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Renewable electricity generation target setting in developing countries: Modeling, policy, and analysis

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ABSTRACT

Many countries have set renewable energy targets in their electricity supply mix to encourage investments in renewable energy technologies. In developing countries, however, many of such targets are either abandoned or fall far short of the target date, primarily due to issues of financing, cost of electricity, and level of unmet demand. This paper presents a Generation Expansion Planning model that can be used to assess such issues when setting a renewable electricity generation target. In particular, the model can be used by developing countries to set renewable electricity generation targets that are in line with their financial ability and thus, stand a higher chance of being achieved. Additionally, the analysis offered can inform developing countries of the cost and benefits of a renewable electricity generation target policy. The usefulness of the model is demonstrated using Ghana as a case. The results indicate that Ghana will need a budget of not less than 1% of its GDP for generation capacity investment if it desires to achieve its 10% renewable electricity generation target by 2030 while keeping unmet demand at reasonable levels. If Ghana however enforces the target at its current capacity investment levels, it risks raising unmet demand levels by an average of 4% per year and cost of electricity provision by about US$224 million annually between 2019 and 2030 when compared to the absence of a renewable electricity generation target.

Introduction

The growing call to reduce carbon dioxide emissions along with cost of electricity generation from renewable sources becoming more competitive (IRENA, 2015a) have energized many countries to set renewable electricity targets in their electricity supply mix. According to the International Energy Agency (IEA, 2017), renewables are now the fastest growing source of world energy, with consumption growing by 3% per year. Data from the IEA reveal that renewable energy accounted for more than two-thirds of the world's 165 GW of new electricity generation capacity installed in 2016 (IEA, 2017). The IEA further estimates that the increasing growth in renewable energy penetration is expected to continue given the technological advances and the continuous decline in capital cost. As a result of these developments, there is a renewed interest by many countries to increase the amount of electricity generated from renewable energy sources. Many countries have thus been setting targets to serve as a motivation to focus and direct resources to meet such renewable energy goals. For example, as of 2015, there were as many as 164 (four times the number in 2005) countries setting at least one type of renewable energy target. A sizable number (131) of these countries are from developing or emerging economies. Almost all the 28 EU countries have renewable energy targets set for 2020. (Klessmann et al., 2011). The United Kingdom for instance has a target of achieving 30% renewable content of its electricity generation mix by 2020 (IRENA, 2015b). China has set a target of 30% renewable electricity consumption by 2030 (IRENA, 2015b). Developing countries are not left out. Ghana has set a target of 10% renewable content of its electricity generation by 2030 - originally set for 2020 (BFT, 2017; Obeng-Darko, 2019). Table 1 lists some countries, their renewable electricity targets, and their due dates.

However, while countries such as China, India, Germany, and U.S.A have made substantial progress (IRENA, 2017), and are stepping up their renewable energy targets, others are either abandoning or revising down their targets. Australia announced to abandon its renewable energy target in favour of coal power generation (Smyth, 2017). Ghana's target of 10% electricity production from renewable electricity (excluding existing large hydroelectric plants) had to be rescheduled to 2030 because, less than 0.3% had been achieved as at the end of 2018 (ECG, 2019c). A number of EU member states such as Ireland, Netherland, and Poland are likely to miss their 2020 renewable energy targets (Hassel et al., 2017; Oyewunmi et al., 2019).

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Table 1
Selected countries and their renewable electricity generation target and due Date.
Source: Adapted from IRENA (2015b, Page 25).

Region	Country	Target (%)	Due Date
Europe	Iceland	100	2020–2021
	Denmark	50	2020–2021
	Germany	35	2020–2021
	United Kingdom	30	2020–2021
	Italy	25	2020–2021
	Ukraine	11	2020–2021
North America	Mexico	≈30	2023–2025
	Costa Rica	100	2020–2021
	Cuba	24	2030–2032
	Dominican Republic	25	2020–2021
South America	Chile	20	2023–2025
	Brazil	85	2023–2025
	Argentina	20	2025
Africa	South Africa	15	2030–2032
	Morocco	25	2020–2021
	Burkina Faso	≈48	2030–2032
	Cape Verde	50	2020–2021
Asia	China	30	2020–2021
	India	≈15	2020–2021
	Japan	≈23	2030–2032
	Indonesia	15	2023–2025
	Philippines	40	2020–2021
Oceania	Australia	20	2020
	New Zealand	90	2025
	Fiji	80	2020–2021

A number of reasons could explain a country's need to abandon, or its failure to meet a proposed renewable energy target. First, although the cost of electricity over the lifespan (i.e. Levelized Cost of Electricity (LCOE)) of some renewable energy technologies is now competitive to that of some conventional generators, their capital cost still remains high (EIA, 2018; Green & Staffell, 2016; Sawin et al., 2018; Tang et al., 2012). This fact is particularly important in the context of developing countries, since it potentially discourages investment in large-scale renewable technologies. This is because, planning for electricity capacity in developing countries sometimes demands that a generator with cheaper capital but relatively higher running cost is favored over a generator with high capital but lower running cost, even if the latter has a lower LCOE than the former. The reason for this stems from the fact that, sinking limited fund for capacity investment in a generator with high investment cost, could lead to capacity shortage in future due to lack of funds (Afful-Dadzie et al., 2017). Shortage in generation capacity in turn leads to high levels of unmet demand, which could be costly to an economy (Africa Progress Panel, 2015; Eberhard et al., 2008). It is estimated that Ghana for instance, lost about $2.1 million per day during a 2014/2015 electricity crisis (Kumi, 2017). Thus, the need to have sufficient generation capacity available to avoid high levels of unmet demand might mean avoiding renewable energy technologies with higher capital cost.

Second, it is a fact that without generous government tax incentives and feed-in tariffs, majority of renewable energy projects, worldwide, would not be financially viable (Green & Staffell, 2016). Germany's renewable energy success for instance, is largely attributed to a subsidy policy which required utilities to buy electricity from renewable generators at prices far above the cost of electricity generation from conventional sources. Such tax incentives and feed-in-tariffs would be unaffordable to most governments in developing countries and can dissuade investment in renewable energy technologies (Frondel et al., 2010; Geels et al., 2017; Zhang et al., 2014). Third, whereas thermal plants can provide electricity at virtually any time, the same cannot be said of some renewable energy technologies such as wind and solar, which tend to be intermittent in intensity. To overcome the intermittency of renewable energy sources, the practice has been to rely on electricity imports from neighbouring countries and backup generators (Green & Staffell, 2016; Hammons, 2008). However, most developing countries already face capacity shortages (Batinge et al., 2019) and cannot afford to spend much needed funds on back-up generators. Fourth, most renewable generators require that they are sited at specific places with significant concentration of wind or solar. This would require significant investment in new transmission lines if such places are far away from existing transmission lines (Schaber et al., 2012).

Given the reasons above, it is not surprising that Ghana for instance, has barely made any progress in achieving its renewable electricity generation target. This also means that for a renewable energy target to be realistic, it must be factored into the long-term planning of energy supply. For electricity systems, this means including such target policies in Generation Expansion Planning (GEP) models so that its impact on electricity supply, particularly, on levels of unmet demand, cost of electricity, and capacity investment needed in meeting demand is analyzed and taken note of. Such models can serve several purposes. First, they are useful in analyzing impact on levels of unmet demand as well as cost of electricity if a renewable electricity target policy were to be adhered. It can also be used to search for a target that meets a desired goal in relation to levels of unmet demand and cost of electricity, given one's financial position. Further, it can as well be used to determine the financial commitment in new generation capacity needed to achieve a proposed renewable electricity target.

This research therefore proposes an enhanced GEP model that can be used to study the purposes listed above when a percentage of a country's electricity generation is to be realized from renewable sources by a specific date. The model is useful especially in an era where the setting of renewable energy target is the norm. In addition, the model is also designed with a focus on peculiarities in developing countries, most especially on difficulties in raising financial resources to fund generation capacities, and concerns about access to electricity. Traditional GEP models in general are solved to determine the optimal time, size, and type of power generators to procure, as well as the electricity to be supplied by each generator, in order to minimize the cost of electricity supply. The traditional GEP model is typically solved subject to electricity demand, generator capacity, and operational constraints. The proposed model augments the traditional GEP model with two important constraints – renewable energy target and generation capacity investment budget constraints. In particular, the generation capacity investment budget constraint is added in order to take into account the financial strength of a country in meeting its renewable electricity target and ultimately, the electricity demand.

The proposed GEP model is developed in the form of a multi-period stochastic mixed-integer linear program (MILP) in order to capture the time period within which the renewable electricity generation target is to be met, as well as uncertainty in some of the model parameters. Stochastic MILP approach is appropriate since solutions from stochastic optimization models have proven to be superior to other techniques when uncertainties in model parameters exist (Awudu & Zhang, 2013; Feng & Ryan, 2013; Jin et al., 2011; Shiina & Birge, 2003). This has led to a number of authors applying stochastic optimization techniques to electricity generation capacity planning. Shiina and Birge (2003) developed a multi-stage stochastic linear integer programming for analyzing electricity generation capacities under uncertainty. Jin et al. (2011) analyzed a long-term GEP problem with uncertainties in future demand and fuel prices based on a multi-period stochastic linear optimization model to determine the type and size of power plants to be constructed over an extended planning horizon. Feng and Ryan (2013), also studied a GEP problem based on a multi-period stochastic linear optimization model under a new scenario generation approach. A GEP model that best describes peculiar conditions faced by electricity generation planners in developing countries is presented in Afful-Dadzie et al. (2017). The authors solved a long-term GEP problem with a budget constraint designed to take into consideration the financial capacity of a country.

Though a number of studies have considered GEP problems with a renewable energy dimension, the focus has not been on electricity production target. Oree et al. (2017) provided a review of GEP techniques with environmental considerations and highlighted the emerging challenges presented by the intermittent nature of some renewable energy sources on power systems. Muis et al. (2010) presented an MILP model for optimal planning of electricity generation schemes to meet a nation's specified CO_2 emission target. Their work is quite different from the renewable electricity production target considered in this work because they focus on selecting generation plants to achieve a certain level of CO_2 emission, whereas we select generation plants to achieve a certain level of electricity production from renewable energy sources. Muis et al. (2010) also did not consider budget constraint and uncertainty in electricity demand and fuel price.

Nomenclature

Indices

i	index for generator type, $i = 1, 2, \ldots, I$
t	index for time period (in years), $t = 1, 2, \ldots, T$
k	index for sub-target period (in years), $k = 1, 2, \ldots, K$
n	index for renewable generator type, $n = 1, 2, \ldots, N$
s	index for scenario, $s = 1, 2, \ldots, S$

Parameters

$C_{i,t}^{TC}$	capital cost of generator type i in period t [\$/MW]
$C_{i,t}^{f}$	annualized fixed cost of generator type i in period t [\$/MW/yr]
C_t^{IM}	cost of imported electricity in period t [\$/MWh]
$P_{i,t}^{co_2}$	CO_2 emissions cost per MWh of electricity generated by generator i in period t [\$/MWh]
A_i	capacity factor of generator type i [%]
H_t	total hours in year t [hours]
ρ_t	proportion of electricity demand in period t that can be served through imports
B_t	budget for additional generation capacity investment in period t [\$]
$M_{i,t}$	minimum amount of electricity generation from generator i in period t.
$C_{i,t}^{c}$	annualized capital cost of generator type i in period t [\$/MW/yr]
W_i^{max}	maximum installed capacity of a new generator type i [MW]
C_t^{U}	cost of unmet demand in period t [\$/MWh]
G_i^{max}	number of generator type i that can be built over the entire planning period
r	periodic discount rate [%]
γ_k	renewable energy target in period k [%]
I_i	initial (i.e. $t = 1$) installed capacity of generator type i [MW]
φ_t	rated capacity degradation factor
B_t^{L}	total of past periods unused budget in period t [\$]

Uncertain parameters

p_s	probability of the occurrence of scenario s
$C_{i,s,t}^{v}$	marginal cost of generation of generator type i under scenario s in period t [\$/MWh]
$D_{s,t}$	electricity demand under scenario s in period t [MWh]

Decision variables

$G_{i,t}$	number of new generator type i to build in period t
$W_{i,t}$	total installed capacity of generator type i available in period t [MW]
$Y_{i,s,t}$	total electricity generated by generator type i under scenario s in period t [MWh]
$Z_{i,t}$	total of new installed capacity of generator type i at time t [MW]
$E_{s,t}^{IM}$	total imported electricity under scenario s in period t [MWh]
$E_{s,t}^{U}$	total unmet demand under scenario s in period t [MWh]

In their work, Arnette and Zobel (2012) provided a multi-objective linear programming (MOLP) model to determine the optimal mix of renewable energy generation technologies and existing fossil fuel facilities on a regional basis. Their model was formulated to enable a decision maker to minimize both annual electricity generation costs and level of greenhouse gas emissions, but with no focus on achieving a desired level of electricity generation from renewable energy sources.

In our related literature search, only Knopf et al. (2015) explicitly consider renewable electricity target in their study. Their model was formulated to find the cost-effective shares of electricity from renewable energy sources to meet the EU's 27% renewable energy target in final energy consumption by 2030. However, their formulation implicitly assumes the availability of adequate capital needed to finance the recommended capacity decision. Note that many developing countries struggle to raise funds to finance generation capacity expansions, and therefore failure to take this into account when setting renewable electricity targets has the tendency to render such targets virtually useless. It is no wonder that for instance, Ghana has achieved only 0.3% of its 10% renewable electricity target with less than a year left to the target date (Obeng-Darko, 2019). Ghana's failure could be attributed to the fact that, the target was set with little consideration to the country's financial ability. Perhaps, the strength of the proposed model over that of Knopf et al. (2015) lies in the fact that it can be used to determine a target and the related financial commitment needed to meet a desired level of electricity demand and cost.

This paper contributes to the literature on energy transition (particularly with regards to developing countries) by providing a unique GEP model for the setting and evaluation of a renewable electricity generation target policies. The paper also contributes to practice by helping developing countries set realistic renewable electricity target that is commensurate to their financial position. The rest of the paper is organized as follows. The next section presents the proposed GEP model with renewable electricity generation target. This is followed by a case study on Ghana's proposed 10% renewable electricity generation target by 2030, an extensive analysis and discussion of the case study results, and conclusion of the study.

Generation expansion planning model with renewable electricity generation target

The proposed GEP model with renewable electricity generation target is represented by Eqs. (1)–(8). The definitions of the parameters and variables of the model are also presented in the nomenclature. A brief explanation of the major components of the model is provided next.

$$\text{Minimize} \sum_{t=1}^{T}\left[\frac{\sum_{i=1}^{I}\left(C_{i,t}^{c}+C_{i,t}^{f}\right)Z_{i,t}+\sum_{s=1}^{S}P_s\left(\sum_{i=1}^{I}\left(C_{i,s,t}^{v}+P_{i,t}^{co_2}\right)Y_{i,s,t}+C_t^{IM}E_{s,t}^{IM}+C_{t}^{U}E_{s,t}^{U}\right)}{(1+r)^{t-1}}\right] \tag{1}$$

$$\sum_{i=1}^{I}Y_{i,s,t}+E_{s,t}^{IM}=D_{s,t}-E_{s,t}^{U}\,\forall s,\forall t \tag{2}$$

$$Y_{i,s,t}\le H_tA_iW_{i,t}(1-\varphi_t)\,\forall i,\forall s,\forall t \tag{3a}$$

$$Y_{i,s,t}\ge M_{i,t}\,\forall i,\forall s,\forall t \tag{3b}$$

$$E_{s,t}^{IM}\le \rho D_{s,t}\,\forall s,\forall t \tag{4}$$

$$Z_{i,t}=Z_{i,t-1}+W_i^{max}G_{i,t}\,\forall i,\forall t \tag{5a}$$

$$W_{i,t} = I_i + Z_{i,t} \forall i, \forall t \quad (5b)$$

$$\sum_{n=1}^{N} Y_{n,s,k} \geq \gamma_k \sum_{i=1}^{I} Y_{i,s,k} \forall s, \forall k \quad (6)$$

$$\sum_{i=1}^{I} C_{i,t}^{TC} W_i^{max} G_{i,t} \leq B_t + (1+r) B_{t-1}^L \forall t \quad (7a)$$

$$B_t^L = B_t + (1+r) B_{t-1}^L - \sum_{i=1}^{I} C_{i,t}^{TC} W_i^{max} G_{i,t} \forall t \quad (7b)$$

$$G_{i,t}, Z_{i,t}, W_{i,t}, Y_{i,s,t}, E_{s,t}^{IM}, E_{s,t}^{U}, \geq 0, G_{i,t} \text{ integer} \forall i, \forall s, \forall t \quad (8)$$

Decision variables

The major variables of interest in the proposed multi-period GEP model are $G_{i,t}$, $Y_{i,s,t}$, $E_{s,t}^{IM}$, and $E_{s,t}^{U}$. In any period, the GEP model is solved to determine $G_{i,t}$, the number of new generator type i to build in period t. The variable $Y_{i,s,t}$, is the electricity generated by generator i in a particular uncertain scenario (e.g. demand and fuel price) in period t, whereas $E_{s,t}^{IM}$, is the amount of electricity imported from neighbouring countries in scenario s in period t. In case the total electricity generated, and the amount imported are not enough to meet the periodic demand $D_{s,t}$, the unmet demand is tracked using the variable $E_{s,t}^{U}$. The remaining variables of the model are $Z_{i,t}$, and $W_{i,t}$ which are respectively used to track the accumulated capacity of new and installed generators since the beginning of the planning period.

Objective function

The objective function of the model which seeks to minimize the cost involved in the provision of electricity over a planned period starting from period $t = 1$ to period T, is represented by Eq. (1). It represents the total of the present value of the several costs incurred over the planning period. The first term of the numerator captures the capital cost and the fixed operating cost for new generation plants built within the planning period. The second term captures the cost incurred in the production of actual electricity. This cost is determined by a generator's marginal cost of electricity generation $C_{i,s,t}^{v}$, emissions cost $P_{i,t}^{co_2}$, and the amount of electricity generated $Y_{i,s,t}$. The third and fourth terms respectively represent the cost of electricity imported from neighbouring countries, and the indirect cost to a country's economy of any level of demand not met.

Model constraints

The objective function of Eq. (1) is determined subject to the following constraints.

Electricity demand and supply

Constraints on electricity demand and supply are modelled using Eq. (2). The left-hand-side is the electricity available for meeting period t demand, and is made up of actual generation and imported electricity from neighbouring countries. Some demand will not be met if electricity demanded is greater than the available supply. The right-hand-side is thus the demand met, which is the difference between the actual electricity demanded, $D_{t,s}$, and demand not met, $E_{t,s}^{U}$. Electricity produced with generators owned by the planner is represented by Eqs. (3a) and (3b). Eq. (3a) ensures that for each generator type i, the total electricity produced at any period t is within the maximum possible electricity it can produce. Eq. (3b) helps to enforce generation from firm and non-firm power plants and enforces a minimum level of production on certain power plants. For example, almost all existing hydro units in the Ghanaian power system produce at a minimum level. The amount of electricity imported is modelled with Eq. (4). Although in some cases electricity can be imported from neighbouring countries, this is usually limited. Eq. (4) is thus designed to account for this restriction.

