Analyses of optimum generation scenarios for sustainable power generation in Ghana

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Abstract: This study examines optimum generation scenarios for Ghana from 2010 to 2040. The Open Source Energy Modelling System (OSeMOSYS), an optimisation model for long term energy planning, which is integrated in Long-range Energy Alternatives Planning (LEAP) tool, was applied to model the generation system. The developed model was applied to the case study of the reference scenario (OPT) which examines the least cost development of the system without any shift in policy. Three groups of policy scenario were developed based on the future possible energy policy direction in Ghana: energy emission targets, carbon taxes and transmission and distribution losses improvements. The model was then used to simulate the development of technologies in each scenario up to 2040 and the level of renewable generation examined. Finally, cost benefit analysis of the policy scenarios, as well as their greenhouse gas mitigation potential were also discussed. The results show that: suitable policies for clean power generation have an important role in CO_2 mitigation in Ghana. The introduction of carbon minimisation policies will also promote diversification of the generation mix with higher penetration of renewable energy technologies, thus reducing the overall fossil fuel generation in Ghana. It further indicated that, significant greenhouse emissions savings is achieved with improvement in transmission and distribution losses.

Keywords: generation; Ghana; greenhouse gases (GHG); LEAP; optimisation; renewable energy

1. Introduction

Ghana faces serious energy related challenges as the country struggles to meet generation requirement. Inadequate expansion plan of the generation system has resulted in (the current) a situation where 65% of the demand is met as at March 2014 [1]. The electricity supply system of the country is characterised by power outages, which has serious implications on the quality of life as well as industrial development. Reliable and affordable electricity generation is an indispensable commodity in the development of any country [2]. This is particularly important especially with the recent development of the country's oil and gas industry, which has a high potential in attracting investors to an expected oil and gas driven economy.

The generation system of Ghana has relied heavily on hydropower for many years. This high hydropower dependence makes the generation system to be influenced by seasonal cycles. Occasional cases of prolonged dry seasons coupled with insufficient rainfall during the raining seasons have resulted in blackouts and power rationing as experienced in 1984 due to the severe drought conditions of 1983 [3]. Thermal power generation was introduced to supplement the conventional Hydroelectricity after the drought in 1983 underscored the need to diversify the country's generation system. The introduction of Thermal power generation occurred in 1997 with the construction of a combined cycle power plant with an installed capacity of 330 MW at Aboadze near Sekondi-Takoradi. The Takoradi Thermal Power Station (TAPCO), as it is officially called, was eventually expanded to 550 MW with the addition of 2 × 110 MW combustion turbine plants in 2000. This marked the beginning of a gradual shift to thermal generation in the country. The installed capacity as at March 2014 was 2851 MW which was made up of 1580 MW (55.4%) from the three hydro dams, 1248 MW (43.77%) from Thermal plants and only 2.5 MW (0.09%) from photovoltaic plant [1]. Volta River Authority (VRA), operates all the plants except Bui, which is operated by Bui Power Authority (BPA). VRA and BPA are both government agencies. Sunon-Asogli and Cenit energy are private entities which contribute about 11.61% of the installed capacity [1]. The additions of these thermal plants, however, have not fully solved the energy supply situation, as load shedding has persisted within the last decade [4].

An analysis of the trend in expansion shows that Ghana is gradually shifting to a predominantly fossil-fuelled thermal generation. However, the adverse environmental and societal impacts and fluctuation in the prices of fossil fuels in the world market has necessitated the exploitation of sustainable power generation technologies. These technologies include renewable energy sources such as hydroelectricity, solar energy, wind, wave energy, bio-energy and geothermal energy. Renewable energy sources are naturally replenished at rates that far exceed their consumption. Ghana is endowed with several renewable energy resources, which can be exploited to help meet its energy requirements. There is an excellent solar radiation all year round, and in every part of the country, with an average radiation of about 5 kWh/m^2. Sites suitable for medium and small hydro power plants have also been identified in various part of the country with a potential of adding over 900 MW to the national grid if fully exploited. Sites near the coastal parts of the country have been mapped with excellent conditions for wind generation [5]. The country also has a huge potential for biomass and waste to energy generation [4].

The main challenge with the implementation of renewable energy systems especially in developing countries such as Ghana has been their high initial capital investment. However, it is expected that advancing scientific knowledge will lead to performance improvements and cost reductions of these technologies in the future. The average cost of installing commercial PV systems for instance, fell from about 9.00 US $/watt in 2002 to 5.00 US $/watt in 2012 [6]. This cost reduction is attributed largely to the fast decline in PV modules cost, which reduced by about 85% to 0.8 US $/watt within the same period [6]. Investment decisions and policies to promote renewable energy system will encourage a more rapid development of these generation systems.

The sustainable energy decision-making is often unique and depends on the circumstances of each planning area. Most studies on the generation system of Ghana have only focused on assessing the renewable potential of Ghana. The energy commission of Ghana has projected demand and supply scenarios for Ghana up to 2020, and their report presented as part of the Strategic National Energy Plan of the country [7]. This report was carried out in 2006 and hence does not fully account for current trends. The analysis does not also consider the impact of future policies or the effect of greenhouse gas emissions. Provisions were not also made to identify least cost options for future generation.

The LEAP tool was applied in [8] to analyse the current generation expansion plan of Ghana and to discuss alternative approaches, pointing out the impact on the environment by different generation systems.This current study aims at developing least cost generation pathways for the generation system of Ghana making use of the available technologies and policy drivers as well as challenges in Ghana. Good decisions, concerning the best choice of technologies for future years, will avoid expensive changes in later years. This study will provide a useful insight to guide energy planers and policy makers by providing policy impact assessment of the optimum generation system of Ghana.

2. Materials and Method

2.1. LEAP/OSeMOSYS optimization model

The Long-range Energy Alternatives Planning (LEAP) system, version 2015.0.30.0 was applied to determine the optimal expansion and dispatch of power plants for Ghana from 2010 to 2040. LEAP is a hybrid energy modelling tool which supports a wide variety of methodologies [9]. The optimisation function in LEAP is performed through integration with Open Source Energy Modelling System (OSeMOSYS) which depends on the GNU Linear Programming Kit (GLPK), for solving large linear programming problems [9]. OSeMOSYS is transparent and straight-forward energy modelling tool which allows for simple refinements for sophisticated analysis [10]. OSeMOSYS model compared favourably when validated with established but not freely available MARKAL/TIMES model [10]. LEAP interface with OSeMOSYS provides a transparent connection which enables LEAP to automatically write data files needed for OSeMOSYS. This enables LEAP users to perform optimisation without directly interacting with OSeMOSYS or GLPK [9].

The LEAP model developed by Stockholm Environmental Institute (SEI) is a widely used energy modelling tool for energy policy analysis and Greenhouse gases (GHG) emission mitigation studies, especially in developing countries. The model was adopted for analysis of alternative scenarios and their implications on the electricity sector of Lebanon [11], for examining high levels of renewable energy technologies in Ireland [12] and most recently, for assessing policies aimed at promoting low carbon development in Nigeria [13]

The objective function of the OSeMOSYS model is to estimate the generation system to meet demand by minimising the total discounted cost [14]:

$$[\, Minimise \sum_{y}\sum_{t}\sum_{r} TC_{y,t,r} = OC_{y,t,r} + CC_{y,t,r} + EP_{y,t,r} - SV_{y,t,r}, \forall y,t,r \,] \qquad (1)$$

Where, TC_{ytr}, $OC_{y,t,r}$, $CC_{y,t,r}$, $TEP_{y,t,r}$, $SV_{y,t,r}$ represents discounted total cost, operating cost, capital cost, technology emission penalty and salvage value respectively. y, t, r, are the year, technology and region indexes respectively. A full description of LEAP methodology is presented in [9].

2.2. Development of Ghana LEAP model

The Ghana LEAP model was designed with 2010 as the base year, to analyse the possible developmental structure of the generation system of Ghana up to 2040. The choice of this base year was due to availability of data on the national census conducted by the Ghana Statistical Service and a national energy survey by the Ghana Energy Commission which were conducted in 2010, providing reliable data for the model. The selection of 2010 also provided opportunity to validate the results with real data for the past years (2010 to 2015).

The Bottom-Up methodology in LEAP was adopted to model the future energy demand. The population of Ghana in 2010 was 24.7 million people which, was projected to be increasing at a growth rate of 2.4% [15]. In 2010, 83.8% of the urban households had access to electricity. Urbanisation in 2010 was 55.8%, which is expected to increase to about 60% by 2040 [15]. Microeconomic input data was taken from Ghana statistical service [16]. The Gross Domestic Product (GDP) growth rate of 8% was used for base case load projection from 2010 to 2020, increasing to 12% from 2020 to 2040 when the power supply is expected to improve. The energy intensity data used for the model was developed from an energy consumption survey conducted by the Energy Commission of Ghana in 2010 [1]. A real discount rate of 10% was assumed, consistent with West Africa Power Pool generation and transmission master plan recommendations [17].

The dependent installed capacity of Ghana in 2010 was 1865 MW consisting of two large hydro dams with a total capacity of 1040 MW with the remaining contribution from six thermal power plants. To model the generation system, the various generating plants were aggregated. This means that single hydro and thermal plants were modelled to represent the system. The maximum capacity addition was assumed based on Ghana Grid Company (GRIDCO) [18] recommendation to ensure stability of the grid, while the maximum availabilities of the Non-Conventional Renewable Energy Technologies were assumed based on the confirmed available resources [5, 7].

The technology cost data was adopted from International Energy Agency [19], National Renewable Energy Laboratory [20] and GRIDCO [18]. The future year investment cost of the conventional energy systems in Ghana (large Hydropower and thermal power) were assumed to be constant throughout the study period while that of renewable systems were assumed to decrease per projections presented in [19]. The prices of fossil fuel resource are particularly very difficult to predict because of its high price fluctuations in the world market. However, the bench-mark fuel price projections in [21] were considered as the most reliable assumptions and hence adopted for this paper.

2.3. Description of scenarios

The scenarios developed are based on cost minimisation with the aim of exploring the potential diversification of the generation system using renewable energy technologies. The scenarios are categorised under four main themes: Reference Scenario (Ref), Carbon Tax scenarios, Energy Efficiency Scenarios and Transmission and Distribution losses scenarios. The policy scenarios are all variations of the Ref scenario under the various constraints described under each scenario. The scenarios represent possible future paths for promoting renewable power generation in Ghana by considering the factors most likely to influence future RET policies in the country. Table 1 show the key elements of the reference and the alternative scenarios.

Table 1. Overview of reference and alternative scenarios.

Reference	**Emission Targets**	**Carbon tax**	**T&D**

Driving philosophy	Follows continues trend in existing energy policies	Inspired by clean technologies and increasing resistance from residents and environmentalist	Inspired by clean technologies and increasing resistance from environmentalist	Inspired by desire to improve the efficiency of the transmission and distribution system
Demand side	The Bottom-Up demand model approach in LEAP was adopted for modelling the future energy demand. Demand projections to follow official projections [16]. Total demand in 2020 will be 18.88 GWh, increasing to 62.5 GWh by 2040.			
Supply side/ constraints	Least cost development of technologies and dispatch schedule determined by LEAP	Least cost system under emission targets constraints. maximum emission.	Least cost system under emission targets constraints.	Least cost with improvements in transmission and distribution losses.

2.3.1. Reference (Ref) scenario

The Ref scenario is the least cost generation system of Ghana calculated by LEAP/OseMOSYS optimisation model without any policy interventions. LEAP/OSeMOSYS developed the least cost model by deciding both the type and size of technologies as well as the dispatch scheduling. This scenario assumes no shift in policy and serves as the reference for analysing the alternate scenarios.

2.3.2. CO_2 emission reduction target scenarios

Ghana, being a non-annexed I country, has no legally binding emission reduction target in place. Thus, studies evaluating the impact of GHG mitigation are limited in the country. However, the consideration of the impact of GHG by different power generation plants, will lead to a more balanced evaluation of these technologies and will also conform to the Bali road map which underscores the need for developing Non-Annex I countries to introduce mitigation actions after 2012 [22].

The study examines three CO_2 reduction scenarios which were developed making use of the Ref scenario emissions as the benchmark. They are: Low Carbon Emission Reduction (ET), Medium Carbon Emission Reduction scenario (ET1) and High Carbon Emission Reduction scenario (ET2) which impose maximum emission targets of 10%, 20% and 30% respectively, of lower emission targets compared to the optimum scenario. These emission targets were based on the official targets presented Ghana’s intended nationally determined contribution (INDC) as part of the country’s Intended Nationally Determined Contribution (GH-INDC) presented to the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015 [23].

2.3.3. Carbon tax scenario

The Kyoto protocol makes provisions for three market-based mechanisms (Clean Development Mechanism (CDM); Joint Implementation (JI) and Emission Trading (ET), that provide additional means for countries with commitment to achieve their set targets. These mechanisms have resulted in the creation of the “carbon market” which enables international trading of emission target points [24]. CDM specifically targets emission reduction projects for developing countries. CDM allows Annex I countries to participate in the implementation of emission reduction projects in non-annex I countries. These projects are then assessed as supplementary to domestic projects, to help achieve their targets. Ghana can therefore benefit significantly from these mechanisms to help develop its abundant renewable energy resources, if the cost of domestic GHG emission reduction is lower than the global carbon price.

Another important source of funding for renewable energy development is the introduction of carbon tax. High investment cost of renewable energy technologies (RET) has been cited widely as one of the most important obstacles hindering their development in the developing world including Ghana. Additional revenue from the implementation of carbon tax could be applied directly to the development of RET. Introduction of carbon tax will also provide a fair appraisal for assessing the performance of different generation technologies. Therefore, three carbon tax scenarios where explored in this study. Low Carbon Tax (CT) scenario imposes US $10/tonne CO_2 introduced in 2020 increasing to US $20/tonne CO_2 in 2030; Medium Carbon Tax (CT1) imposes US $$30/tonne CO_2 introduced in 2020 increasing to US $60/tonne in 2030; High Carbon Tax (CT2) imposes US $50/tonne CO_2 introduced in 2020 increasing to US $100/tonne in 2030.

2.3.4. