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Stakeholder-guided, model-based scenarios for a climate- and water-smart electricity transition in Ghana and Burkina Faso☆

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ABSTRACT

In support of West Africa's potential energy transition under climate change, an international team of scientists and a wide range of local stakeholders in Ghana and Burkina Faso jointly assessed different mitigation and adaptation pathways for energy and water supply and demand, including their implications for achieving SDGs, in a transdisciplinary approach. They iteratively co-developed a range of future scenarios based on i) stakeholder knowledge and priorities, ii) countries' national plans, and iii) simulations with a set of complementary energy and water models. Unlike current national plans, the more ambitious scenarios indicate that the projected rapid increase in electricity demand could be met almost entirely from renewables, but that a diversification beyond hydropower will be necessary. Phasing out fossil fuels would bring West African countries's energy policies in line with Paris Agreement targets and generate additional socio-economic and environmental co-benefits.

1. Introduction

In West Africa, climate change, in combination with other environmental and socio-economic pressures, is already threatening energy and water security, livelihoods, and sustainable development [1–4]. Therefore, climate change mitigation and adaptation measures need to go hand in hand [5]. The urgency of simultaneously addressing climate and development issues presents an opportunity for West African states to initiate a rapid transformation of their energy and electricity sectors towards renewable energy sources while striving to obtain electricity access for all.[1]

As pointed out by Ref. [6]; many African countries are in a good position for such a transformation thanks to an abundance of renewable resources, provided that they can attract the required international finance for building up the required infrastructure for electricity generation, transport, storage and use [6,7]. Doing so would enable West African nations to align with the global target of achieving net-zero CO_2 emissions by mid-century to keep global warming well below 2 °C, with

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efforts toward 1.5 °C as per the Paris Agreement [8,9]. Beyond achieving climate neutrality, there is a need to reach general socio-economic targets, expressed through the Sustainable Development Goals (SDGs), to improve societal well-being and environmental integrity to help to meet sustainability criteria for development cooperation. These targets should be harmonised with climate neutrality objectives as much as possible.

Energy is critical for development, and improved access to renewable and clean energy is the focus of Sustainable Development Goal 7 or SDG7 [10]. Electricity from renewables has several co-benefits for sustainable development, such as improved health (SDG 3), education (SDG 4), and business opportunities (SDG 8) [8]; chapter 17, [11]). A climate-smart[2] transition to renewables in the electricity sector (i.e. climate mitigation) must inevitably address the impacts of climate change (i.e. climate adaptation), e.g., changing water availability. For instance, electricity generation from hydropower, but also from thermal power plants (requiring cooling water), may have to adapt to increasing variability and extremes of water availability.

Hydropower is currently the dominant source of renewable electricity production in West Africa, and even the main source of electricity overall in certain countries, leaving the sector vulnerable to water scarcity and droughts. In combination with climate change, water demands from other sectors also drive water scarcity. More recently, renewable contributions to the power sector have become more diversified beyond hydropower [12]; Renewable Energy and Energy Efficiency Status Report). Increasing the contribution of solar and wind to the electricity mix, however, may pose challenges due to the intermittency of these sources, thus requiring intelligent design of electricity systems [13,14]. Among others, [15] show that higher levels of renewable energy can also lead to higher cost-effectiveness and at the same time creat additional jobs.

As suggested by the EU Africa Strategy (2020) [16], the SDGs can only be achieved in low-carbon, resource-efficient and climate resilient economies. For achieving those objectives, systemic and transdisciplinary approaches are essential for generating the required transition knowledge. Such processes enable integrated planning of climate adaptation, mitigation, and sustainable development (e.g. Ref. [17], and in particular, coordination across the energy and water sectors, to minimize cross-sectoral trade-offs and enhance synergies.

Such integrated or "nexus" approaches [18,19] and their complex challenges require the close and continuous collaboration of scientists and stakeholders as a prerequisite for generating state-of-the-art information for policy and decision making. Such **co-development between scientists and stakeholders** of science-based, relevant and actionable knowledge for direct implementation in planning and management is at the heart of what are called "climate services"—the provision of useful information to relevant stakeholders based on climate and related data.

The CIREG (Climate Information for Integrated Renewable Electricity Generation) climate services project (see Acknowledgements), implemented across the period 2018–2021, piloted such a participatory approach, jointly developed by stakeholders from Ghana and Burkina Faso and international scientists. The overall goal of the project was to assess pathways to meet energy and water demands in West African countries, with Ghana and Burkina Faso as particular focus countries, given future climate change impacts and socio-economic changes. A consortium of academic institutions[3] provided the scientific underpinning for this co-development process. Scientific inputs ranged from short-term and seasonal predictions of e.g. water demand to long-term projections of climate variables and impacts, integrated with context-specific technical and environmental information. These scientific inputs were subsequently tailored to the needs expressed by stakeholders in an iterative process. Thus, the CIREG project aimed to support a climate- and water-smart transition of the electricity sector and related aspects of sustainable development such as food and water security. Along the way, the CIREG project built capacity of local stakeholders, policymakers and decisionmakers from the energy and water sectors in Ghana and Burkina Faso for integrated planning and the use of scenario and modelling tools.

The main goal of this paper is to provide an overview of the scientific approaches, methods, and results co-generated by scientists and stakeholders during the CIREG project. The authors of this paper, who were all involved in-depth in the CIREG project, believe this may provide a valuable learning moment for other future projects to implement and further develop similar participatory methods in which international and local teams work together to create meaningful scenarios while building institutional capacity.

The iterative integration of scientific results with stakeholders' knowledge, priorities, needs, and assumptions was achieved through participatory scenario development. These participatory scenarios were formalized and quantified with the help of the energy and water scenario planning tools LEAP and WEAP. This paper describes the scenario co-development process with three underlying input pillars, which provided inputs for LEAP and WEAP:

i. A systematic assessment of national climate, energy and water documents, strategies, policies, and development plans, to inform the scenarios about national priorities and ambition levels;
ii. Scientific model simulations with two other tools, namely CIREG's hydropower dispatch (REVUB) and river flow (SWIM) models, which were coupled to LEAP and WEAP to study the potential responses of the energy and water systems to climate change and operational interventions;
iii. Targeted and regular stakeholder-scientist dialogues[4] for iterative scenario development, providing targeted scenario inputs.

This paper further describes the participatory scenario development process, and highlights the interlinkages between the energy and water sectors that the model coupling emphasized, showing the need to overcome siloed approaches in planning and management. The paper presents critical outcomes of the integrated scenarios, including synergies and trade-offs between achieving climate-, energy- and water-related objectives. This central outcome of the CIREG project is meant to support evidence- and science-based integrated planning and management of energy and water resources in the context of a sustainability transition of the electricity sector. Finally, the paper provides lessons learned and recommendations for participatory co-development processes and effective climate services.

This paper is organised as follows. Section 2 details the methods used in the participatory scenario development, following the three pillars mentioned above. Section 3 explains the different scenarios that were designed, and their input assumptions, data and methods. Section 4 covers results on energy and water supply and demand under the different scenarios. Section 5 provides a discussion of the obtained results, and Section 6 summarises conclusions and lessons learnt.

2. Materials and methods: input pillars

In this section, the three input pillars for the developed scenarios tools are described in more detail: i) systematic assessment of national documents, ii) the energy and water process models REVUB and SWIM, and iii) the stakeholder-scientist dialogues for participatory scenario

[2] "climate-smart" here used as being climate-resilient AND low-carbon.

[3] West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL); Potsdam Institute for Climate Impact Research (PIK); Stockholm Environment Institute (SEI); Vrije Universiteit Brussel (VUB); World Resources Institute (WRI), Danish Technical University (DTU); Zentrum für Entwicklungsforschung (ZEF).

[4] See list of participating stakeholders in the supplementary material.

development:

2.1. Pillar 1: systematic assessment of national documents, strategies, policies, and development plans

The systematic assessment of national plans was based on a thorough review of national documents, strategies, policies, and development plans, e.g., Nationally Determined Contributions (NDCs), National Appropriate Mitigation Actions (NAMA), and National Renewable Energy Action Plans (NREAP), among others. The focus was on identifying both quantitative and qualitative objectives and targets for each sector, as well as specific measures to achieve those targets. These measures were also used in the national scenarios developed by Ref. [20].

The national development plans frame the sectoral plans by describing how specific sectoral targets and measures contribute to the achievement of overarching development goals such as poverty alleviation and human well-being. An overview of the national documents and plans assessed in CIREG and used for the "National Plans" scenario is given in Supplementary Table 1 in the Supplementary Material. Note that almost all plans and targets focus on the short to medium-term future (until 2030).

2.2. Pillar 2: CIREG's energy and water models

The energy and water scenarios are based on simulations of supply and demand for electricity and water under climate change. CIREG's central scenario tools LEAP and WEAP were informed by detailed process simulations in the electricity (REVUB) and water (SWIM) models. These now well-established scientific models, REVUB [21]— which was developed within the CIREG project —and SWIM [22,23] provide additional supply-side information necessary as input to water and energy planning. These two process models have been extensively applied to the West African context and proven to work well for this context. LEAP and WEAP (which have been successfully applied in many countries and basins around the world) integrate this information with demand side projections, based on national plans and stakeholder inputs. The combination of REVUB and SWIM with LEAP and WEAP as input for the development of integrated energy and water scenarios is illustrated schematically in Fig. 1. Each of the four models and tools is introduced in more detail below.

Energy scenarios under climate change and opportunities for increasing renewable electricity generation were simulated with the **Renewable Electricity Variability Upscaling and Balancing (REVUB)** model [21] as input into LEAP. REVUB was used to assess the spatio-temporal synergies between solar photovoltaic and wind power potential (intermittent resources) on the one hand, and flexibly dispatchable hydropower on the other hand, thus estimating spatiotemporal synergies and complementarities between these different energy sources.

Hydrological and water management impacts of the climate scenarios were assessed with the **Soil and Water Integrated Model (SWIM)** [22,23], a semi-distributed and process-based eco-hydrological model operating at a daily time step. SWIM river discharge simulations were used as input into WEAP to evaluate climate change impacts on water availability and use and hydropower production.

The **Low Emissions Analysis Platform (LEAP)** [24] is a tool for participatory scenario development and strategic planning and management and for policy and decision support. LEAP has evolved from a pure energy modelling tool to a modular platform for scenario analysis of energy, greenhouse gas emissions, and co-benefits e.g. in air pollution abatement [25,26]. In CIREG, LEAP integrates results from REVUB and WEAP with priorities of stakeholders and national plans. High temporal resolution data, in particular solar PV, hydropower, and electricity demands were pre-processed in REVUB before being aggregated into daily timesteps with daytime and night time temporal slices in LEAP (resulting in 730 slices per year). In this project, LEAP was run at monthly resolution with two time-slices representing daytime and night-time for each month.

The **Water Evaluation and Planning (WEAP)** tool [27] has a similar function as LEAP, but for the water sector, i.e., participatory scenario development in support of strategic planning and policy support [28–30]. WEAP uses basic principles of water balance accounting and represents water systems, i.e. supplies, demands, and infrastructure at reduced complexity. An iterative linear programming algorithm prioritizes water allocations under scarcity [27]. In CIREG, WEAP integrated water supplies under climate change as derived from the SWIM model with water demands, infrastructure information, and projections from stakeholders and national plans.

The conjunctive use of LEAP and WEAP for integrated energy and water sector planning and management has been tested in various geographical and socio-economic contexts before [31,32]; Johnson et al., 2018). In the CIREG project, WEAP and LEAP were soft-coupled to assess electricity-water linkages, trade-offs, and synergies under climate change and infrastructure and management interventions, with a focus on hydropower.

2.3. Pillar 3: Stakeholder-scientist dialogues and participatory scenario development

Throughout the CIREG project, the participatory scenario tools LEAP and WEAP were continuously adapted to the respective contexts and planning, management and policy needs, jointly by stakeholders and project scientists. In several iterations, scientific data from the process models was integrated with stakeholder needs, priorities, and knowledge, followed by improvement in model parameterizations and scenario adjustments and subsequent re-evaluation of the scenario outcomes in the next iteration loop. This iterative stakeholder-scientist process continued throughout the CIREG project, using all available formats and opportunities, including physical and virtual meetings, visits to key institutions, and on-site and online training sessions.

The dialogue started with critical priorities identified by stakeholders in each country or basin (see Table 1).

These issues were addressed iteratively throughout the project in the stakeholder-scientist dialogues and dedicated trainings (note that this paper does not discuss all of the issues in detail). Stakeholders involved in these dialogues and trainings ranged from the Energy Commission (Ghana), which had already used LEAP for energy planning (updating their LEAP model during the CIREG project), to e.g. the Water Resources Commission (Ghana), which had already used WEAP for water management, and the Volta River Authority (Ghana), which manages thermal and hydropower plants, including the Akosombo dam. The full range of stakeholders from the different countries involved in the CIREG dialogues is listed in Supplementary Table 3 of the Supplementary Material.

CIREG's starting point for the Volta basin was an earlier WEAP application developed by the Volta Basin Authority and the IUCN PAGEV[5] project, jointly with IWMI[6] and IRD[7]. During CIREG, this model application was updated with the latest data on new hydropower dams and reservoirs (e.g., storage capacity, dead storage, volume elevation, year of commissioning, etc.) based on stakeholders' knowledge and additional literature (see Supplementary Table 2 in the Supplementary Material). The CIREG WEAP Volta tool now covers all primary water supplies, users, and their (actual and projected) demands in the entire basin, including dams along the principal rivers.

CIREG's LEAP models were developed at the national level for Burkina Faso and Ghana. Hence, WEAP and LEAP cover different spatial

[5] Project for Improving Water Governance in the Volta Basin.

[6] International Water Management Institute.

[7] L'Institut de Recherche pour le Développement, French Development Research Institute.

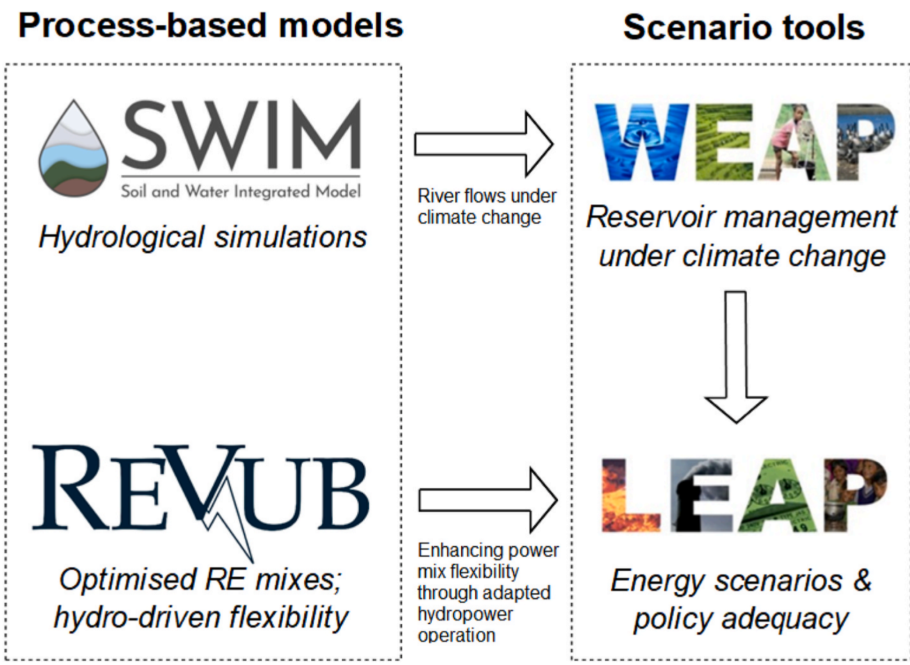

Fig. 1. Modelling framework, exchange of data & information between models.

Table 1
Topics and information needs identified in the early phase of the project by CIREG stakeholders.

Topics considered critical priorities	Information needs identified
Hydropower potential	Inflow into and hydropower production of existing and planned dams under climate change
Potential of planned Pwalugu dam (Ghana)	• Integrated management of this multi-purpose dam under climate change: hydropower, irrigation and domestic water supply, flood control, environmental flows • Siltation of the dam • Impact on Lake Volta
Potential of planned Bagré Aval and Samendéni dams (Burkina Faso)	Integrated management of multi-purpose dams under climate change: hydropower, irrigation and domestic water supply, flood control, environmental flows
Domestic water supply to Ouagadougou (Burkina Faso) under climate change	• Assessment of the future water demand • Reliability of the supply from Ziga and Loumbila dams
Capacity building on WEAP and LEAP tools	Existing capacity of involved stakeholders to develop scenarios for electricity demand and supply
Flexible hydropower and solar photovoltaic integration (Ghana)	Optimisation of complementary production of solar and hydropower, informing the growing interest in floating solar photovoltaics on Ghana's Akosombo and Bui reservoirs

domains: WEAP covers the Volta River basin, while the LEAP models focus at the national level on Burkina Faso and Ghana. In WEAP, water demands were distributed spatially explicitly within the basin, while electricity demands were aggregated to the national level in LEAP.

The synthesis and integration of all available scientific and stakeholder data and information in the WEAP and LEAP scenario tools enabled the identification of potential systemic hotspots, bottlenecks, trade-offs, and opportunities for sustainable and integrated generation, management, provisioning and use of electricity and water.

As an extension of the stakeholder-scientist dialogues, a set of hands-on training sessions with focus on LEAP and WEAP, with introductions to the REVUB and SWIM models, were held by the CIREG project. Over the period from February 2018 until December 2020, six workshops were held, three in Ouagadougou, two in Accra and one virtual (during pandemic-related travel restrictions). These training sessions aimed to build capacity with local stakeholders on energy and water system modelling, the associated data management, and the operational use of the tools in planning and management; while at the same time also improving stakeholders' skills in assessing the systemic impacts of climate change and in developing integrated electricity and water solutions in the context of the SDG targets. Participants were mainly from Ghana and Burkina Faso, but several interested representatives from Niger and Togo also joined the sessions (see Table 3).

3. CIREG's scenario hierarchy as co-developed by stakeholders and scientists

For assessing the combined and systemic effects of climate and other changes and different management interventions, stakeholders and scientists agreed, in the course of their dialogue, on five scenarios, which were deemed to represent the most relevant climate, socio-economic and policy projections and development trajectories of the electricity and water sectors. These five scenarios built upon each other to form a comprehensive storyline, each scenario introducing new elements as compared to the previous. The hierarchy is illustrated schematically in Fig. 2, and explained below.

3.1. Overview of scenarios

Scenario (1) **Business-as-usual (BAU)**: This scenario aimed to show what would happen with energy and water supply and demand in Ghana and Burkina Faso if current trends were to continue into the future. Extrapolating recent trends, a "business-as-usual" pathway is thus obtained.

Scenario (2) **Climate Change**: This scenario aimed to show how a business-as-usual policy (Scenario 1) would be affected by projected climate change and land use change effects on river discharge (and consequently hydropower generation) and irrigation demand. We use two combinations of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), namely SSP1/RCP2.6 and SSP3/RCP7.0, to assess these impacts.

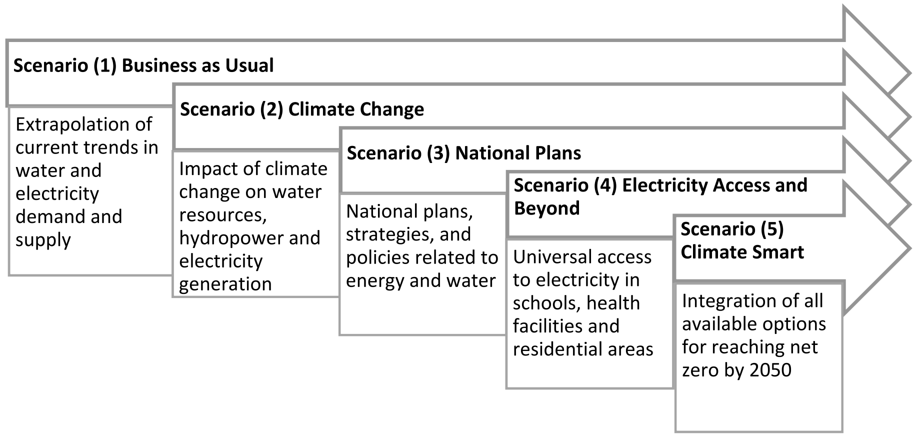

Fig. 2. Scenario hierarchy for energy and water supply and demand in Ghana and Burkina Faso.

Scenario (3) **National Plans**: This scenario built upon Scenario 2 by aiming to show how energy and water demands could be met differently than under business-as-usual. It explores what it would mean if countries successfully implemented their national climate, energy and water policies, as expressed through NDCs, NREAPs and NREMPs and other targets for electricity and water supply and demand.

