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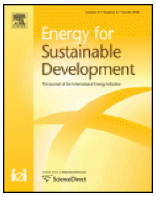

Implications of large hydro dams for decarbonising Ghana's energy consistent with Paris climate objectives

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ABSTRACT

Hydropower is a renewable source of electricity generation that is a common feature of Nationally Determined Contributions (NDC), especially in developing countries. However, far from benign, research shows that significant greenhouse gas (GHG) emissions emanate from shallow reservoirs when they are sited in the tropics. Ghana provides a case study for exploring the implications of hydro reservoir emissions within a future energy system consistent with the Paris climate objectives. Being a fast-developing country, Ghana needs to generate significant amounts of low-carbon electricity to meet growing demand over the coming 30 years. Analysis of existing Ghanaian dams (Akosombo, Kpong and Bui) and the forthcoming Pwalugu dam suggests that their average emissions intensities (gCO_2/kWh) are similar to those of coal-fired power stations during the first 30 years of their operating lifetime. The case study demonstrates that cumulative (post-2020) carbon dioxide emissions from the planned and identified hydro resources will consume 40 % of Ghana's Paris-compliant carbon budget, yet provide just under 1 % of its future energy demand (under Paris-compliant scenarios). The analysis suggests that new hydropower in the tropics can significantly reduce the emission space available for other sectors such as transport and industry when faced with a highly restricted emissions budget. In conclusion, for Ghana specifically, rather than constructing more dams, energy efficiency and diversifying renewable energy supply options, including floating solar power, would deliver an energy transition for Ghana that is much more closely aligned with the Paris goals.

Introduction

Since the adoption of the 2015 Paris Climate Agreement (United Nations Framework Convention on Climate Change, 2016), there has been an increase in efforts to implement climate action across the world. Amongst these is a portfolio of strategies for decarbonising the current fossil-dominated energy system using existing ‘low-carbon’ technologies (Asmelash et al., 2020). One such strategy is building hydropower, an ostensibly low-carbon source of electricity. However, a growing body of research suggests there are significant greenhouse gas (GHG) emissions from hydro reservoirs, particularly when shallow reservoirs are sited in low-lying tropical regions (Almeida et al., 2019; Barros et al., 2011; Deemer et al., 2016; Scherer & Pfister, 2016). It is expected that the construction of hydropower dams is projected to increase significantly as part of the energy transition within those developing countries where resources are still available (Zarfl et al., 2015).

It is against such a backdrop that this paper explores the mitigation efforts for Ghana, a developing nation with both a growing economy and the potential for further hydropower development. It examines the role of new large hydropower resources in relation to both the country's Nationally Determined Contributions (NDC) and longer-run Paris-compliant mitigation pathways. Given Ghana is a rapidly growing economy, it needs new sources of electricity supply to meet its increasing electricity demand. Not only do these new supply options need to be deployed fast and at scale to meet such demand, but they also need to be aligned with the temperature commitments of the Paris Agreement.

The Paris Climate Agreement requires all the party countries to outline and communicate their post-2020 climate actions through NDCs (UNFCCC, n.d.). NDCs are self-defined mitigation goals, developed in the context of parties' national circumstances, capabilities, and priorities to limit the global average temperature rise to “well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature

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increase to 1.5°C" (United Nations Framework Convention on Climate Change, 2016). Developing countries are encouraged to submit reduction targets in light of their national circumstances, whereas developed countries need to submit economy-wide absolute emissions reduction targets. About 90 % of the NDC submissions refer to renewable energy as climate action, particularly within developing nations (IRENA, 2019). It is expected that hydropower may play a significant role in NDCs for those countries with substantial hydro resource potential (Carvajal & Li, 2019). Around 17 % of global electricity generation in 2020 was from hydropower (REN21, 2021), the equivalent of 3.6 % of global final energy consumption (FEC). In Ghana, about 37 % of the electricity generated in 2020 was from three hydro reservoirs, Akosombo, Kpong and Bui (Energy Commission of Ghana, 2022). A further 16 dams, with a total capacity of 850 MW, are identified for construction over the coming years (Energy Commission of Ghana, 2018). It is within this bigger picture that Ghana's future energy and electricity demand requirements, and the implications of new hydropower in the supply mix, are assessed.

The paper comprises four sections. The first provides an overview of Ghana's energy policy and its NDCs, followed by a detailed assessment of its energy demand and low-carbon supply options. The third examines GHG emissions from Ghanaian hydro reservoirs. Finally, and building on the energy scenarios and estimates of reservoir emissions, the implications of the Paris Agreement for delivering a low-emission energy transition for Ghana are discussed by estimating Ghana's fair share of the post-2020 global carbon budget.

Literature review

Overview of Ghana's NDC and energy policy

Ghana is one of the fast-developing countries in Sub-Saharan Africa, with average GDP growth of ~5 % per annum during the last three decades (World Bank, 2022). The discovery of crude oil in commercial quantities has, since 2007, led to Ghana becoming a lower-middle-income country, with ongoing exploitation of oil and gas resources seen as key to continued GDP growth. As a result, Ghana is a net exporter of both gas and oil. Moreover, Ghana is the leading West African recipient of Foreign Direct Investment for manufacturing, which has driven significant growth in the industrial sector, and now accounts for nearly a quarter of Ghana's annual GDP (Abokyi et al., 2019). Expanding industrial output while relying on fossil fuels sharply increased Ghana's total GHG emissions, which reached 42.2 $MtCO_2e$ (27.3 $MtCO_2$) in 2016; that is 66 % (62 % for CO_2) above 1990 levels (Environmental Protection Agency, 2020). An important note here is that the GDP, energy consumption and population are rising faster than CO_2 emissions.[1]

Ghana is a signatory to the Paris Agreement and has two targets for 2030. Both targets are set relative to a business-as-usual (BAU) outlook and are based on historical GHG emissions from 1990 to 2012. The targets, one unconditional and one conditional (on "$22.6 billion in investments from domestic and international public and private sources") aim to lower GHG emissions by 15 % and 45 %, respectively, relative to the projected BAU emission of 73.95 $MtCO_2e$ in 2030[2] (Government of Ghana, 2015). Ghana's NDC is anchored in its national development framework, the National Climate Change Policy (NCCP), the Low Carbon Development Strategy, amongst other strategic plans for addressing climate change. Ghana's national policy initiatives and strategies are intended to act as a catalyst for all actors at different governance levels to mainstream climate change in their medium-term development plans and budgeting guidelines. The legislative instruments to mainstream and facilitate the implementation of mitigation and adaptation programmes in Ghana, include Energy Efficiency (LI 1815; LI 1932; LI 1937; LI 1958; LI 1970) alongside the Renewable Energy Act (2011). Additionally, Ghana has launched several initiatives and flagship programmes across the energy sectors, such as: the expansion of inter and intra-city mass transportation modes (rail and bus transit systems); promotion of energy efficiency programmes, such as the adoption of compact fluorescent lighting and light-emitting diode bulbs; and the scaling up of renewable electricity generation by 10 % by 2020, etc. (Gyamfi et al., 2018; Kumi, 2017; Obeng-Darko, 2019).

Ghana's 2010 'National Energy Policy' outlined the policy direction regarding the issues and challenges relating to their three sub-sectors: power, petroleum and renewable energy. Key highlights of the goals and objectives for the sub-sector policy framework include:

i. expanding electricity supply infrastructure from about 2000 MW in 2010 to 5000 MW in 2015;
ii. achieving universal access to the national electricity grid by 2020 through the National Electrification Scheme;
iii. ensuring power supply security through increasing and diversifying the fuel mix;
iv. sustaining the exploitation and utilisation of Ghana's petroleum endowment for the overall benefit of all Ghanaians.
v. universal access to reliable and affordable cleaner energy services such as Liquefied Petroleum Gas;
vi. increasing the proportion of renewable energy (solar, wind, mini-hydro and waste to energy) in the supply mix; and
vii. promoting sustained regeneration of biomass resources and efficient biomass utilisation technologies.

According to Ghana's Ministry of Energy, about 80 % of the 2010 energy policy objectives were achieved by 2020 (Mahu, 2021). The installed capacity goal for electricity was only achieved in 2019, and only 85 % of the population had, at least, some access to electricity for the same period (Energy Commission of Ghana, 2022). The above goals highlight some of the challenges for achieving climate objectives ranging from competing agendas between sub-sectors, institutional capacity, lack of coordination between sectors and institutions,[3] planning priorities for Sustainable Development Goals (SDGs) and NDCs (Agyekum, 2020).

Ghana's power sector was monopolised by the Volta River Authority (VRA)[4] until the 1990s, generating and transmitting electricity to every region of the country and distributing it to the northern sector of the country. Electricity generation relied on large hydro dams, seen as a symbol of self-reliance, social progress, and economic liberation. The energy sector reform (funded by the World Bank in the 1990s) followed by Ghana's first Strategic National Energy Plan (SNEP) from 2006 to 2020 released in 2006 (Essandoh-Yeddu et al., 2006) recommended formally splitting the country's vertically integrated power supply structure into the three functions of generation, transmission and distribution. With the announcement of the new Plan based on the recommendations, new generating companies, mainly based on oil and gas, emerged, which also helped diversify Ghana's generation portfolio.

