case scenario. This implies that the excess generation from renewable plants in Ghana would rather be cost-effectively transmitted to Burkina Faso and Mali, particularly considering the commissioning of the Bolga (Ghana)-Bobo (Burkina Faso)-Sikasso (Mali) interconnection line. As for future interconnection lines between Ghana and Mali through Burkina Faso, and between Côte d'Ivoire and Mali, Fig. 10b shows that such lines could cost-effectively be built as double-circuit lines from the year 2026 although most of the exchanges would follow the initial unidirectional flow. This would allow exports of excess renewable generation from/to Ghana to/from Burkina Faso, to/from Mali. This bidirectional feature would also allow flows of excess PV and wind generation from Mali to Côte d'Ivoire during evening peak times, thus enhancing renewable dispatch factors and reducing spillage.

In summary, this paper shows that the optimal dispatch schedule found by SDDP uses the tie-lines between countries in a better way than the current operation in addition to saving system operating costs and reducing renewable curtailments of the entire region.

5. Policy implications and conclusions

The region of West Africa exhibits an obvious dichotomy between the regional endowment of renewable energy and the practical implementation of its sustainable energy policy aspirations. The current frameworks modelled under this study's base case scenario show missed opportunities for bridging the supply-demand gap in all countries, not only in terms of VRE generation capacity, but also of transmission capacity.

On the one hand, enhancing the generation capacity expansion modelling with geospatial electrification analysis allowed considering the realities of demand distribution across territories, as well as characterizing VRE resource spatial and time distribution. In particular, the latter led to unravelling the potential for wind generation in three countries with strong wind-PV complementarities, including coastal Ghana, which has otherwise been long excluded from being wind suitable areas based on average values. This is consistent with the outcomes of the growing body of literature on VRE development in West Africa. It is worth mentioning that the REZs considered in Burkina Faso do not account for the instability and insecurity dimensions resulting in the loss of state territory due to terrorism in the Sahel region, recently approaching 40%, and primarily concerning the Northern and Eastern parts of the country [41]. Notwithstanding, it is to be highlighted that the Desert to Power initiative led by the African Development Bank with the technical and financial support of the EU, the Green Climate Fund, and the French Development Agency among others, precisely intends to spur socio-economic growth through grid and off-grid energy solutions as a way to counteract with a pivotal root cause of youth and women wide recruitment into terrorist groups [42].

On the other hand, West Africa must design its power pooling so that spatial and temporal variations in VRE supply are properly taken into account in capacity expansion and investment planning if it is to achieve its ultimate goal of creating a regionally competitive area. Comprehensive planning is an important exercise that can help mobilize both local and foreign investment to fund cross-border power projects. Indeed, sound planning of power pooling beyond reducing the transaction costs of trade, is a key enabling factor for enhancing cross-border power trading. Burkina Faso, Côte d'Ivoire, Ghana, and Mali are increasingly seeking public-private investment in power infrastructure and have expressed the need for greater involvement of the private sector, as a means to tackle the lack of financial resources faced by governments and to promote private sector participation and boost their confidence in the sector. Recent trends indicate that these countries will attract more local and international private investors for energy infrastructure development [3]. In such countries where the generation segment is unbundled, IPP generation is expected to increasingly contribute to new VRE capacity additions. Hence, raising the much-needed investment in these countries and other WAPP countries, in general, will necessitate effectively creating an enabling environment for private sector participation as prescribed by the ECOWAS Energy Protocol [43]. This implies building an institutional infrastructure that promotes an efficient market design yielding adequate economic signals for encouraging cross-border power trade and incentivizing investment in the physical power infrastructure. This is especially true in the case of large-scale penetration of VRE generation which disrupts the traditional cost structure and operations of power systems by their lower predictability leading to supply fluctuations in time and space, and requires power system flexibility [44]–[47].

Current frameworks suggest that WAPP is set to follow the traditional path of developed countries. Clearly, there is a dormant opportunity for leapfrogging in the region to design suitable mechanisms for high penetration of intermittent RE. However, this should in fact build on the past and current experiences of more advanced regions that reveal complexities in addressing the imperfections of 20th-century approaches partially stemming from uncoordinated RE national policies and regulations. While models and lessons learnt may be leveraged upon to inform a successful design of the WAPP for the benefit of the countries and their people, past and current landscapes clearly highlight that each region and country have their own specificities and challenges which need to be duly accounted for on an individual basis. As such, ECOWAS Member States participating in the WAPP should endeavor in developing their signature solution regional electricity market which makes provision for the specific opportunities and challenges of the countries involved. Thus, scholarly research in this field should dutifully evolve to provide evidence-based analyses and proposals able to guide the WAPP organization, power utilities, national policymakers, regulatory authorities, and VRE business developers into co-creating and implementing West Africa's signature solution to regional electricity trade as a powerful tool for sustainable and just socio-economic development.