Scenario (4) **Universal electricity access and beyond**: Building upon Scenario 3, this scenario includes the additional energy demands for achieving universal electricity access for residential, educational, and medical facilities (single-stage tier advancement in electricity access based on rural and urban population grouping). This scenario thus assumed an ambitious policy to provide universal electricity access within the assessed timeframes, which goes beyond current policy targets in ambition. "Beyond" refers to the World Bank's multi-tier framework of electricity access that includes quality, quantity, and availability of electricity ("Beyond connections", [33]).

Scenario (5) "**Climate-smart**": This final scenario, building upon Scenario 4, explored opportunities to reach climate neutrality in the electricity sector while achieving universal electricity access. These opportunities mostly relate to adopting a low carbon energy mix, through an increase in variable renewable electricity contribution (in particular, solar and wind) to about 60% of total electricity generation until 2050, harnessing the flexibility of existing and planned hydropower to integrate these variable resources into the mix, as well as investing in bioenergy and waste-to-energy projects.

Note that higher-order scenarios inherit the assumptions and data from (and hence build on) parent scenarios, meaning, for example the Climate Smart scenario (5) includes the data and assumptions from all other scenarios, the Universal Access scenario (4) includes those from scenarios 1–3, *etc.*, exchanging in each higher-order scenario only those data that are directly related to the newly introduced assumptions. Scenario (5) is particularly important in that it includes key development objectives in terms of universal electricity access, demonstrating that these can be met while simultaneously (almost) achieving climate neutrality in the electricity sector.

This scenario hierarchy was primarily implemented in the LEAP energy scenario tool. Wherever relevant and necessary, scenario elements were also implemented in the WEAP water scenario tool.

The following section presents more detailed assumptions and data used in the different scenarios.

3.2. Data and assumptions used for the scenarios

3.2.1. Demographic and economic drivers of water and energy demands

WEAP and LEAP are driven by water and energy demands, respectively, and hence use demographic and macro-economic growth trends for projecting future demands. Current and projected demand and supply data were consolidated from expert knowledge and relevant national statistics, policies, strategies, and plans, including NDCs and SDGs. For details on the inputs used to parameterize WEAP and LEAP, the reader is referred to Supplementary Table 4 in the Supplementary Material.

3.2.2. Historical and future water demand trends

Following stakeholders' expert knowledge, the most substantial future increases in domestic water demands were implemented in WEAP scenarios for the cities of Ouagadougou and Koudougou in Burkina Faso and Tamale in Ghana, based on data provided by the *Direction Générale des Ressources en Eau* (Burkina Faso) and the *Water Resources Commission* (Ghana). Similarly, the most substantial increases in irrigation water demands were projected and implemented in WEAP for Bagré in Burkina Faso and a new irrigation scheme in conjunction with the commissioning of the Pwalugu dam in Ghana.

At Bagré, data provided by the organization managing the irrigation scheme, *Bagré Pôle*, shows that there has been a continuous expansion of irrigated areas and, therefore, water demand from the reservoir since 1997. This historical trend is projected into the future until it reaches its maximum of about 540 Mm^3/year as per data from Bagré Pôle (illustrated in Fig. 3 below). Studies available from the Water Resources Commission (Ghana) indicate that the new Pwalugu dam is expected to serve an irrigation area of 25,000 ha, equivalent to an irrigation water demand of about 600 Mm^3/year. Additional cooling water demand for electricity generation from the thermal power plants was estimated to be about 25 Mm^3/year, according to Ref. [34] in a fossil fuel-dominated electricity grid under the BAU scenario.

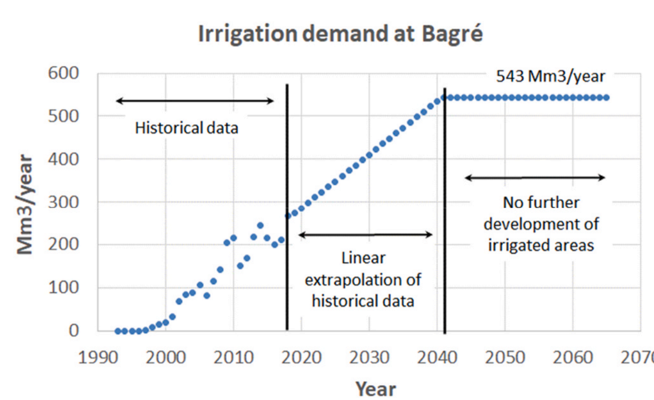

Fig. 3. Stylized implementation of future water demand in WEAP, based on current trends, here for Bagré irrigation demand (based on data obtained through dialogue with the Bagré Pôle agency).

3.2.3. Future water supply trends

Changes in future water supply will primarily be due to climate change and to the development of water infrastructure (expansion of existing irrigation and new irrigation schemes from the multi-purpose Pwalugu dam) according to national plans. With the help of the SWIM model, projected changes in temperature, precipitation, and solar radiation were translated into changes in river discharge using an ensemble of eight downscaled and bias-adjusted Global Climate Models from CMIP6 [35] and ISIMIP [36], for the SSP1-RCP2.6 and SSP3-RCP7.0 scenarios (see Fig. 1 and the Supplementary Material).

Hydropower was therefore constrained by annual average availability based on the average of RCP 2.6 and RCP 8.5 emissions pathway between 2035 and 2065, for modelling impacts of climate change under Scenario 2.

3.2.4. Historical and future electricity demand and supply trends

For Ghana, historic electricity supply data implemented in the CIREG LEAP model were based on the annual energy outlook [37], and trends of the past ten years were extrapolated into the future in Scenario 1 (business-as-usual).

LEAP uses demographic and economic growth and value-added trends within the different sectors to project future electricity demands. Projections for specific companies and sectors in Ghana, such as VALCo (Volta Aluminium Company) and Mines, were adopted from the supply master plans. Resources were then allocated to these demands, considering generation source efficiencies and transmission and distribution losses. The dispatch order in LEAP is determined by load duration curves and pre-set criteria such as merit order and availability [38,39]; 2019).

The demand data for Scenario 3 (National Plans) for Ghana is based on official national plans, including the Nationally Determined Contributions, the Integrated Power System Master Plan, the Renewable Energy Master Plan 2019, and the National Renewable Energy Action Plan [38]; ICF & Energy Commission of Ghana, [40]; [41]; [42]) [20]. provides an overview of the plans. The stakeholder-scientist dialogues in Ghana agreed to base the National Plans scenario on the medium-term projections (until 2030) of the Renewable Energy Master Plan Energy Outlook (2019). Their implementation in LEAP was aligned with projections of renewable energy targets from the Nationally Determined Contributions and the National Renewable Energy Master Plan (NREAP) to meet the growing future demands while expanding renewables and reducing (technical and commercial) losses to an average of 19% in 2024, 15.5% in 2030 and 12% in 2050, in particular for the two leading players NEDCO (Northern Electricity Distribution Company) and ECG (Electricity Company of Ghana) [43]. In Scenario 3, Ghana's electricity exports of about 1350 GWh in 2020 are projected to increase to 3500 GWh by 2035 and 4100 GWh by 2040 [43].

Scenario 3 for Burkina Faso relied mainly on historical electricity consumption data (Ministère de l'Energie, 2017) [44]. The implementation of this scenario in LEAP also uses data from the Plan d'Action National des Energies Renouvelables (PANER) for electricity generation [45]. Transmission and distribution losses for Burkina Faso are projected to drop from 17% in 2020 to 10% in 2030 and 6% in 2050. National plans aim for renewable electricity shares to rise from 24% in 2020 to 36% in 2030. Further investment may enable 50 MW of concentrated solar power, 200 MW of photovoltaic, 30 MW of hydropower generation, and 7.5 MW of biomass (PANER). Off-grid supply will expand to 36% of total supply by 2030 through mini-grids and other distributed systems fields [45]. By 2050 about half of the rural population is projected to be served by decentralized (off-grid) electricity, while 100% of the urban population will be served by grid electricity. Burkina Faso has no official electricity import projection; however, we adopted an average import growth rate of 5% annually in the LEAP model.

In Scenario 4 (Universal Access), residential electricity use was assumed to move from Tier 2 (up to 365 kWh/yr) to Tier 3 (up to 1250 kWh/yr) for rural areas and from Tier 3 to Tier 4 (up to 3000 kWh/yr per household) for cities, in line with [46]. This increase can be attributed to growth in household electrical appliances such as air conditioners, refrigerators, washing machines, and other devices [47–49]. This substantial increase in demand in Scenario 4 could reduce the share of renewables in electricity supply compared to Scenario 3, unless renewables are rapidly expanded (as in Scenario 5).

Under all scenarios, we assumed that the hourly energy consumption pattern of electricity would not vary substantially in the mid-term projection.

In Scenario 5 (Climate Smart), with its maximized renewable energy contribution, electricity-based GHG emissions will approach net-zero by 2050 in both countries. For that, Ghana is projected to use a mix of strategies for achieving that net-zero goal, including variable renewable energy integration [21], exploitation of all available resources such as hydropower in Ntesero, Kulpawn and other reservoirs [50], and utilization of biomass, municipal solid waste, and other forms of bioenergy [51,52]. Through adapted hydropower reservoir operation in support of grid integration of variable renewables, 1515 MW of solar could be backed by Akosombo hydropower and 372 MW by the Bui hydropower. Furthermore, Ghana's technical wind potential is estimated at 5 GW MW [53] and its potential for energy from agricultural biomass is almost 20 GW [51,52]. Through the stakeholder dialogues, we assumed bioenergy could reach a share of 15% in Ghana's electricity generation mix by 2050.

In Burkina Faso, the strategic focus for achieving net zero by 2050 in the Climate Smart scenario (5) will be on harnessing all techno-economically viable hydropower plants in Bontioli, Bougouriba, Folozo, Gongourou, and Noumbiel [54], eventually providing an additional 110 MW to the existing capacity mix. About 518 MW additional capacity of future dams were identified on the Black and White Volta Rivers, which would be economically viable. Total potentials for wind power were estimated to be about 10 GW of wind power, 82 GW of solar power and 1000 MW from biomass [54]. From those potentials, we assumed that 50% of future electricity will come from solar photovoltaic and wind energy, supported by advancements in technology and controls, regional trade, and geographical location smoothening [55].