From 2012 to 2016, Ghana experienced a severe power crisis due to (1) a West African gas pipeline rupture and (2) below-average rainfall contributing to a fall in hydropower generation leading to reservoir overuse (Dye, 2022). As a result, there were increasing blackouts and brownouts constraining industrial production and economic development (Diawuo et al., 2020). The relatively severe load shedding saw

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[1] Growth rates for population (2.2 %), GDP (5 %), FEC (2.7 %) and CO_2 emissions (5 %) are average values between 2015 and 2019.

[2] An absolute change of 45 % and −4 % relative to 2016 GHG emissions. Ghana has revised the NDC's to achieve an absolute emissions reduction of 64 $MtCO_2e$ by 2030 from nine unconditional measures and 25 conditional measures compared to baseline emissions of 58.8 $MtCO_2e$ in 2019 (MESTI, 2021). It is difficult to establish a quantifiable emission pathway from revised NDCs as most of the reductions are from LULUCF and waste sectors.

[3] Presently the National Development Planning Commission and the Environmental Protection Agency of Ghana jointly coordinate the SDGs and the NDCs for Ghana.

[4] Currently, VRA has the largest share (about 56 %) of the energy market in Ghana.

the Government sign ‘take or pay’ contracts that led to a rapid increase in generation capacity. By 2020, installed grid capacity had expanded to 5288 MW (primarily thermal power) from 2831 MW in 2014. Consequently, electricity supply outstripped the growth in peak load, where demand only rose to 3090 MW by 2020 (Energy Commission of Ghana, 2022). This led to an oversupply in generation capacity, which severely affected the economy and left a bill reaching 4 %–5 % of GDP in 2018 (Dye, 2022; World Bank, 2018). The high capital costs of this increased generation capacity resulted in relatively high electricity tariffs, which pushed many commercial and industrial consumers to look to alternative supply solutions such as renewables. Despite this significant imbalance between generation capacity and peak demand, there have been renewed interests in large dam projects in Ghana, driven by the anticipated increase in future electricity demand (Energy Commission of Ghana, 2019b; Mosello et al., 2017). Additionally, Ghana is intending to increase its export of electricity (from 1.7TWh in 2020) (Energy Commission of Ghana, 2022) to neighbouring countries by expanding its grid infrastructure.

The promotion of renewable energy technologies in Ghana dates back to the 1990s, exemplified in ‘Vision 2020’ (published in 1995), which proposed wide-scale solar and bioenergy development. However, in practice very little in terms of renewable power generation capacity has been installed (Aboagye et al., 2021). The SNEP1 targeted 10 % of renewables (excluding hydro) in the national electricity mix for 2020; in reality, <1 % was achieved. Some of the challenges that hinder renewable energy development in Ghana include: inadequate financing schemes, complex legal and regulatory frameworks, high capital costs, theft, and lack of skill development (Aboagye et al., 2021). Consequently, in 2018 the 10 % renewable energy goal in the national energy mix was extended to 2030.

In 2019 Ghana introduced the Renewable Energy Master Plan (REMP), an investment framework with private sector participation to promote and develop renewable energy resources with specific targets and a roadmap (Energy Commission of Ghana, 2019a). As part of this Plan, several economic and legislative instruments have been implemented including, substantial tax reduction; exemption of import duty on electricity generation plants and materials/equipment for manufacturing or assembling; capacity building in renewable energy development; and support for research and development to accelerate the deployment of renewable technologies (Aboagye et al., 2021). While the above enabling environment could overcome challenges in the deployment of renewables, substantial investment in renewable technologies is needed from the Government if the ambitions of the REMP are to be realised (Aboagye et al., 2021).

Energy outlook for Ghana

Ghana's primary energy supply includes hydropower (5 %), biomass (35 %), petroleum products (35 %) and natural gas (25 %) to meet their FEC of 101 TWh in 2020 (Energy Commission of Ghana, 2022) as shown in Fig. 1. While electricity is only 16.4 % of Ghana's demand (16.5 TWh), electricity demand is growing at a faster pace (8.4 % pa) compared to the final energy (3.4 % pa) both over 2016–2020 (Fig. 2) (Energy Commission of Ghana, 2022). Since 2010, most of the increases in energy demand have been met through oil and natural gas supply, whereas energy generation from hydro has been relatively stable. Renewables, excluding hydro, make up <1 % of the electricity generation from an installed capacity of about 59 MW in 2020 (Energy Commission of Ghana, 2022).

Demand outlook

The revised SNEP published in 2019 by Ghana's Energy Commission (SNEP II) developed two energy demand scenarios, Business-as-usual (BAU) and Accelerated Economic Growth (AEG), both extending out to 2030. Under these scenarios, FEC would increase to about 181 TWh (BAU) and 257 TWh (AEG) by 2030, whereas electricity demand increases to 31 TWh and 48 TWh for the same period (Energy Commission of Ghana, 2019b). There are limited peer-reviewed studies on Ghana's future energy outlook, and most focus exclusively on electricity. A demand projection study using GDP and population growth rates estimate FEC of 179 TWh by 2030 with an electricity demand of 42 to 44 TWh (Kemausuor et al., 2015). This study anticipates high demand for diesel fuel (one-third of all final energy) in the transport, industry and agriculture sectors.

Studies that focus exclusively on electricity demand using historical growth rates or GDP and population growth rates show a range of values from 18 TWh (Sarkodie, 2017) to 30 TWh (Mensah et al., 2021) and 52 TWh (Essandoh-Yeddu et al., 2017) by 2030. Based on historical growth rates (Awopone et al., 2017; Diawuo et al., 2020), electricity demand is projected to increase up to 55–62 TWh by 2040. Only two studies show electricity demand up to 2050, ranging from 60 TWh (Akom et al., 2020) to 106 TWh (Mensah et al., 2021).

Supply outlook

Ghana has a significant renewable and wider low-carbon resource potential, particularly photovoltaics (PV), related to the former, and future nuclear generation for the latter. The REMP (Energy Commission of Ghana, 2019a) estimates a capacity addition of about 200 MW per annum is required to meet the increasing electricity demand. Within this, REMP has set a target of 1364 MW (150 MW small/medium hydro, 327 MW wind, 668 MW solar, 122 MW bioenergy and 50 MW

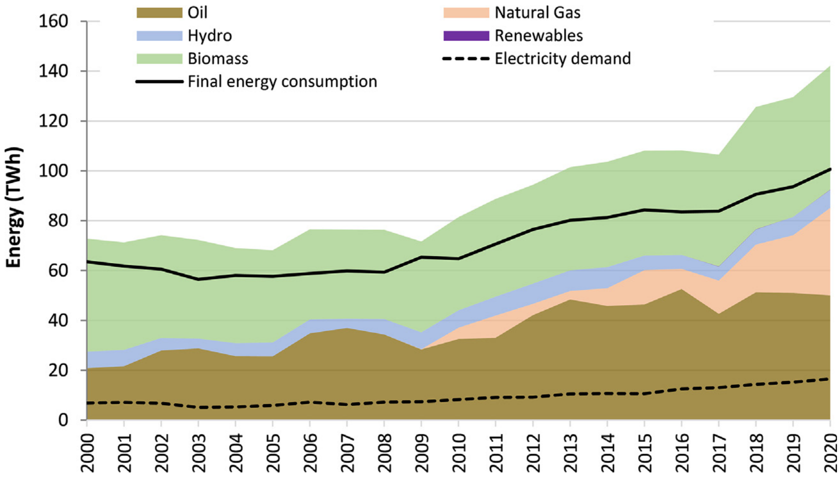

Fig. 1. Ghana's primary energy by source along with final energy consumption and electricity demand from 2000 to 2020 (Energy Commission of Ghana, 2022).