It is important to note that achieving universal access to electricity alone will not be sufficient to achieve socioeconomic development goals because it demands broader reforms in the macroeconomic environment [39], [40], particularly in terms of corporate regulation. Indeed, Sub-Saharan Africa has long been the region with the least business-friendly environment, trailed by South Asia, despite significant advances in recent years [42], [43]. In 2017 for instance, the region's gap between regulatory efficiency and regulatory quality improved three times as much as the average of OECD high-income countries compared to 2016, according to the World's Bank Doing Business Report [48]. However, the 2020 rankings (the latest) show that West African countries made the cut only for the bottom half of the 190 countries assessed, ranked between 110th (Cote d'Ivoire) and 174th (Guinea Bissau) [49]. The predicted economies of scale with competitive power pooling and increased private sector participation will be difficult to accomplish in the face of resource mobilization issues without macroeconomic settings favorable to the large growth of national electricity market sizes.

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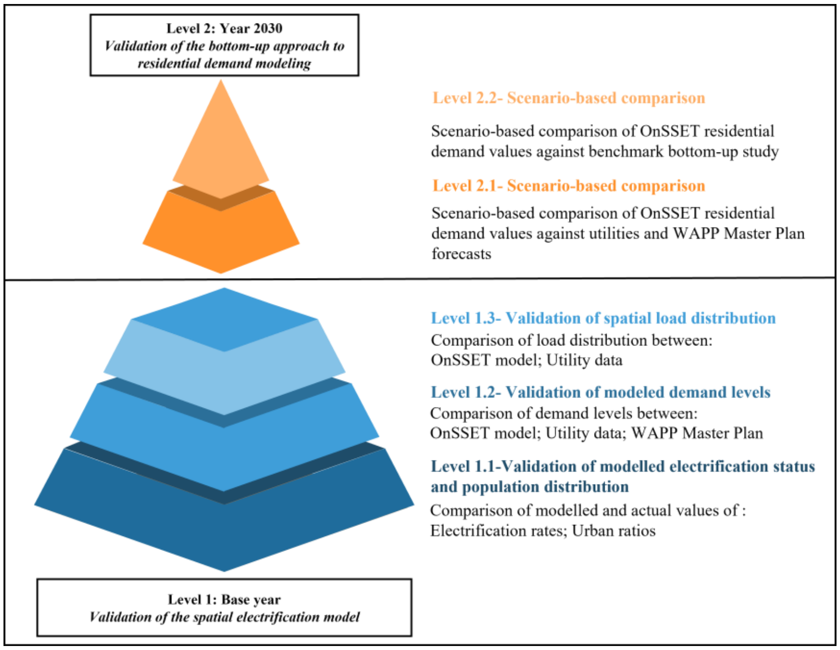
Appendix A

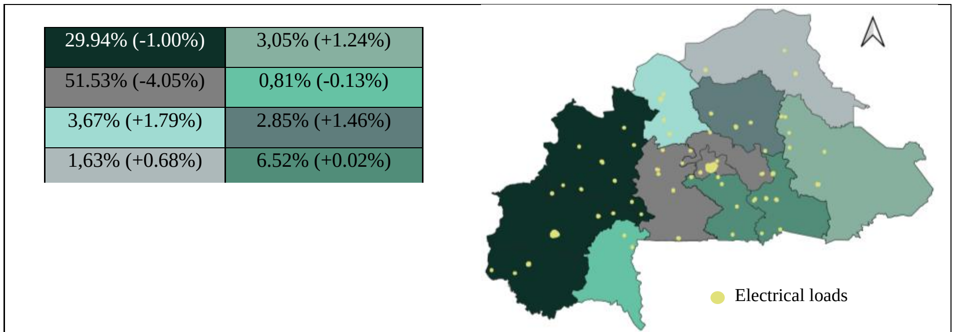
- Two-level validation process of spatial electrification analysis for use as spatially-resolved demand input data in SDDP



