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Sustainable planning of the energy-water-food nexus using decision making tools

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ABSTRACT

Developing countries struggle to implement suitable electric power and water services, failing to match infrastructure with urban expansion. Integrated modelling of urban water and power systems would facilitate the investment and planning processes, but there is a crucial gap to be filled with regards to extending models to incorporate the food supply in developing contexts. In this paper, a holistic methodology and platform to support the resilient and sustainable planning at city region level for multiple sectors was developed for applications in urban energy systems (UES) and the energy-water-food nexus, combining agent-based modelling - to simulate and forecast resource demands on spatial and temporal scales - with resource network optimization, which incorporates capital expenditures, operational costs, environmental impacts and the opportunity cost of food production foregone (OPF). Via a scenario based approach, innovative water supply and energy deployment policies are presented, which address the provision of clean energy for every citizen and demonstrate the potential effects of climate change. The results highlighted the vulnerability of Ghanas power generation infrastructure and the need for diversification. Feed-in tariffs and investment into supporting infrastructure and agriculture intensification will effectively increase the share of renewable energy and reduce carbon emissions.

1. Introduction

The United Nations' Sustainable Development Goals (UN SDGs) condense the major challenges faced by human society into 17 categories (United Nations Department of Economic and Social Affairs, 2015), the core of which are the basic human needs of energy, water and food. Ambitious 2030 targets have been set by the UN in each of these categories; those which are addressed in this study are illustrated in Fig. 1. The scale of the challenge is compounded by a continually growing global population, which is expected to reach 8.5 billion in 2030. More than half of this growth is expected to occur in Africa (United Nations Department, 2015). Furthermore, the proportion of the global population living in urban settlements is projected to grow to 60% by 2030, from an estimated 54.5% in 2016 (United Nations Department, 2016). To put this into perspective, cities in developing countries will need to meet the demands of an additional 70 million people each year over the next 20 years (Miralles-Wilhelm, 2016). International research has discovered that urban settlements are the key drivers of energy and water usage as well as the associated carbon emissions (Phdungsilp, 2010).

Tackling these challenges is especially urgent in view of a rapidly shrinking carbon budget. According to Rogelj et al. (2016), in order to limit global warming to below 2°C relative to pre-industrial levels with a probability greater than 66%, carbon prices of more than $\$40/tCO_2$ eq have to be introduced, whereas a carbon credit price of $\$20/tCO_2$ eq would only increase the probability of avoiding 2°C of global warming to about 50%. Remaining below the 1.5°C limit enshrined in the Paris Agreement will require even more urgent and drastic emissions reductions, as the threshold avoidance budget (TAB) for 2°C is 590-1240 $GtCO_2$, or only 15–30 years of carbon dioxide (CO_2) emissions at 2014 levels.

Meeting these requirements is complicated by the fact that the three basic resources are highly intertwined (Schlör et al., 2017; Garcia and You, 2016). Their interactions are collectively termed the Energy-Water-Food (EWF) nexus, which is mapped out in Fig. 2. For example, rural energy access is a key driver in growing economies (SDG 8),

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Fig. 1. Addressed United Nations' Sustainable Development Goals numbered by respective category (United Nations Department, 2015, Griggs et al., 2013).

Fig. 1. (*continued*)

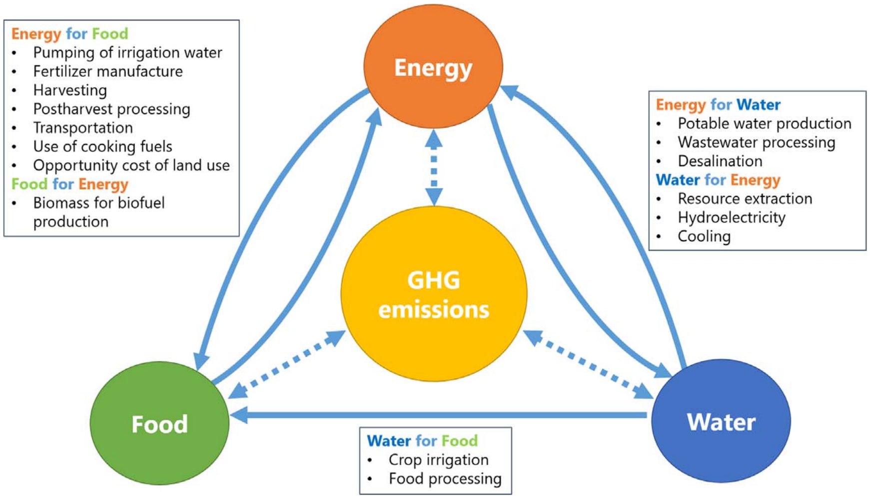


Fig. 2. Energy-Water-Food Nexus.

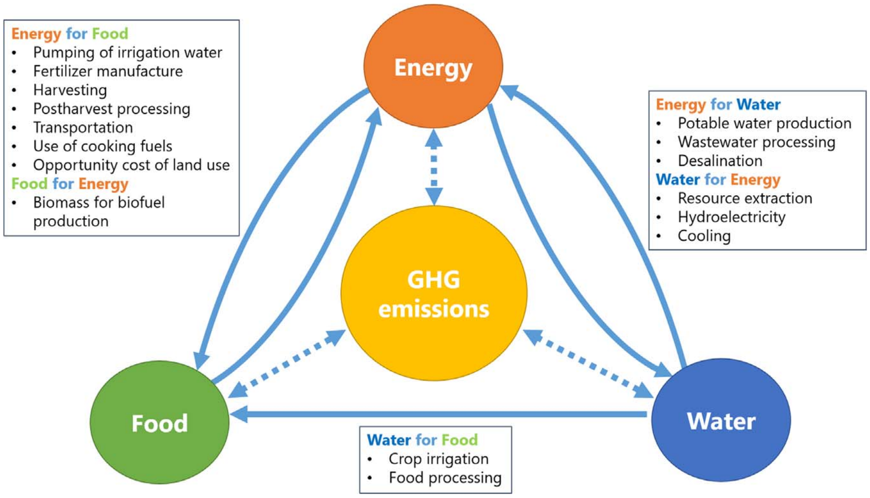


Fig. 2. (*continued*)

improving healthcare services (SDG 3), reducing poverty (SDG 1), as well as providing more reliable and cleaner food and water supply (SDG 2 & 6). However, meeting this demand with fossil fuel-fired power generation instead of renewable energy (SDG 7) will release more greenhouse gases (GHGs) that exacerbate climate change (SDG 13), in turn threatening the security of energy, water and food supply.

Currently, there are still 1.3 billion people worldwide with no access to electricity (Alstone et al., 2015). Increasing electrification also increases water demand due to thermal power stations and fuel extraction facilities. However, half of the world's population is projected to be residing in areas of high water stress by 2030, adversely affecting food and energy security (World Water Assessment Program (WWAP), 2012). Furthermore, global population growth is expected to lead to a proportional increase in food demand of about 50% by 2050 (World Bank, 2016). This highlights the need to understand and quantify interactions between the various resource requirements, to meet future demands without sacrificing any one component of the nexus (Lubega and Farid, 2014). Studying the nexus is important in pursuing balanced solutions to resource, economic and environmental problems (Chen and Chen, 2016a; Conway et al., 2015).

As a result of the increasing population growth, current energy and urban water systems are expanding, putting increasing pressure on existing land and inland waters used for food production. Increasing attention has accordingly been paid to their environmental (Bleischwitz and Bringezu, 2009) and socio-economic impacts (Chen and Chen, 2016b; Gu et al., 2014). Therefore, sustainable urban development and prudent management of agricultural land, inland and marine waters are crucial. The former is particularly important for low- to middle- income countries, as they are associated with the highest rate of urbanization but have insufficient planning capacity, resulting in significant challenges in handling their growth without compromising the ability of future generations to meet their demands (Cohen, 2006). A systematic approach is required to address these impacts and evaluate optimized strategies for infrastructure investment (Villarroel Walker et al., 2014).

Computational modelling is a powerful tool to quantify interactions within the EWF nexus while aiding sustainable decision-making. The effects of novel technologies on urban energy and water systems typically only become apparent after widespread implementation; computer simulation tools provide an additional means to test their feasibility prior to their implementation (Hering et al., 2013). Current approaches combine data collection and calculations to develop a model of the current urban environments, based on their population characteristics (such as access to infrastructure), as exemplified by Wang et al.'s study identifying energy efficiency drivers (Wang et al., 2017b). Integrated solutions, however, can be useful to guide political decisions towards more advanced technologies, while utilizing limited funds as effectively as possible. Simulation and optimization models which provide insights into the future demands of urban 'socio-technical' systems under different environmental and socio-economic scenarios form an integrated solution (Fiksel, 2003). Endo et al.'s review on quantitative and qualitative methods for EWF nexus analysis identified the suitability of Optimization Management Models to explicitly represent the interaction of natural resources and reveal trade-offs inherent in the EWF nexus, while using economic optimization to determine how to allocate scarce resources over time to maximize societies' overall welfare (Endo et al., 2015). Moreover, Greening and Bernow successfully identified multi-criteria decision-making (MCDM) methods, as a suitable tool within an integrated assessment to address a variety of stakeholders (Greening and Bernow, 2004).

A review of previous work reveals many promising directions for progress in the field of energy systems modelling. Keirstead et al.'s (2012) review of urban energy systems modelling stated four major challenges for future model development: complexity, data availability and uncertainty, model integration, and policy relevance. For example, while a current multi-objective optimization framework by Kravanja and Čuček (2013) objectively quantifies the environmental burden (eco-cost), the direct impacts of policies is not considered in the objective function. Pfenninger et al. (2014) have also identified a need in the field of energy systems modelling to improve the resolution of demand in time and space and capture the human dimension. To address this issue, Keles et al. (2016) adopted agent-based simulations as an adequate methodology to evaluate resource demands. Moreover, Johnson et al. (2015) state that in the current state-of-the-art modelling of the EWF nexus, only about 4.4% of studies address the entire EWF nexus. Most modelling approaches have only examined interactions between two of the three EWF sectors (Bazilian et al., 2011) such as Dubreuil et al.'s (2013) optimization framework that incorporates water and energy. Nevertheless, there is an emerging trend to study these systems together for improved resource efficiency and synergies (Fang and Chen, 2017; Kan et al., 2016). Furthermore, past work has not extensively analysed the impacts of climate change and policy interventions on the interacting EWF nexus. A review by Johnson et al. found that current modelling approaches do not consider hydroclimatic change (Johnson et al., 2015). In particular, the effect of climate change on inland water levels is not evaluated with regards to the EWF nexus. The proposed research agenda by Miralles-Wilhelm also suggested that future work should characterize and prioritize alternative sequences of financial investment (Miralles-Wilhelm, 2016).

The devised model can be classified as integration based on co-decision (Veldhuis and Yang, 2017; Hang et al., 2016). In this class of decision-making tools Zhang and Vesselinov (2017) have presented the most integrated model to-date addressing all nodes of the EWF nexus, but with a limited technology selection for the power sector while considering raw source water directly rather than its processing to produce drinking water along with not considering the residential waste water treatment sector. In this model, these limitations were addressed, while the food sector was addressed via a cost coefficient acting as a penalty function - the opportunity cost of food production foregone.

Building on the work by Triantafyllidis et al. (2017) and Wang et al. (2017a), this article addresses some of the aforementioned issues by illustrating the use of an agent-based model (ABM), which simulates human activities and behaviour, accounting for factors such as human activities as well as demographic and socio-economic changes, while resolving details in time and space. It is shown that the developed modelling framework can adapt to more than two resource systems to obtain the inherent demand respectively (three resources are examined in this work: potable water, waste water, and electrical power for demonstration purpose). A model for the power sector is introduced, following the creation of economic cost functions for various power generating technologies which are parametrized by time. Furthermore, the novel concept of the opportunity cost of food production foregone is introduced, creating a direct link between food production and land use. The opportunity cost, the global warming potential and economic cost are incorporated into an optimization problem, on the basis of their equivalent monetary value in contrast to subjective weighting coefficients, as found in the past work by Wang et al. (2017c), thereby addressing all nodes of the EWF nexus. The effect of an integrated analysis with the power sector on the water sector is demonstrated, while it is shown that a high water price or a water resource constraint are needed to highlight the well-known disparity in the water footprint between different power generation technologies in the power generation mixture. This work also involves the creation of multiple scenarios, which explore the effect of carbon credit price variations, feed-in-tariffs and agricultural intensification (thereby illustrating the framework's relevance to policy and investment decision-making), as well as the impact of climate change on inland waters and energy production. Thereby, it is illustrated that objective function is directly affected by environmental policies, with several constraints capturing the effect of government spending and climate change on the nexus' nodes. Overall, a platform is developed that can model the temporal and spatial performance of a city, and the impacts of technology, policy, and planning decisions to improve resource management, inclusive of environmental, social, and economic value.

The rest of the article is structured as follows. Section 2 will first describe the overall methodology, model structure, and formulation of the optimization problem step-by-step. Section 3 demonstrates how the introduced methodology is applied to a Sub-Saharan African city region to achieve cost-optimal and sustainable development plans, especially in the water, sanitation, and energy sectors. Here, “city region” refers to a metropolitan area and surrounding regions which share infrastructure and are thus suitably treated with a network optimization approach. A scenario-based analysis and discussion are presented in Section 4. Conclusions and future work are discussed in Section 5.

2. Methodology

The research methodology is based on a combination of a socio-demographic module, an agent-based model, and a mixed-integer linear optimization model for technology and investment allocation. The overall model structure is first discussed, followed by a detailed explanation of all optimization metrics.

2.1. Model structure

The socio-demographic module models population changes year by year, from the base year 2010 to the modelled year, then breaks down the population by characteristics in master tables. The evolved population characteristics are utilized by the agent-based model to create a representative population of agents - citizens, companies, and other sectors. The aggregate of the agents’ behaviour results in demand profiles for resources which are recorded in time intervals of 5 min over the course of a day, to provide high granularity. The resource-technology network (RTN) utilizes mixed-integer linear optimization to determine the best way to allocate and invest in technologies, while the demand profiles for resources act as a constraint. The objective function is weighted with four metrics; capital expenditure (CAPEX), operating expenditure (OPEX), CO_2 emissions, and the opportunity cost of food production foregone. The number of metrics is open to additions depending on relative importance in an application.

2.2. Socio-demographic and agent-based model formulation

The socio-demographic and agent-based models provide demand profiles as the foundation of further supply-side optimization. It starts with a master table for the baseline year, which categorizes the whole population into over 3700 possible categories following a representative distribution. Each category share a distinct combination of characteristics including district, gender, age group, workforce, income, access to drinking and non-drinking water infrastructure, rationing policy and toilet type. Company agents are also created with four different attributes: district, sector, water use and waste water production. The master table is updated for the desired future years considering rates of birth, death, ageing, and migration. The socio-economic changes in employment are then calculated with a logistics curve fitted by real-world data. Income level changes (between low, medium and high) are calculated and represented with forecasts. Moreover, the company count is adjusted in proportion to the changes in employment, which is used as basis for non-residential resource demand estimation.