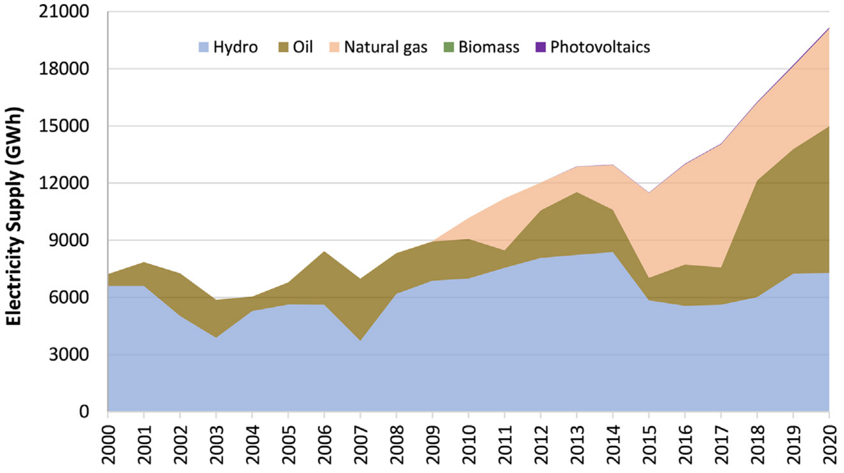

Fig. 2. Ghana's electricity supply by fuel from 2000 to 2020 (Energy Commission of Ghana, 2022).

wave/tidal) generation capacity by 2030 from renewables. Yet REMP does not state the future demand or supply requirements, and the 1364 MW target capacity is relatively small compared to the anticipated demand estimated under SNEPII. Despite the modest targets, the Ministry of Energy expects only 10 % of the electricity capacity by 2030 (8000 MW) to be supplied by renewables (Mahu, 2021).

Within the wider literature, the techno-economic analysis of power generation expansion plans for Ghana shows that at least 16 GW of installed capacity is needed to meet the electricity demand of 62 TWh by 2040 (Awopone et al., 2017). As of 2020, Ghana's installed power generation capacity was 5.34 GW (Energy Commission of Ghana, 2022). Meanwhile, a cost-optimised low-carbon supply development study suggests an additional capacity of up to 22 GW with an annual electricity generation of 48–57 TWh by 2040 is possible (Diawuo et al., 2020). However, this study's maximum share of renewables is limited to 52 % of the final demand, which still falls short of the deep decarbonisation of the power sector needed to address climate change objectives. Mensah et al. (2021), under their 'best policy' scenarios with 100 % renewables, have estimated power generation of up to 125 TWh by 2050. This study shows the crucial role of PV, which generates 76–92 % of the electricity demand from an installed capacity of 62 GW (Mensah et al., 2021).

Hydropower

Hydropower accounts for 7 % of the FEC in Ghana from three large dams – Akosombo (1020 MW), Kpong (160 MW) and Bui (404 MW) – generating about 7.3 TWh of electricity annually (Energy Commission of Ghana, 2022). The reservoir built for the Akosombo dam is the largest in the world by surface area and is situated <200 m above sea level (Darko et al., 2019). The further resource potential for large hydro is estimated as 1200 MW (Agyekum, 2020), in which 850 MW from 16 sites are identified as exploitable with a potential generation of 3.6 TWh per year (Energy Commission of Ghana, 2018; Singh et al., 2015). Within the identified resources, Pwalugu (60 MW) is already under construction and Hemang (60 MW), Daboye (40 MW), Jambito (55 MW) as well as Juale (90 MW) are in the planning stages (Energy Commission of Ghana, 2019a). There are significant challenges for the planned dams to be built, such as illegal mining in the catchment area which increases the sedimentation rates, flooding of large cocoa plantations which is a major export product and transboundary issues (Mahu, 2021).

Bioenergy

Ghana has a significant biomass resource potential using energy crops, wood and crop residues, animal manures, and municipal solid & liquid wastes.[5] Biomass has been an important fuel supply, and accounts for approximately 35 % of the primary energy supply. About 84 % of the biomass (firewood and charcoal) is used in the residential sector for cooking and heating (Energy Commission of Ghana, 2022). Apart from firewood and charcoal, energy from biomass (e.g. biofuels and biogas) remains largely untapped. The REMP envisages production of liquid biofuels from multi-purpose crops (e.g. palm oil, coconut, sugar cane) and energy generation from solid wood waste (sawmill and agro-residues) and biogas (agricultural and industrial organic waste) (Energy Commission of Ghana, 2019a). Currently, there is only one dedicated biomass power station in Ghana which uses bio-waste to generate 100 kW (Safisana power plant). In addition, sawmill residues and oil palm waste are used in co-generation plants, but with a total capacity of only about 6 MW (Aboagye et al., 2021). REMP also envisages deploying 3 million energy-efficient domestic cookstoves and 18,000 commercial cookstoves by 2030 (Energy Commission of Ghana, 2019a).

While there is considerable resource potential for energy crops, alongside biofuel-specific plantations (320,000 ha oil palm and 1534 ha jatropha), uncertainty over the continuous supply of resources (Aboagye et al., 2021) means biomass is underutilised for large-scale energy generation. Estimates of the technical potential of bioenergy range from 48 TWh (residues and waste) (Mensah et al., 2021) to 76 TWh (crops, residues and waste) (Kemausuor et al., 2015). For electricity alone, Kemausuor et al. (2015) estimate 1.78 TWh can be generated by 2030, whereas Mensah et al. (2021) suggest 18 TWh is feasible by 2050, and could play a vital role in balancing the electricity grid dominated by PV.

However, and despite its potential, there are significant environmental and social concerns associated with biofuel crops. Jatropha production contributes to deforestation and land-related conflicts in Ghana. Appropriation of land linked to conservation projects, biofuel production, carbon offset schemes, etc. has impacted the livelihood of indigenous communities in many parts of the world (Fairhead et al., 2012). The production of energy crops is dependent on soil fertility which puts pressure on forests and food production. Recognising both the social and environmental concerns, Ghana not only needs to consider proven biofuel crops but also wider stakeholder participation, new business models and clear policy drivers (Ahmed et al., 2017). In summary, the range of technical resource estimates suggests that between 48 and 76 TWh of bioenergy is available in the future, but broader environmental and social concerns may severely limit these.

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[5] Residues and 'wastes' often fulfil some other function in the economy, so their use as a biomass resource needs to be considered against their use elsewhere.

Wind energy

Onshore wind resource potential in Ghana is marginal, with mean inland wind speeds of only 4–6 m/s at 100 m above sea level (Technical University of Denmark (DTU), n.d.). Most onshore wind resources are along the coast (wind speeds typically around 9 m/s), on the Kwahu plateau and on the northern borders, which collectively gives a gross potential of 5640 MW (Aboagye et al., 2021). Onshore wind generation analysis ranges from 83 TWh using a GIS approach (Mentis et al., 2015) to a theoretical 600 TWh, assuming turbines were sited on all land areas that have > 20 % capacity factor (Hermann et al., 2014). With about 550 km of coastline, there is potential for offshore wind, but establishing robust estimates would require detailed resource analysis. Assuming a mean installed power density of 7.2 MW/km^2 achieved in Europe (Enevoldsen & Jacobson, 2021), 52 GW of wind capacity could be installed 40 km offshore and along just one-third of the coastline (160 TWh at 35 % capacity factor). In summary, the range of resource estimates suggests that about 240 TWh of wind energy is available.

Solar energy

Ghana has a significant solar resource that receives on average 5.1 kWh/m^2/day (Suri et al., 2020) of solar irradiation for an energy potential of 9722 TWh/year (Aboagye et al., 2021; Kuamoah, 2020). When covering 5 % of land area (van de Ven et al., 2021), including reservoirs, buildings and parking lots, about 1800 TWh of solar energy is available with a modest power density of 100 MW/^{2} (Lee et al., 2020) and a capacity factor of 18 % (Agyekum, 2021). Floating solar photovoltaic (FPV) combined with hydropower is increasingly popular, reducing capital costs and variability in generation. Taking into consideration the distances from the site location to the transmission lines (<80 km), as well as minimum and maximum distances from the shoreline, a conservative estimate is that up to 10 % of a reservoir surface area is suitable for FPV (Lee et al., 2020). Building on Lee et al. (2020), about 150 TWh of electricity can be generated from the existing and Pwalugu reservoirs (based on a capacity factor of 18 %). Recently, the Bui dam commissioned a 5 MW FPV as part of the Bui Power Authorities' goal of 250 MW FPV from the dam site. Considering Ghana already has a large reservoir surface area, FPVs could play a significant role in Ghana's future electricity provision and arguably reduce or even eliminate the need for further large hydropower. In summary, the resource estimate suggests 1800 TWh of solar energy is feasible, including FPVs.

Other renewables and nuclear

While there is resource potential for tidal and wave, they are relatively new for Ghana (Kuamoah, 2020), and REMP has proposed 50 MW of wave power by 2030. Ghana has ambitions to construct nuclear power stations and signed a 'Memorandum of Understanding' with Russia to build a 1200 MW nuclear power plant by 2030, with the scope to extend the site to 4400 MW later (Agyekum, Velkin, & Hossain, 2020). However, there are significant barriers to implementing nuclear power in Ghana, including inadequate financing, unstable governance and the inappropriateness of the existing skills base (Agyekum, Ansah, & Afornu, 2020).

To examine the carbon implications of the energy development plans described in the Demand outlook section and to gain insights into Ghana's energy transition, three heuristic scenarios of demand and hydro capacity are developed in this paper. The scenarios all present plausible futures using a top-down approach based on socioeconomic and technological development, and all include substantial consultation with Ghanaian energy experts and policymakers.

Hydro reservoir emissions

Several studies (Barros et al., 2011; Deemer et al., 2016; Harrison et al., 2021; Prairie et al., 2018) show hydro reservoirs are a source of GHG emissions due to the flooding of land from siting dams, subsequently causing microbial decomposition of organic matter. The impoundment of water increases sedimentation and decay rates of organic matter, resulting in both CO_2 and methane (CH_4) emissions. The emission rate varies significantly between reservoirs, driven by environmental and topographical factors. The key predictor variables for emissions include, but are not limited to, the mean air temperature, thermocline depth, water residence time (WRT), total phosphorous concentration, soil carbon content and annual discharge from the catchment (Barros et al., 2011;Deemer et al., 2016 ; Prairie et al., 2018, 2021). These emissions are then released through multiple pathways, including diffusion, bubbling and degassing (downstream of the reservoirs) (Deemer et al., 2016; Prairie et al., 2018).

There are significant challenges in quantifying reservoir emissions accurately (Prairie et al., 2018). This arises from several factors: limited case studies that have quantified the complete carbon footprint of individual reservoirs, the untangling of pre-and post-impoundment balances (before and after construction), and the complexities in biogeochemical processes involved in an aquatic system (Deemer et al., 2016; Prairie et al., 2018, 2021). Meanwhile, quantifying carbon burials in sediments, the impact of eutrophication and newly identified emission flux pathways, bring further challenges when determining accurately reservoir emissions. Emissions from reservoirs in tropical regions are typically higher than those in temperate and boreal areas due to high volumes of flooded biomass, higher soil carbon levels, increased primary productivity and warmer water temperatures (Deemer et al., 2016; Harrison et al., 2021; Prairie et al., 2021).

Estimating net GHG emissions from reservoirs (the difference between post and pre-impoundment emissions) is an appropriate way to legitimately attribute the emissions to the creation of a reservoir (Levasseur et al., 2021; Prairie et al., 2018). Additionally, emissions need to be rightfully attributed to the reservoir purpose such as irrigation, electricity generation or flood control. To estimate the net biogenic emissions attributed to hydropower generation, reliable emission flux rates from the reservoir surface area over time and estimates of carbon sinks and sources prior to the flooding are required (Levasseur et al., 2021). When subsequently comparing emissions with other sources of electricity generation, broader factors, particularly the design life of different generating options and how quickly specific global temperatures may occur, all need to be considered.

Emissions from the reservoir related to its age have further implications for warming over different time horizons. Both CH_4 and CO_2 emissions from reservoirs surge immediately after impoundment and decline sharply in the following years. High CO_2 emissions during the first decade after flooding are due to the decay of labile organic matter (decomposable by microbes) present prior to the flooding. The decay rates of organic matter diminish over time as the remaining organic matter becomes increasingly recalcitrant to degradation. Similarly, much of the CH_4 emissions occur within the first 20 years following impoundment (Briones Hidrovo et al., 2017; Lovelock et al., 2019; Prairie et al., 2018).

The emission intensity (emissions released per unit of electricity produced) is a useful metric to compare different generation technologies. Hydropower emission intensity is often calculated based on the cumulative net emissions over 100 years, given that the lifetime of a reservoir is typical of that order (Levasseur et al., 2021). However, to examine the scale of the mitigation challenge in meeting the Paris 'well below 2°C' temperature goal, it is essential to determine the reservoir emissions over shorter time horizons. At the current global emissions rate, a warming of 1.5 °C since pre-industrial levels is likely to be reached in the 2030s and a warming of 2 °C is expected by the 2050s (IPCC, 2021). To adequately illustrate the scale of emission reductions required from the Ghanaian energy system (including emissions associated with its reservoirs) this paper uses a carbon budget framework based on the IPCC's AR6 headline budget values.

Paris Agreement and the allocation of a 'fair' carbon budget for Ghana

While carbon budgets have been used to inform mitigation policies since 2006 (Bows-Larkin et al., 2006), it is only since the fifth Assessment report of the IPCC (2014) that the concept of a carbon budget has been increasingly used to downscale global climate objectives to help frame national mitigation policies (Anderson et al., 2020). Carbon budgets are the total amount of CO_2 emissions that can be released to the atmosphere by human activities for a given probability of a given temperature rise. A range of global carbon budgets is provided in the IPCC's AR6 report (IPCC, 2021), which can be further downscaled to guide permissible carbon budgets for individual nations (Anderson et al., 2020; Clarke et al., 2014). Several 'effort sharing' or 'burden-sharing' approaches have been suggested to allocate the remaining global carbon budget to nations based on various interpretations of equity, justice and concepts of distributive fairness (Clarke et al., 2014). Clarke et al. (2014) summarise seven distinct allocation categories[6] using three equity principles of responsibility, capability, egalitarian, and its combinations (Höhne et al., 2014; Robiou du Pont et al., 2016). While numerous interpretations of these principles are available (Jabbari et al., 2020) most approaches are focused around equality and responsibility (reflecting population distribution of equal per capita basis) or grandfathering (country share is determined by its share of global emissions) (Raupach et al., 2014). However, as ongoing and high levels of emissions have rapidly shrunk the available carbon budget, a purely equitable division of the 1.5 to 2 °C budget is no longer viable (Jabbari et al., 2020; van den Berg et al., 2019). Despite this, the Paris Agreement, through to the Glasgow Climate Pact, acknowledge how the mitigation efforts of developing nations' will vary from those of developed nations (based on the principle of "common but differentiated responsibilities and respective capabilities"; CBDR&RC). Building on a practical interpretation of this equity dimension, Anderson et al. (2020) established energy-only carbon budgets for 'developing' and 'developed' country parties, recognising peaking of emissions in 'developing' country parties will take longer (article 4.1) than the 'developed' parties. Consequently, and with this paper's specific focus on energy, Anderson et al.'s (2020) approach is extrapolated here to give a range of Paris-compliant energy-only carbon budgets for Ghana.

Material and methods

In this study, the focus is on the role of future dams in Ghana's energy system. Only CO_2 emissions from the reservoirs are considered in the carbon budget analysis, with the other GHGs addressed separately. Ghana's future energy requirements, including electricity demand, are assessed using three heuristic energy-system scenarios. Emissions from three hydropower scenarios are then estimated and set against Ghana's Paris-compliant carbon budget and in the context of the wider energy scenarios. The results for the hydro schemes are reported as emissions per energy unit (gCO_2e/kWh) and emission fluxes (tCO_2 $year^{-1}$), averaged over time horizons of 10, 20, 30 and 100 years. The energy-only carbon budget for Ghana is reported in $MtCO_2$, downscaled from the IPCC AR6 report (IPCC, 2021). The data and methods used are described below.

Carbon budgets and Ghana's climate mitigation goal

The remaining carbon budget for Ghana's energy system is determined from the IPCC AR6 global budget of 700 $GtCO_2$ from 2020 (IPCC, 2021), subsequently downscaled to the 'Developing Country' parties (Anderson et al., 2020). This headline budget relates to a mean surface temperature rise of 1.7 °C (for 66 % of TCRE[7] (IPCC, 2021)) which here is taken to adequately reflect the Paris temperature commitments for 'well below 2°C and pursue efforts to limit to 1.5°C'. To determine the energy-only carbon budget, appropriate deductions are made for land-use land-use change and forestry (LULUCF) and process emissions from cement. LULUCF emissions are assumed to be compensated by sinks over the budget period, however, 60 $GtCO_2$ is deducted to account for process emissions from cement production (Anderson et al., 2020). This gives a total remaining global budget of 640 $GtCO_2$. Building on Anderson et al.'s (2020) interpretation of the Paris framing of equity and the UNFCCC's principle of CBDR&RC, a proportion of the remaining global budget is initially allocated to 'developing' country parties. The updated value, based on AR6, is 510 $GtCO_2$. Downscaling this value through a process of grandfathering (based on emission shares for 2013–2017) permits an estimate of Ghana's carbon budget for 2020–2100 to be made using Eq. (1).

$$B_i = \frac{f_{i,t=(2013\ -\ 2017)}}{F_{t=(2013\ -\ 2017)}} \cdot \mathrm{B} \tag{1}$$

B = carbon budget; t = year; i = country; f_i are the emissions for country i; and F is the corresponding emissions for the world.

An emission reduction pathway, associated with the estimated carbon budget, is then derived. This assumes Ghana peaks its emissions by 2026 before reducing emissions at a constant average annual mitigation rate (13.9 %) to reach zero, dictated by the size of the remaining carbon budget. This emission reduction pathway is then compared to Ghana's NDC's (energy-only CO_2) submitted to the UNFCCC (Environmental Protection Agency, 2020; Government of Ghana, 2015). CO_2 emission datasets are taken from Ghana's fourth national communication to the UNFCCC (Environmental Protection Agency, 2020).

Development of energy demand and hydropower scenarios

The three heuristic energy demand scenarios (Local, Hybrid and Central), developed for this paper, are all constrained within a carbon budget detailed in the Carbon budgets and Ghana's climate mitigation goal section. The scenarios are co-designed with Ghanaian experts from the Council for Scientific and Industrial Research (CSIR) and the Energy Commission. Other stakeholders (VRA, GRIDCo and Ghanaian Ministry of Energy) were consulted, and their contribution was considered in constructing the scenarios. Scenarios vary by the level of urbanisation, type of industry, operational structure of the energy system and levels of digitalisation. The latter of these was judged by some of the stakeholders to contribute to a more efficient 'whole system approach' to the economy, improving the integration of business and industry demands and helping them become more energy efficient. For each scenario, a set of fixed final energy values were given for petroleum and biomass resources (Table 1). Biomass supply is constrained by resource availability, as noted in the Bioenergy section. The remaining energy used in the scenarios is electricity, which includes its use in hydrogen production. As a result of the different levels of energy demand in each scenario, the electrification rates of energy vary between the scenarios.

The detailed scenario descriptions and assumptions are shown in Table 1. The scenarios are underpinned by a set of relationships between energy consumption and economic development, with all three scenarios maintaining near-to-medium term economic growth. For the scenario development, population projections to 2100 are taken from the

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[6] Responsibility; Capability; Equality; Responsibility, Capability and need; Equal cumulative per capita emissions; Staged approaches and Equal marginal abatement costs.

[7] Transient climate response to cumulative emissions (TCRE) is the ratio of global mean warming in °C to cumulative CO_2 emissions. TCRE is estimated using historical observations of warming and temperature response for a hypothetical scenario where CO_2 rises at 1 % pa from pre-industrial to the time of a doubling of CO_2 concentration in atmosphere (IPCC, 2021).

Table 1
Ghana's energy demand and hydropower scenario descriptions and assumptions.

Scenarios	Local	Hybrid	Central
Energy system characteristics	• Low demand is driven by highly efficient use of energy • Low urbanisation • Localised energy generation & use of micro grids • Few heavy industries • High levels of efficient small-scale bioenergy • High levels of distributed electrification • High levels of digitalisation for the entire economy	• Medium energy demand • Medium urbanisation • A mix of localised & large power stations. • Some heavy industries • A mix of hydrogen and biofuels • A mix of distributed and central electrification • Digitalisation in larger cities/towns, less in rural areas	• High energy demand • High urbanisation • Large power stations including offshore wind • Large-scale heavy industries • High levels of hydrogen • High levels of centralised electrification • Digitalisation only in larger cities
	Energy consumption is increasingly decoupled from GDP growth	Energy conservation measures may promote economic growth	Energy consumption is essential for GDP growth
Citizens engagement	Highly engaged citizens	Some citizen engagements	Less engaged citizens
Parameter	Final energy consumption rises at 2.6 % pa. in 2020, dropping to 1.9 % pa. by 2050	Final energy consumption rises at 3.1 % pa from 2020 to 2050	Final energy consumption rises at 5 % pa from 2020 to 2050
	Based on the UN medium variant population projection (2.1 % pa. in 2020 falling to 1.4 % pa. by 2050) and a rise in per capita energy at 0.5 % pa	Based on energy-GDP elasticity (0.63) to GDP growth rate of 5 % pa (average 2015–2019) [Based on PPP (constant 2017 International $)]	Based on a GDP growth rate of 5 % pa (average 2015–2019). [Based on PPP (constant 2017 International $)]
	Per capita annual energy use increases linearly from 3239 kWh in 2020 to 3798 kWh by 2050	Per capita annual energy use increases linearly from 3239 kWh in 2020 to 4875 kWh by 2050	Per capita annual energy use increases linearly from 3239 kWh in 2020 to 8269 kWh by 2050.
	Per capita annual electricity rises from 532 kWh to 2520 kWh by 2050	Per capita annual electricity rises from 532 kWh to 3597 kWh by 2050	Per capita annual electricity rises from 532 kWh to 6991 kWh by 2050
Bioenergy supply in TWh	2020 – 35, 2030 – 50 2040 – 60, 2050 – 65	2020 – 35, 2030 – 50 2040 – 60, 2050 – 65	2020 – 35, 2030 – 50 2040 – 60, 2050 – 65
Petroleum supply in TWh	2020 – 49, 2030 – 49 2040 – 16, 2050 – 1	2020 – 49, 2030 – 49 2040 – 16, 2050 – 1	2020 – 49, 2030 – 49 2040 – 16, 2050 – 1
Hydropower capacity	1640 MW (7.5 TWh) including Pwalugu dam (60 MW).	1919 MW (8.6 TWh) including Juale, Jambito, Daboye, Hemang and Pwalugu.	2434 MW (11 TWh) including all 16 potential sites (850 MW)

UN World Population Prospects (United Nations, 2019), whereas GDP datasets are taken from the World Development Indicators (World Bank, 2022). The starting point data used to define a 2020 baseline energy system is taken from Ghana's annual energy statistics (Energy Commission of Ghana, 2022).

Summaries of the energy demand characteristics of the three demand scenarios

The 'Local' scenario assumes that Ghana's citizens will be highly engaged in energy conservation and climate change mitigation, resulting in a society actively engaged in driving the efficient use of energy. This scenario is underpinned by a 'neutrality hypothesis' whereby energy consumption and economic growth are increasingly decoupled (Menegaki & Tugcu, 2016). Energy demand in this scenario is based on 0.5 % pa growth rates of per capita energy use (average of 2015–2019) from 2020. The population will grow at a starting rate of 2.1 % in 2020, decreasing linearly to 1.4 % by 2050 as forecast by the UN. In contrast, the 'Central' scenario assumes Ghana's citizens will be less engaged in energy conservation and climate change mitigation, resulting in a large increase in energy demand. This scenario is characterised by a 'growth hypothesis' where energy consumption is a major contributor to economic growth (Menegaki & Tugcu, 2016). Here the total FEC rises at 5 % pa from 2020 to 2050 in line with the GDP growth rate (2015–2019). The 'Hybrid' scenario has elements of both the 'Local' and 'Central' scenarios, with Ghana's citizens having moderate levels of engagement with energy conservation and climate change mitigation. This scenario is supported by a 'conservation hypothesis' where certain energy conservation measures are assumed to promote economic growth (Menegaki & Tugcu, 2016). Here the FEC rises at 3.1 % per annum to 2050, continuing Ghana's energy-GDP elasticity (0.63 for 2015–2019) with GDP growing at 5 % pa.

Summary of the hydropower contribution to the three scenarios

The hydropower capacity varies for each of the three scenarios – providing a further heuristic dimension to their development. The 'Local' scenario has no additional large hydropower other than the Pwalugu, leading to a total installed capacity of 1640 MW. In the 'Hybrid' scenario, the planned four dams in REMP (Hemang, Juale, Daboye and Jambito) are built along with Pwalugu, raising the capacity to 1919 MW. In the 'Central' scenario, all 16 potential schemes are built, leading to a cumulative capacity of 2434 MW. Any run-off hydro schemes are excluded from this analysis as they do not have reservoirs. The annual hydro generation (GWh per year) for each scenario is taken from Singh et al. (2015).

Emissions from reservoirs

The net GHG emissions from Ghanaian reservoirs are estimated using two different approaches - the G-Res tool (version 3.1) and generic values from Barros et al. (2011), Deemer et al. (2016) and Scherer and Pfister (2016).

G-res is a publicly available web-based tool (https://g-res.hydropower.org/) developed by the International Hydropower Association (IHA) and the UNESCO Chair in Global Environmental Change (Prairie et al., 2021; Prairie et al., 2017). The tool estimates net emissions from reservoirs based on statistical relationships derived from published studies on GHG fluxes as a function of site-specific variables such as latitude, age and flooded soil carbon content (Prairie et al., 2017). Post-impoundment emissions in this approach consider CH_4 fluxes from bubbling, diffusion and degassing, and CO_2 fluxes through diffusion from the reservoir surface. Pre-impoundment fluxes are estimated for different types of land cover (i.e. wetland, forest, grassland, etc.) sited in various climatic zones and with diverse soil types, using emission factors published in the 2006 IPCC guidelines for national GHG inventories. Both the net GHG and CO_2-only emissions from Akosombo, Bui, Kpong and Pwalugu were estimated separately using G-Res version 3.1. Input data for G-Res were obtained from the Ghanaian stakeholders (Volta River Authority, Bui Power Authority, and Water Research Institute at the Council for Scientific and Industrial Research) and are available in the Supporting Information (S1 Table).