Generation capacity

The available generation capacity of the generators is modelled with Eqs. (5a) and (5b). The cumulative capacity of new generators installed since the start of the planning period is tracked with Eq. (5a), whilesEq. (5b) does the same as Eq. (5a) but includes capacity that existed before the start of the planning period.

Renewable electricity target

The renewable electricity generation target to be achieved is represented by Eq. (6), which ensures that total electricity generation from renewable energy sources at the target due date, meets the target. For practical purposes, a target due in period T (i.e. the end of the planning period) is divided into sub-targets due at selected periods $k = 1, 2, \ldots, K$. For example, Argentina aims to achieve a 20% renewable energy penetration in 2025. However, this target is divided into sub-targets of 12% by 2019, 16% by 2021, 18% by 2023 and 20% by 2025 (Pink, 2018). The left-hand-side of Eq. (6) ensures that the sum total of all electricity generation coming from renewable technologies meet the target percentage for a selected period k. One could replace Eq. (6) with Eq. (9) below, if the focus of the target is on generation capacity, and specific megawatts of capacity are to be achieved for individual renewable energy technologies at targeted periods. Here, $W_{n,k}$, and $F_{n,k}$ are respectively, the actual attained megawatts, and the targeted megawatts capacity from renewable energy technology n in targeted period k. For example, while Ghana has set an overall renewable electricity generation target of 10% by 2030, its renewable energy master plan has specific capacity target for each renewable technology.

$$W_{n,k} \geq F_{n,k} \forall n, \forall k \quad (9)$$

Capacity investment budget constraints

The ability of a country to finance additional generation capacity needed in period t is modelled with Eq. (7a). The equation ensures that at any period t, the money spent on new generators is within the allocated budget for that period. The total budget available in any period consists of the planned budget for the period and the unused funds in the previous period. The unused funds are tracked with Eq. (7b) and assumed to earn interest each period at a rate of r%. The integer and non-negativity constraints expressed in Eq. (8) complete the proposed GEP model.

The proposed GEP model is unique in the sense that, in addition to the usual GEP output, it can be used to determine the financial commitment needed to bring to fruition a desired renewable target that meets an acceptable level of unmet demand and cost of electricity provision. On the other hand, the model can be used to determine a target that accommodates a country's financial ability, and the tolerance level of unmet demand and electricity generation cost. Most importantly, given a country's financial ability, it can be used to analyze the impact on electricity supply (in terms of cost of electricity and levels of unmet demand) should a target be adhered to. We note here that the proposed GEP model only focuses on the generation side of the electric power system and does not consider transmission constraints and investment.

Case study on Ghana's 10% renewable electricity generation target policy

We begin the case study with an overview of the electricity generation sector of Ghana in relation to current installed and dependable generation capacity, electricity generation trend, and a brief information of the country's renewable energy master plan.

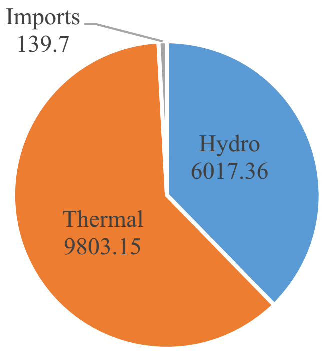

Fig. 1. Electricity generation in Ghana by Source in 2018.
(Source: ECG (2019c)).

Generation capacity

Ghana is a developing country with an electricity generation sector made up of both public and private companies. The public companies consist of two authorities, namely Volta River Authority (in charge of the Akosombo hydroelectric dam, and government owned thermal plants), and Bui Power Authority, in charge of the Bui hydroelectric dam. The private companies consist of a vibrant group of Independent Power Producers (IPP), currently commanding about 32% of the country's installed generation capacity. IPPs usually sell electricity to the country on Take-Or-Pay contract, where the government is obliged to buy a stipulated amount of electricity within an agreed period from the IPP or pay the IPP a penalty. Electricity generated is transmitted to consumers by the Ghana Grid Company Limited (GridCo). As at the end of 2018, the country had an installed and dependable generation capacity totaling 4533 MW and 4048 MW respectively (ECG, 2019c). The installed capacity comprises of 2906 MW thermal, 1584 MW hydroelectric, and 42.5 MW solar. As shown in Fig. 1, about 58.14% of the 15,960.3 GWh of electricity generated by Ghana in 2018 came from thermal, followed by hydroelectric with 39.6%, and 2.26% by imports (ECG, 2019c). There is also a total of 530 MW of dependable committed capacity of combined circle gas turbines for 2019 (ECG, 2019c). Plans are far advanced for the construction of a 700 MW coal-fired plant with a potential to be increased to 2000 MW.

Electricity demand trend

The annual electricity generated in Ghana from 2001 to 2017 is as shown in Fig. 2. Altogether, the average annual growth rate of electricity generated within the stated period stood at roughly 4.4%. However, this data does not include demand not met, especially during the major electricity crisis in 2003, 2007, and 2015 when the annual growth rates were negative. The average annual growth rate is 10.52% if one excludes data from 2003, 2007, and 2015. Also, this data does not include the frequent load shedding and blackouts experienced whenever demand exceeds supply. Adding demand not met, and the fact that 17.5% of the population did not have access to electricity in 2016, the average annual growth rate could be far higher. In fact, the 2018 projected demand growth rate by the national grid operator was 15.01% (GridCo, 2017).

The Ghana renewable energy master plan

Ghana has set a target to generate at least 10% of its electricity from renewable technologies by 2030 (originally by 2020). This target focuses mainly on solar, wind, and biomass technologies as well as smaller hydroelectric plants. To achieve the 10% target, the country has drawn up an ambitious renewable energy master plan (as presented in Table 2) that aims to add about 200 MegaWatt-peak (MWp) from smaller hydro and wave plants, 741.3 MWp from solar, 327 MWp from wind, and 122 MWp from biomass technologies. In the master plan, the country expects to have in place a total of 194.74 MWp of renewable energy capacity by 2020, 936.64 MWp by 2025, and 1353.63 MWp by 2030 towards electricity generation. More than 80% of the planned capacity is targeted at utility scaled renewable technologies, whereas at least 8% is targeted at rooftop solar installations. However, as at the end of 2018, less than 1% (42.5 MWp) of the country's installed capacity came from renewable generators (excluding existing large hydroelectric plants). In fact, out of the 15,906.36 GWh of electricity generated in 2018, there was virtually no contribution from renewable energy technologies that qualifies under the renewable energy target[1] (ECG, 2019c). The meager renewable energy capacity achieved so far, prompted the government to extend the 10% renewable electricity generation target to the year 2030.

Model parameters

This section presents the parameters used in running the model for the case study, starting with data on electricity demand, followed by information on candidate generators, costs, budget for additional capacity investment, and assumed parameters.

Electricity demand

Electricity demand exhibits an increasing trend over time mainly due to population and economic growth. The demand trend is modelled using the trend formula in Eq. (10), where demand in period t, $D_{s,\,t}$, is a $\widetilde{w}_t$ percentage increase over $D_{s,\,t-1}$, the demand in period $t-1$. The parameter $\widetilde{w}_t$ is the percentage increase in demand from period $t-1$ to period t. In practice, $\widetilde{w}_t$ is unknown and captures the uncertainty in electricity demand. Although unknown, it is usually modelled with a probability distribution based on past data. Based on Ghana's electricity generation from 2000 to 2017, and adjusting to account for the electric power crisis in 2003, 2007, and 2015, the best fitted distribution for $\widetilde{w}_t$ was a triangular distribution of *Triang* (1%, 7%, 15%). This is interpreted to mean that the annual percentage increase in electricity demand is most likely to be 7%, but could be as low as 1%, and as high as 15%. To capture the uncertainty in the electricity demand data over the planning period, we follow the Monte-Carlo approach in Breeden and Ingram (2010) to generate demand forecast. To do this, and for each period, a random draw is taken from *Triang* (1%, 7%, 15%) for $\widetilde{w}_t$ which is then used in Eq. (10) to obtain a demand forecast. The set of demand forecast for each period together forms one scenario. The process is repeated several times depending on the number of scenarios needed to characterize the uncertainty. This case study used 20 scenarios with equal probability of occurrence to characterize the demand uncertainty. The Mean Absolute Percentage Error (MAPE) of the scenarios was less than 8% signifying a highly accurate forecast in relation to the national forecast.

$$D_{s,t} = (1+\widetilde{w}_t)D_{s,t-1} \qquad (10)$$

Table 3 presents five electricity demand scenarios from 2019 to 2027. These were determined using the recorded actual electricity supply of 15,960.36 GWh in 2018 as found in ECG (2019c) as the starting value for $D_{s,\,t-1}$. Also shown in the last two columns of Table 3 are the national annual average forecasts for 2019–2027 (ECG, 2019c, page 62–63). The 2019 national annual average forecast of 17,237.8 GWh is a base case demand forecast representing a percentage growth of 8% over that of 2018. The corresponding high case forecast is 18,013.96 GWh, representing a growth rate of 12.9%. As shown in Table 3, the generated scenarios show a reasonable deviation from the national average

[1] The 10% electricity generation target excludes hydro generators of 100 MW and above, as well as all existing hydro generators. See the footnote on page iv of the Ghana Renewable Energy Master Plan (ECG, 2019a).