3.2.5. Additional assumptions and constraints for the Climate Smart scenario

The Climate Smart scenario (5) is much more ambitious than current national plans, aiming at almost complete decarbonization of the electricity sector, through higher exploitation of the available renewable energy resources. In LEAP, we prioritized their dispatch by merit ordering as follows: (a) renewable and variable sources such as solar PV and wind are dispatched at full capacity (b), all hydropower are set at merit order 1, whereas other renewables (e.g. biomass and biogas) are set at merit order 2. Gas turbines and fuel oil have the lowest priority and are dispatched at merit orders 3 and 4 respectively.

Moreover, for achieving maximum utilization of solar power while mitigating its variability at hourly and seasonal time scale, the LEAP model used the results of the REVUB model, which determines an optimized (hourly time resolution) combination of flexibly dispatched reservoir hydropower and solar photovoltaics, with hydropower designed to ramp up and down in the evenings and mornings as solar generation changes, as discussed by Ref. [21]. In this case, the hourly resolution of solar photovoltaic power availability in Ghana and Burkina Faso for 365 days was derived from the ERA-5 reanalysis and provided as LEAP input data for aggregated timestep scenario modelling at a much lower resolution of 730 time steps per year. From climate change models, no significant change in solar insolation is expected until 2050, assuming similar annual solar PV generation profiles [21]. Given that the LEAP model does not support grid stability studies under high penetration of variable renewables, the total contribution of solar and wind power to the final electricity generation mix in the grid was capped at an annual average of 50% [56] to avoid spurious scenario results in which variable renewables reach potentially unrealistic shares of electricity supply.

Fig. 4 shows an example of how hydropower from Akosombo in Ghana could work in tandem with solar PV, as provided by the hydropower dispatch model REVUB: Hydropower ramps down during periods of high solar power generation. This output from Ref. [21] was used as input for Scenario 5 to reflect adapted hydropower operation under high penetration of variable renewables.

4. Results

4.1. Climate change impacts on hydropower generation

The climate change impacts on hydropower generation are assessed in Scenario 2 and thus are also included in the subsequent scenarios (3–5). SWIM model simulations show increasing annual inflows into the Bagré reservoir and Lake Volta under climate change. This increase is mainly due to larger inflows in the rainy season, while the simulated changes of inflows during the dry season are minor (see Fig. 1 in the Supplementary Material).

Impacts of climate change scenarios on hydropower generation were examined with WEAP and LEAP against a historical period starting in 1994, following the commissioning of the Bagré dam, and up until 2016, which is the last year of available historical data. Two future time horizons were chosen for climate projection: 2030, representing the average of the years 2015–2045, and 2050, representing the average of the years 2035–2065.

The projected increase in discharge logically accumulates from upstream to downstream in the basin, in Lake Volta, which translates into an increase in hydropower production in Akosombo of about 7% by 2030 (5550 GWh/yr) and 5% by 2050 (5450 GWh/yr) compared to the historical period. The planned expansion of the irrigation areas by the Bagré dam in Burkina Faso will, however, increase water demands and thus reduce the water available for hydropower by about 12% [4]. The greater simulated inflow into the Bagré reservoir under climate change does not fully compensate for this increase in irrigation water demand, overall leading to a slight decrease in hydropower production of about 7% by 2030 (55 GWh/yr) and 11% by 2050 (52 GWh/yr). This reduction in hydropower production will be concentrated at the end of the dry season, in May and June, following the peak of irrigation demand, while there will be an increase in hydropower production during the rainy season. Fig. 5 illustrates these results.

The climate change simulations further show an increase in discharge variability from 2040 onwards in the SSP3-RCP7.0 scenario, while the variability of hydropower production decreases at Akosombo, as shown by the smaller boxes for the future time horizons in Fig. 5. This is due to hydropower production being partly stabilized by higher water levels, and the large storage capacity of Lake Volta.

Hydropower production in the planned new dams Bagré Aval (Burkina Faso) and Pwalugu (Ghana) is projected to show typical seasonal patterns, the one at Bagré Aval being very similar to that at Bagré, with an average production of about 60 GWh/yr and 270 GWh/yr respectively for 2030 and 2050.

The increase in river discharge could increase hydropower contribution to Ghana's overall grid electricity mix in 2030 to 26% in the Climate Change scenario (2) compared to 23% in the BAU scenario (1).

4.2. Electricity scenarios and projected demand-supply gaps

In Ghana, electricity demands are projected to grow from 16474 GWh/yr in 2020 to about 27000 GWh/yr in 2030 and 51000 GWh/yr in 2050 under Scenario 1 (business-as-usual), mainly driven by economic and demographic growth. To match this demand, supply would need to grow to about 35000 GWh/yr in 2030 and 69,000 GWh/yr in 2050, given technical and commercial transmission and distribution losses in Ghana of about 30%. The industrial and commercial sectors account for 66% of total electricity demand, while the residential sector accounts for 30%.

Given the additional electricity needs for meeting development goals, in Scenario 4 (Universal Access), electricity demands will be significantly higher than in the BAU scenario (1), by 4000 GWh/yr in 2030 and 9000 GWh/yr in 2050.

Fig. 6a illustrates Ghana's electricity supply and demand trends for the different scenarios.

In Burkina Faso, electricity demand is projected to reach almost 5000 GWh/yr in 2030 and 15000 GWh/yr in 2050 for Scenario 1. Taking into account losses, supply would accordingly need to grow to about 5400 GWh/yr in 2030 and 17200 GWh/yr in 2050s. The industrial & commercial sectors account for 83% and the residential sector for 17% of total demand. In Scenario 4, demand will increase more strongly, to about 6100 GWh/yr in 2030 and 20000 GWh/yr in 2050.

Fig. 6b illustrates Burkina's electricity supply and demand trends for the different scenarios.

According to national plans (scenario 3), reducing transmission and distribution losses can save Ghana about 4000 GWh/yr and Burkina

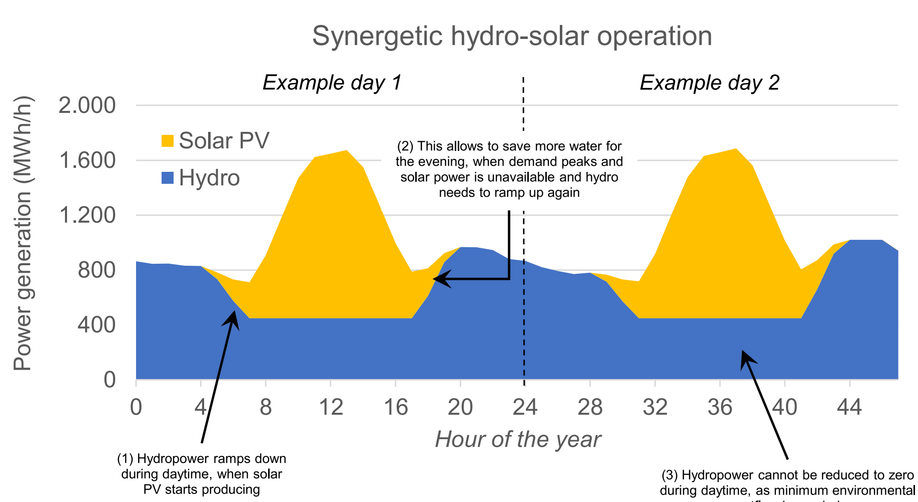

Fig. 4. Flexible electricity generation for Akosombo from the REVUB model, in blue the baseload and flexible generation from Akosombo supporting solar PV through up- and down-ramping, in yellow the solar PV profiles whose power mix integration is supported by Akosombo. We show an average of the first 48 h of the year from a simulation spanning 17 hydro-meteorological years from Ref. [21]. The figure explains various elements of synergetic hydro-solar operation, labeled (1)–(3).

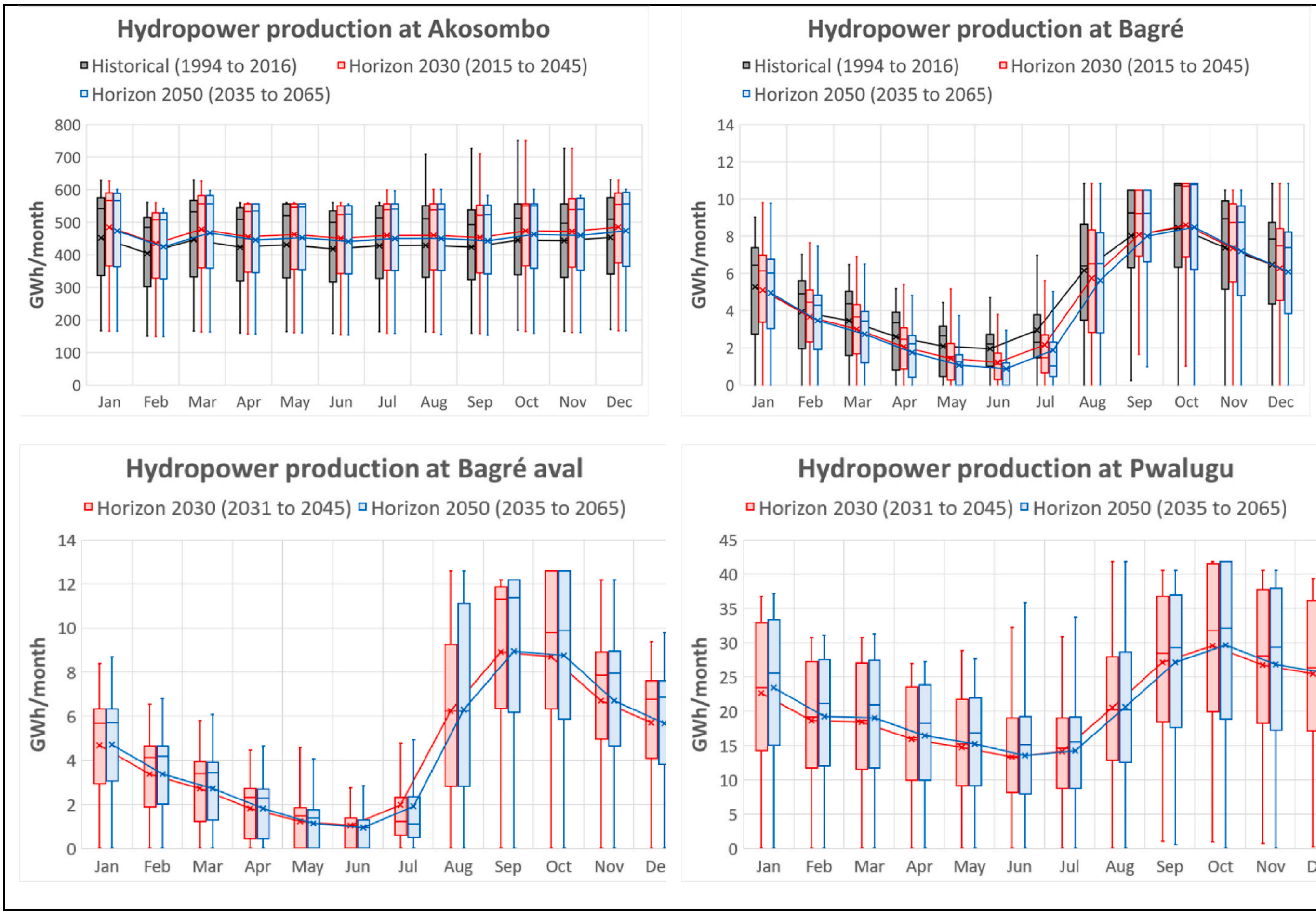

Fig. 5. Hydropower production for the historical period and time horizons 2030 and 2050 for the existing dams Akosombo and Bagré and for 2030 and 2050 for the planned dams Bagré aval and Pwalugu. The dots and connecting line represent the average monthly production, the box the range containing 50% of the simulations, the horizontal line in the box the median, and the whiskers the extremes.

about 1300 GWh/yr in 2030, compared to Scenario 1.