Generic area-based (areal) emission factors for hydro reservoirs at global and regional scales (measured in average emission fluxes per sq. m) are proposed by Barros et al. (2011) and Deemer et al. (2016). Scherer and Pfister (2016) offer similar generic values for CO_2 and CH_4 but relative to kWh generated. These generic areal emission values (see Table 2) are based on statistical relationships derived from empirical studies across diverse climatic zones. The areal emissions factors in Table 2 are multiplied by the ratio of molecular weights of gases and the sum of average reservoir surface areas, to give the total annual emissions for each reservoir. In contrast, the carbon intensity values in Table 2 are multiplied by the average annual hydropower generation (2019–2020) to give an estimate of total annual emissions.

From here, the net annual emissions estimated for each reservoir are then allocated to the various reservoir services, including electricity generation. The annual reservoir emissions (from all the reservoirs in each of the different scenarios) are then estimated by multiplying the aggregated carbon intensity of existing and Pwalugu hydro with the potential electricity generation under each scenario in Table 1. An assumption is made here that all other remaining hydropower stations will have the combined carbon intensity of existing and Pwalugu dams over a 100-year time period. The annual values of reservoir emissions over 100 years are then summed to estimate the cumulative emissions.

To estimate the emissions for a specific year post-2020, it is necessary to assess the rate of decline in GHGs over time. To this end, Prairie et al. (2021), show that the rates of decline decrease with time (faster in the initial years post-impoundment and slower later on). The temporal variation of CO_2 emission flux rates from reservoirs can be expressed using Eq. (2) from Prairie et al. (2021).

$$\begin{aligned} &\mathrm{CO_2\ emissions}\left(\mathrm{Age_{yr}}\right) \\ &\quad = 10^{\left(1.860-0.330*\ \log10\left(Age_{yr}\right)+0.0332*T_{eff}+0.0799*\ \log10(A_{res})+0.0155*C_{soil}+0.2263*\ \log10(TP)\right)} \end{aligned} \tag{2}$$

where $\mathrm{Age_{yr}}$ is the reservoir age in years

T_{eff} is the effective temperature derived from the surface air temperature using Eqs. (3) and (4).

$$\text{Effective temperature, } T_{\mathrm{eff}} = \frac{\log 10(\mathit{Average}(12\ \mathit{month\ temperature\ correction\ coefficient}))}{0.05} \tag{3}$$

$$\text{Temperature correction coefficient} = 10^{(\mathit{temperature\ per\ month}*0.05)} \tag{4}$$

A_{res} is the surface area of the reservoir

C_{soil} is the soil carbon content prior to the flooding

TP is the reservoir total phosphorus concentration.

Based on the net emissions from the G-res tool (version 3.1) emissions for each year over 100 years post impoundment are then estimated using Eq. (2).

The impoundment year for Pwalugu is estimated as 2025 (Volta River Authority, 2021), and an assumption is made for the impoundment of planned dams as 2028. For all remaining reservoirs, this paper assumes that construction will be completed by 2032. The carbon intensity of these reservoirs is then estimated by dividing the net emissions by the average annual power generation. The post-2020 emissions from individual reservoirs are then used to evaluate dams' emission implications within the three energy scenarios.

Table 2

Average annual areal emission rates and carbon intensity values (over a 100-year time horizon) for hydro reservoirs from literature.

Study	CO_2 emissions	CH_4 emissions
Barros et al. (2011) for non-amazonian tropical regions	916 $gCO_2/m^2/year$	20 $gCH_4/m^2/year$
Deemer et al. (2016) for tropical regions	875 $gCO_2/m^2/year$	46 $gCH_4/m^2/year$
Scherer and Pfister (2016) for Ghanaian reservoirs	409 gCO_2/kWh	59 gCH_4/kWh

Results and discussion

Three heuristic energy demand and hydropower scenarios are used for this analysis – all exploring the emission implications of hydroelectric expansion (Table 1), which is then evaluated against a Paris-compliant carbon budget for Ghana's energy system. The scenarios offer a heuristic framework for Ghana's energy system development that aligns with the Paris Agreement. The results are sensitive to various factors, including the carbon budget allocation principles, energy demand scenario assumptions and electrification rates, and the G-Res model assumptions on emission estimates.

Energy demand

The assumptions applied in the scenarios and described in Table 1 saw Ghana's FEC in 2050 to rise between 198 and 430 TWh, an increase of 2 to 4.3 times compared to 2020 (Fig. 3). Of this FEC, electricity demand is between 131 and 364 TWh, an increase of 8 to 22 times compared to 2020. To put this into context, Ghana's 2020 FEC is about 1.6 times higher than in 2000, whereas electricity demand has increased by 2.4 times. The heuristic scenarios in this paper assume a significant rise in electrification rates until 2050. The 'Local' scenario has 66 % of energy demand electrified, whereas for the 'Hybrid' and 'Central' scenarios, this rises to 74 % and 85 %, respectively, compared to 16.4 % in 2020. Although such electrification rates are ambitious, they are widely considered to be the preferred decarbonisation route for transport, heat and industry (Mühlenhoff & Bonadio, 2020; REN21, 2021; Tsiropoulos et al., 2020). That said, it is also widely understood that significant amounts of storage and demand management would be required if such demand is to be met from variable renewable sources such as solar and wind.

Ghana's per capita annual consumption of electricity (532 kWh) and energy (3239 kWh) in 2020 – often considered as an index for development – place the country in the low-income group of countries. Whist, a sizable increase in demand is expected, due to strong linkages to economic growth (Sorrell, 2015), the 'Local' scenario, with its focus on demand reduction, energy efficiency improvements and higher levels of distributed generation could limit the electricity demand to around 131TWh in 2050 (8 times the 2020 value). The per-capita energy use under the 'Local' scenario rises to 3798 kWh by 2050 while per-capita electricity use has a more significant rate of increase, to 2520 kWh. The 'Central' scenario envisages much higher growth in demand (5 % pa out to 2050) driven mainly by industrialisation. High electrification rates under this scenario lead to an increase in electricity demand of 22 times. In this scenario, per-capita energy use rises to 8269 kWh by 2050 while per-capita electricity use rises to 6991 kWh. To put this in context, the UK's per-capita energy and electricity demand was, respectively, 24,059 kWh and 4411 kWh in 2019 (Department for Business Energy and Industrial Strategy, 2022). Under the 'Hybrid' scenario, which has elements of both the 'Local' and 'Central' scenarios, electricity demand is increased to 187 TWh (11 times). Hence, per-capita, energy use rises to 4875 kWh by 2050 while per-capita electricity use rises to 3597 kWh. All three scenarios suggest that high levels of intermittent renewables (solar and wind) are needed from 2030 onwards to be consistent with the Paris Agreement.

Hydropower and reservoir emissions

Full deployment of Ghana's additional hydropower potential (850 MW) could generate up to 3.57 TWh of electricity per annum or 11 TWh in total, including existing dams. The 'Central' scenario assumes this full deployment, with hydro subsequently providing 3 % of annual electricity demand. However, for the 'Local' scenario, with much lower

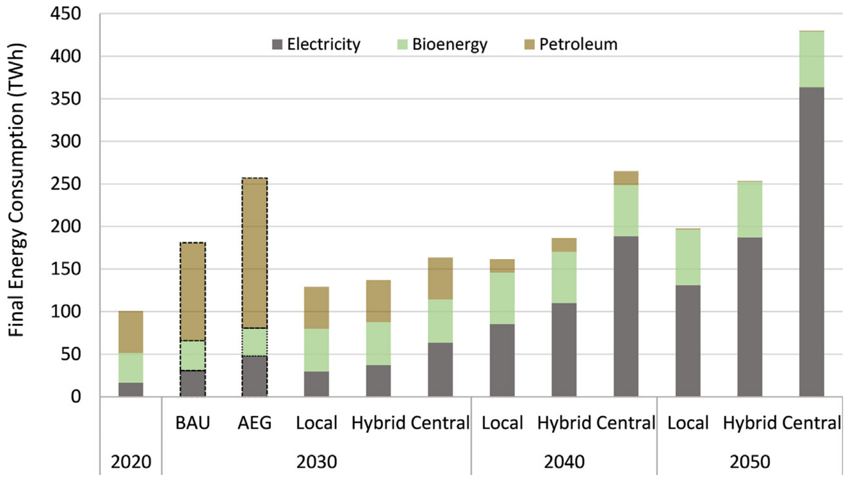

Fig. 3. Final energy consumption in Ghana by fuel under three scenarios and Ghana's Strategic National Energy Plan's Business as Usual (BAU) and Accelerated Economic Growth (AEG) scenarios.

Table 3
Average reservoir emission intensity allocated to electricity generation estimated using the G-res model over time horizons of 10, 20, 30 and 80 years from 2020 and over 100-year post-impoundment.