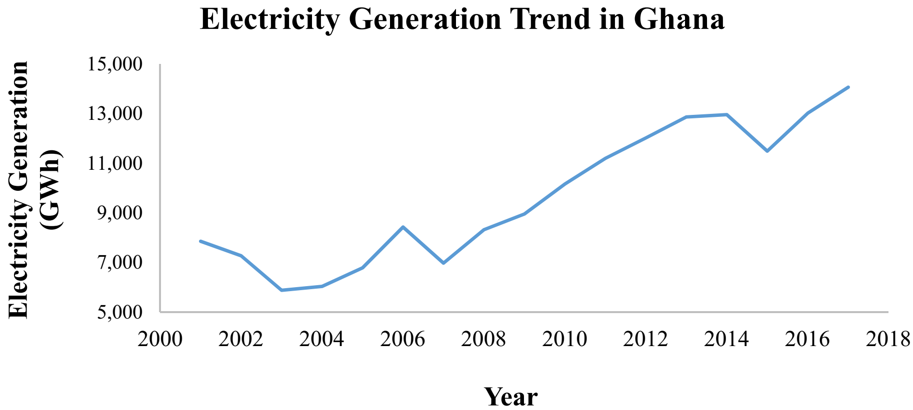

Fig. 2. Trend chart of annual electricity generation in Ghana.
Source: ECG (2013, page 7), and ECG (2019b, page 8).

Table 2
Electricity generation capacity expansion plan for renewable energy technologies in Ghana.
Source: ECG (2019a).

Technology	Project	Units	2015	2020	2025	2030	Cumulative (2030)
Solar	Utility scale	MWp	22.5	130	195	100	447.5
	Distributed Solar PV	MWp	2	18	80	100	200
	Standalone Solar PV	MWp	2	8	5	5	20
	Solar Street/Community lighting	MWp	3	4	4	14	25
	Solar irrigation	MWp	2.8	6	20	20	48.8
Wind	Utility scale	MWp	0	0	275	50	325
	Standalone Wind Systems	MWp	0.01	0.1	0.9	1	2
Biomass	Utility-scale/co-generation	MWp	0	0	72	0	72
	Waste-to-Energy Utility Scale	MWp	0.1	0	30	20	50.1
	Small/Medium Hydro Plants	MWp	0	0.03	80	70	150.03
Hydro/Wave Power	Wave Power	MWp	0	5	0	45	50
Hybrid Mini- Grid	Mini/Micro-grid	MWp	–	–	–	12	12
Total		MWp	32.41	171.13	761.9	437	1402.43

annual forecast, and better capture uncertainty in expected demand compared to the two national forecasts. In other words, any of the 20 scenarios is likely to occur. The strength of the proposed stochastic model approach is that all 20 scenarios are used to derive a solution that is better suited to the demand uncertainty present.

Generator technical information

The types of electric generators considered in the case study along with their technical and cost data are presented in Table 4. Seven different kinds of generators were considered. These were hydroelectric (HYDRO), Combined Circle Gas Turbine (CCGT1 and CCGT2), Open Circle Gas Turbine (OCGT), Coal (COAL1 and COAL2), Onshore Wind (WIND1 and WIND2), Solar (SOLAR1 and SOLAR2), and biomass (BIOMASS), for a total of eleven generator types. Out of these, only HYDRO, WIND1, WIND2, SOALR1, SOLAR2, and BIOMASS are eligible to be selected to meet the 10% renewable electricity target. The model assumes not more than four hydro generators of size 60 MW each, can be constructed in the planning period. This is in accordance with the remaining significant hydroelectric opportunities in Ghana. To account for this assumption, Eq. (11) was added to the proposed model for the case study. Although Ghana currently has thermal capacities of various sizes from as low as 22 MW to as high as 470 MW, we considered only the capacity sizes of 300 MW and 450 MW for the Combined Circle Gas Turbines and 150 MW for the Open Circle Gas Turbines to reflect the recent capacity investment trend. For this reason, existing CCGT plants of capacities less than 300 MW were grouped together under CCGT1 and those above under CCGT2. Note that the Dependable capacity in Table 4 include committed capacity of 190 MW and 340 MW respectively for CCGT1 and CCGT2 for 2019 (ECG, 2019c). The capacity factor for the hydro and thermal plants were estimated based on supply data from ECG (2019c), while that of wind and solar were taken from IRENA (2018), and biomass from EIA (2019b).

$$\sum_{t=1}^{T} G_{HYDRO,t} \leq 4 \forall i, \forall t \tag{11}$$

Table 3
Example forecast of possible electricity demand for Ghana. Data under Scen-3, Scen-7, Scen-11, Scen-16, and Scen-19 are possible electricity demand path for Ghana from 2019 to 2027. Data under 'National (Base)' and 'National (High)' are the officially reported base and high demand case scenarios from the 2019 Ghana electricity supply plan issued by the Ghana Energy Commission (ECG, 2019c).

Year	Scen-3	Scen-7	Scen-11	Scen-16	Scen-19	National (base)	National (high)
2019	17,019	17,518.8	18,141.1	17,258.4	17,047.3	17,237.80	18,014.00
2020	17,768	19,365.7	19,924.2	18,736.2	18,261.2	18,249.50	20,070.50
2021	19,327.4	20,372.1	21,547.7	19,564.7	19,604.9	18,918.00	21,398.70
2022	20,214.1	21,856.4	23,347.9	20,203.2	20,931.5	21,108.30	24,189.90
2023	21,240.6	24,294.5	24,689.3	21,940.5	22,521.3	22,186.90	25,899.70
2024	22,645.8	26,873.5	26,560.2	24,298.6	24,605.2	24,931.40	28,999.10
2025	23,513.9	28,720.1	29,267.3	26,402.4	27,337.4	25,690.50	30,391.00
2026	25,497.7	30,799.7	32,487.8	28,243.9	29,461.3	26,476.10	31,857.00
2027	27,850.3	32,775	33,721.4	29,646	30,269.1	27,214.60	33,332.60

Capital, fixed operating and maintenance (O&M), and emissions costs

The Capital, Fixed O&M, and Emissions costs for the generators at the beginning of the planning period (i.e. 2019) are presented in Column 6 to 8 of Table 4. With the exception of capital cost for WIND1, WIND2,

Table 4
Parameters for the beginning period (2019) of the GEP planning horizon for eleven candidate generation plants. These include dependable committed capacity of 190 MW for CCGT1 and 340 MW for CCGT2.
Source: (GridCo, 2011; EIA, 2019; EIA, 2019b; EIA, 2018; EIA, 2016; EIA, 2013; IRENA, 2018; IRENA, 2012; ECG, 2019c).

Generator type	Rated Capacity (MW)	Dependable Capacity (MW)	Capacity Factor	Generator Life span (yrs)	Capital cost (1000 $/MW)	Fixed O&M cost ($/MW/year)	Emissions Cost ($/MWh)	Variable O&M Cost, excluding fuel ($/MWh)	Generator Degradation Factor
HYDRO	60	1365	47.5%	60	5000	15,000	0	2	0.003
CCGT1	300	888	40.5%	25	1057	10,100	6.7	2	0.003
CCGT2	450	1300	40.5%	25	1104	10,100	6.7	2	0.003
OCGT	150	1039.6	40.5%	25	678	6870	8.2	10.7	0.003
COAL1	250	0	50%	35	3818	42,100	16.2	4.6	0.003
COAL2	350	0	50%	35	3636	42,100	16.2	4.6	0.005
WIND1	50	0	16.5%	20	1877	39,700	0	9.5	0.005
WIND2	100	0	16.5%	20	1657	47,470	0	9.5	0.016
SOLAR1	20	42.5	19.5%	20	2671	23,400	0	0	0.016
SOLAR2	50	0	19.5%	20	2434	22,020	0	0	0.005
BIOMASS	50	0	50%	30	3837	112,150	8.1	5.6	0.005

SOLAR1, and SOLAR2, the values for the rest of the planning period (i.e. 2020–2030) for these costs were determined by increasing that of an immediate past year by 0.5%. On the other hand, the capital cost for the periods after 2019 for WIND1, WIND2, SOLAR1, and SOLAR2 were determined by decreasing that of the immediate past year by 0.5%. The decrease in this case is to reflect the continuous decline in investment cost of wind and solar plants. The emission cost is based on the assumption of a $15 per ton of CO_2 emission (roughly half of what is charged in most high income countries). This is set to reflect the economic valuation in developing countries relative to developed countries. Also, the emission cost of biomass is set at half that of coal to accommodate either side of the argument for and against the notion of biomass as a carbon-neutral fuel.

Marginal cost of generation

The marginal cost of generation is dependent on the amount of electricity generated, which is made up of two parts namely, marginal cost of fuel, and variable O&M cost. The Variable O&M cost for the generators in the beginning of the planning period is given in column 9 of Table 4. The Variable O&M cost for the subsequent periods after the beginning period were determined in the same way as that of the other costs by increasing the immediate past year's cost by 0.5%. The variable O&M cost for onshore wind in 2019 is given as $9.5/MWh according to data in the generation master plan of Ghana (GridCo, 2011), and similar estimates as found in (IRENA, 2012).

The marginal cost of fuel component is assumed to be uncertain for the generators. However, that of generator types WIND1, WIND2, SOLAR1, and SOLAR2 are assumed to have a marginal fuel cost of $0/MWh, while that of HYDRO is set at $2/MWh based on data from the operator of the largest hydroelectric dam in Ghana. Table A.1 in Appendix A gives a breakdown of how the marginal fuel cost for CCGT1, CCGT2, OCGT, COAL1, COAL2, and BIOMASS were generated.

Capacity investment budget constraint

It is assumed that the financial resource available for investment in new generation capacity is limited. This assumption is important, otherwise achieving a renewable target is trivial. Public utility companies in developing countries are hardly able to finance new generation capacity through revenues from electricity generated because of low electricity prices to make electricity affordable to the populace. As a result, these public utilities are generally supported by the government each year in the financing of new generation capacity. We assume that a portion of the country's annual GDP is allocated for the financing of new generation capacity. GDP values are assumed to increase each year over the planning period by 4% based on Ghana's 2017 GDP value of $58.99 Billion. Four different types of budget constraints are considered in order to analyze the impact of budget limitation on the level of unmet demand and cost of electricity provision. These are budgets equivalent to 0.5%, 0.75%, 1.0%, and 1.25% of Ghana's annual GDP. It is worth noting that currently, Ghana spends around 0.75% of its GDP on new generation capacity investment.[2]

Other assumptions

The model assumes that the 10% renewable target is spread within the planning period, and that at least 1%, 4%, 7%, and 10% of total electricity production in 2020, 2023, 2026, and 2030 respectively should come from renewable energy sources, as is done in practice. The remaining assumed parameters used to run the GEP model are given in Table 5. The cost of unmet demand at the beginning of the planning period is set at a moderate value of $225/MWh. However note that this cost could be higher given that Ghana lost an estimated $2.1 million a day during the 2014/2015 electricity crisis (Kumi, 2017). In fact, the Ghana Energy Commission estimates the cost of unmet demand at $1000/MWh (GridCo, 2011). Also, Ghana and Ivory Coast trade electricity with each other when the need arises. We assume the amount of electricity imported cannot exceed 4% of Ghana's annual demand. This percentage is in agreement with the annual importation figures in the electricity supply plan of Ghana. Electricity is imported at an assumed cost of $150/MWh.

We also assume that existing hydro generators operates exclusively as base plants (as is primarily the case in Ghana) and sets the minimum production at 80% of the total energy equivalent to the right hand side of Eq. (3a). Also, OCGT plants are assumed to be peaking plants. In addition, it is assumed that no generator (including existing ones) would be retired within the planning period. Lastly, electricity demand is the sum of all demand throughout the entire year.

Table 5
Additional model parameters.

Parameter	Value
Cost of unmet energy ($/MWh)	225
Cost of imported electricity ($/MWh)	150
Annual interest rate for discounting (%)	12
Number of hours in a year	8760

Case study results and analysis

The stochastic MILP-GEP model with renewable electricity production target was programmed using the General Algebraic Modelling

[2] The 0.75% GDP spending was estimated based on data on new generation capacity additions provided in the annual Electricity Supply Plan of Ghana provided by the Ghana Energy Commission. See (page 27, Table 22 of ECG, 2019c).

System (GAMS) optimization software and solved using the ILOG CPLEX 12.6.0.0 solver. The result of the case study is presented next, starting with new generation capacity additions and percentages of electricity generation from renewable energy generators, followed by levels of unmet demand, and lastly total cost of electricity provision. The results are provided for both the case of when a renewable electricity production target policy is in place (*Target*), and when there is no target policy in place (*No Target*). We consider four budgetary policies for new generation capacity investment, with the aim of understanding the impact of budget constraint on installed generation capacity, levels of unmet demand and cost of electricity provision. We also consider the imaginary case where there is sufficient financial resource to put into perspective the advantage richer countries have over poorer countries in the energy transition process.

New generation capacity additions

When available generation capacity is not enough to meet demand, the resulting demand not met leads to economic loss to a country. As such, the impact of a renewable electricity generation target policy on generation capacity must be analyzed, especially when a country is constrained financially in what it can allocate for new generation capacity investment. Table 6 presents the result on cumulative new installed generation capacity within the planning period for four different capacity financing budget allocations and the case when there is sufficient budget under both *Target* and *No Target* policies. In general, unless during or prior to a due date of a sub-target, there is more generation capacity available under the *No Target* policy than under the *Target* policy. Also, and as expected, generation capacity in a given period increases with increasing budget.

Fig. 3a–c also gives a breakdown of the cumulative new installed capacity for the selected generator types at the sub-targets dates under both *Target* and *No Target* policies for different capacity financing budget allocations. As shown in Fig. 3a, under the *No Target* policy, no renewable energy generator is considered for new generation capacity at budget allocations of 0.5% and 0.75% of GDP. It can also be seen in Fig. 3b that even at higher budget allocations of 1% and 1.25% of GDP, the size of renewable energy generation capacity recommended as part of the required new generation capacity under the *No Target* policy is quite insignificant when compared to non-renewable generation capacity. This is a clear sign that under current conditions, non-renewable energy generators are perceived to be more cost-effective than renewable energy generators when a country faces challenges raising the needed financial resource for new generation capacity investment. This conclusion is supported by the recommended generation mix under the *Target* case in Fig. 3a and b, where the renewable energy generators recommended are mainly for the purpose of meeting the renewable electricity target and nothing more.

Looking closely at Fig. 3a and b also reveals that the size of renewable energy generators (albeit insignificant) increases with increasing budget allocations under both the *Target* and *No Target* cases. This leads to an interesting observation when there is sufficient budget for capacity financing as shown in Fig. 3c. In this case, virtually all new generation capacities come from the renewable energy generation plant, SOLAR2, whether under the *Target* or *No Target* policy. Note also that the generation capacity needed in this case is almost twice that needed under the 1.25% budget allocation which is the closest budget needed to ensure all demand is met when a renewable electricity target is enforced. This is not unusual given the low capacity factor of solar plants. However, the total capital cost needed to finance such size of generation capacity will be enormous, and quite frankly impractical.

The preference for renewable energy generators under a sufficient budget in Fig. 3c also gives an indication that renewable energy generators are not favored under the other four budget allocations purely because of financial constraint. This goes to support the argument that at current cost estimates, some renewable energy technologies are cost effective if one is not constrained financially. On the other hand, if one is constrained financially, then given the current high capital cost of renewable technologies, very little capacity will be available to satisfy demand if renewable generators are preferred over conventional generators.

Result in Fig. 3a–c can be used as a guide in selecting the cost effective renewable energy generators to fulfil a planned renewable electricity target when facing a budget constraint. In general, the optimal decision under the *Target* policy when facing generation capacity investment budget of 0.5% and 0.75% of GDP is to go for biomass. Just like the Ghana Renewable Energy Master (REMP) plan, a mix of biomass, wind, solar and small hydro is recommended at relatively higher budget allocations of 1.0% and 1.25% of GDP for new capacity investment. When there is sufficient financial resources available however (see Fig. 3c), solar appears to be the best option among all renewable energy generators.

Percentage of electricity generated

The pattern in the generation capacity additions is also reflected in the percentage of electricity generation coming from renewable energy generators as seen in Table 7. It can be observed under the *Target* policy that, under all four budget allocations, renewable energy generators appear to be procured mainly for the sake of meeting the target. This statement is supported by the fact that only the sub-target year of 2020 appears to have had a renewable electricity content significantly more

Table 6
Cumulative new installed generation capacity (in MW) within the planning period when a 10% renewable electricity generation target is enforced (*Target*), and when not enforced (*No Target*) at annual capacity investment funds of 0.50%, 0.75%, 1.0%, and 1.25% of Ghana's GDP, and when there is sufficient budget. The sub-target due dates are 2020, 2023, 2026, and 2030.

Year	0.5% of GDP		0.75% of GDP		1.0% of GDP		1.25% of GDP		Sufficient Budget	
	Target	No Target	Target	No Target	Target	No Target	Target	No Target	Target	No Target
2019	0	0	0	0	0	0	0	0	2190	2190
2020	50	300	400	300	350	600	700	750	3240	3240
2021	350	600	700	900	1100	1200	1450	1500	4190	4190
2022	800	900	1300	1350	1700	1800	2350	2250	5390	5390
2023	900	1200	1450	1950	1870	2550	2530	3000	6540	6540
2024	1200	1650	2050	2400	2620	3300	3280	3240	8090	8090
2025	1500	1950	2500	3000	3220	4050	4090	4140	9790	9790
2026	1670	2250	2700	3600	3440	4560	4590	5040	10,940	10,940
2027	1970	2850	3300	4200	4190	5070	5490	5940	12,190	12,190
2028	2420	3300	3900	4800	4990	5820	6540	6890	14,140	14,140
2029	2520	3750	4060	5420	5440	6720	6990	7640	15,190	15,190
2030	2670	4220	4310	6170	5690	7620	7540	8640	16,740	16,740

than what is desired under the *Target* policy. Much of the renewable energy content attained in 2020 is due to the 42.5 MW of solar capacity that existed before the start of the planning period. Also, the percentage of renewable electricity achieved under any *Target* policy in Table 7 appears to be roughly the same even when the allocated budget increases (from 0.5% to 1.25% of GDP), which is an indication that renewable electricity is only considered just for the sake of meeting the target.