While decentralized solutions can also play a role in rural and isolated areas in achieving universal access to electricity [45], [57], their contribution will likely remain below 1% of the total electricity supply.

4.3. Transition to renewables – pathways under different scenarios

To meet growing electricity demands, including those arising from achieving development objectives, using renewable sources and in line with the Paris Agreement, it will be necessary to quickly phase out fossil fuels, which in turn requires restructuring investments in the electricity sector, exploiting all available renewable electricity sources in combination with efficiency improvements, demand-side management, and increased energy storage for buffering fluctuations. In this study, we focus on the expansion of renewable electricity sources.

Hydropower has traditionally played a key role in Ghana, contributing over 80% of total electricity in 2000, about 70% in 2010, and 35% in 2020 (based on VRA inputs during the stakeholder – science dialogues). The potential for further expansion of hydropower in Ghana and Burkina Faso is very limited. While increasing river discharge under climate change can increase hydropower contribution somewhat, this increase is small compared to growing demand, in particular when striving for universal electricity access (Scenario 4). Accordingly, there is a risk that growing electricity demands will be met by increasing fossil fuel use, unless renewables (mainly solar and wind) are ramped up rapidly.

When promoting renewables according to the National Plans scenario (3), they could contribute 43% of total grid electricity by 2030, compared to 27% in the BAU scenario (1) in Ghana, of which hydro still remains by far the largest fraction. In Burkina Faso, by 2030, renewables would meet 27% of the total electricity demand (other renewables contributing more than twice the amount of hydropower) according to the National Plans scenario (3), compared to 16% in the BAU scenario (1).

The Climate Smart scenario (5) is much more ambitious, going well beyond national plans. By 2030 the contribution of other renewables besides hydropower could be twice as high as foreseen in the National Plans (3) scenario. For 2050 the Climate Smart scenario demonstrates that a combination of supply and demand-side measures can increase the contribution of renewables to about 90% of total electricity demand. Solar PV emerges as the largest electricity source by far, which is in line with model results by Ref. [58].

Fig. 7 illustrates the grid electricity mix by source for Ghana and Burkina Faso for each scenario. It shows that in all scenarios, the electricity sector still mostly depends on fossil fuels by 2030. Only by rigorously pursuing the climate neutrality agenda of the climate smart scenario, Ghana and Burkina Faso could phase out fossil fuels and replace them with renewables by 2050. The composition of renewables in the Climate Smart Scenario (5) in 2050 is further detailed for the different sources in the right-hand bar. Note that all scenarios assume some dependency of Burkina Faso on electricity imports also in the future.

The exact contribution of each electricity source per scenario is shown in Supplementary Table 5 in the Supplementary Material.

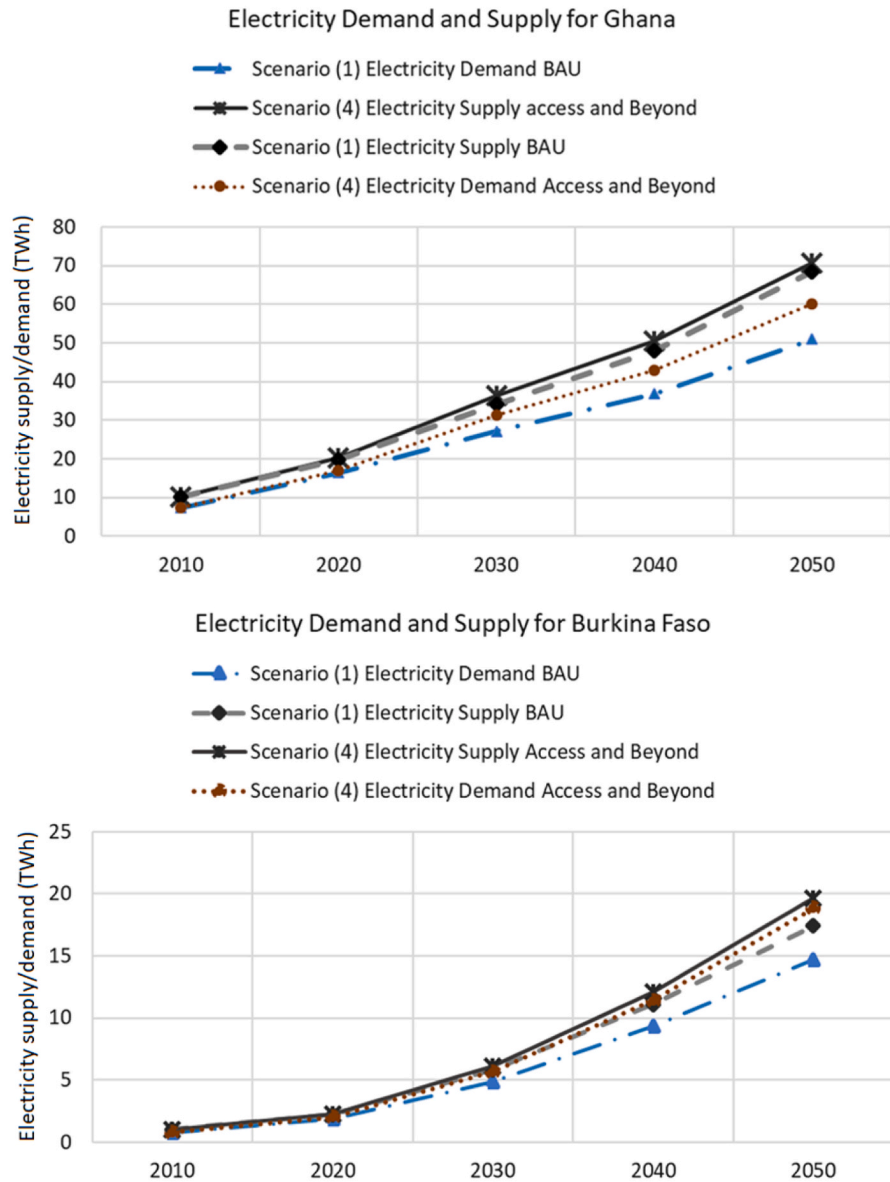

Fig. 6. a Projected electricity demand and supply in Ghana. b Projected electricity demand and supply in Burkina Faso.

Fig. 8 shows the annual emissions of greenhouse gases for each of the five scenarios in 2050 and the development of these emissions over time for the BAU (1) and Climate Smart (5) scenarios for Ghana and Burkina Faso, as well as the contribution of each electricity source to the total capacity for the Climate Smart (5) scenario in 2050.

While an economic analysis was not part of the CIREG energy modelling, there is increasing evidence that renewables, already now and increasingly so in the future, outcompete fossil fuels in terms of electricity generation costs (Adeoye et al., 2018, [59]; [60]; [61]; [1] chapter 6). Any new fossil fuel-related infrastructure included in the national plans, with its expected lifespan of ca. 30 years, is likely to become an obstacle to the country's climate neutrality ambitions very soon. A related risk is the loss of export opportunities for products that are not climate-neutral when being produced with fossil electricity. International investments in fossil-based enterprises and projects are also decreasing quickly [62,63].

5. Discussion

The CIREG project set out to support, through its transdisciplinary approach, the transition towards sustainable, climate- and water-smart electricity systems in West Africa. Central tenets of the project are the integrated climate, energy, and water scenarios, as co-generated in stakeholder-scientist dialogues, underpinned by stakeholder expertise and scientific evidence derived from the integrated CIREG modelling tools.

On the water side, the scientific analyses show that climate change will have some impact on hydrology and water availability in Ghana and Burkina Faso, resulting in an increase in river discharge and hydropower production. At the same time, climate change, with its higher temperatures together with other factors will significantly increase irrigation water demand (and also energy demand for pumping) which in turn will reduce water available for hydropower production [4]. Competition for - and possibly also conflicts over - scarce water resources is likely to increase, and integrated, ideally transboundary, planning is therefore required. The CIREG dialogue supported by the LEAP-WEAP scenario tools has successfully piloted such planning in Ghana and Burkina Faso.