	Carbon emissions gCO_2/kWh				
	100-year period post-impoundment	10 year (2020–2030)	20 year (2020–2040)	30 year (2020–2050)	80 year (2020–2100)
Akosombo	507	202	170	141	58
Kpong	11	8	7	6	3
Bui	140	312	255	217	117
Pwalugu	415	2193	1428	1111	540
Local scenario	391	222	190	159	73
Hybrid scenario	406	276	298	261	134
Central scenario	411	219	395	374	212

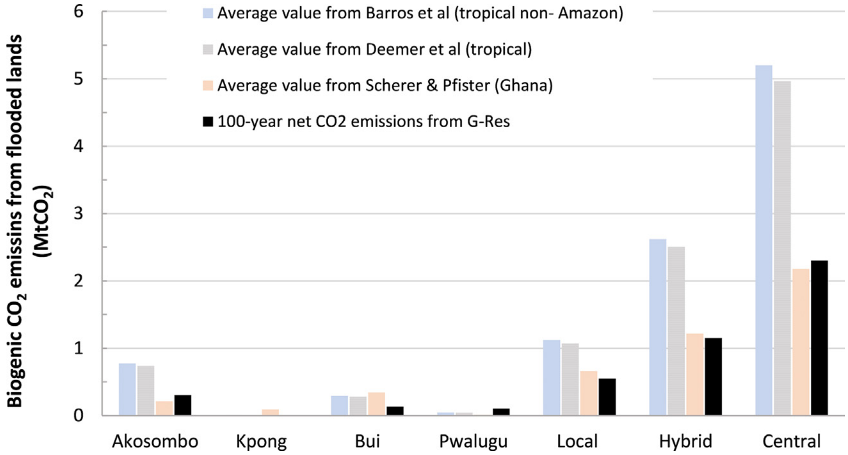

Fig. 4. Annual carbon emissions estimated using different approaches from Ghana's existing and future reservoirs for the budget period (2020–2100).

overall energy and electricity demand and with only the Pwalugu (60 MW) dam added to existing capacity, the contribution of hydro to meeting total electricity demand rises to 6 %. It is essential to note that the Pwalugu dam is already under construction and is anticipated to contribute an additional 210 GWh of electricity post-2025 (Sackey et al., 2020).

The net carbon intensity from hydropower generation for the three existing hydro reservoirs and the proposed Pwalugu dam for the budget period (2020–2100) is estimated as outlined in the Emissions from reservoirs section and shown in Table 3 and Fig. 4. Compared to generic approaches, the G-res model is more appropriate as it takes into account the reservoirs' specific characteristics (e.g., primary productivity, temperature, depth) in the estimation (Prairie et al., 2021). The G-res results show that the Akosombo and Pwalugu dams have GHG emission intensities similar to a gas-fired power station[8] over a 100-year time horizon. However, for new dams such as Pwalugu, average emission intensities are typically more than a coal-fired power station[9] in the first 30 years (Table 3); this is contrary to the environmental impact assessment finding of Pwalugu dam as a low carbon development (Sackey et al., 2020). Assuming future hydro dams have similar emission intensities (100-year time horizon) to the combined average of existing and Pwalugu, Ghana's future dams, including Pwalugu, are estimated to release 1.4 $MtCO_2$ (2.0 $MtCO_2e$ including methane) annually (Figs. 4, 5, A1

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[8] Direct emissions for a combined cycle gas turbine power station is ~370 gCO2e/kWh (Schlömer et al., 2014).

[9] Direct emissions for a coal power station is ~760 gCO2e/kWh (Schlömer et al., 2014).

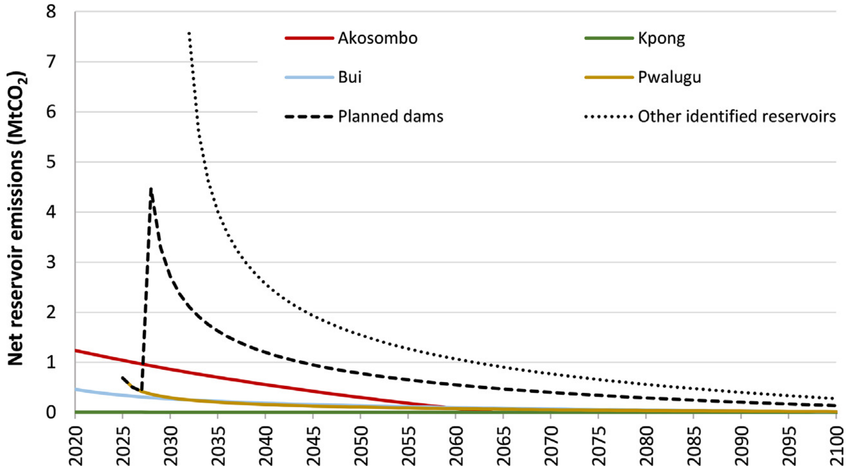

Fig. 5. Net emissions from existing and future Ghanaian reservoirs based on the G-Res model for the carbon budget period of 2020–2100.

and A2). As discussed in the Hydro reservoir emissions section, reservoir emissions are related to the age of dam impoundment, with Figs. 5 and A1 demonstrating how emissions from hydropower decline sharply post-impoundment. The cumulative emissions (2020–2100) from dams in the scenarios range from 44 MtCO$_2$ ('Local' scenario) to 184 MtCO$_2$ ('Central' scenario). Within this, the planned dams alone would emit 57 MtCO$_2$, whereas all the identified 16 dams would emit 149 MtCO$_2$.

The output from G-Res demonstrates how the emission intensities for Akosombo and Pwalugu are three times higher than the level estimated for the Bui dam. When compared to Akosombo and Pwalugu, Bui is deeper and therefore has a significantly lower percentage of the littoral area (% of the total reservoir surface area shallower than 3 m). Moreover, Bui has a relatively lower WRT, soil carbon content and total phosphor in the reservoir compared to Akosombo and Pwalugu. The upstream of Kpong is smaller with its flow controlled by Akosombo and with it operating as a run-of-the-river plant. Hence emissions attributed to Kpong are significantly lower when compared to those of the other dams in Ghana.

The emissions from future reservoirs estimated here are subject to uncertainties on the reservoir characteristics, such as soil organic carbon content, primary productivity and the timing of future dam's impoundment. Additionally, G-res model assumptions on the predictor variables using regression are based on a limited observation range and rely on generic emission factors for different land cover types (Prairie et al., 2021). In addition to these uncertainties, climate variability is likely to impact the water-level changes in the reservoirs, with implications for the level of emissions. Recent satellite data already suggests about 15 % reduction in the surface area of global reservoirs (Keller et al., 2021). The exposure of sediments in the drawdown areas exacerbate near-medium term emissions (Keller et al., 2021), with Ghana prone to climate variability and with reductions in rainfall already observed (Dye, 2022).

Remaining carbon budget for Ghana

The Paris-compliant carbon budget for Ghana's energy system is estimated as 374 MtCO$_2$ from 2020. The emission reduction pathway associated with the remaining budget is compared against Ghana's NDC submission (energy-only CO$_2$) to the UNFCCC, as illustrated in Fig. 6. This demonstrates a budget that needs to comprise both energy-related, industrial and land-use change CO$_2$ emissions. The energy-related CO$_2$ emissions in 2016 are already higher than the proposed emissions under the conditional target. The emission pathways show that while the conditional NDC target is broadly consistent with the Paris objectives (if raised to a starting level that matches the current empirical and reported data), Ghana's unconditional NDC falls far short of anything even approaching a fair contribution to the Paris temperature commitments.

The cumulative carbon emissions from Ghana's reservoirs determined here have significant implications for Ghana's remaining carbon

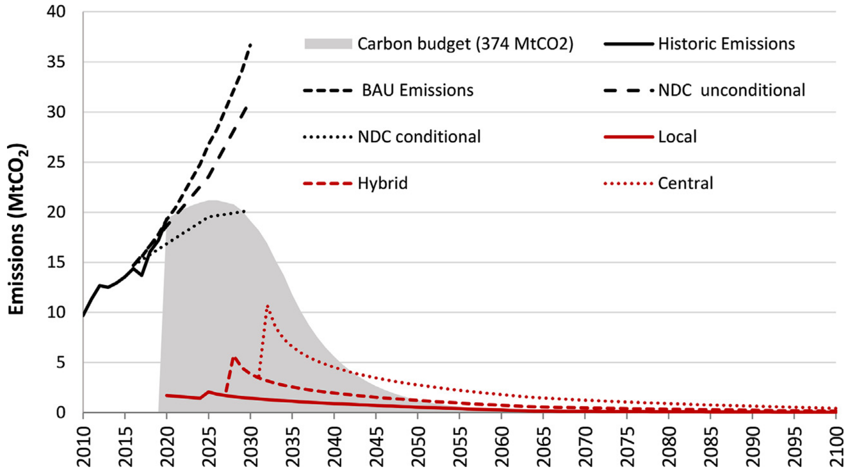

Fig. 6. A stylised plot of Ghana's Paris-aligned energy-only carbon budget (assuming emissions reach a peak in 2026, before rolling over to achieve an average annual reduction rate of 13.9 %) compared to Ghana's Nationally Determined Contribution to UNFCCC (adjusted to energy-only CO$_2$) and reservoir emissions from the scenarios

budget, accounting for 12 %, 25 % and 49 %, respectively, for the three scenarios. Planned dams alone contribute to 15 % of the budget, and if all identified dams are built, 40 % of the budget will be used. Given the heavily front-loaded emissions intensity of new dams (particularly in the first 20 years post-impoundment), they have significant implications for Ghana's emissions pathways consistent with its Paris-compliant carbon budget. For example, the new Pwalugu dam alone takes about 2 % of the carbon budget but only provides 0.2 % of energy demand in 2030, dropping to 0.1 % in 2050 even under the most energy-efficient scenario (Local). Given that electricity generation is about a third of all energy-related emissions in 2016 and transport accounts for half of all energy emissions (Environmental Protection Agency, 2020), any new carbon-intensive power plants risk pushing Ghana beyond its Paris-compliant budget. Consequently, there will be less emission space for sectors such as transport and industry if carbon-intensive power plants (such as dams) are built. Moreover, as Ghana is increasingly affected by rising temperatures and decreasing rainfall (Asare-Nuamah & Botchway, 2019), emissions could be exacerbated through intense water use for irrigation and power generation (increasing areas of ‘drawdown’).