The percentage of renewable electricity achieved under a *No Target* policy in Table 7 appears quite insignificant. However, though small, it can be seen that the content appears to increase with increasing budget allocations. For example, the renewable electricity percentage under a *No Target* policy is 1.1% under a budget allocation of 1.0% of GDP compared to 3.7% under a 1.25% GDP budget in the year 2026. Similarly, it is 1.5% under a 1.0% GDP budget but 4.7% under a 1.25% GDP budget in the year 2030 under a *No Target* policy.

In line with the fact that virtually only renewable generators are considered for new capacity additions when there is sufficient budget for generation capacity investment (see Fig. 3c), the percentage of renewable electricity increases drastically within the planning period under the *Sufficient Budget* case, whether under a *Target* or the *No Target* policy (from 33.1% in 2020 to as high as 72.8% in 2030).

Level of unmet demand

The percentage of unmet demand (i.e. electricity demanded but not met due to insufficient generation capacity) under *Target* and *No Target* policies for the different budget allocations are given in Table 8. As a direct effect of the results on capacity additions from Sub-section 4.1, level of unmet demand is generally higher under the *Target* case than under the *No Target* case. For example, at budget allocation of 0.5% of GDP under the *Target* policy, the level of unmet demand is 6.2% in 2020, reaching 32.2% in 2030 (which is the target due date). Similarly, the level of unmet demand is 3.4% in 2020 and rises to 14.0% by 2030 under the *Target* policy for a budget allocation of 0.75% of GDP. In contrast, the level of unmet demand reduces by more than half under the *No Target* policy for the same budget allocations of 0.5% and 0.75% of GDP from 2021 to 2030. From capacity investment levels of 1.0% of GDP onwards, the level of unmet demand reduces drastically as more generation capacity becomes available. Even then, the levels under the *Target* policy are still more than under the *No Target* policy.

Graphs comparing levels of unmet demand between the *Target* and the *No Target* policies at the sub-target due dates are shown in Fig. 4. In conclusion, Table 8 and Fig. 4 make it clear that in order to keep unmet demand at a reasonable level, Ghana might need to have in place an amount of not less than 1% of GDP towards financing new generation capacity if it were to follow through with its 10% renewable electricity target policy. Note that without the renewable target in place, an equivalent budget allocation of 0.75% of GDP guarantees reasonably low levels of unmet demand comparable to a developing country such as Ghana. The 0.75% GDP is of particular interest since it closely matches the required investment for the trend of additional generation capacity needs reported in the annual electricity supply plan of Ghana (based on investment cost of a natural gas generation plant).

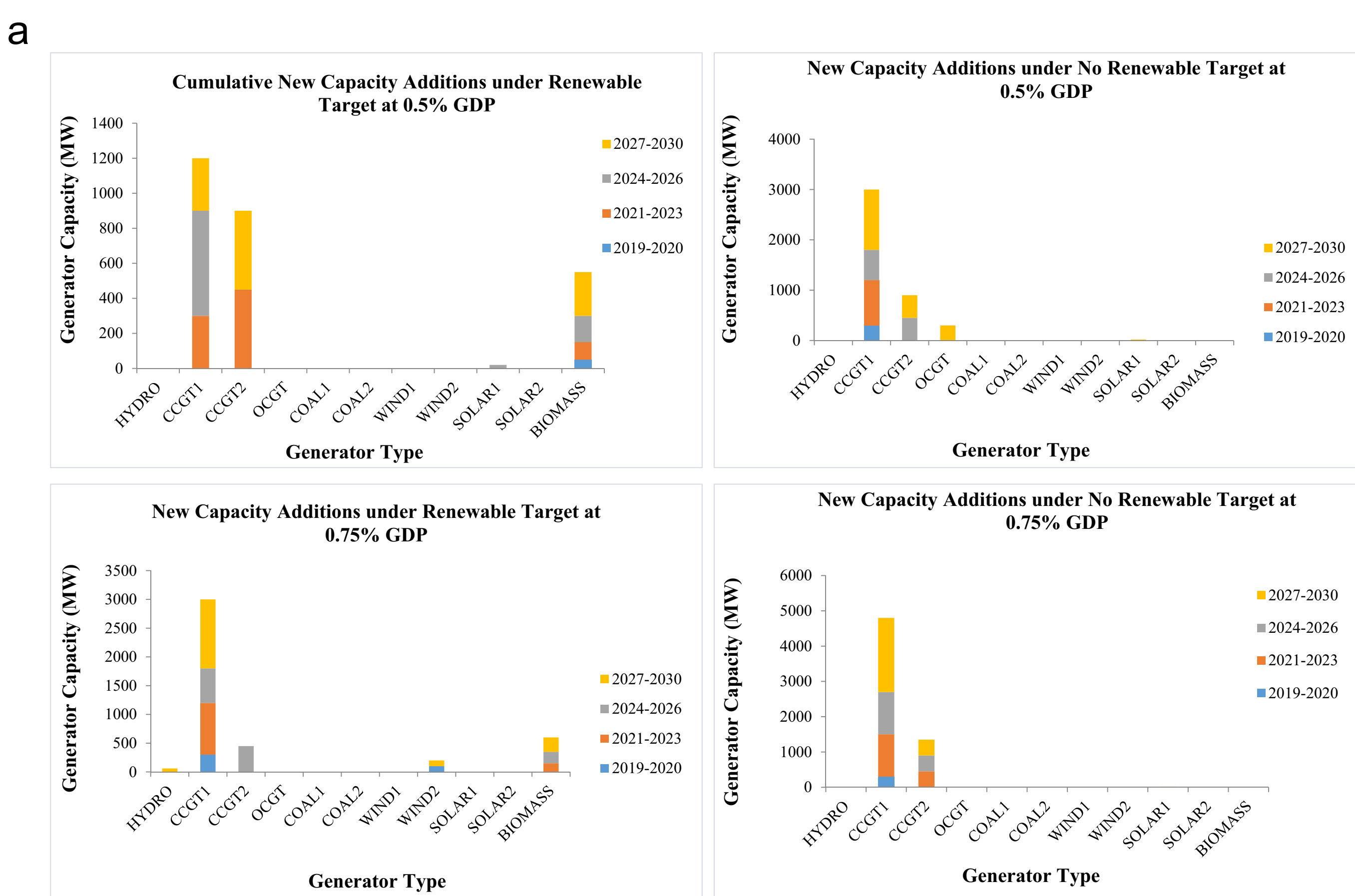

Fig. 3. a. Cumulative capacities of recommend new generator types during the sub-target years of 2020, 2023, 2026, and 2030 under both *Target* and *No Target* policies for generation capacity investment equivalent of 0.5% and 0.75% of Ghana's annual GDP. b. Cumulative capacities of recommend new generator types during the sub-target years of 2020, 2023, 2026, and 2030 under both *Target* and *No-Target* policies for generation capacity investment equivalent of 1.0%, and 1.25% of Ghana's annual GDP. c. Cumulative capacities of recommend new generator types during the sub-target years of 2020, 2023, 2026, and 2030 under sufficient budget for generation capacity investment. The graph is the same under both *Target* and *No Target* policies.

b

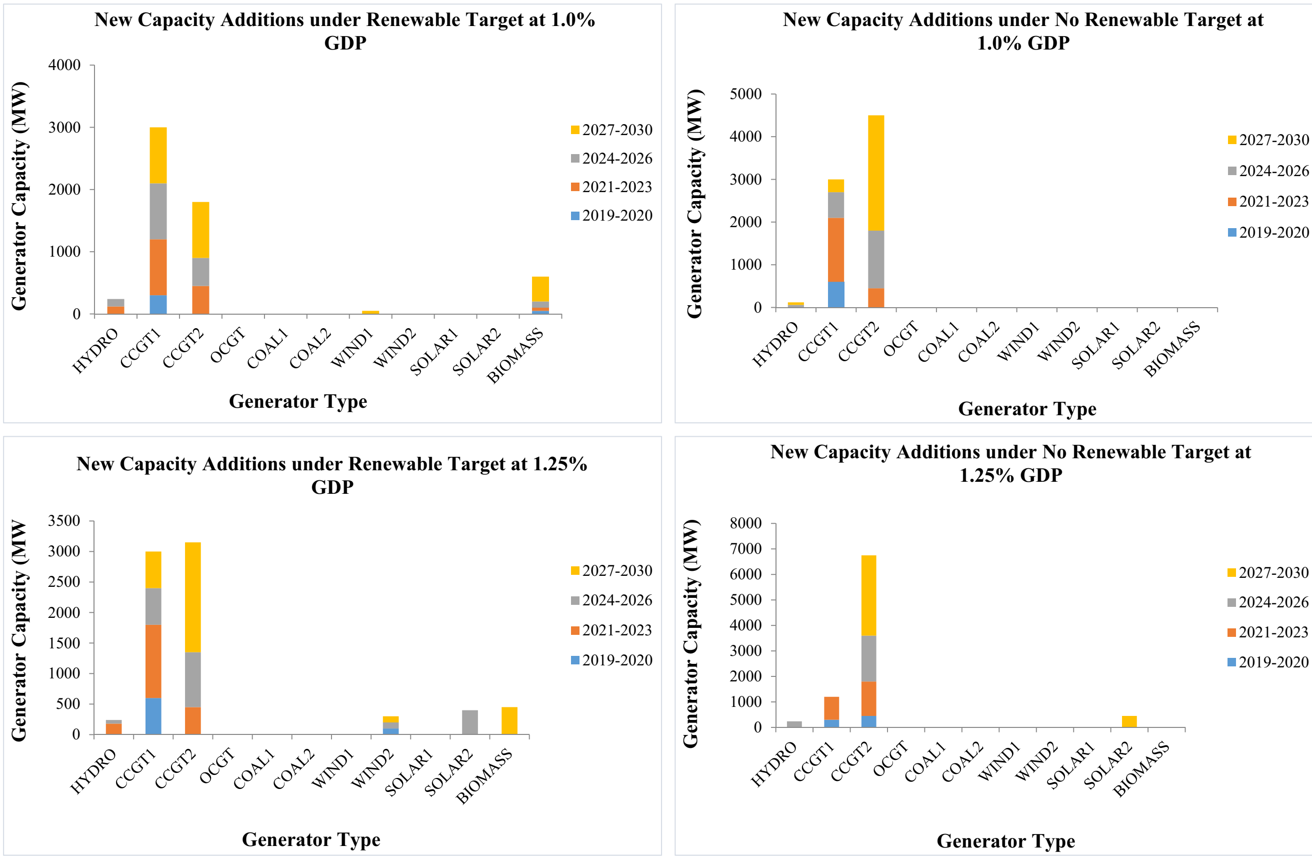

Fig. 3 (*continued*).

Cost of electricity provision

The total cost of providing electricity within the planning period under both the *Target* and the *No Target* policies for the four budget allocations, and when there is sufficient budget are presented in Table 9. The term *Total Cost* gives the total cost of electricity provision (including cost of unmet demand) for the *Target* and *No Target* policies. The annual expenses for capacity investment was not considered in the *Total Cost* analysis since it is meant (in theory) to be recovered by the end of the plant's life through the capacity charge component in the objective function. A plot of the total costs for the selected budget allocations, and under sufficient budget is shown in Fig. 5. It can be seen that total cost of electricity provision is higher under the *Target* policy than under the *No Target* policy under all budget allocations, signifying an increase in cost for the 10% electricity generation target policy. The term *Extra Cost for Enforcing the Target* gives the difference between the total cost of electricity provision under the *Target* and *No Target* policies. These are extra cost incurred for enforcing the renewable target policy. The extra cost in an annual basis using the discounted rate of 12% per year is also given in column 5 of Table 9. It can be observed that the extra costs are significant enough to

c

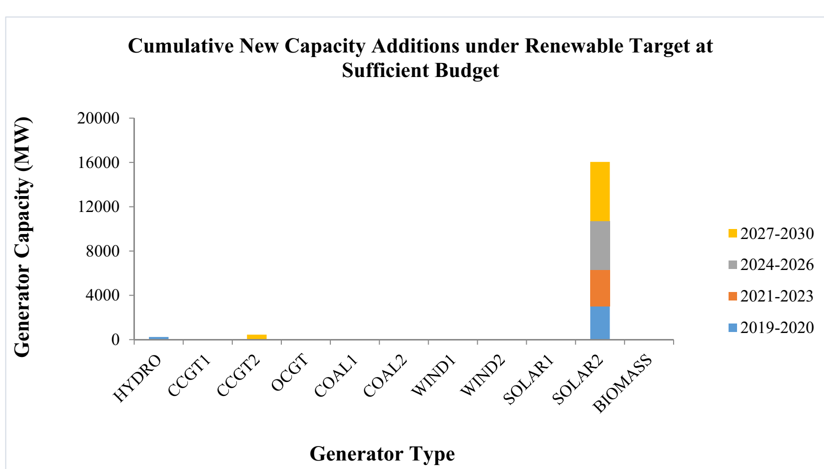

Fig. 3 (*continued*).

Table 7
Percentage of electricity generation from renewable generators at sub-target due dates when a 10% renewable electricity generation target is enforced (*Target*), and when not enforced (*No Target*) at annual capacity addition funds of 0.50%, 0.75%, 1.0%, and 1.25% of Ghana's GDP.

Year	0.5% of GDP		0.75% of GDP		1.0% of GDP		1.25% of GDP		Sufficient budget	
	Target achieved (%)		Target achieved (%)		Target achieved (%)		Target achieved (%)		Target achieved (%)	
	Target	No target	Target	No target	Target	No target	Target	No target	Target	No target
2020	1.7	0.4	1.3	0.4	1.7	0.4	1.2	0.4	33.1	33.1
2023	4.0	0.3	4.1	0.3	4.5	0.3	4.2	0.3	50.3	50.3
2026	7.0	0.3	7.0	0.3	7.2	1.1	7.2	3.7	66.1	66.1
2030	10.0	0.3	10.1	0.3	10.3	1.5	10.6	4.7	72.8	72.8

Table 8
Percentage levels of unmet demand when a 10% renewable electricity generation target is enforced (*Target*), and when not enforced (*No Target*) at annual generation capacity addition funds of 0.50%, 0.75%, 1.0%, and 1.25% of Ghana's GDP.

Year	0.5% of GDP		0.75% of GDP		1% of GDP		1.25% of GDP	
	Target	No target	Target	No target	Target	No target	Target	No target
2019	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2020	6.2	3.7	3.4	3.7	3.4	2.6	2.5	2.1
2021	5.6	2.8	2.4	0.8	0.5	0.4	0.2	0.1
2022	5.8	4.4	1.3	0.8	0.0	0.0	0.0	0.0
2023	19.1	6.5	5.3	1.4	1.5	0.4	1.0	0.0
2024	13.1	7.9	4.5	2.2	1.0	0.1	0.1	0.1
2025	13.7	8.6	4.0	1.5	0.7	0.0	0.0	0.0
2026	27.0	10.8	11.3	1.8	3.9	0.5	1.8	0.2
2027	18.2	9.4	5.4	1.3	1.1	0.0	0.0	0.0
2028	20.0	11.6	6.4	1.8	1.2	0.0	0.0	0.0
2029	23.5	12.4	9.3	2.3	1.9	0.0	0.0	0.0
2030	32.2	14.6	14.0	2.3	4.0	0.0	0.6	0.0

discourage a developing country from attempting to increase the renewable content of its electricity consumption. However, it can also be seen that the total cost (and also extra cost) decreases with increasing budget allocations.

The last row of Table 9 gives the cost of electricity provision when there is sufficient financial resource to finance new generation capacity additions. In this case, the cost of electricity provision is the same under both the *Target* and *No Target* policies. However, this cost is less than that of 1.25% GDP budget allocation. The difference is as high as US $1396.9 Billion and US$1167.6 Billion when under the *Target* and *No Target* policies respectively over the planning period. This translates to a savings of US$225.5 Million and US$188.5 Million annually over the 1.25% GDP budget allocation. These savings are realized partly from the zero operational cost of the massive renewable energy generators recommended under sufficient budget. However, note that this can only be realized if one can source the enormous financial resources needed to purchase the needed capacity to meet the expected demand. In 2020 for instance, the capacity financing required will be almost US $2.54 Billion, roughly 3.8% of Ghana's projected GDP used in this study.

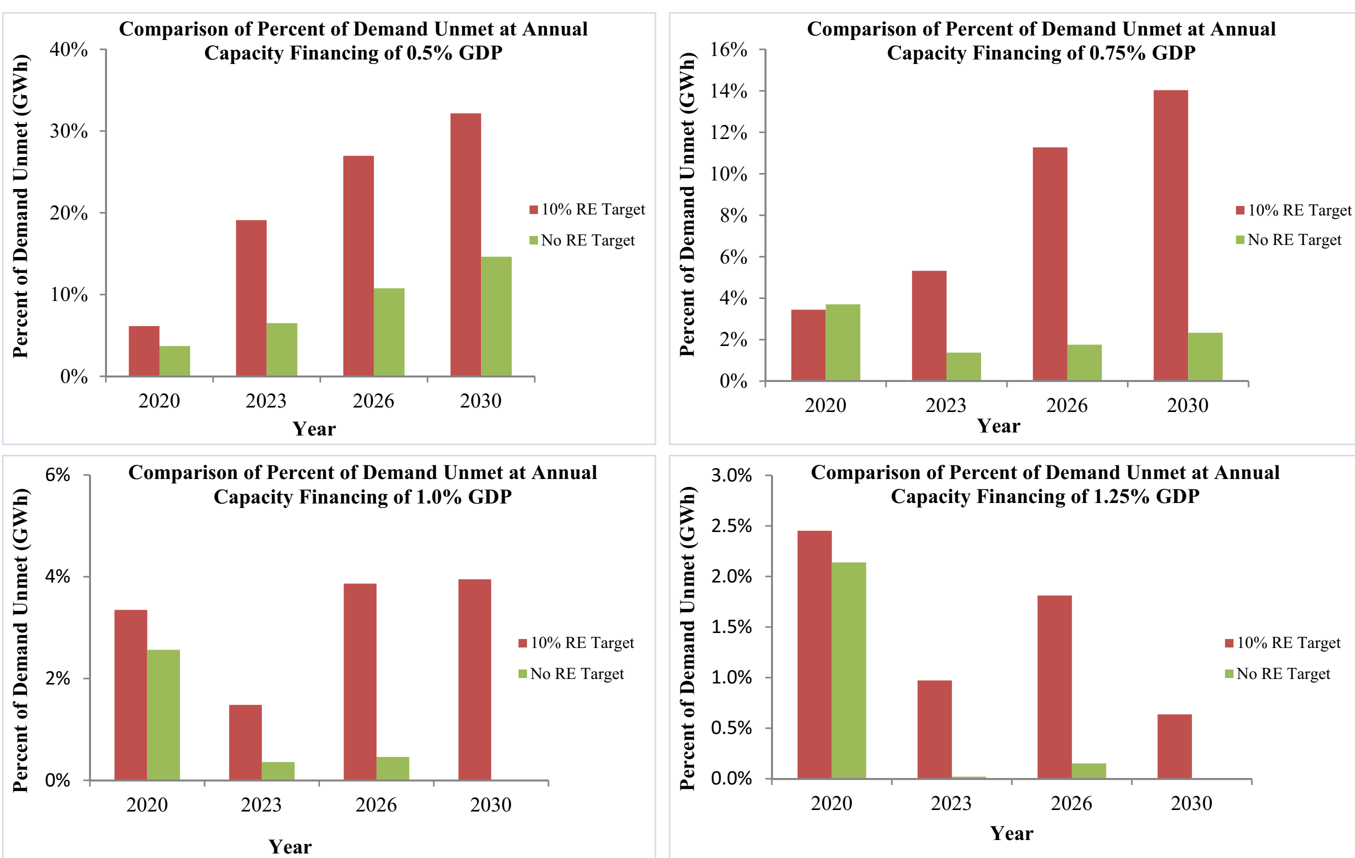

Fig. 4. Comparison of percentage levels of unmet demand when a 10% renewable electricity generation target is enforced (*Target*), and when not enforced (*No Target*) at annual capacity addition financing budget of 0.75%, 1.0%, 1.25%, and 1.5% of Ghana's GDP during the sub-target years of 2020, 2023, 2026, and 2030.