Climate change impacts on the electricity sector include the lower yield of photovoltaics at higher temperatures; but climate change is only estimated to have a minor effect on solar energy production in West

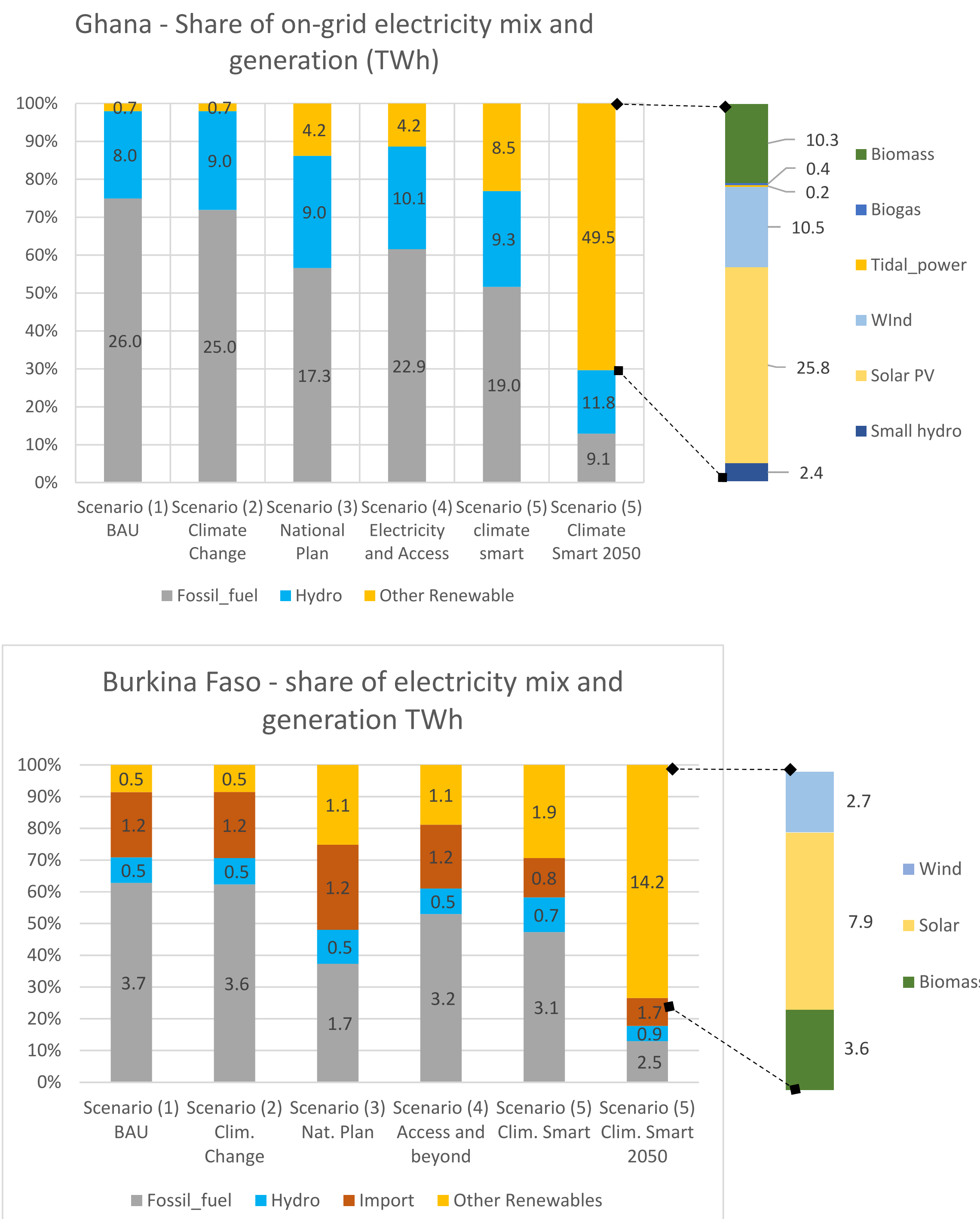

Fig. 7. a Ghana's electricity mix in the different scenarios in % (left-hand scale) and in TWh/yr (numbers in bars) for the year 2030, except for scenario 5 which is for 2030 & 2050. b: Burkina Faso's electricity mix in the different scenarios in % (left-hand scale) and in TWh/yr (numbers in bars) for 2030 except for scenario 5 which is for 2030 & 2050.

Africa [21,64]. Moreover, climate change will affect the demand for space cooling. Although Ghana and Burkina Faso already have a hot climate today, the number of cooling degree days (CDDs) will increase further, and so will the demand for air conditioning (AC). However, income is a strong determinant of whether households can afford AC [65] and therefore plays a key role, together with the increase in CDDs, in increasing electricity demand from AC. These factors together determine how the hourly electricity demand curves may change.

Beyond the climate change-driven need for more space cooling, electricity demand also continues to increase in both Ghana and Burkina Faso due to demographic, social and economic drivers (the combined systemic impacts of these drivers have been assessed in LEAP). Both countries, but especially Burkina Faso – where currently less than 20% of the population and less than 5% of the rural population have access to electricity [66,67], still need to improve universal electricity access, to enable sustainable development as specified for example in SDG 7 (and represented in Scenario 3). To avoid fossil-fuels being used to meet this increasing electricity demand, both countries need to quickly raise their

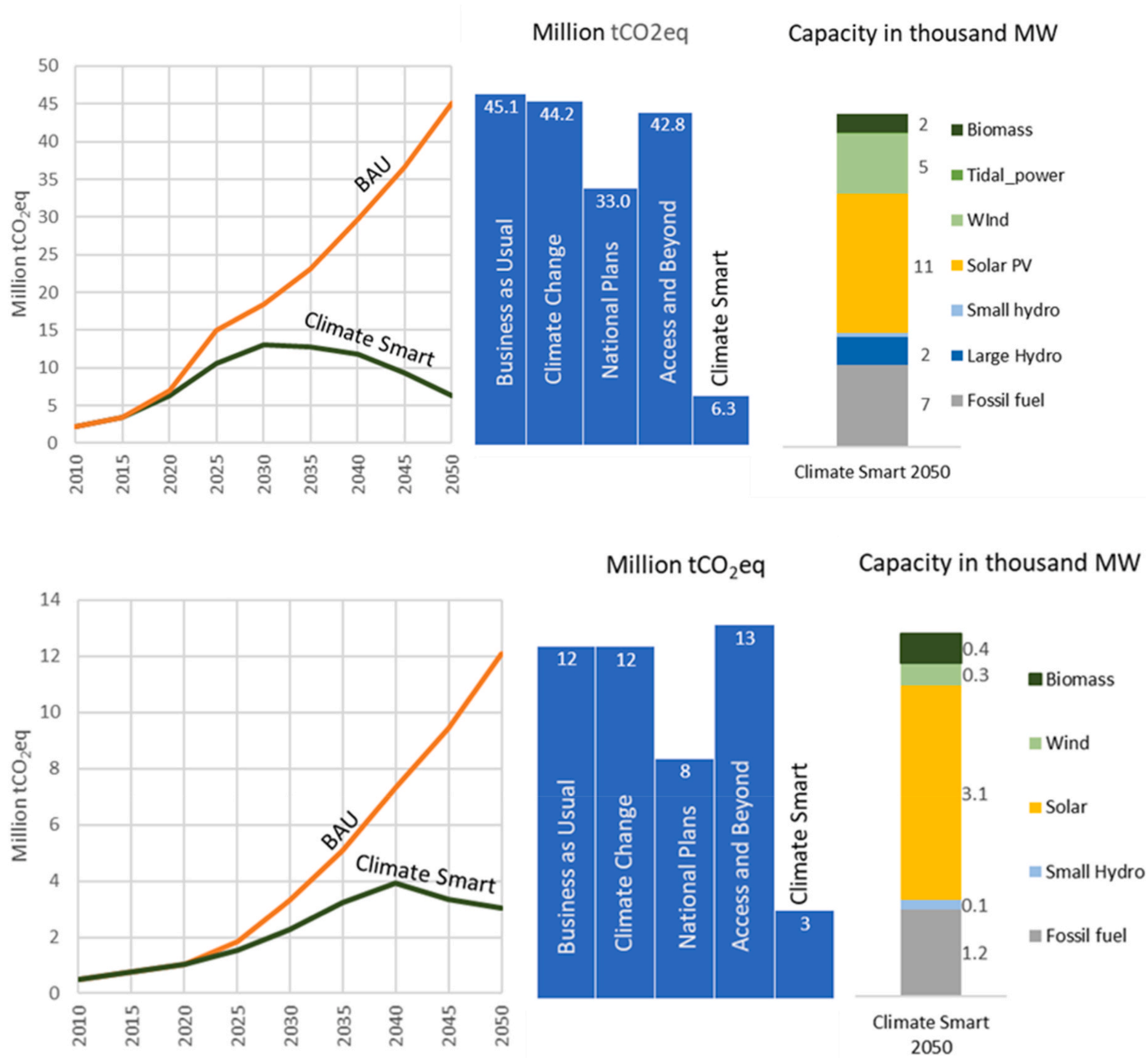

Fig. 8. a Emission pathways towards a zero-carbon electricity system for Ghana and electricity generation capacities for the Climate Smart (5) scenario in 2050. b. Emission pathways towards a zero-carbon electricity system for Burkina Faso and electricity generation capacities for the Climate Smart (5) scenario in 2050.

ambitions in expanding renewables, e.g., in upcoming NDC revisions, as mandated under the Paris Agreement. Existing opportunities for ramping up renewables have been included in the most ambitious Scenario 5. For these opportunities to materialize, international climate finance will be very important.

One substantial opportunity lies in exploiting the complementarities of different renewables, mainly hydro, solar, and wind. This opportunity has been included in the Climate Smart scenario (5), based on REVUB assessments [21], building on the finding by Ref. [13] that additional hydroelectric storage helps to buffer fluctuations in new wind and solar contributions. Diversification and complementary generation of electricity from different renewables can increase overall reliability and system resilience vis-à-vis climate change and extreme events and, as a co-benefit (when diversifying beyond hydropower), potentially take some pressure off water resources and, with that improve the management of aquatic ecosystems (addressing SDG 14). Other co-benefits include reduced air pollution and associated health benefits (SDG 3) that come with phasing out fossil fuel combustion, as well as creating new jobs through the expansion of solar and wind power [58] and providing new business opportunities (SDG 8).

More opportunities for accelerating the energy transition towards renewables arise from transboundary collaboration and power pooling, with electricity imports and exports across national borders, which can reduce cost and load shedding and improve supply security ([68], [69], [21,70]. Such opportunities can be extended even further toward multi-dimensional transboundary benefit sharing, across the energy, water and other sectors [71]. These opportunities need to be further assessed by continuing the transdisciplinary process that has been successfully established in CIREG.

In the Climate Smart scenario (5), we have shown that combinations of different measures can add up to almost 100% renewable energy in electricity production, much more than foreseen in the current national plans. Supply-side contributions to this target include further development of renewables such as solar and wind, sustainable use of bioenergy, waste-to-energy, and others. We do not claim that these represent a comprehensive set of measures; rather, they serve to indicate that going beyond national plans in ambition appears possible.