While non-CO_2 emissions are not considered directly in carbon budget analysis, high methane emissions from reservoirs further restrict the remaining carbon budget available for the energy system. This is due to implicit assumptions on future non-CO_2 emissions globally when determining the remaining carbon budget. Large-scale development of dam projects globally, particularly in the tropics, could increase non-CO_2 emissions, with the risk of reducing the available global carbon budget. In Ghana, methane emissions from hydro reservoirs are estimated to be around 1.7 $MtCO_2e$ pa under the ‘Central’ scenario and 1.2 $MtCO_2e$ pa under the ‘Local’ scenario over a 100-year time frame.

Future energy supply

The energy resource analysis in the Energy outlook for Ghana section suggests Ghana can meet all of its electricity demand from solar, wind and biomass, along with the existing hydropower. The findings are complementary to Mensah et al.'s (2021) Ghanaian case study, with the latter going on to conclude that a 100 % renewable-based power supply would be cost-effective for Sub-Saharan Africa. Given that Ghana has a sufficiently large reservoir surface area, FPVs alone could provide about half of Ghana's electricity demand under the ‘Central’ scenario (from 10 % of existing and Pwalugu reservoir surfaces). FPVs are also cost-effective as some of the generation could be shared with the existing transmission systems for hydro.

The results of the analysis in this paper suggest that technologies such as solar, wind and biomass should, at least from an emissions perspective, be given priority over new hydro in Ghana's low-emissions energy future. As illustrated in Figs. 5 & 6 and shown in the Remaining carbon budget for Ghana section building new hydro dams will only serve to increase emissions significantly, thereby jeopardising Ghana's prospects of meeting its Paris-compliant carbon budget. In contrast, lifecycle emissions for solar and wind are only 11 to 48 gCO_2e/kWh with no direct emissions. Emissions from biomass are largely related to infrastructure and supply chain which can be reduced by using domestic biomass sources as outlined in the Bioenergy section. This compares with direct emissions of ~370 gCO_2e/kWh for a combined cycle gas turbine power station and ~760 gCO_2e/kWh for a coal power station (Schlömer et al., 2014). However, increasing the use of bioenergy to meet the demand may lead to deforestation for growing energy crops and environmental concerns as outlined in the Bioenergy section. Meanwhile, a development approach using solar and wind power with storage technologies might be more cost-effective than building new grid infrastructure (Adaramola et al., 2017; Mensah et al., 2021), which also helps achieve universal electricity access.

Conclusion

The heuristic scenarios developed in this paper illustrate how expanding hydropower in tropical regions, such as Ghana, as part of a low-carbon energy transition, is misguided and risks compromising Paris-compliant carbon budgets. This is contrary to what is typically assumed given hydro's ‘low emission’ badging. Specifically, when sited in the tropics, the high levels of emissions (per kWh) produced in the two to three decades following the construction of a new dam are similar to those from a coal-fired power station.

The scenarios also demonstrate that large-scale implementation of low-carbon supply technologies in the 2020s is essential for meeting growing electricity demand in fast-developing countries like Ghana. What is clear from this analysis is that even when hydropower plays only a small role (850 MW i.e., 0.8 % of energy supply) in meeting Ghana's future electricity demand, it consumes 40 % of the national carbon budget. This leaves much less emission space for sectors such as transport and industry, despite them needing more time to decarbonise compared with the power sector. Moreover, given that Ghana is experiencing decreasing rainfall due to climate change, reservoirs are also expected to be subject to the overuse of water, which in turn exposes drawdown areas that further increase greenhouse gas emissions.

To conclude, this paper makes clear that rather than constructing still more dams, energy efficiency and demand management alongside expanding and diversifying renewable supply (e.g. onshore and offshore wind through to floating and land-based solar) offers Ghana a lower carbon and potentially more prosperous energy future.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2022.10.011.

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.

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Appendix 1

Table A1
Reservoir emission intensity allocated to electricity generation estimated using different approaches over a 100-year time horizon.

	Carbon emissions gCO_2/kWh				Greenhouse gas emissions gCO_2e/kWh			
	Barros et al	Deemer et al	Scherer & Pfister, Ghana	G-Res tool	Barros et al	Deemer et al	Scherer & Pfister, Ghana	G-Res tool
Akosombo	1181	1128	327	511	2059	4577	1942	705
Kpong	41	39	409	11	71	158	2427	22

(continued on next page)

Table A1 (*continued*)

	Carbon emissions gCO_2/kWh				Greenhouse gas emissions gCO_2e/kWh			
	Barros et al	Deemer et al	Scherer & Pfister, Ghana	G-Res tool	Barros et al	Deemer et al	Scherer & Pfister, Ghana	G-Res tool
Bui	281	269	327	141	490	1090	1942	238
Pwalugu	673	642	164	419	1173	2608	971	570
Local scenario	895	855	331	393	1561	3470	1965	553

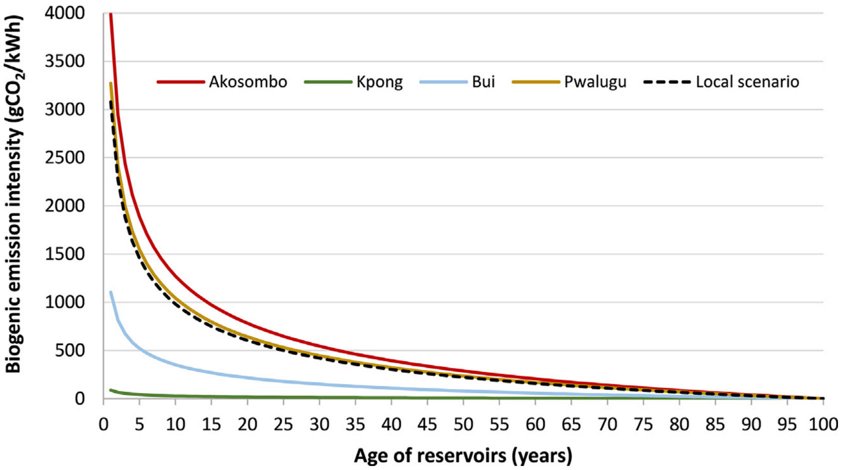

Fig. A1. Emission intensity of existing and under construction Ghanaian reservoirs based on the G-Res model over 100 years.

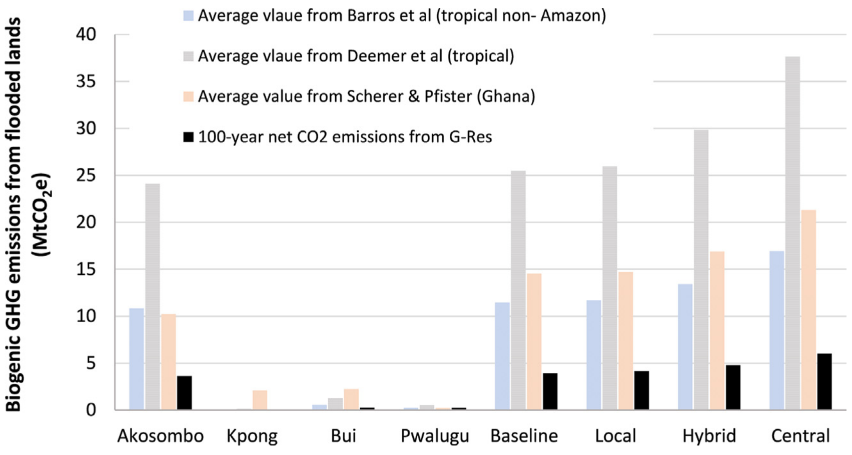

Fig. A2. Annual greenhouse gas emissions estimated using different approaches from Ghana's reservoirs over a 100-year period using GWP 100.

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