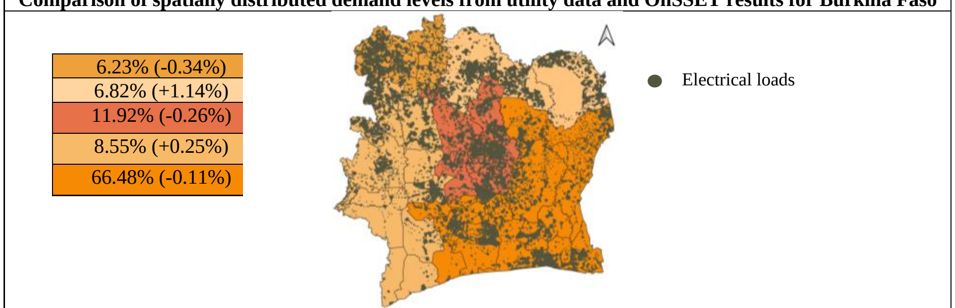
The results show that:

(1) In the base year, the actual and modelled values of national electrification rates and urbanisation are close enough, hence demonstrating the ability of OnSSET to accurately model urban and rural areas, as well as to estimate electrification levels.
(2) In the base year, the OnSSET modelled demand levels utility data are similar to those in the WAPP Master Plan and the power utility data.
(3) In the base year, the spatial distributions of demand levels modelled by OnSSET (represented as weights in the total grid demand) are close to actual values of bus data provided by the respective national utilities.
(4) In the final year, the OnSSET modelling yields appreciable results which are consistent with utility forecasts for national demand and with the first-ever bottom-up study [17] for demand at household level.

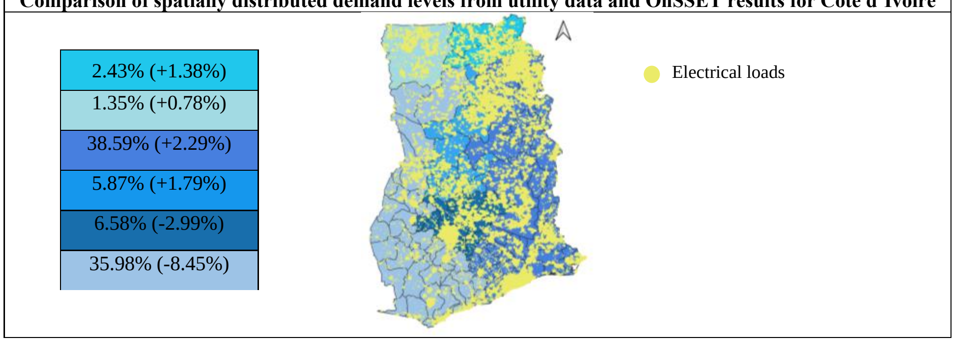
- Spatial load distributions in each study country



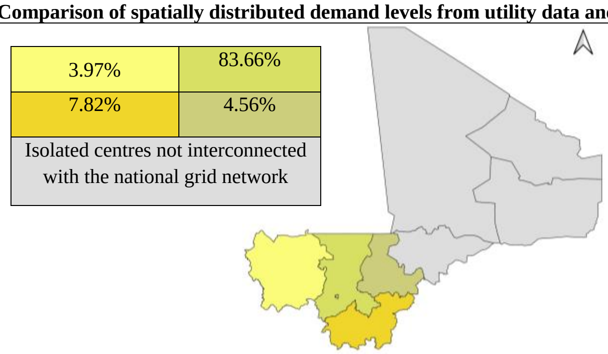
Comparison of spatially distributed demand levels from utility data and OnSSET results for Burkina Faso



Comparison of spatially distributed demand levels from utility data and OnSSET results for Côte d’Ivoire



Comparison of spatially distributed demand levels from utility data and OnSSET results for Ghana



Mapping of electrical loads in Mali

The spatial distribution of loads based on utility data from 2017 (the latest year available), Considering that OnSSET modelling could not be performed and that the insecurity situation in Northern Mali, which is not yet interconnected with the national grid, it was deemed appropriate, to lay the hypothesis that electricity demand will not increase sufficiently to justify large-scale grid interconnection investments. Indeed, with the insecurity environment prevailing in this region for over a decade [50], it could be reasonably expected that the investment risks would constrain such commitments from technical and financial partners, who currently dominate investment in the sector. Therefore, it is assumed that until 2040, no isolated center will be connected to the grid.

Acknowledgments

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