Demand-side measures, which were not part of the modelling, could further aim to improve resource use efficiencies, e.g. through improved irrigation, reducing transmission losses, building codes, consumer choices, etc. Technological and digital developments present ample opportunities to further integrate renewables into the electricity system, such as innovations in power generation, distributed storage options, wholesaling and retailing, better access to data and information, and the possibility of flexible generation and consumption patterns including "prosumer" schemes. In any future work, all of these supply and demand side measures could be analyzed in greater detail individually or in combination with others, for their systemic effects, with the CIREG scenario tools. While we have not included financial analyses in CIREG, these could form part of future work in conjunction with CIREG-style analysis as well.

Given the urgency and complexities of transforming the electricity sector as an important part of any national climate neutrality pathway and wider SDG agenda, all opportunities need to be rapidly assessed for their feasibility and (often cross-sectoral) sustainability implications through further stakeholder science dialogues. We suggest to take the integrated LEAP-WEAP energy and water modelling and scenario planning further to provide stakeholders and scientists with the evidence base as a reality check for new integrated solutions, across sectors, space and time, to simultaneously achieve climate, energy and water targets. Integrated and effective solutions could include for example new multi-functional dams, climate- and energy-smart irrigation, reduced water demand for cooling with phasing out of thermal power plants [19], water-smart diversification of renewable electricity generation, complementary grid, mini-grid and off-grid electricity also coupled with more electricity storage [66,67] and zoning of (de-) centralized and distributed electrification [72], as well as climate- and energy-smart water solutions such as desalination with renewable energy. All of these went beyond the scope of the current project, but could form part of future initiatives.

More inter- and transdisciplinary research as piloted in CIREG is needed to further support the required transformation, systematically assessing water demands of the different elements of the energy system, e.g., hydropower, cooling water demands of fossil fuel power plants, water demands to clean PV panels, as well as water demands for growing biomass (for food, feed, fibre and energy), and how these can be met sustainably given all other competing water demands and changing water availability under climate change. At the same time, the energy demands of the different elements of the water system also need to be assessed, in particular for water pumping, e.g., drinking water supply, irrigation and other uses, water treatment, and desalination.

6. Conclusions

The CIREG project has piloted a transdisciplinary approach in two West African countries, in support of a climate neutrality and sustainability transition of the electricity sector. Local stakeholders and scientists jointly co-developed a set of five scenarios for assessing the systemic energy- and water-related effects of different interventions under climate change.

With the help of these scenarios and the underlying scenario tools, we could show that renewables could almost completely replace fossil fuels in the electricity sector, even under high demand scenarios, in Ghana and Burkina Faso. More specifically, the scenario results show that a rapid increase in electricity demand, in particular when striving for universal electricity access for all (as stipulated in the national planning and in the SDGs), would outpace the projected increase in hydropower production from new reservoirs and climate change. However, expansion of other renewables (primarily solar and wind) and their integration with hydropower and better coordination of the different electricity supply- and demand-side options can close the demand-supply gap, now and in the future. Renewable potentials have been assessed in this study to be far greater than projected in the national plans, and in view of the emerging challenges, national plans could be ratcheted up accordingly.

In the water sector, we find that rapidly growing water demands for the different uses (agriculture, industry, households) compete with hydropower water demands, calling for better coordination of the different water demands and supplies, as well as integrated planning and management across the energy and water sectors, while getting on track for climate neutrality. Stakeholders and scientists concluded that integrated planning and policy making, across energy, water, environment, climate and development goals, has to complement current sectoral approaches. Increasing transmission interconnections for electricity also beyond national boundaries can further increase co-benefits and increase resilience to climate change.

From testing different technical interventions in WEAP and LEAP, it also became clear that climate-smart electricity systems are no longer limited by available technologies or economic constraints but are a matter of national priorities (e.g. in the NDCs). Only through co-developing the scenarios jointly by stakeholders and scientists, it was possible to arrive at these evidence-based (based on inputs from state-of-the-art energy and water process models) and action-oriented conclusions, which bridge different sectors and development goals. The CIREG project has been a first step in promoting continuous collaboration between stakeholders and scientists and towards institutionalizing climate services. More transdisciplinary work will be required to take these initial conclusions further, addressing in more detail stakeholder questions and sustainability challenges.

The CIREG project was initially conceived as an applied research project; thus, stakeholders were not involved in formulating the original research questions. In the course of the project, however, these were adapted to the needs of the stakeholders through iterative dialogues and eventually. Project results were presented to senior officials, with the hope that these would eventually percolate through to policy and decision-making.

At the meta-level, we found that such a transdisciplinary approach and collaboration between stakeholders and scientists is a rather uncommon modus operandi on both sides. It requires a large amount of time, and the results do not necessarily fit standard scientific formats well. The long review process of this paper may be a case in point.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2023.101149.

References

[1] IPCC, Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, https://doi.org/10.1017/9781009325844#.

[2] J. Adegoke, M.B. Sylla, A.Y. Bossa, O.K. Ogunjobi, j. Adounkpe, Regional climate change series: floods. WASCAL, Accra, Ghana (2019) 114. https://wascal.org/wascal-outdoors-west-african-climate-change-book-series-on-floods/.

[3] S. Salack, C. Klein, A. Giannini, B. Sarr, O.N. Worou, N. Belko, J. Bliefernicht, H. Kunstmann, Global warming induced hybrid rainy seasons in the Sahel, Environ. Res. Lett. 11 (2016), 104008.
[4] S. Liersch, H. Koch, J.A. Abungba, S. Salack, F.F. Hattermann, Attributing synergies and trade-offs in water resources planning and management in the Volta River basin under climate change, Environ. Res. Lett. (1) (2023), 014032, https://doi.org/10.1088/1748-9326/acad14.
[5] P. Antwi-Agyei, A.J. Dougill, T.P. Agyekum, L.C. Stringer, Alignment between nationally determined contributions and the sustainable development goals for West Africa, Clim. Pol. (2018), https://doi.org/10.1080/14693062.2018.1431199.
[6] M. Ram, et al., Global energy transition to 100% renewables by 2050: not fiction, but much needed impetus for developing economies to leapfrog into a sustainable future, Energy 246 (2022).
[7] IEA, International Energy Agency, Net Zero by 2050, A Roadmap for the Global Energy Sector, Flagship Report, 2021.
[8] IPCC, Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022. https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf.
[9] UNFCCC, Paris Agreement, 2015. FCCC/CP.
[10] UN, Transforming Our World, the 2030 Agenda for Sustainable Development, 2015 available at: https://sdgs.un.org/2030agenda. (Accessed 10 May 2022).
[11] M. Camara, M. Thompson-Hall, Strengthening understanding on renewable energy access for broader development outcomes in West Africa, in: V. Naddeo, K.H. Choo, M. Ksibi (Eds.), Water-Energy-Nexus in the Ecological Transition. Advances in Science, Technology & Innovation, Springer, Cham, 2022, https://doi.org/10.1007/978-3-031-00808-5_16.
[12] ECOWAS, Renewable Energy and Energy Efficiency Status Report, Economic Community of West African States, 2014.
[13] D.K. Danso, F. Baptiste, H. Benoit, D. Arona, Assessing hydropower flexibility for integrating solar and wind energy in West Africa using dynamic programming and sensitivity analysis, J. Clean. Prod. 287 (2021), 125559, https://doi.org/10.1016/j.jclepro.2020.125559.
[14] A. Sainz Mapes, Morten Andreas Dahl larsen M.A, Projected future European power sector water usage across power scenarios and corresponding trends in water availability, Journal of Environmental Management (2023), https://doi.org/10.1016/j.jenvman.2023.118208.
[15] J. Dankwa Ampa, S. Afrane, B. Li, H. Adun, E. Bonah Agyekum, A. Abdu Yusuf, O. Bamisile, H. Liu, The overarching role of electric vehicles, power-to-hydrogen, and pumped hydro storage technologies in maximizing renewable energy integration and power generation in Sub-Saharan Africa, J. Energy Storage 67 (2023), 107602.
[16] European Commission, A Comprehensive EU Strategy for Africa, Policy Department for External Relations, Directorate General for External Policies of the Union, 2020, p. 506, 603.
[17] S. Salack, S. Sanfo, M. Sidibe, et al., Low-cost adaptation options to support green growth in agriculture, water resources, and coastal zones, Nat. Comm. (Preprint) (2022).
[18] H. Hoff, Understanding the Nexus, Scientific Background Paper for the Bonn 2011 Conference: the Water, Energy and Food Security Nexus, SEI, Stockholm, 2011.
[19] M. De Felice, I. Gonzalez Aparicio, T. Huld, S. Busch, I. Hidalgo Gonzales, Analysis of the Water-Power Nexus in the West African Power Pool, in: JRC Technical Reports, JRC115157, EUR 29617 EN, Publications Office of the European Union, Luxembourg, 2019, https://doi.org/10.2760/362802.
[20] DTU, Review of National Development and NDC and SDG Plans for Inter-linkages with REG (Renewable Electricity Generation), 2018. CIREG deliverable D 4.1.
[21] S. Sterl, I. Vanderkelen, C.J. Chawanda, D. Russo, R.J. Brecha, A. van Griensven, N. P.M. van Lipzig, W. Thiery, Smart renewable electricity portfolios in West Africa, Nat. Sustain. (3) (2020) 710–719, https://doi.org/10.1038/s41893-020-0539-0.
[22] V. Krysanova, F. Hattermann, F. Wechsung, Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment, Hydrol. Process. 19 (3) (2005) 763–783, https://doi.org/10.1002/hyp.5619.
[23] V. Krysanova, F. Hattermann, S. Huang, C. Hesse, T. Vetter, S. Liersch, H. Koch, Z. W. Kundzewicz, Modelling climate and land use change impacts with SWIM: lessons learnt from multiple applications, Hydrol. Sci. J. 60 (4) (2015) 606–635, https://doi.org/10.1080/02626667.2014.925560.
[24] C. Heaps, Energy Planning and Policy Analysis, SEI Factsheet, 2008.
[25] P. Kuldna, K. Peterson, R. Kuhi-Thalfeldt, Knowledge brokering on emissions modelling in Strategic Environmental Assessment of Estonian energy policy with special reference to the LEAP model, Environ. Impact Assess. Rev. 54 (2015) 55–60, https://doi.org/10.1016/j.eiar.2015.06.001.
[26] J.C.I. Kuylenstierna, C.G. Heaps, T. Ahmed, H.W. Vallack, W.K. Hicks, M. R. Ashmore, C.S. Malley, G. Wang, E.N. Lefèvre, S.C. Anenberg, F. Lacey, D. T. Shindell, U. Bhattacharjee, D.K. Henze, Development of the low emissions analysis platform – integrated benefits calculator (LEAP-IBC) tool to assess air quality and climate co-benefits: application for Bangladesh, Environ. Int. 145 (2020), 106155, https://doi.org/10.1016/j.envint.2020.106155.
[27] D. Yates, J. Sieber, D. Purkey, A. Huber-Lee, WEAP21—a demand-, priority-, and preference-driven water planning model, Water Int. 30 (4) (2005) 487–500, https://doi.org/10.1080/02508060508691893.
[28] T. Condom, M. Escobar, D. Purkey, J.C. Pouget, W. Suarez, C. Ramos, J. Apaestegui, A. Tacsi, J. Gomez, Simulating the implications of glaciers' retreat for water management: a case study in the Rio Santa basin, Peru, Water Int. 37 (4) (2012) 442–459, https://doi.org/10.1080/02508060.2012.706773.
[29] A. Alamanos, D. Latinopoulos, S. Xenarios, G. Tziatzios, N. Mylopoulos, A. Loukas, Combining hydro-economic and water quality modeling for optimal management of a degraded watershed, J. Hydroinf. 21 (6) (2019) 1118–1129, https://doi.org/10.2166/hydro.2019.079.
[30] A.G. Bhave, L. Bulcock, S. Dessai, D. Conway, G. Jewitt, A.J. Dougill, S.R. Kolusu, D. Mkwambisi, Lake Malawi's threshold behaviour: a stakeholder-informed model to simulate sensitivity to climate change, J. Hydrol. 584 (2020), 124671, https://doi.org/10.1016/j.jhydrol.2020.124671.
[31] L.L. Dale, N. Karali, D. Millstein, M. Carnall, S. Vicuña, N. Borchers, E. Bustos, J. O'Hagan, D. Purkey, C. Heaps, J. Sieber, W.D. Collins, M.D. Sohn, An integrated assessment of water-energy and climate change in sacramento, California: how strong is the nexus? Climatic Change 132 (2) (2015) 223–235, https://doi.org/10.1007/s10584-015-1370-x.
[32] L. Karlberg, H. Hoff, T. Amsalu, K. Andersson, T. Binnington, F. Flores-López, A. de Bruin, S.F. Gebrehiwot, B. Gedif, F. zur Heide, O. Johnson, M. Osbeck, C. Young, C., Tackling complexity: understanding the food-energy-environement nexus in Ethiopia's lake tana sub-basin, Water Altern. (WaA) 8 (1) (2015) 710–733.
[33] World Bank, Energy sector management assistance Program, in: Beyond Connections: Energy Access Redefined, 2015. https://www.esmap.org/mtf_multi-tier_framework_for_energy_access.
[34] S.Y. Pan, S.W. Snyder, A.I. Packman, Y.J. Lin, P.C. Chiang, Cooling water use in thermoelectric power generation and its associated challenges for addressing water-energy nexus, Water-Energy Nexus 1 (1) (2018) 26–41, https://doi.org/10.1016/j.wen.2018.04.002.
[35] S. Lange, Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1.0), Geosci. Model Dev. (GMD) 12 (2019) 3055–3307.
[36] L. Warszawski, K. Frieler, V. Huber, F. Piontek, O. Serdeczny, J. Schewe, The inter-sectoral impact model intercomparison project (ISI–MIP): project framework, Proc. Natl. Acad. Sci. USA 111 (2014) 3228–3232.
[37] Energy Commission Ghana, Energy (Supply and Demand) Outlook for Ghana, 2019, 2019.
[38] Energy Commission, Electricity Supply Plan for Ghana, 2019, 2019.
[39] Energy Commission Ghana, ENERGY (SUPPLY AND DEMAND) OUTLOOK FOR GHANA, 2018, 2018.
[40] Energy Comission of Ghana, National energy statistics 2000—2019. https://www.energycom.gov.gh/files/2020%20ENERGY%20STATISTICS-revised.pdf, 2019.
[41] Ministry of Power, & ECREEE, Ghana Renewable Energy Action Plan (2015—2020), 2015.
[42] Republic of Ghana, in: 2019 Electricity Supply Plan for Ghana, National Plan, 2019.
[43] ICF, & Energy Commission of Ghana, Integrated power systems master plan for Ghana, Main Report ume 2 (2019).
[44] Ministère des Mines et de l'Energie, Annuaire statistique 2016 du Ministère de l'Energie. http://cns.bf/IMG/pdf/as_me_2016_version_finale.pdf, 2017.
[45] Ministère des Mines et de l'Energie, CEDEAO, Plan d'Action National des Energies Renouvelables (PANER), Centre pour les Energies Renouvelables et l'Efficacité Energétique de la CEDEAO (CEREEC), 2015.
[46] M. Bhatia, N. Angelou, ESMAP: beyond connection energy access redefined, Technical Report, Conceptualisation Report, The World Bank (2015). https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y.
[47] GSS, Ghana Living Standard Survey: Report of the Fifth Round (GLSS 5), 2008.
[48] GSS, Ghana Living Standard Survey Round 6 (GLSS), Main Report, 2014.
[49] GSS, Ghana Statistical Service (GSS), Rebased 2013-2018, Annual Gross Domestic Product, 2019, p. 11.
[50] D. Darko, M. Whyte-Kpessa, E. Obuobie, P. Siakwah, O. Torto, D. Tsikata, The Context and Politics of Decision Making on Large Dams in Ghana: an Overview (002), 2019 (FutureDAMS Working Paper).
[51] B. Amuzu-Sefordzi, J. Huang, D. Sowa, T. Baddoo, Biomass-derived hydrogen energy potential in Africa, Environ. Prog. Sustain. Energy 35 (2015), https://doi.org/10.1002/ep.12212.
[52] J. Darkwa Nelson, J.K. Calautit, M. Worall, R. Mokaya, E.A. Adjei, F. Kemausuor, J. Ahiekpor, Potential of bioenergy in rural Ghana, Sustainability 13 (2021) 381, https://doi.org/10.3390/su13010381.
[53] IRENA, Rethinking energy: renewable energy and climate change. www.irena.org/publications, 2015.
[54] IRENA, Planning and prospects for renewable power: West Africa. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Nov/IRENA_Planning_West_Africa_2018.pdf, 2018.
[55] IRENA, Rethinking Energy 2017: Accelerating the Global Energy Transformation, 2017, p. 130.
[56] IRENA, Planning and prospects for renewable power: eastern and southern Africa, international renewable energy agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_Planning_Prospects_Africa_2021.pdfO. Johnson, 2021.
[57] Ministry of Energy, Ghana Renewable Energy Master Plan, 2019. http://www.energycom.gov.gh/files/Renewable-Energy-Masterplan-February-2019.pdf.
[58] A.S. Oyewo, A. Aghahosseini, M. Ram, C. Breyer, Transition towards decarbonised power systems and its socioeconomic impacts in West Africa, Renew. Energy 154 (2020) 1092–1112, https://doi.org/10.1016/j.renene.2020.03.085.
[59] IRENA, Renewable Power Generation Costs in 2020, International Renewable Energy Agency, 2020, 978-92-9260-348-9.
[60] Lazard, Lazard's levelized cost of energy analysis - version 15. https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/, 2021.
[61] Lazard, Lazard's levelized cost of storage analysis - version 7. https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/, 2021.

[62] N. Johnson, V. Krey, D.L. McCollum, S. Rao K, K. Riahi, J. Rogelj, Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants, Technol. Forecast. Soc. Change 90 (2015) 89–102, https://doi.org/10.1016/j.techfore.2014.02.028. ISSN 0040-1625.

[63] J.F. Mercure, H. Pollitt, J.E. Viñuales, et al., Macroeconomic impact of stranded fossil fuel assets, Nat. Clim. Change 8 (2018) 588–593, https://doi.org/10.1038/s41558-018-0182-1.

[64] M. Erim Agbor, et al., Potential impacts of climate change on global solar radiation and PV output using the CMIP6 model in West Africa, Cleaner Engineering and Technology 13 (2023), https://doi.org/10.1016/j.clet.2023.100630.

[65] M.A. McNeil, V.E. Letschert, Future air conditioning energy consumption in developing countries and what can be done about it: the potential of efficiency in the residential sector, in: European Council for an Energy Efficient Economys, ECEEE Summer Study Proceedings, 2007, 978-91-633-0899-4.

[66] M. Moner-Girona, K. Bodis, T. Huld, I. Kougias, S. Szabo, Universal access to electricity in Burkina Faso: scaling up renewable energy technologies, Environ. Res. Lett. 11 (2016), 084010.

[67] M. Moner-Girona, K. Bodis, B. Korgo, T. Huld, I. Kougias, I. Pinedo-Pascua, F. Monforti- Ferrario, S. Szabo, Mapping the Least-Cost Option for Rural Electrification in Burkina Faso – Scaling up Renewable Energies, JRC Science for Policy Report, 2017, https://doi.org/10.2760/900097N. JRC102198, EUR 28514 EN Publications Office of the European Union.

[68] O. Adeoye, C. Spataru, Sustainable development of the West African Power Pool: increasing solar energy integration and regional electricity trade, Energy for Sustainable Development 45 (2018) 124–134, https://doi.org/10.1016/j.esd.2018.05.007.

[69] O. Adeoye, C. Spataru, Quantifying the integration of renewable energy sources in West Africa's interconnected electricity network, Renew. Sustain. Energy Rev. 120 (2020), 109647, https://doi.org/10.1016/j.rser.2019.109647.

[70] S. Sterl, D. Fadly, S. Liersch, et al., Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam, Nat. Energy 6 (2021) 407–418, https://doi.org/10.1038/s41560-021-00799-5.

[71] J. Granit, M. Fogde, H. Hoff, J. Joyce, L. Karlberg, J.L. Kuylenstierna, A. Rosemarin, Unpacking the Water-Energy-Food Nexus: Tools for Assessment and Cooperation along a Continuum, vol. 45, Cooperation for a Water Wise World, 2013.

[72] M. Bissiri, P. Moura, N.C. Figueiredo, P. Pereira da Silva, A geospatial approach towards defining cost-optimal electrification pathways in West Africa, Energy 200 (2020), 117471, https://doi.org/10.1016/j.energy.2020.117471.

[73] M. Howells, J. Quiros-Tortos, R. Morrison, et al, Energy System Analytics and Good Governance - U4RIA Goals of Energy Modelling for Policy Support, 10 March 2021, PREPRINT, 2021, https://doi.org/10.21203/rs.3.rs-311311/v1 (Version 1).