With the master tables ready for a specific year, the agent-based model draws a random sample of agents from the population master table of the relevant year, using the proportion of the population in each category as a probability. Each agent is allocated a home district, as well as a work location if applicable (depending on its work force status). The ABM estimates water and electric power use characteristics for each agent type on discrete time intervals (e.g. daily or hourly). It selects suitable regression functions using the data to obtain a time-dependent formula that can describe the trends and value range of water or power demand of each agent. The agents’ activities are then randomized with a mean starting time, standard deviation and probability of starting, which link the water or power demands with spacial locations. Finally, the temporal and spatial specific demand data is scaled up from the simulated sample to the entire population, and output to the RTN.

2.3. Optimization model formulation

The RTN utilizes mixed-integer linear optimization to determine the best way to allocate and invest in technologies for water, waste water and power plants. The objective function, which is given by Eqs. (1) and (2), is weighted with four metrics, which are CAPEX, OPEX, CO_2 emissions, and opportunity cost of food production foregone (OPF). Additional constraints are given by the investment balance, resource balance and production constraints which are illustrated by Eqs. (3), (4), (5) and (6), respectively. It should be noted that an overall area constraint has been approximated via individual and location-specific maximum technology units constraints using a set of heuristics. The corresponding nomenclature is summarized at the end of the paper.

$$Z = \sum_{m,tm} OBJWT_{(m,tm)} \cdot VM_{(m,tm)} \quad \textit{Objective function} \tag{1}$$

$$\begin{aligned} VM_{(m,tm)} = & \sum_{i,j} VIJ_{(j,i,tm,m)} \cdot INV_{(j,i,tm)} \\ & + \sum_{i,j,t} VPJ_{(j,i,tm,m)} \cdot P_{(j,i,t,tm)} \\ & + \sum_{i,i',r,t} VQ_{(r,tm,m)} \cdot dist_{(i,i')} \cdot Q_{(r,i,i',t,tm)} \\ & + \sum_{i,i',r} VY_{(r,tm,m)} \cdot dist_{(i,i')} \cdot Y_{(r,i,i',tm)} \\ & + \sum_{i,r,t} VI_{(r,tm,m)} \cdot IM_{(r,i,t,tm)} \\ & + \sum_{j,r} OPFCC_{(j,i,r,tm,m)} \cdot AT_{(j,r,tm)} \quad \textit{Calculation of metrics} \end{aligned} \tag{2}$$

$$N_{(j,i,tm)} = N_{(j,i,tm-1)} + INV_{(j,i,tm)} \quad \textit{Technology balances} \tag{3}$$

$$\begin{aligned} D_{(r,i,t,m)} = & \sum MU_{(j,r)} \cdot P_{(j,i,t,tm)} \\ & + (1 - lp) \sum Q_{(r,i',i,t,tm)} \\ & - \sum Q_{(r,i,i',t,tm)} \\ & + IM_{(r,i,t,tm)} \quad \forall \ r \quad \textit{Resource balances} \end{aligned} \tag{4}$$

$$P_{(j,i,t,tm)} \geq P_{min\ (j,i,tm)} \cdot N_{(j,i,tm)} \cdot CF_{(j)} \cdot CAP_{(j)} \quad \textit{Minimum production constraints} \tag{5}$$

$$P_{(j,i,t,tm)} \leq N_{(j,i,tm)} \cdot CF_{(j)} \cdot CAP_{(j)} \quad \textit{Maximum production constraints} \tag{6}$$

$$N_{(j,i,tm)} \leq N_{max\ (j,i,tm)} \quad \textit{Maximum technology units constraints} \tag{7}$$

$$Q_{(r,i,i',t,tm)} - \frac{Q_{max}}{(PHI_{(t)}/8700)} \cdot Y_{(r,i,i',tm)} \leq 0 \quad \forall \ r \quad \textit{Flow constraints} \tag{8}$$

2.3.1. Power dissipation and water leakage

The electricity grid was modelled as a set of nodes connected by electricity transmission lines, with a specific transmission loss associated with each line. At each node, there is a certain electricity demand, a certain generation capacity, and a technology-specific potential for (further) installation of power generation technologies. In the first iteration of the platform, which focused on the water sectors, the loss of water from the pipeline networks for waste and drinking water was modelled as a linear equation of the water flow rate. For the electricity grid, it was originally intended to model the power dissipation by the well-known relationship presented in Eq. (9), where I_e is the current, R is the resistivity per unit area and $dist_{(i,i')}$ is the distance between a set of nodes.

$$P_{Loss} = I_e^2 R \times dist_{(i,i')} \tag{9}$$

However, the specific transmission loss associated with each line based on the distance between the nodes was instead modelled as a linear function of the power provided at the source. The power is multiplied with total electricity loss ratios, for which extensive data sources are available (Jimnez et al., 2014). This was due to the significant uncertainty inherent in the resistivity, for which data is not readily available. Moreover, given the linear relationship between the power output at the source and the current, assuming the same voltage at every power generating source, Eq. (9) would induce an non-linearity into the system, converting the problem into an MINLP and giving a lower rate of convergence. The benefits of the nonlinear relationship were deemed not to be significant enough to outweigh the increased computational time.

As a result of the adverse effects of higher leakages, power dissipation, power-line and pipe construction costs on the objective value, the water and energy flows between the different regions are inherently optimized. For illustrating purposes, Fig. 3 illustrates the optimized resource flow network for the baseline scenario with all metrics active.

2.4. Optimization metrics

The CAPEX metric was given a weighting of one, whereas the OPEX metric was given a weighting of 15 to make CAPEX and OPEX comparable, since a period of 15 years was considered. The mean of the carbon credit prices required to avoid 2 °C of global warming to a probability of 50% and 66% was used as an estimate for the initial cost coefficient of the CO_2 emissions (Rogelj et al., 2013).

The direct land use by power generation technologies is included as a metric with an opportunity cost of food production foregone cost coefficient (OPFCC) in the optimization problem. It is assumed that sufficient inputs for crops and livestock are available, and that all crops are rain-fed and no fertilizers are used. Moreover, it was found that Ghana's agricultural sector primarily relies on tractors and fishing boats (both powered by combustion engines) during primary processing while electricity requirements during the harvest are negligible (Diao et al., 2014). It should be noted that final food processing and packaging have not been considered, due to its food-specific energy and water requirements. Thus, food production can operate at normal productivity and is only limited by the amount of area available. If crops can be grown on marginal land, however, as in the case of miscanthus, the OPFCC is dropped for the cultivation of the biomass.

The OPFCC is calculated by Eq. (11). The subscripts j and k refer to power generation technologies and type of area used, respectively. V is the yearly economic value of food produced on area of type k satisfying all demand for food, A_k is the area of type k used per year to produce sufficient food such that all demand is serviced, and f is the fraction of the total area required by technology j which is of type k. Moreover, $A_{k,P}$ is the area of type k actually used for food production, ϵ_k is the monetary yield of food production from area type k, $D_{F,k}$ is the monetary value of the total demand for food produced via type k while $S_{F,k}$ is the monetary value of the actual supply of food by the domestic industry produced from area type k. To formulate an explicit and compact expression of the OPFCC it was assumed that the demand for food is perfectly inelastic. The less area is available for food production the higher the marginal cost of food production due to diminishing returns from additional land and waters producing lower yields. Given the inelastic demand, this increase in production costs is passed on to consumers, resulting in higher food prices. By assuming that the yield and price of food are perfectly inversely related, the monetary yield of food production remains constant and can thus be assumed to be independent of the amount of area already used/cultivated. In addition, it was assumed that food will only be exported once the domestic demand for food has been satisfied. Moreover, it is assumed that the level of food imports is pre-specified by policy makers and constant - these assumptions will become particularly important in Section 4.5.5.

$$\begin{aligned} \textit{For} \quad S_F < D_F, \quad OPFCC_j & = \sum_{j,k} \frac{D_{F,k} - S_{F,k}}{A_k - A_{k,P}} \times f_{j,k} \\ & = \sum_{j,k} \frac{\epsilon_k (A_k - A_{k,P})}{A_k - A_{k,P}} \times f_{j,k} = \sum_{j,k} \frac{V_k}{A_k} \times f_{j,k} \end{aligned} \tag{10}$$

$$OPFCC_j = \begin{cases} \sum_{j,k} \frac{V_k}{A_k} \times f_{j,k}, & \text{if } S_F < D_F \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

Given the metric's identity, it acts as a soft penalty function to approach the implied inequality of total domestic demand for food less food imports being less or equal to the domestic supply of food. This metric quantifies the value of agricultural and fishery products that could have been produced per unit area used for electricity generating purposes. According to Firebaugh (2003), the average value of food consumed in Ghana is $780 per person per year. Thus, the OPF can be expressed as the number of people that could be fed instead of building one plant. Even though not all the land required for the overall process - in particular, land used for mining - is expected to be in the investigated

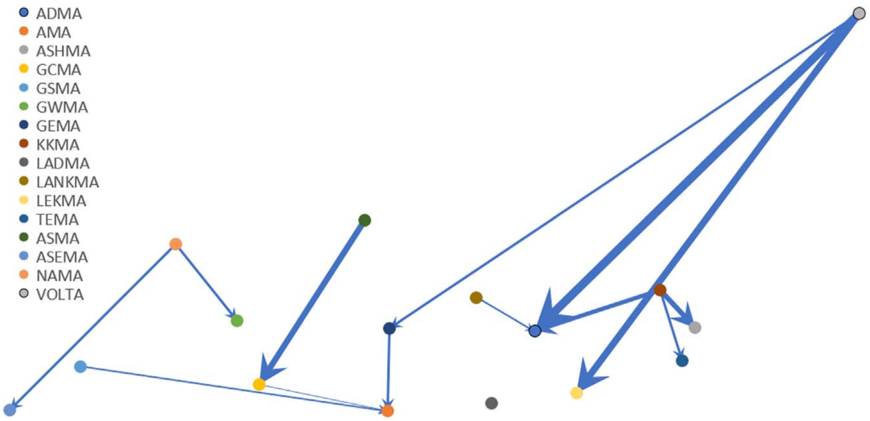


Fig. 3. Energy network structure with distances drawn to scale.

country, it is assumed that the agricultural and fishery efficiency per unit area, and the average value of food produced per unit area per year, are the same across the border. An analysis of the future variation of the OPFCC was found to be complex and beyond the scope of this paper, due to the variety of competing effects as well as the lack of available data.

It is also noted that electricity-generating technologies with a low capacity factor create an additional cost associated with intermittency. However, specific data on the cost per unit of electric power produced is only available for high penetrations of wind and solar power of 20% and above (Heptonstall et al., 2015). Moreover, Gross et al's evidence suggests that up to a 30% penetration level, the additional costs of transmission and networks due to intermittency are in the range of 5–20 per MWh produced by solar and wind power (Gross, . et al., 2017). While transmission reinforcement benefits the whole system, the additional cost for transmission and networks has been incorporated in the variable costs of solar and wind power, following Gross et al's study. The effect of intermittency is only considered on transmission and network costs, while a resulting reduction in thermal plant efficiency was neglected at penetrations below 20% which is in accordance with Gross et al's study (Gross, . et al., 2017). This could be justified by geographical smoothing, demand-side flexibility and installing redundant renewable capacity (Shah et al., 2013).

3. Case study

The model can adapt to different resources, demographics, geographical locations, policies, economies and economic drivers. The Greater Accra Metropolitan Area (GAMA), which is home to the capital city of Ghana and is the most populous region of the country, was chosen as a case study for the platform because of the low maturity of Ghana's energy, sanitation and hygiene sectors, and the consequent pressing need for increased capacity in these sectors. In addition to this, Ghana shows similar characteristics to other developing countries, is experiencing the emerging consequences of climate change, and has shown initiative and the required political stability to carry out planning and investment into its energy, water and sanitation sectors.

3.1. Data collection

Demographic and socio-economic data was obtained from a combination of national statistics from the Ghana Statistical Service and fieldwork. Technology process blocks for various water processing technologies were constructed through literature review, involving data collection on the overnight capital cost, and fixed and variable operating costs per year from scientific papers, industrial and government reports. Projections for the individual economic cost up to 2030 are obtained by applying exponential smoothing followed by auto-regressive techniques to the gathered data. Using derived projections, the capital and operational cost per unit energy produced were calculated for each individual power generating technology and year. Data on direct land use due to power generation was sourced from scientific papers, industrial or government reports. If available, the land requirement of individual processes in the life cycle of a technology was totalled. Otherwise, the best available overall value for the land use was used. Water use for power generation technologies was estimated from a life cycle assessment (LCA) review and harmonization study by Meldrum et al. (2013). The biofuel crops (miscanthus and sugarcane) were assumed to be rain-fed. CO_2 emission factors were obtained from an LCA harmonization study by Heath et al. at the National Renewable Energy Laboratory (NREL) (Heath and Mann, 2012). An estimate of current fossil fuel prices is based on the Global Economic Monitor

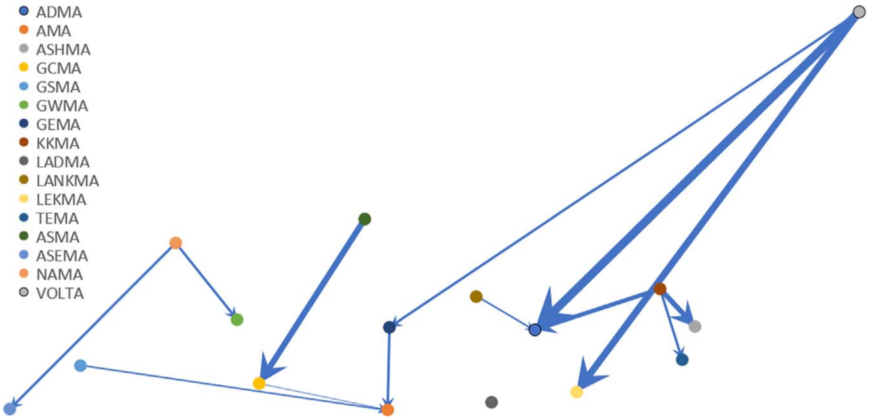
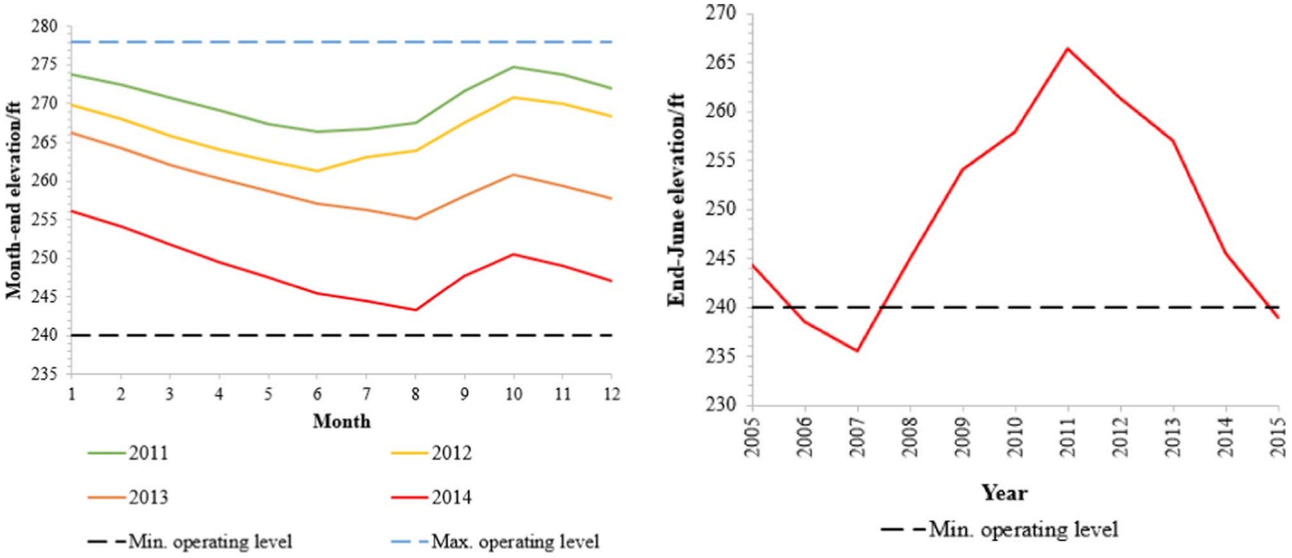