Table 9
Cost of electricity provision when a 10% renewable electricity generation target is enforced (*Target*), and when not enforced (*No Target*) at annual capacity addition funds of 0.50%, 0.75%, 1.0%, and 1.25% of Ghana's GDP, and at sufficient budget, during the planning period from 2019 to 2030.

Annual capacity financing	Total cost (millions)		Extra cost for enforcing target (millions)	
	Target	No target	From 2019 to 2030	Annual
0.5% of GDP	$16,262.24	$14,639.91	$1622.33	$261.90
0.75% of GDP	$14,035.56	$12,648.40	$1387.16	$223.94
1.0% of GDP	$12,389.61	$11,663.64	$725.97	$117.20
1.25% of GDP	$11,446.86	$11,217.63	$229.24	$37.01
Sufficient budget	$10,050.00	$10,050.00	$0.00	$0.00

In summary, and according to current cost figures, the cost incurred for transitioning from conventional energy to renewable energy is manageable if a country has sufficient financial resources for generation capacity investment. This is not a surprise, since the main hindrance to renewable energy adoption is capital cost. This also supports the evidence on the ground where (perhaps with the exception of Brazil and India), it appears that the countries making significant headways in the energy transition process are those having relatively stronger economies (e.g. Germany, United States, China, and countries from the European Union).

Conclusion and policy implications

This paper developed an electricity Generation Expansion Planning (GEP) model for the setting of renewable electricity generation target in developing countries. To do this, two important constraints in the form of a target on the percentage of electricity generation from renewable energy sources, and a limit on funds for new generation capacity investments were incorporated into a standard GEP model. The model was developed in the form of a multi-period stochastic mixed integer linear program (MILP) to allow for long-term planning as well as to account for uncertainty in model parameters (electricity demand and fuel price). Additionally, the objective function was designed to help determine cost of electricity provision, including cost of unmet demand when a renewable electricity target is adhered to.

Applying the model to the case of Ghana's 10% renewable electricity target policy, revealed insightful lessons. First and foremost, the cost of electricity from some renewable generators are on the whole cost

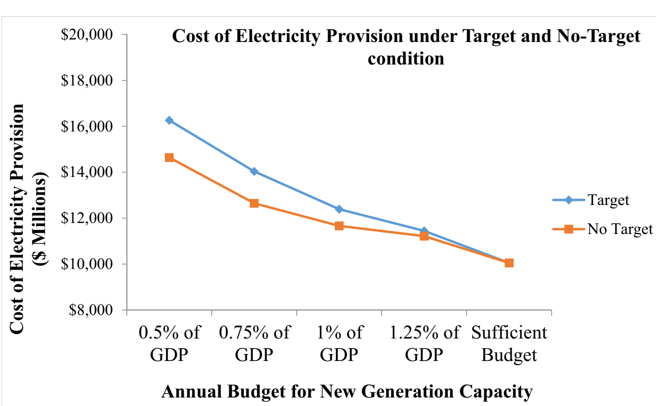

Fig. 5. Plot of cost of electricity provision under a 10% renewable electricity generation target and under a no target policy at annual generation capacity addition financing budget equivalent to 0.5%, 0.75%, 1.0%, and 1.25% of Ghana's GDP, and at sufficient budget, during the planning period from 2019 to 2030.

competitive with conventional energy generators. This is in agreement with the current Levelized Cost of Electricity (LCOE) estimates from the International Renewable Energy Agency (IRENA). However, this is only true when there is sufficient financial resource available to fund the needed generation capacity. Otherwise, if unable to raise such funds, one risk facing high levels of unmet demand (due to capacity shortages), as well as increase in cost of electricity provision when factoring in economic losses due to unmet demand. In the case of Ghana, it might need to allocate at least 1.0% of its GDP (which is approximately 25% increase of current annual capacity addition expenses) to capacity financing in order to meet its 10% renewable electricity generation target by 2030. This is the only way possible if it wishes to keep levels of unmet demand and cost of electricity provision at reasonable levels. Sticking to current expenditure levels while attempting to achieve the target can lead to levels of unmet demand that could be as high as 14% in 2030, and cost of electricity provision rising by as much as $224 million per year. It is therefore not a surprise that Ghana has not been able to achieve even 0.3% of its original 10% target set for 2020 (now scheduled to 2030). In sum, any developing country contemplating on increasing the share of renewable electricity in its electricity supply mix must be adequately prepared to increase the amount it spends on financing new generation capacity additions.

The second insight follows from the first, which is that, without enough financial resources the only way for developing countries to improve their already low electricity access rate, as well as meet the increasing growth in electricity demand is to, rather unfortunately, continue to use conventional energy sources. This places developing countries at a disadvantage in the world's quest to transition from fossil fuel based energy to renewable energy.

This paper contributes to literature, particularly in the research area of energy transition by providing a unique GEP model for the setting and evaluation of a renewable electricity generation target policies. The paper also provides a cost-benefit analysis procedure for estimating the additional cost or benefit related to the cost of electricity provision for a proposed renewable electricity production target.

The proposed GEP model also offers a number of practical contributions. The model can be used to search for the reasonable target that is commensurate to a country's financial position, and the level of unmet electricity demand and extra cost it is willing to tolerate. Such a target will have a high chance of being achieved. Similarly, for a proposed target in mind, the model will allow for the assessment of the financial commitment needed, and the expected level of unmet electricity demand and cost of electricity provision. The special features of the proposed model not only fits electricity planning practices in developing countries, but also brings to bare matters of greater concern in these countries as far as energy transition is concerned - the inclusion of a budget constraint captures the struggle to raise the needed capital for new generation capacity, whereas the provision for the estimation of level of unmet energy helps to foresee the impact on the already dire levels of unmet demand. Finally, the model's output in terms of the recommended generator types, their size, and timing will serve as a guide for cost-effective electricity planning towards the achievement of a planned renewable electricity target.

A limitation of this research is that due to the unavailability of local cost data, most plant costs were taken from international reports such as the Energy Information Administration of the U.S. Plant costs data such as capital cost, fixed cost, and operational cost tend to be higher in developing countries than in the U.S., and could lead to higher electricity cost overall. Yet, we also note that renewable energy auctions in some countries such as South Africa have led to the procurement of renewable energy capacities at competitive and at times, much lower costs than previously assumed (Eberhard, 2013). Thus, obtaining credible local plant cost data is important for policy analysis using the proposed model.

A potential related future work could look into directly modeling the intermittency of the energy sources for the renewable generators to estimate the level of back-up capacity needed to prevent system failure.

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 A. A description of the estimation of the marginal cost of fuel for electricity generation, and plots of cumulative capacities of recommend new generator types for electricity generation

Table A.1
Summary of electricity price estimation for coal, natural gas, and biomass.

Fuel	Price estimation	Explanation and conversion to $/MWh
Coal prices ($/tonne)	27 + 101 ∗ BETA (0.655, 0.848)	There is a proposed 700 MW coal plant project between government of Ghana and Shenzhen Energy group of China. A Chinese company will build the proposed coal plant: therefore, coal price (in $/tonne) data from 2000 to 2016 were obtained from the BP Statistical Review of World Energy (2017) using the China Qinhuagdao coal prices (which includes delivery price). Using the Arena Input Analyzer, the best distribution fit for coal price was a Beta distribution of the form *27 + 101 ∗ BETA (0.655, 0.848)*. This value is then converted to $/MWh by multiplying by 0.538.
Gas prices ($/MMBtu)	Market Price: 2 + GAMMA (1.89, 1.28) Delivery: 4.8	The natural gas price is made up of two components; market price and delivery cost. The market price component was derived based on the Henry Hub monthly natural gas prices from 1997 to 2017 (EIA, 2017). Using the Arena Input Analyzer, and the annual average of the monthly prices, the best distribution fit for the market price was a Gamma distribution of the form *2 + GAMMA (1.89, 1.28)*. The delivery cost is based on data from the Ghana Energy Commission and was taken to be $4.8/MMBtu. The total estimated price was then converted to $/MWh by multiplying by an amount of 6.6.
Biomass prices ($/MWh)	NORM (50, 5)	Biomass prices were assume to follow a normal distribution with a mean of $50/MWh and a standard deviation of $5/MWh based on projected imported biomass feedstock prices for the UK heat sector (E4tech, 2010).

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