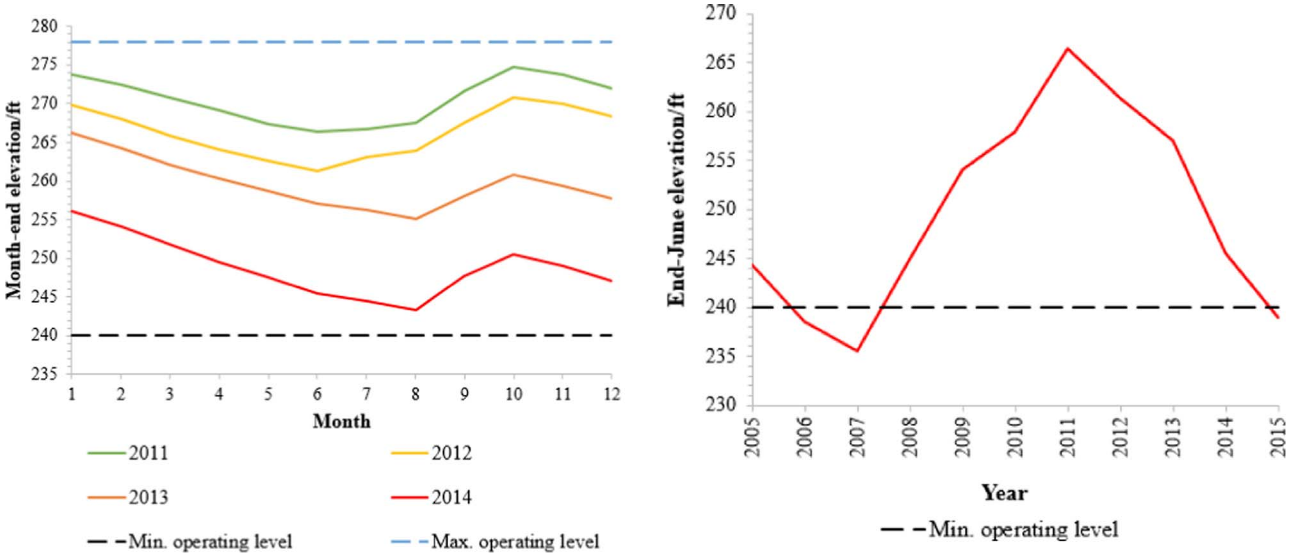
Fig. 3. (*continued*)



(a) Month-end elevation from 2011 to 2014

(b) End-June elevation from 2005 to 2015

Fig. 4. Elevation of the Akosombo dam reservoir (Energy Commission of Ghana, 2016, Martinez, 2015).



(a) Month-end elevation from 2011 to 2014

(b) End-June elevation from 2005 to 2015

Fig. 4. (*continued*)

(GEM) Commodities data bank (World Bank, 2016). The electricity import price from Côte d'Ivoire to Ghana was taken as $0.11/kWh or $0.03/MJ (Asare, 2016).

3.2. Electricity supply

In parallel with the SDGs, ex-UN Secretary-General Ban Ki-moon launched the Sustainable Energy for All initiative, aiming to achieve universal access to modern energy services by 2030. Ghana has a more ambitious goal of providing universal electricity access by 2020 (GME, 2010). Furthermore, the country has passed a Renewable Energy Act in Parliament, setting a target of a 10% of renewable energy in the country's energy mix by 2020 (renewable energy as defined by the Act includes wind, solar, hydro, biomass, biofuel, landfill gas, sewage gas, geothermal energy and ocean energy). The country's installed generation capacity at the end of 2015 was 3655.5 MW, mainly consisting of thermal and hydroelectric power generation. Ghana also imported 250 MW from Côte d'Ivoire in December 2015 (Mieu and McTernan, 2016), which is enabled by the interconnection of the two countries electrical grids as part of the West African Power Pool (WAPP).

However, the Ghana power sector has been beleaguered with challenges, including over-reliance on hydroelectric and natural gas generation, obsolete power supply infrastructure and inadequate investment therein, high transmission and distribution losses, inadequate regulatory capacity and enforcement, as well as operational and management difficulties. These issues have contributed to frequent power outages and load shedding, though the power crises of 1998, 2002 and 2007 were primarily caused by low rainfall in the Volta River basin (Eshun and Amoako-Tuffour, 2016).

Reliable and resilient power supply is essential to an economy's development. According to Fritsch and Poudineh (2016), Ghana currently loses one percent in economic growth per year due to energy

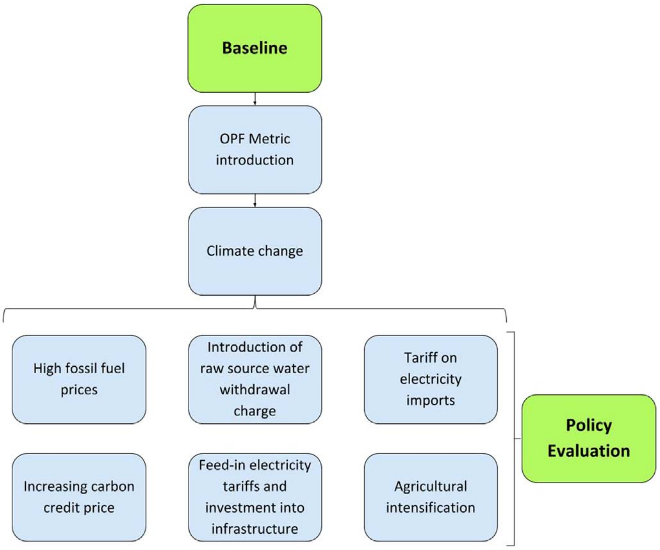


Fig. 5. Schematic of scenarios.

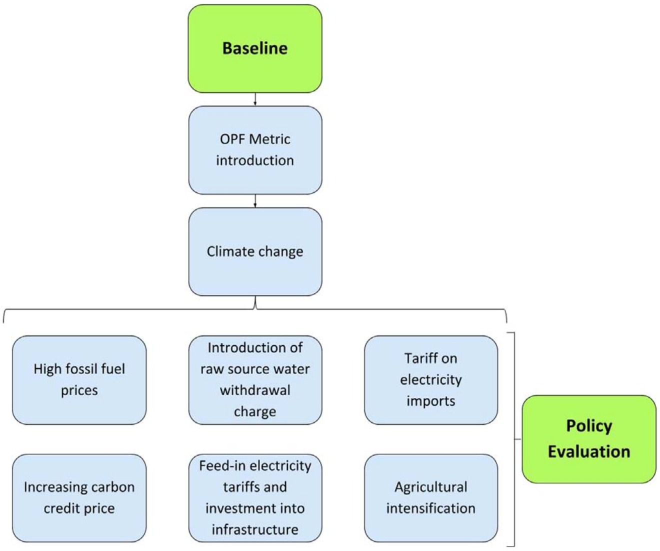


Fig. 5. (*continued*)

insecurity. From a 2014 survey of 1250 medium and small enterprises (MSEs), the Institute of Statistical, Social and Economic Research (ISSER) in Ghana estimated that power crises cause losses of $686.4 million per annum (Institute of Statistical, 2015). Given Ghana's history of importing energy while suffering from blackouts due to insufficient power generation, power exports were not considered . (If the government were to set export targets, however, these could be simulated via additional demand at the border regions.)

3.2.1. *Hydroelectricity*

43.2% of Ghanas power generation mix is supplied by hydropower, 65% of which is from the Akosombo dam. However, water levels in the Akosombo dam reservoir (Lake Volta) are highly variable, making the power system highly reliant on precipitation and thus vulnerable to climate change (Brew-Hammond and Kemausuor, 2007). In June of 2006, 2007 (coinciding with a power crisis) and 2015, the water level dropped below the minimum operable level of 73 m (Agency, 2015). Fig. 4a shows the monthly water level trend from 2011 to 2014, and Fig. 4 shows the water level at end-June, in the middle of the dry season.

The other two major hydroelectric plants are Kpong (downstream of Akosombo) and Bui (in the Northern region of Ghana). There is some opportunity to develop small hydropower sites in the country (Khalil, 2015; Kalitsi, 2003). However, the uncertainty in the future security of hydroelectricity supply reflects a need to diversify the power sector of Ghana.

3.2.2. *Thermal generation*

Natural gas is the most cleanly burning fossil fuel available (U.S. Energy Information Administration (EIA), 2016). Ghana services 56.2% of its electricity demand with thermal power stations, which operate on different mixes of natural gas, light cycle oil (LCO), distillate fuel oil (DFO), and heavy fuel oil (HFO) (Energy Commission of Ghana, 2016). The natural gas power stations servicing GAMA receive their gas from Nigerian imports through the West African Gas Pipeline (WAGP). However, the WAGP has proved to be unreliable and insufficient.

In 2007, the Jubilee oil and gas fields were discovered off the Ghanaian coast, followed by the discovery of Tweneboa, Enyenra, and Ntomme gas and oil fields. However, the associated gas reserves have not yet been utilized, as the government has banned the flaring of gas (Fritsch and Poudineh, 2016). Nevertheless, the utilization of the domestic gas fields would offer a reliable and cheaper alternative to the WAGP and illustrates the great potential for further natural gas power stations in Ghana.

Thermal coal is an abundant and cheap energy source which is widely used in countries such as China, India and the United States. It is the largest global source of electricity (40% of supply in 2015) but is also generally the most carbon-intensive fossil fuel. Coal is not currently used in Ghana for power. The government also recently rejected the permit for a 700 MW coal plant; according to the Minister of Environment, Science, Technology and Innovation, due to the ratification of the Paris Agreement, the government will not permit coal plants in the future (Domfeh, 2016). Carbon capture and storage (CCS) has the potential to dramatically reduce emissions from coal and gas generation, but is still in development.

3.2.3. *Nuclear power*

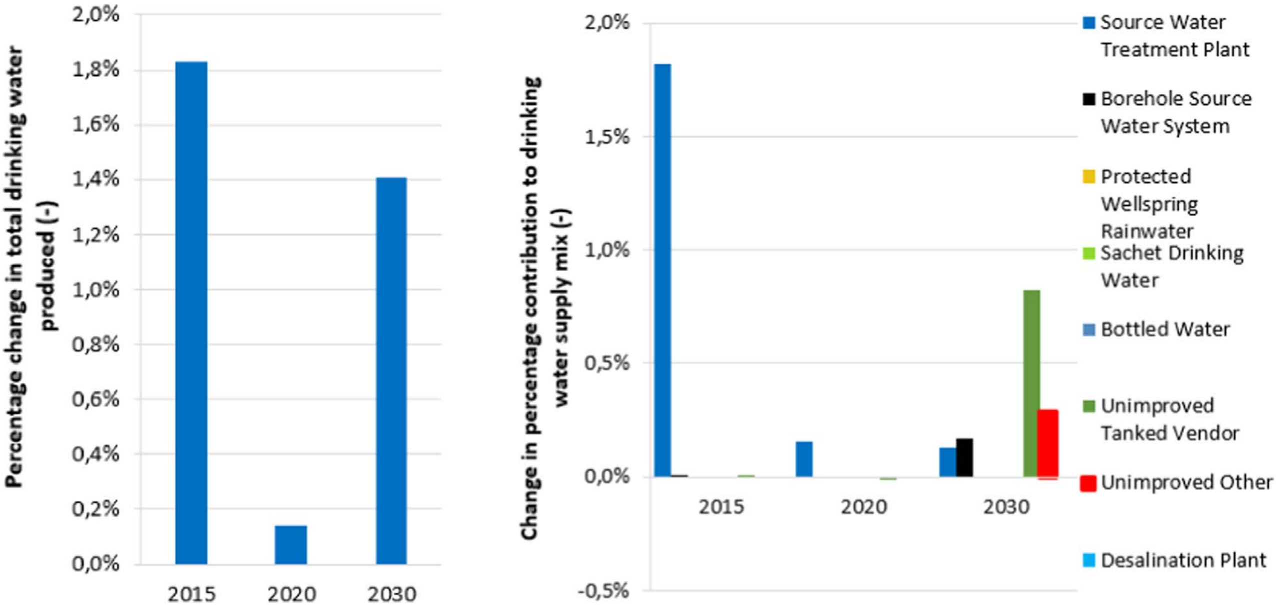
Nuclear power generation can supply large quantities of base load power with low life cycle carbon emissions. However, this comes with a very high investment cost and a requirement for operational expertise due to safety concerns. Furthermore, an important constraint to consider with high capacity generation technologies such as nuclear power is that any power plant unit should not exceed 10% of the total electricity grid capacity in a country, to avoid grid instability or unreliability (International Atomic Energy Agency (IAEA), 2009).

In Ghana, there has been bipartisan support for nuclear power in recent years (Ramana and Agyapong, 2016). In 2012, Rosatom signed the Memorandum of Cooperation in the peaceful use of atomic energy with Ghana, which included provisions for assistance in constructing nuclear power infrastructure (Atominfo.ru, 2012). This was followed by the 2015 Intergovernmental Agreement on the peaceful use of atomic energy (Rosatom, 2016).

3.2.4. *Solar power*

As Sub-Saharan countries like Ghana benefit from high radiation intensities, solar power has significant potential to help achieve Ghana's 2020 renewable energy target. However, as of December 2015, only 0.6% of installed capacity was solar power. In 2011, work began on the 155 MW Nzema project; it is expected to be fully operational by 2017 and will be Africa's largest solar photovoltaic (PV) power plant (Blue Energy, 2015).

Concentrated solar power (CSP) or solar thermal energy offers several advantages over photovoltaic power, such as its ability to provide distributable power using thermal energy storage systems (Mehos et al., 2016). However, CSP plants require direct sunlight, while Ghana



(a) Percentage increase in the production of drinking water

(b) Change in the percentage contribution to the total drinking water production of each technology

Fig. 6. Change in the drinking water production due to the introduction of the power sector.

experiences about 100 cloudy days a year, making photovoltaic power the preferred form of solar energy in Ghana (Vaughan, 2012).

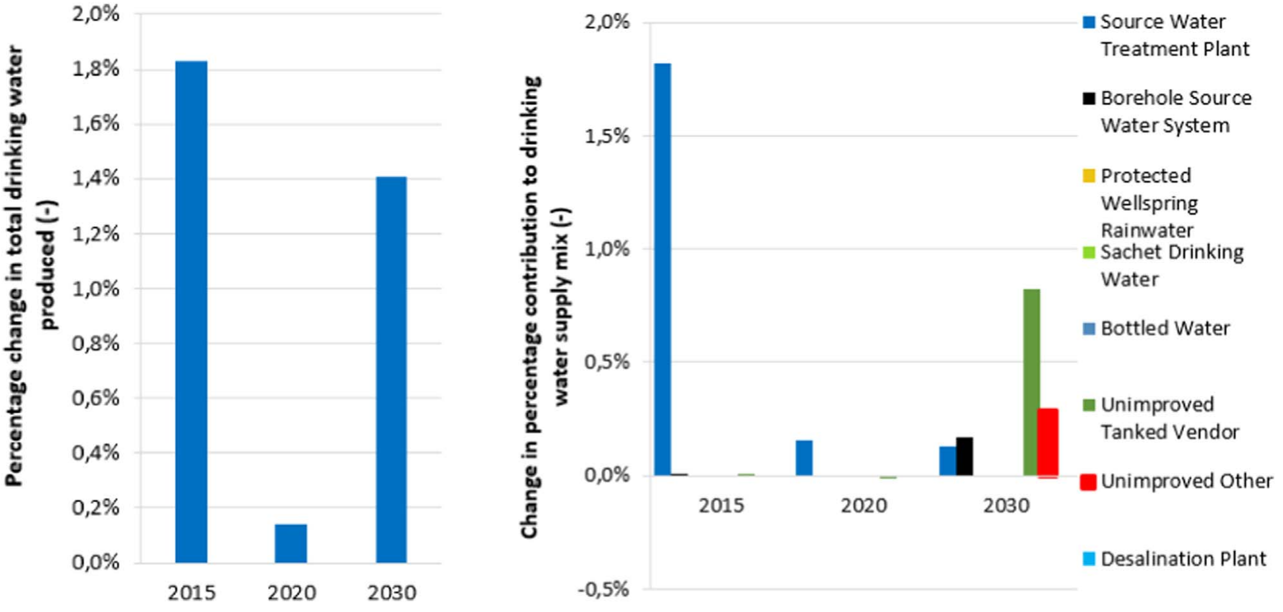
3.2.5. *Wind power*

Onshore wind is one of the cheapest renewable energy technologies currently available, whereas offshore wind is one of the most expensive (AG, 2014, 2016). The biggest impacts of wind farms are their large land requirement and, in the case of offshore wind farms, the disturbance to marine ecosystems (Bergström et al., 2014).

Ghana shows some potential for the deployment for wind farms. The Ayitepa Wind Farm (onshore) was opened in early 2016 on Ghana's east coast, providing 225 MW of its electricity demand (Federal Ministry, 2015).

3.2.6. *Biofuel*

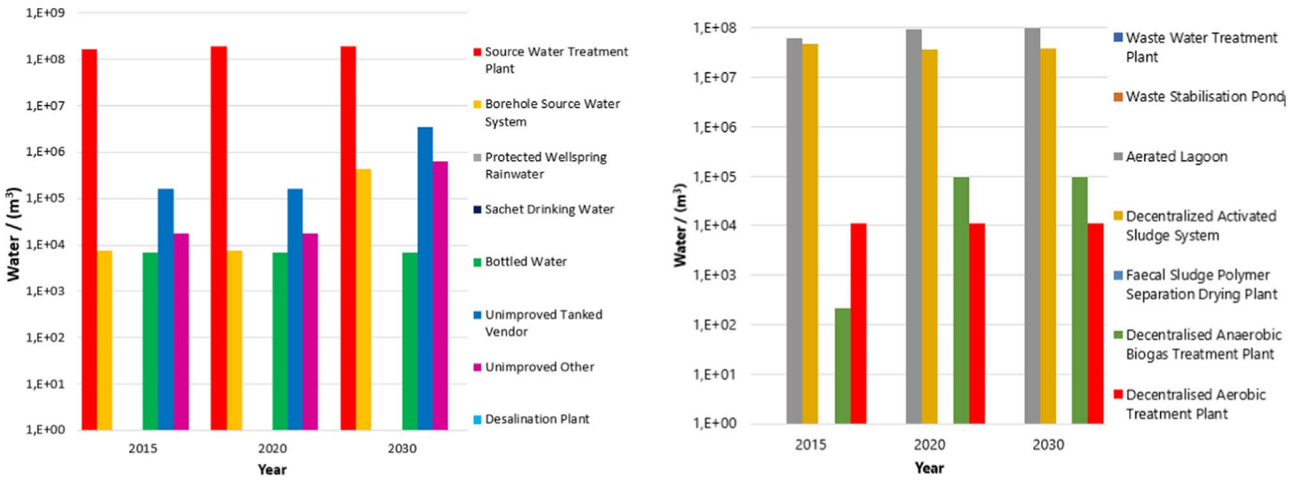
First-generation bioethanol derived from sugars in arable crops, such as sugar cane or cassava, is a mature renewable energy technology, especially in the transport sector. In Brazil, flexible-fuel



(a) Percentage increase in the production of drinking water

(b) Change in the percentage contribution to the total drinking water production of each technology

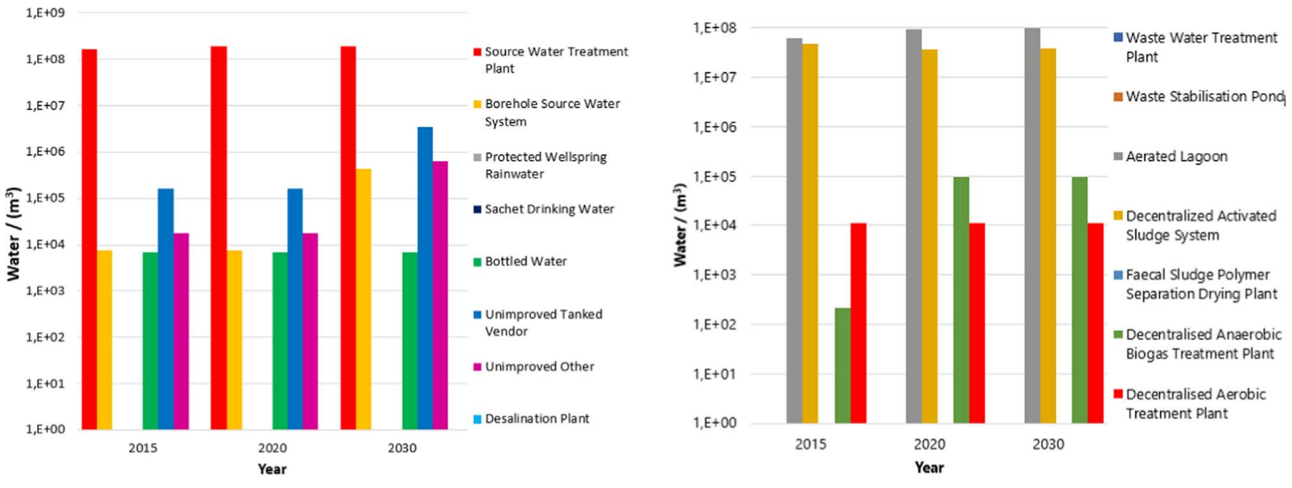
Fig. 6. (*continued*)



(a) Production rates of potable water

(b) Treatment rates of waste water

Fig. 7. Production and treatment rates by drinking water and wastewater technology type.



(a) Production rates of potable water

(b) Treatment rates of waste water

Fig. 7. (*continued*)

vehicles enable consumers to use gasoline, neat sugarcane ethanol, or any blend of these as fuel. The use of ethanol as a fuel for power production was also tested in Brazil in 2010 (Patel, 2010). Ethanol offers several advantages, such as clean burning and low net carbon emissions compared to conventional fossil fuels.

Ghana's location in the biomass-poverty belt, a term which refers to the tropical and subtropical regions of the world where extreme poverty coincides with high bioenergy potential, makes it suitable for piloting a bio-economy (Johnson and Batidzirai, 2012). The FAO's methodology for assessing agricultural resources and potential, Global Agro-Ecological Zones (GAEZ), has found that Ghana has land that is moderately to very suitable for the cultivation of rain-fed energy crops such as sugar cane and cassava (Food and Agriculture Organization, 2016, 2012).

Second-generation biofuels are produced using lignocellulosic biomass, a cheap and abundant non-food material from plants (Naik et al., 2010), predominantly composed of carbohydrates and lignin. Grasses such as Miscanthus can be grown as a source of lignocellulose, with several advantages: they are perennial (only require planting once) and fast growing, have low fertilizer requirements and a high net energy yield of about 540%, and can grow on marginal land (Schmidt et al., 2015). Their disadvantages include requiring extensive processing to be converted to ethanol, taking several years to reach harvest density, and requiring moist soil (Biofuel, 2016).

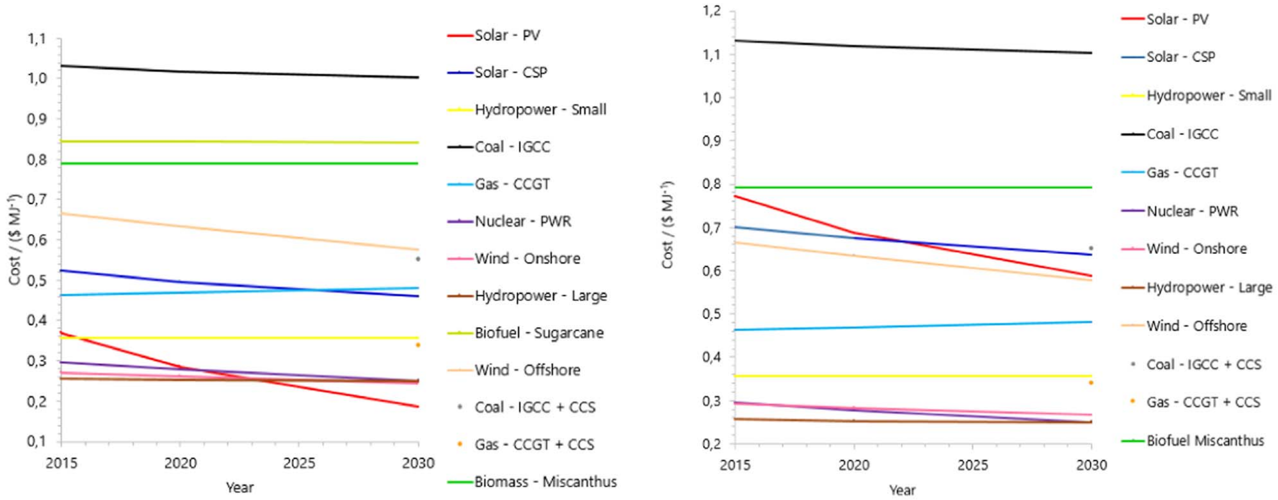
Biomass can also be directly combusted to generate power. In future, coal plants could be retrofitted to enable direct biomass combustion, perhaps in combination with CCS as a negative emissions technology (Cuellar, 2012).

4. Scenarios and policy evaluation

4.1. Scenario outline

The applied method for the detailed case study is scenario-based optimization. Different scenarios that incorporate factors such as variability in utility demand, technology capacity, area availability, policy-induced economic drivers, and loosening and tightening of allocation constraints, can be implemented in the mixed-integer linear optimization problem.

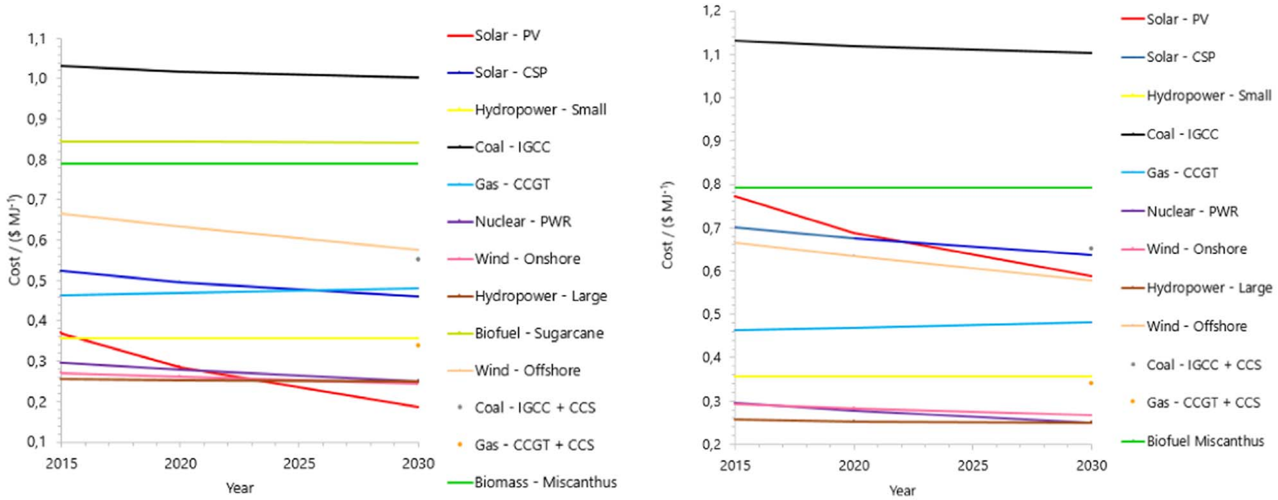
A set of scenarios consisting of possible system developments in the context of GAMA was created to illustrate the application of the model. The scenarios first incorporate scaling for technological development, followed by the effects of climate change and related policies. All



(a) Economic cost and GHG emissions (low fossil fuel prices)

(b) Economic cost, opportunity cost of food production foregone and cost of carbon emissions (low fossil fuel prices)

Fig. 8. Combined cost of generation technologies (Sugarcane biofuel technology was excluded from plot (b), due to its significantly larger cost compared to all other technologies).



(a) Economic cost and GHG emissions (low fossil fuel prices)

(b) Economic cost, opportunity cost of food production foregone and cost of carbon emissions (low fossil fuel prices)

Fig. 8. (*continued*)

changes are made sequentially so that their effects can be clearly discerned. The detailed progression is illustrated in Fig. 5.

In this section, we will demonstrate and evaluate how the methodology and the model can be utilized to plan power generation, urban water and sanitation infrastructure, as well as aid policy-making and evaluation. An evaluation of the OPF optimization metric is carried out, a brief overview of the scenarios' outcomes for 2030 is given and two scenarios illustrating the effect of climate change and agricultural intensification are discussed. It is noted that the major time periods*tm* in the RTN are the modelled years (2015, 2020 and 2030) and can be interpreted as the year in which any facility recommended by the optimization should start operating. For the purposes of this case study, there are no distinct minor time periods *t*, which can be entered as fractions of a single day in the model.

4.2. Potable and residential/industrial waste water

The nexus interaction between the water sectors (potable water and wastewater) and the power sector is the electricity requirement of converting raw source water to potable water, and processing wastewater. The additional cost of electricity has a particular impact on the drinking water sector. Fig. 6a illustrates that the introduction of the power sector into the model increases the overall level of drinking water production. This is the result of a different spatial allocation of the technologies, which in turn results in an higher amount of water being lost from the system via leaks. Moreover, Fig. 6b highlights that there is little restructuring of the drinking water technology mixture following the introduction of the power sector, as there are no significant reductions in the production of drinking water by any

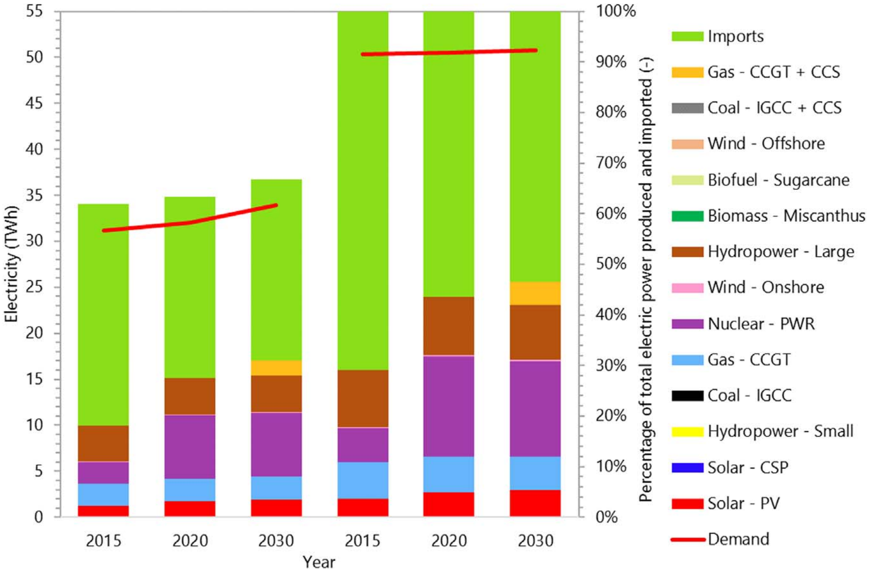


Fig. 9. Baseline power generation mix, considering economic cost & CO_2 emissions (absolute & relative values).

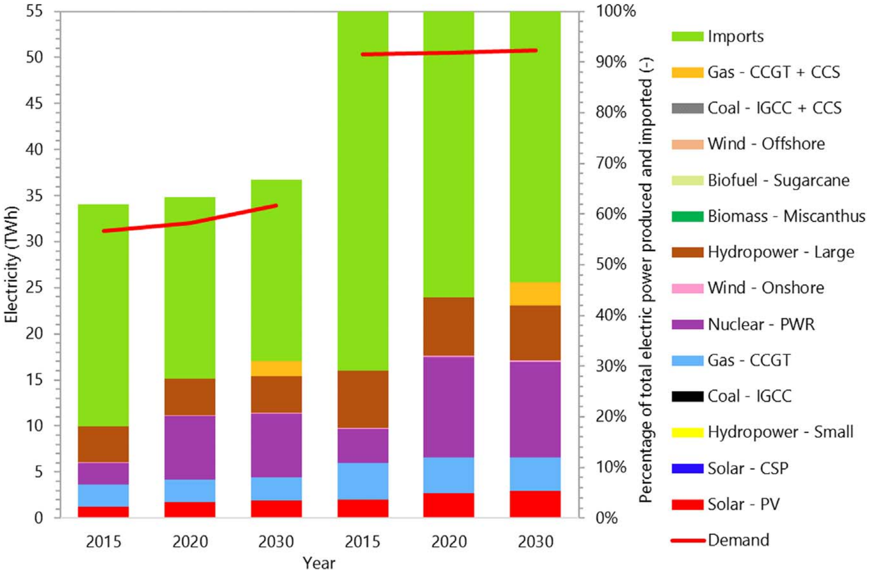
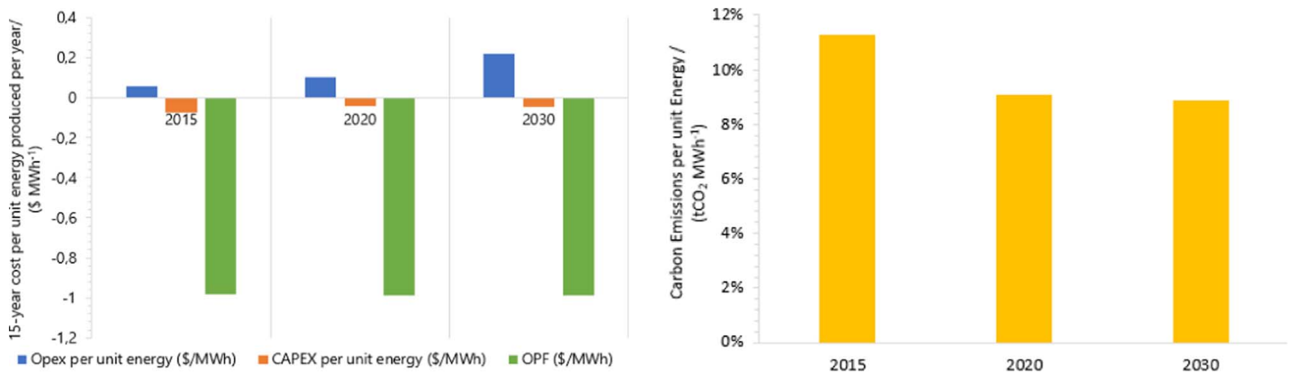


Fig. 9. (*continued*)

Table 1

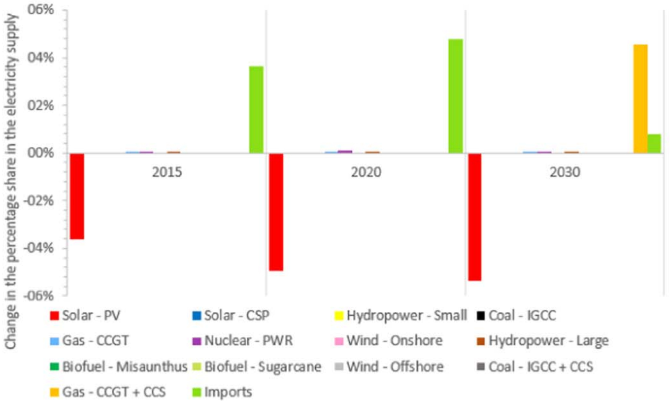
Characteristics of power generation technology (cost associated with 2030).

Technology	Subtype	Number of people fed (per plant per year)	Capacity (MW)	CAPEX (USD per MJ)	OPEX (USD per MJ)	GHG (kg CO_2 eq per MJ)
Photovoltaic	P-Si, ground	4334	20	0.169	0.0000844	0.0337
CSP	Trough	9865	50	0.266	0.0121	0.0273
Hydropower	Small	1	2	0.299	0.00359	0.00657
Hydropower	Large	1561	1180	0.216	0.00199	0.00676
Coal	IGCC	101,104	500	0.164	0.00647	1.65
Gas	CCGT	4	250	0.0768	0.00854	0.612
Coal	IGCC + CCS	101,104	500	0.279	0.00828	0.330
Gas	CCGT + CCS	4	250	0.119	0.0110	0.122
Nuclear	PWR	62	300	0.153	0.00570	0.0256
Wind	Onshore	63	3	0.167	0.00494	0.00970
Wind	Offshore	3	3.6	0.366	0.0140	0.00297
Biomass	Miscanthus	4747	500	0.324	0.0307	0.0105
Biofuel	Sugarcane	191,434	87	0.121	0.0473	0.0213



(a) Change in costs per unit energy

(b) Change in carbon emissions per unit energy



(c) Change in the optimal power technology mix

Fig. 10. Impacts by the introduction of the OPF metric.

technology. This is because the difference in the cost of electricity between the different technologies is insufficient to result in a different optimal solution becoming available.

The feedback from the power sector to the water sector is the additional wastewater resulting from the power sector. During the operation of the considered power plants, water is primarily used as a cooling fluid. The effluent water stream composition is often not significantly altered and is returned to the atmosphere via cooling towers or fed back to local water sources such as rivers and the sea. Therefore, the main source of wastewater originating from the power generating sector occurs during the construction of the individual plants and its components. This resulting industrial wastewater was considered to have different processing requirements than residential wastewater and was not considered in this analysis.

The turnover of water by thermal power plants is high; the majority of the water is fed back to local water reservoirs, while a significant amount of water is lost in the short-term to the atmosphere. Nevertheless, a change in the monetary cost of the net consumption of water by the different technologies is insufficient to result in a different allocation of power plants, at current prices of water. The small impact of the water sector on the power generating sector presents a different result from the well-known disparity in water footprint between different power generation technologies. However, it is illustrated in Section 4.5.2 that higher charges for raw source water change the monetary cost of the net consumption of water significantly enough to highlight the disparity in water footprint between different power generation technologies. In addition, the introduction of a constraint limiting the total water withdrawal significantly, which could be used to simulate extreme water shortage, would result in a power generation technology mix which reflects the disparity in water footprints.

Therefore, changes in the power generation mixture were found to show insignificant effects on the wastewater treatment sector, resulting in a wastewater treatment demand being primarily dictated by the residential sector and the evolution of its population. This agrees with the findings by Wang and Chen (2016) revealing that the effect of the nexus on water networks is smaller than energy networks. The resulting investment profiles for the potable water (Fig. 7a) and wastewater sectors (Fig. 7b) are therefore similar to previous work by Wang et al., and show negligible changes from scenario to scenario (Wang et al., 2017a).

4.3. Electric power generation

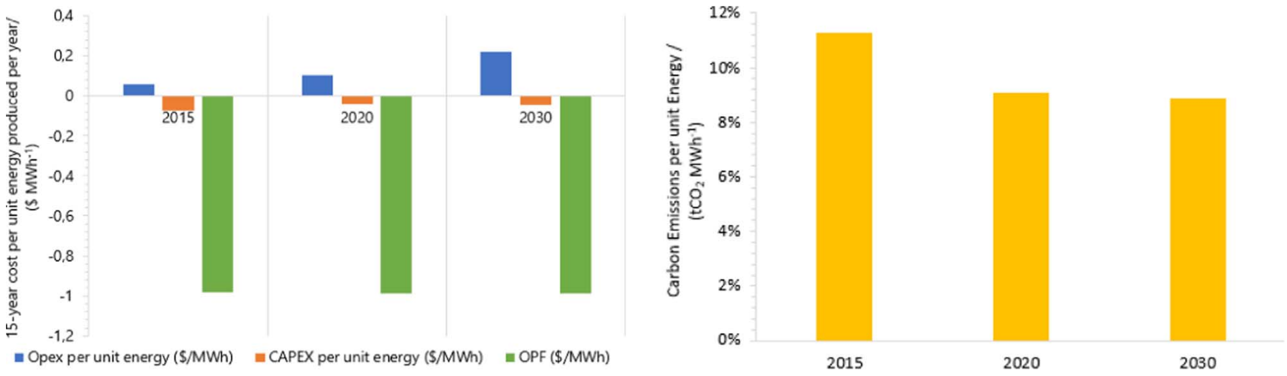
4.3.1. Baseline

The baseline scenario considers only the metrics introduced by Wang et al. (2017a), i.e. the economic costs and CO_2 emissions, with carbon credit prices acting as the cost coefficient for the CO_2 emissions in this investigation. It should be noted that a carbon credit price of 30$/tCO$_2$ is used as theemissions cost coefficient unless otherwise stated.

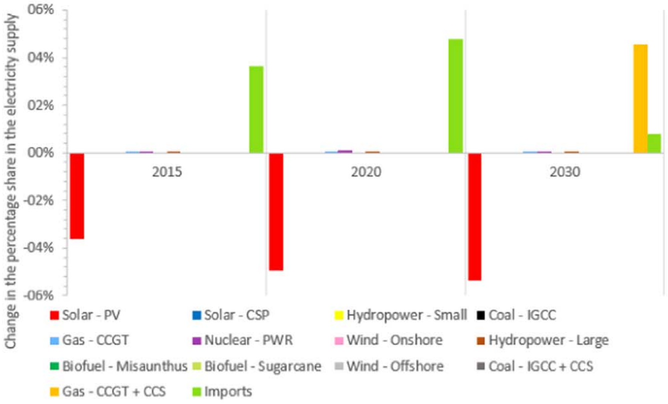
The respective aggregated cost profile of the individual technologies are shown in Fig. 8a. It should be noted that CCS supported technologies are only represented as dots as they are expected to be unavailable before 2030. The cost profiles in turn resulted in the recommended technology profile illustrated by Fig. 9.

4.3.2. Optimization metric - evaluation

Following the introduced baseline scenario which incentivizes the use of low-cost and low-emission technologies, the OPF can be included as a system performance metric to incentivize the use of technologies with small area requirements, and thus ensure the ability to cope with



(a) Change in costs per unit energy (b) Change in carbon emissions per unit energy



(c) Change in the optimal power technology mix

Fig. 10. (*continued*)

future increases in food demand. The implementation of this metric in the optimization problem results in a shift in the power generating technologies' relative costs, as can be inferred from a comparison between Figs. 8a and b.

The comparison reveals that when this metric is introduced, technologies with large area requirements, such as solar power and biomass based technologies, suffer significantly relative to other technologies, while technologies mostly located in inland or marine waters do not. This is due to the relatively lower food production rate per unit area by the fishery industry compared to the agricultural industry. For instance, PV is less cost efficient than offshore wind farms and CSP plants up to 2032 and 2022, respectively, when OPF is considered, but outperformed both technologies in the baseline scenario. The technologies which benefit the most in relative terms are nuclear, hydropower, wind farms and natural gas, due to their low area requirement per unit power produced. Table 1 illustrates the technologies' characteristics.

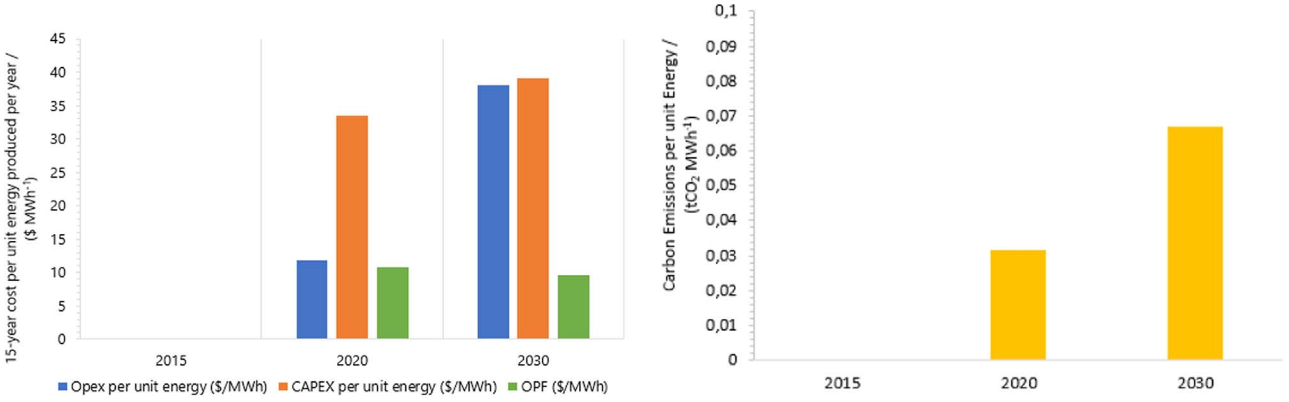
The changes in the RTN-suggested investment profile due to the introduction of the OPF metric are illustrated in Fig. 10c, illustrating a shift away from solar PV in favour of imports and natural gas with CCS in 2030. The resulting increase in cost for all technologies leads to imported electricity becoming even more competitive. This is because a land use was not assigned to imports, as there was no opportunity cost of domestic food production associated with the land use in countries other than Ghana. The changes to the cost profile may be inferred from Fig. 10a, showing a significant decrease in the OPF per unit energy by 0.95–0.99 $/MWh at the cost of higher OPEX and carbon emissions per unit energy by at most 0.22 and 0.11 $/MWh. The significant decrease in OPF per unit energy is evidence that the introduced metric is effective in reducing the land requirement by the power generation infrastructure and securing future food production.

4.4. Climate change

The impacts of climate change and the urgent need for mitigation and adaptation call for actions in every aspect of governmental decision-making. As previously discussed, it was projected that the capacity of hydropower in Ghana will continue to decrease in future years, as climate change progresses. To incorporate this into the model, the capacity factors of hydropower post-2015 were decreased from 0.386 to 0.3 in 2020 and 0.1 in 2030. Furthermore, climate change will adversely influence crop yields, so the land requirements of biofuel technologies were increased accordingly.

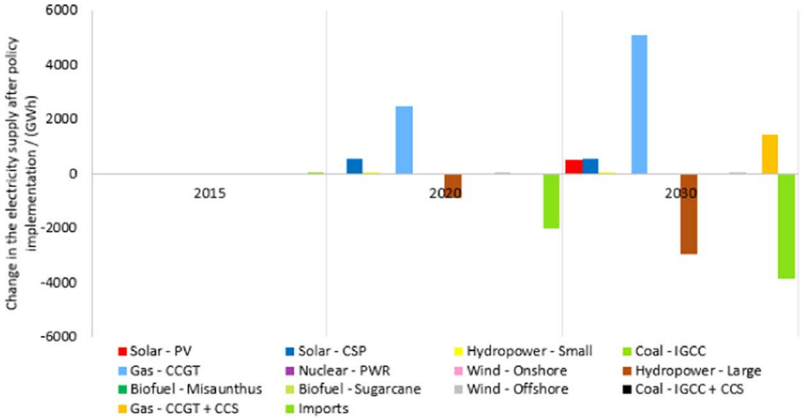
As Fig. 11a and b illustrate, the reduction in the capacity factor of large hydropower stations results in an increase of all costs and carbon emissions, as the demand previously serviced by large hydropower is now supplied by higher-emissions technologies, which are also more expensive with respect to CAPEX, OPEX and OPF. Fig. 11c shows that the reduction in the capacity factor of large-scale hydropower results primarily in an increased use of offshore wind farms, CSP, and imports, in both 2020 and 2030. The increase in imports highlights the dependence of Ghana's domestic electricity production on the Akosombo and Kpong dams, and the need for further diversification. The increase in the land requirement of biofuel technologies has further worsened their economics, making them even more unfavorable according to the model. However, since the biofuel technologies were not previously selected, the generation mix is unchanged by this increase.

This scenario demonstrates that the RTN can be used to model the effects of climate change on the energy sector. Other climate change-related impacts could be modelled by varying technologies' requirements for resources such as raw source water, capacity factors, or the maximum number of plants allowed for a technology.



(a) Change in costs per unit energy

(b) Change in carbon emissions per unit energy



(c) Change in capacity of each power generating technology

Fig. 11. Effects due to climate change.

4.5. *Policy evaluation*

A selection of potential policy interventions is discussed here. The effects on the power generation technology mixture by a specific tariff on electricity imports, a charge for raw source water and increased carbon credit prices are individually investigated, and a qualitative assessment of investment into renewable energy-supporting infrastructure is presented.

4.5.1. *Tariff*

Ghana currently relies partially on importing electricity from other countries. To improve the country's autonomy the government may want to introduce a tariff on energy importing. The implementation of a tariff scheme resulted in an increase in all economic costs and a significant increase in the OPF and carbon emissions per unit energy domestically produced by \$28/MWh (see Fig. 12a) and 0.22tCO_2/MWh (see Fig. 12b). It is found that the implementation of a tariff is expected to reduce imports by 4.9 TWh per year, which is compensated for by an increase in the power production from natural gas by 5.1 TWh per year as shown in Fig. 12c. Moreover, small increases in the power production from solar power are seen.

4.5.2. *Charge for raw source water*

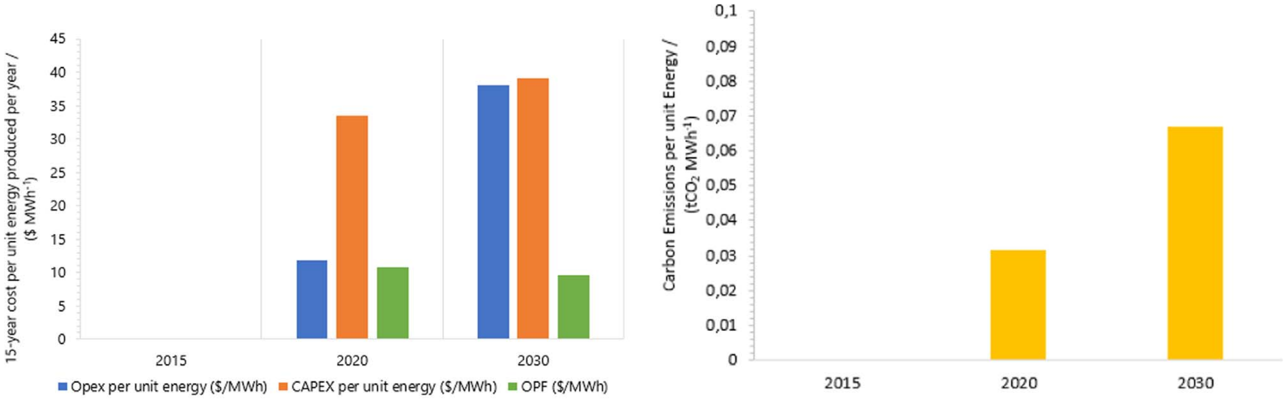
Climate change effects may lead to a fall in inland water levels, and subsequent water scarcity. In such a scenario, the government could discourage the use of raw source water by the imposition of a charge on raw source water. The model recommends the switch of 0.5 TWh (Fig. 12c) of electricity produced by CSP towards imports and natural gas with CCS. Due to the relatively small amount of reallocated electricity production, only small changes in the costs are seen.

4.5.3. *Increase of carbon credit price*

Market-based solutions such as carbon credits can reduce the carbon emissions of the domestic power sector. In this scenario, an introduction of a carbon credit price of \$0.05/$kgCO_2$ and \$0.14/$kgCO_2$ in 2020 and 2030, respectively, is considered. The model recommends the substitution of natural gas power stations with solar PV and CSP plants, along with the introduction of power plants using the direct combustion of Miscanthus.

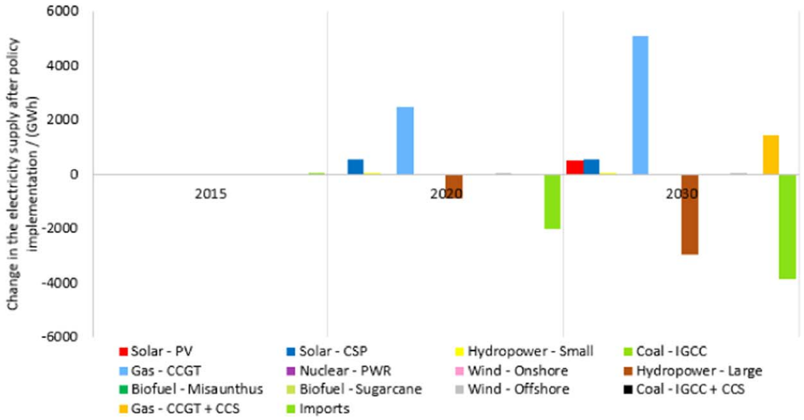
The significant shift in technologies achieved by the high carbon credit price in 2030 results in a decrease in carbon emissions by 0.20 tCO_2/MWh (Fig. 12b). This is only achieved at a very high increase in capital cost and OPF of \$184/MWh (Fig. 12a) and \$98/MWh, respectively, illustrating that although the introduction of high carbon prices results in a large reduction in the amount of carbon emissions, it makes entering the market for domestic energy production in Ghana unattractive, unless the high capital costs are passed on to consumers via a higher electricity price. In addition, the large increase in OPF indicates a decrease in domestic food security.

It was also found that the magnitude of the decrease in the electricity supplied by natural gas is limited by the capacity of natural gas already allocated in previous years. This phenomenon of locking in of natural gas infrastructure emphasizes the need for sustainable, long-term planning, which includes more investment in Ghana's



(a) Change in costs per unit energy

(b) Change in carbon emissions per unit energy



(c) Change in capacity of each power generating technology

Fig. 11. (*continued*)

infrastructure and making more locations available for additional solar, wind and biofuel capacity. The change in the RTN-suggested investment profile demonstrates the model's ability to indicate shifts in the power generation mix towards low-emission technologies due to carbon prices, within the limits of feasible additional capacity.

4.5.4. *Renewable penetration supported by feed-in-tariffs and infrastructure investment*

The introduction of a feed-in tariff (FIT) encourages the installation of renewable power generation sites by the private and the commercial sector. In particular, the increased production of electric power from renewable sources via small privately-owned units increases the maximum potential capacity of specific power generation technologies. The government can selectively favour a technology via a higher feed-in tariff. The most feasible technologies would be solar PV and small hydropower, as well as offshore wind farms, with regard to the commercial power generating sector.

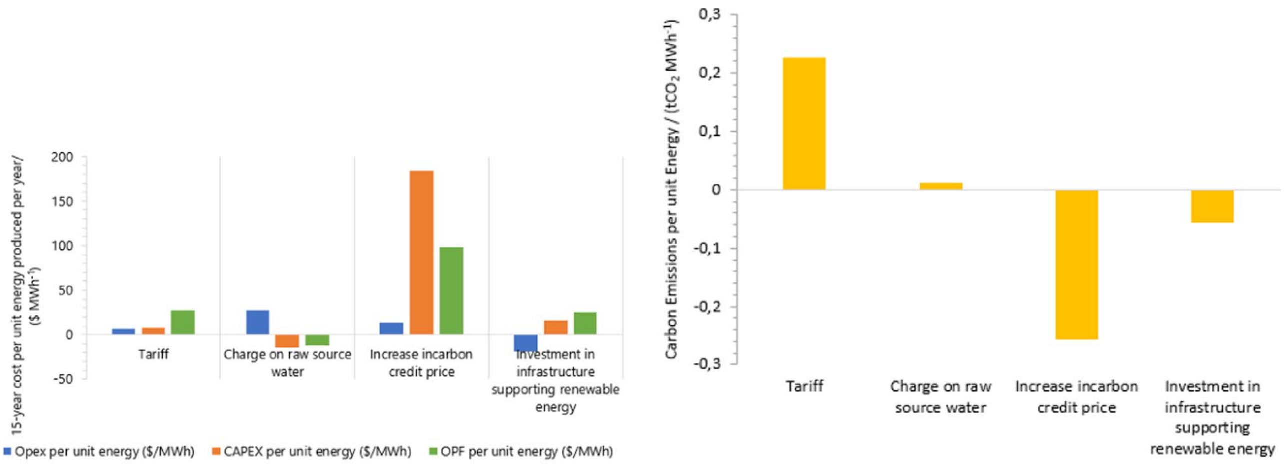
By extending and improving Ghana's electrical grid in various regions - particularly in northern Ghana, which benefits from high solar irradiation - new locations for solar power plants could become available. To simulate this, the maximum allowed number of PV solar power plants was increased by a factor of 1.5. Furthermore, recent improvement of the fiscal and regulatory framework for hydropower and for private sector investments in renewable energy in Ghana have made further development of small hydropower stations more attractive (Khalil, 2015). The maximum number of small hydropower units was therefore increased from 1 to 60 units with 2 MW of capacity each, which gives a total capacity that is double that of a planned hydro site on the Pra River (Agency, 2014).

As a result of these adjustments, the model suggests an increase in the capacity of PV by 1.0 TWh per year in 2030 (Fig. 12c). The model suggests investing in the maximum possible capacity of small hydropower. This shows that, by varying such a set of constraints, improvements in the domestic infrastructure can be accounted for, leading to a contribution of 15.8% from renewable technologies to the generation mix by 2030.

In consequence, the resulting operating cost and carbon emissions per unit energy are \$19.0/MWh (Fig. 12a) and 0.06 tCO_2/MWh (Fig. 12b) lower in 2030 compared to pre-infrastructure investment levels, while the capital cost and OPF per unit energy increase by \$16/MWh and \$25.0/MWh, respectively. (Fig. 12a). This scenario illustrates the great importance of investment into infrastructure as a measure to reduce carbon emissions, with the side effects including an acceptable increase in OPF, and balanced increases and decreases in economic cost.

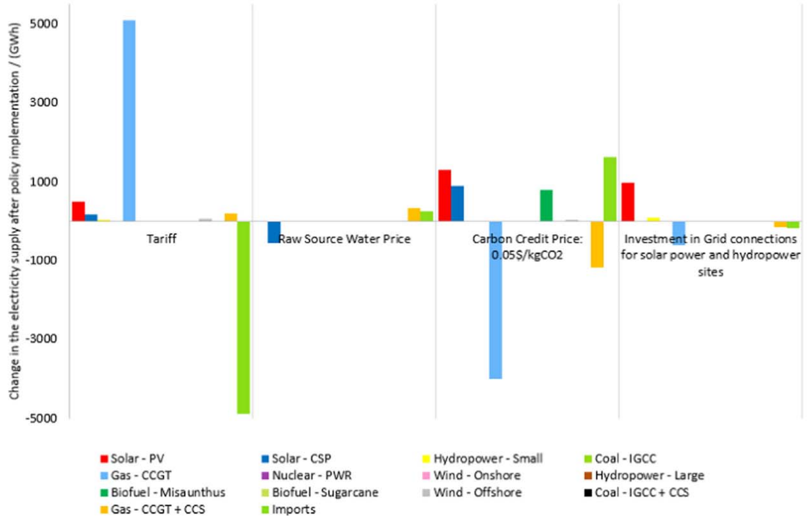
4.5.5. *Agricultural intensification*

The agricultural sector in sub-Saharan Africa suffers from a significant yield gap overall. For instance, Ghana's maize yield is 150% lower than South Africa's (Adjei-Nsiah et al., 2016). Due to this yield gap, the agricultural sector requires more land to achieve the same rate of food production. An increase in the agricultural efficiency will reduce the area required per unit of food, while the cost of food production will decrease as a result of the higher agricultural efficiency.



(a) Change in costs per unit energy

(b) Change in carbon emissions per unit energy



(c) Change in capacity of each power generating technology

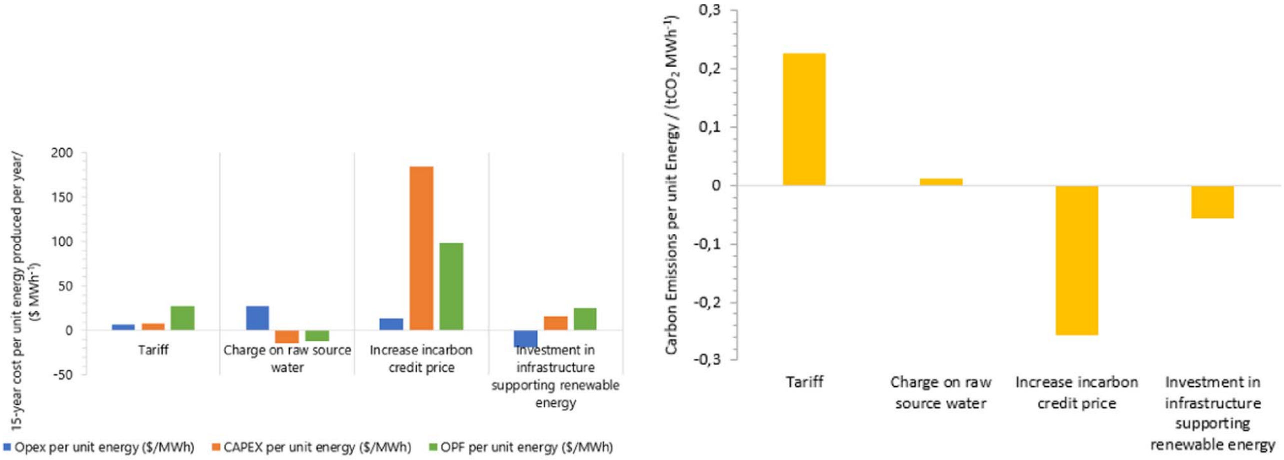
Fig. 12. Aggregated effects of policy interventions in 2030.

Assuming the absence of food imports and exports along with perfectly inelastic domestic demand for food, and given the fragmented nature of Ghana's agricultural industry, which results in a low price setting ability and low profit margins, any improvement in efficiency and fall in production costs will be passed on to consumers. This results in an increase the food supply at every price level, shifting the food supply curve down, and hence reducing the equilibrium price of food. The OPF per unit area will increase by a relatively small factor in comparison to the factor of decrease in the area required to service the total demand, which is inversely proportional to the increase in the agricultural yield. Hence, the aggregated OPF of land based technologies shows a net decrease. This represents a rather non-intuitive result. As only half of the original area is now cultivated, it can thus be assumed that the other half of the original area becomes available with a zero opportunity cost of food production, following the definition of the OPFCC. Hence, the aggregate OPFCC of all land-based technologies in Ghana would decrease, resulting in a corresponding reduction in the costs of all technologies.

A comparison between Fig. 13a and b reveals that because of agricultural intensification:

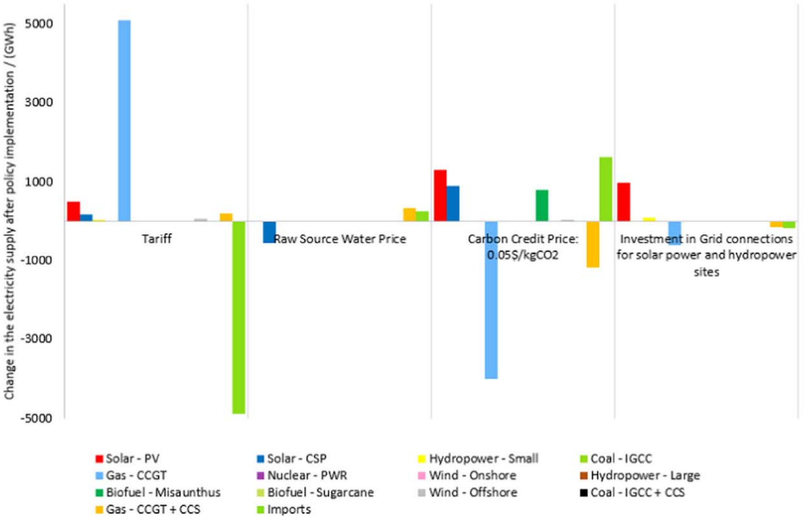
- The cost of PV decreases significantly in relative terms, making it immediately more cost efficient than CSP, natural gas with CCS and offshore wind farms, and more cost efficient than natural gas by 2017.
- CSP is more competitive than offshore wind farms between 2015 and 2027.
- Even though sugarcane biofuel experiences the largest reduction in cost, it remains uncompetitive compared to all other technologies, excluding coal power plants which are even less cost efficient by 2021 than sugarcane based biofuel.

Following the cost reduction in PV and CSP, an increase in the recommended use of solar power technologies can be observed (see Fig. 14c). However, since the cost reduction in PV was much greater than in CSP, PV is used in 2020, unlike in the previous scenario where CSP was selected in 2020. By 2030, PV reaches its maximum allowed capacity, so CSP is introduced, supplying 5.8% of total production. In 2030, the 0.18 TWh and 1.08 TWh increases in PV and CSP capacity, respectively, are accompanied by a 0.53 TWh decrease in the amount of electricity imported and supplied by natural gas with CCS. Since the cap



(a) Change in costs per unit energy

(b) Change in carbon emissions per unit energy



(c) Change in capacity of each power generating technology

Fig. 12. (*continued*)

for Miscanthus power plants is reached, no more were introduced. This illustrates the benefits that the reduction of the crop yield gap has, not only on Ghana's food security, but also on certain power generation technologies such as PV and CSP. The net result is a generation mix consisting of a higher proportion of low emission technologies.

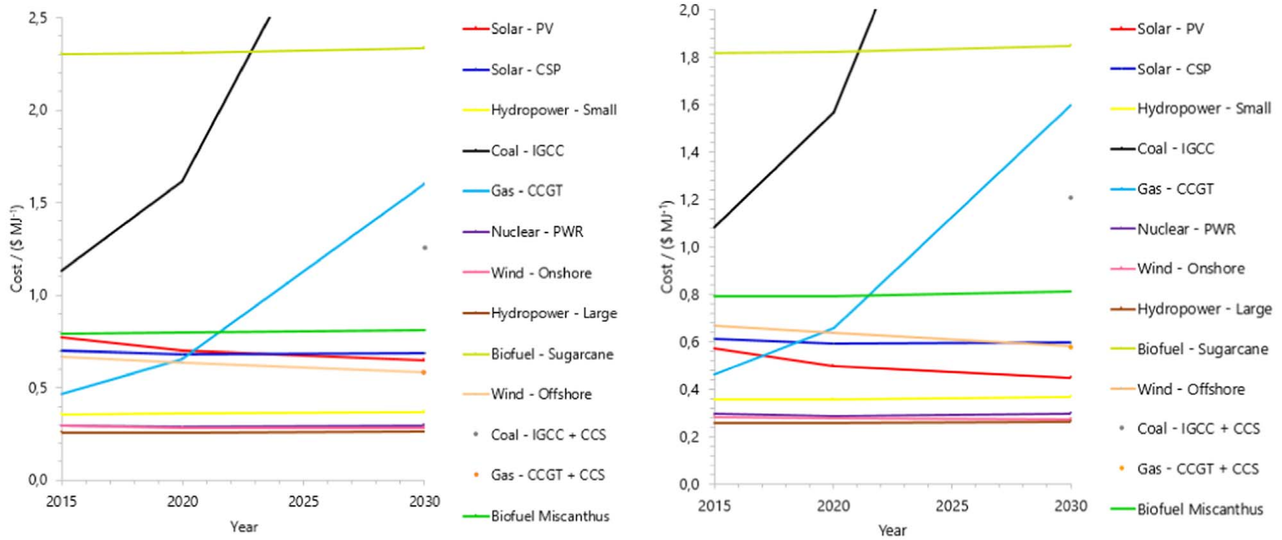
The agricultural intensification results in a lower OPF for all land based technologies. Therefore, a marginal change in the OPF is observed in 2020 while a large decrease of \$57/MWh is seen in 2030 (Fig. 14a). This illustrates the importance of investment into Ghana's agricultural efficiency improving its food security in the long run.

Due to the partial replacement of offshore wind farms and CSP with PV, which has a lower capital cost, the overall capital cost decreases in 2020 by \$14/MWh compared to the previous scenario. Similarly, the operating cost decreases in 2020 by \$23/MWh. Following the increase in the number of solar photovoltaic and significant increase in CSP power plants compared to the previous scenario, an increase in capital cost and operating cost by \$21/MWh and \$2.0/MWh, respectively, is seen in 2030, as imports and CCS supported natural gas are replaced. Nevertheless, the increase in solar plants leads to a further decrease in carbon emissions by 0.03 tCO_2/MWh in 2030 (Fig. 14b). In addition, the resulting increased agricultural efficiency is likely to be converted to a higher net income per capita, decreasing the price elasticity of electricity demand. This in turn allows for a higher electricity price to be charged, compounding the increased competitiveness of more expensive renewable energy sources. From this scenario, it is apparent that an investment into Ghana's agricultural efficiency improving the agricultural yield is highly important to secure Ghana's food production in the short-run, increase net income per capita, and also decrease carbon emissions in both the short and long run at only small variations in capital and operational costs.

4.5.6. *Feasibility and cross border comparative analysis of GHG emissions*

Fig. 15 summarises the average cost factors and carbon dioxide emission factors for all considered scenarios. The carbon dioxide emission factor increased as a tariff was introduced on importing power. The effects of climate change caused a decrease in the capacity of the large-scale Akosombo hydropower plant, resulting in higher CO_2 emissions. The reduction in CSP capacity resulting from the introduction of a charge for raw source water increased emissions to 1.08 tCO_2/MWh. On the other hand, the higher fossil fuel prices, the increase in carbon credit prices, the investments into the agricultural sector and infrastructure all contributed to the decrease of the average emission factor down to 0.72 tCO_2/MWh.

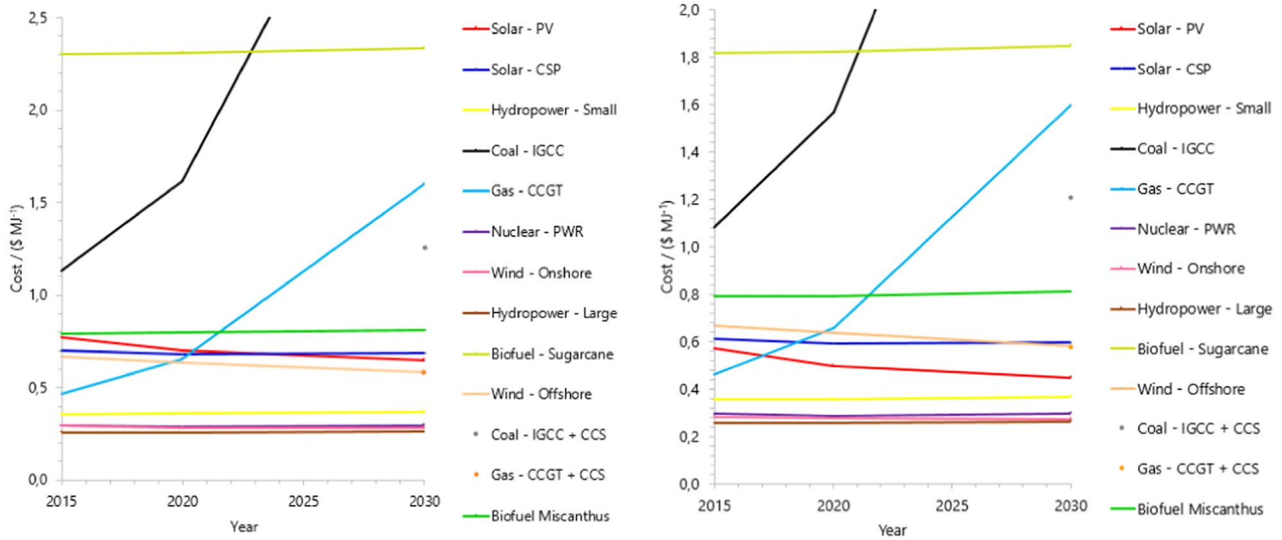
The final emission factor is comparable to those of other developed countries such as Germany and Israel, which have emission factors of 0.67 tCO_2/MWh and 0.74 tCO_2/MWh respectively, suggesting the technology investment profile is achievable for Ghana while achieving full electrification (Brander et al., 2011).



(a) Economic cost, opportunity cost of food production foregone and cost of carbon emissions, after carbon price increase (high fossil fuel prices)

(b) Economic cost, opportunity cost of food production foregone and cost of carbon emissions, after introduction of increasing carbon prices and the reduction of Ghanas crop yield gap (high fossil fuel prices)

Fig. 13. Combined cost of generation technologies with agricultural intensification effects.



(a) Economic cost, opportunity cost of food production foregone and cost of carbon emissions, after carbon price increase (high fossil fuel prices)

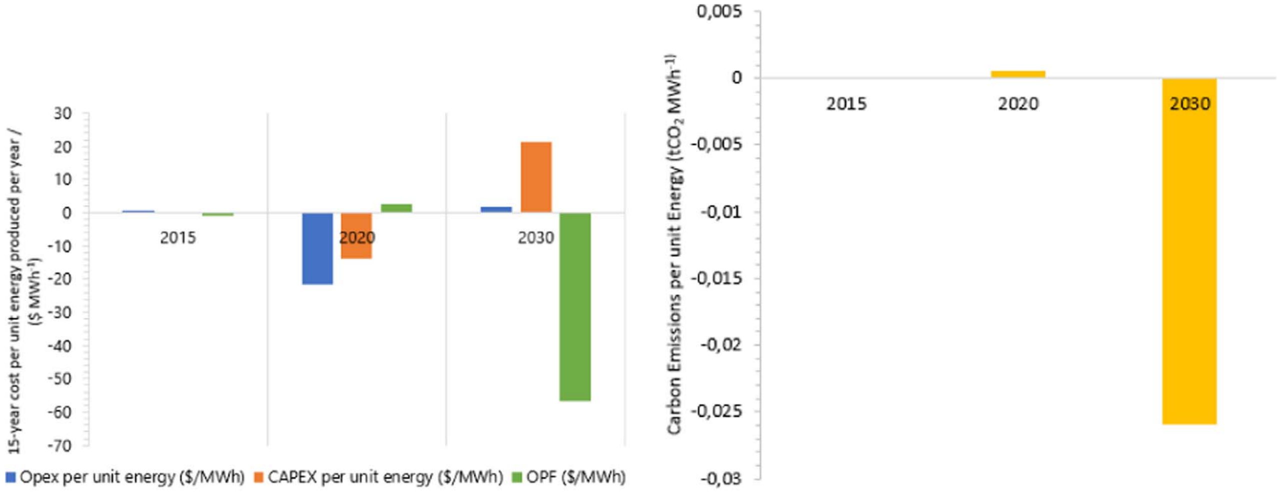
(b) Economic cost, opportunity cost of food production foregone and cost of carbon emissions, after introduction of increasing carbon prices and the reduction of Ghanas crop yield gap (high fossil fuel prices)

Fig. 13. (*continued*)

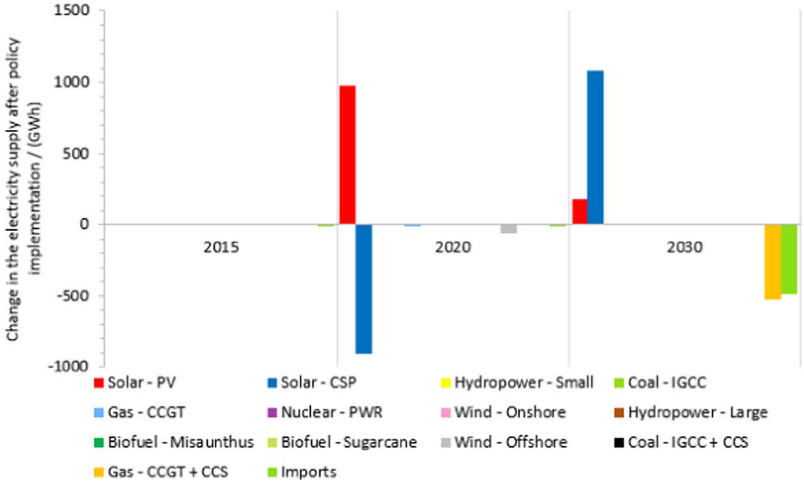
5. Conclusion and policy implications

In conclusion, a modelling framework was successfully developed to simultaneously optimize investment in power generation and water infrastructure. A methodology was derived to calculate the opportunity cost of food production foregone of a power generating technology based on its area requirement. This opportunity cost of food production foregone was introduced as a novel metric to the optimization problem, which then touches on all three components of the energy-water-food nexus.

The framework's ability to simulate the effects of climate change, technology development and water scarcity-related policies on the power generating sector was demonstrated. The effects of climate change on the suggested power generation technology mix illustrate the vulnerability of Ghana's power generation infrastructure and highlights its need for diversification. Furthermore, results indicated that the feedback from the power sector to the drinking water processing facilities does not result in a qualitative restructuring, whereas it does so for the residential wastewater treatment sector.



(a) Change in costs per unit energy (b) Change in carbon emissions per unit energy



(c) Change in capacity of each power generating technology

Fig. 14. Change in costs, emissions and mix of power technologies with agricultural intensification effects.

Moreover, it was illustrated how the model can be used to aid policy decision-making, in particular carbon emissions-reduction policies. It was found that increasing carbon credit prices is only effective at very high prices (of the order of \$100/tCO$_2$), at which the energy mix shifts away from natural gas towards solar and biofuel technologies. There is also a trade-off between the emissions factor and capital expenditure.

Investment into the agricultural yield gap was identified to not only be beneficial for Ghana's small local communities, but also result in an increased use of solar power (with a preference for photovoltaic over solar thermal power). This also reduces carbon emissions and the opportunity cost of food production foregone. In addition, the increased agricultural efficiency achieves a higher net income per capita, and decreasing the price elasticity of electricity may compound the competitiveness of more expensive renewable energy sources. Additionally, feed-in tariffs and investment into supporting infrastructure were identified as effective measures to diversify the country's power generation mixture selectively towards more costly and area-intensive renewable energy sources.

This study has revealed several directions for future work, such as the consideration of planning and commissioning time of power generation infrastructure in the optimization model, as well as a complete sensitivity analysis on the results from the models, taking parameter uncertainties into account with statistical techniques such as Latin Hypercube Sampling or Monte Carlo methods. Another feature to be added is an iterative procedure for finding the threshold value of parameters; for example, the value of the carbon tax at which a significant shift to renewables occurs in the energy mix.

Other possible areas to investigate are the effectiveness of social tariffs and subsidies to the poor domestic population, which proved to significantly boost electrification via renewable energy sources in Latin America, and the inclusion of social costs into the existing framework (Banal-Estaol et al., 2017; Huhtala and Remes, 2017). In addition, the existing framework (consisting of the water, waste water and power sector) could be extended to the residential housing sector.

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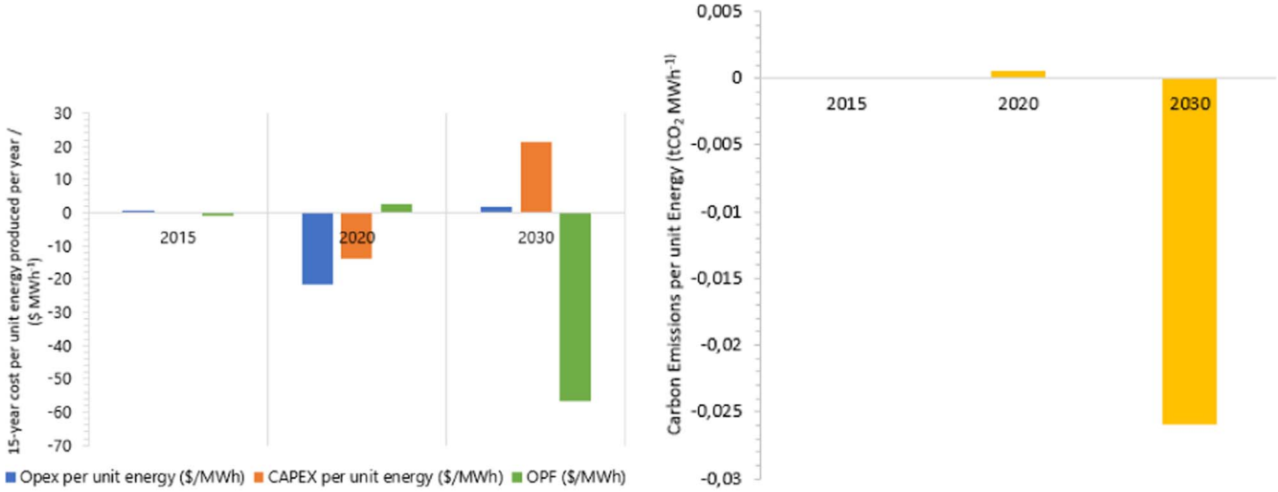
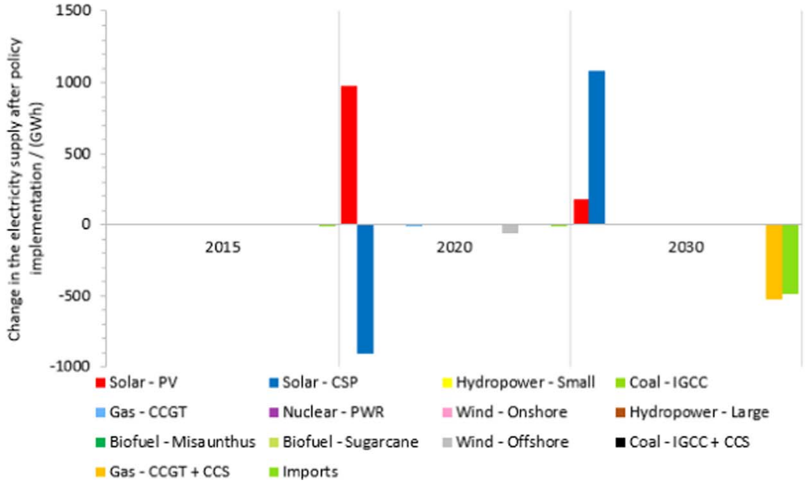


(a) Change in costs per unit energy

(b) Change in carbon emissions per unit energy



(c) Change in capacity of each power generating technology

Fig. 14. (*continued*)

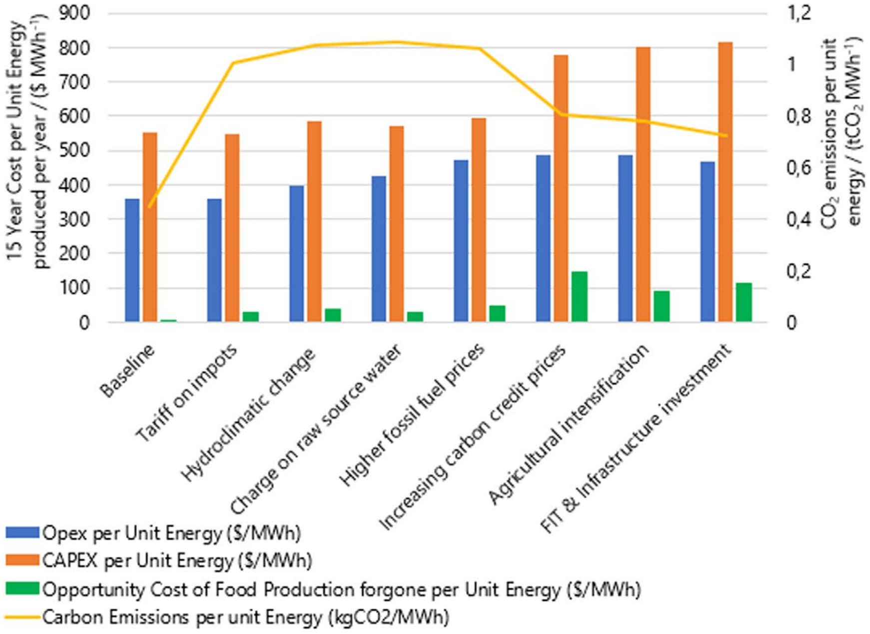


Fig. 15. Economic cost, opportunity cost of food production foregone and carbon emissions in 2030.

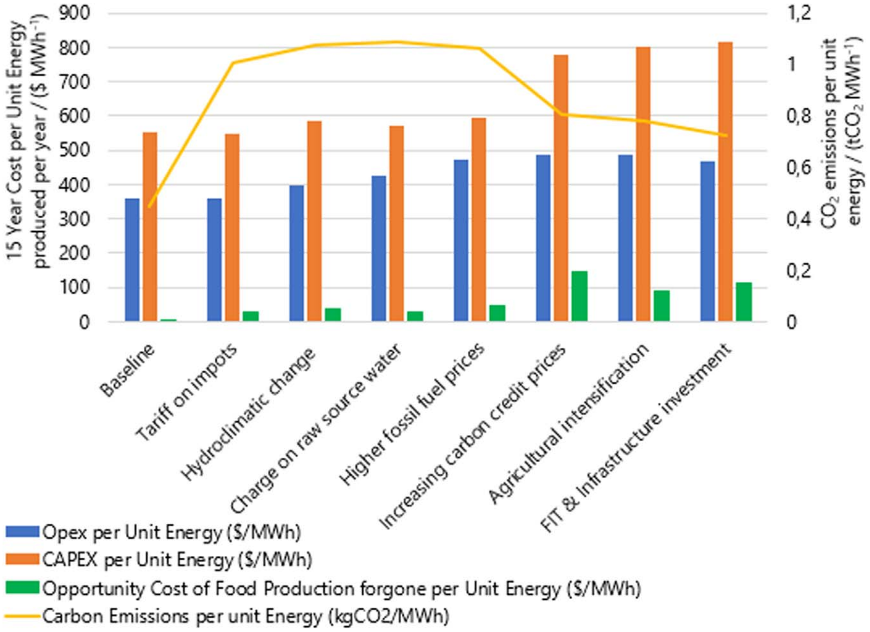


Fig. 15. (*continued*)

Appendix A. Nomenclature

Symbol	Definition	Units
A_k	Area of food sector, k, currently used per years (2016) to achieve full supply of food	m^2 yr^{-1}
$A_{k,P}$	Area of food sector, k, actually being used for production per years	m^2 yr^{-1}
AT_j	Total area used by technology, j	m^2
CAP	the nameplate capacity of each technology	$r.\ d.$
$CAPEX$	Capital expenditure	$
CF	The capacity factor of each technology	–
D	The resource demand	$r.\ d.$
D_F	The total demand for food less imports	$
$dist_{(i,i')}$	The length of a pipe or grid connection built from i to i'	km
ϵ_k	Monetary yield - Value of food produced by food sector, k, per unit area	$\$\ m^{-2}$
$f_{j,k}$	Fraction of the total area required by the power generation technology, j, located in an area relevant to sector, k	–
I_e	Electric current	A
i, i'	The spatial districts which each have associated resource demands	–
IM	The amount of imports	$r.\ d.$
INV	The number of additional technology units invested in j technologies	–
j	Power generation or water technology	–
k	Sector k: Agriculture, inland fishery, or marine fishery	–
lp	The pipe leakage or transmission loss. This was changed from a value of 27% for water sector to 22%, which is the proportion of electric power losses due to transmission and distribution in Ghana (IEA Statistics, 2014)	–
m	Optimization metrics, which include CAPEX, OPEX, environmental cost (quantified here as CO_2 emissions, but which can be extended to other substances with environmental impacts) and OPF	–
MU	Vectors//matrix which represent resource inputs and outputs for each technology unit	$r.\ d.$
N	The number of units of each technology	–
N_{max}	The maximum number of units of a technology allowed in a subregion	–
$OBJWT$	The relative weighting given to each metric	–
$OPEX$	Operating expenditure	$
$OPFCC_j$	Opportunity cost of food production foregone cost coefficient of technology, j	$\$\ m^{-2}$
P	The production rate of a resource	$r.\ d.$
P_{min}	The minimum proportion of production at which technologies are allowed to operate, so that existing facilities are not left dormant. The exception to this are stopgap technologies, such as sachet drinking water or borehole source, which are only necessary in the absence of centralized clean water supply infrastructure.	–
PHI	hours assigned for a year, at each minor time period t	hr
Q	The total flow rate of each resource	$r.\ d.$

Q_{max}	Maximum flow rate of resources in all pipes/lines	$r.\ d.$
R	Resistivity per unit area	$\omega\ m^{-1}$
r	The resource or waste inputs or outputs, which can be raw source water, waste water, process chemicals, solid waste, electricity, labour.	–
S_F	The domestic supply of food	$
t	Minor time period, as fractions of a single day	–
tm	Major time period, as years	yr
V_k	The economic value of agricultural or fishery goods produced by sector, k, per year	$ yr^{-1}
VI	The cost of imports	$
VIJ	The capital expenditure (CAPEX) of a technology over a 15-year period	$
VM	The summation of the values of each metric across the entire resource-technology network	$
VPJ	The operating expenditure (OPEX) of a technology over a 15-year period	$
VQ	The unit cost of resource flow	$
VY	The unit cost of additional pipeline or grid	$
Y	A binary variable indicating the existence of a pipe or grid connection (0 = not connected, 1 = connected)	–
Z	The objective function	$

N.B. *r. d.* indicates that the unit depends on the relevant resource.

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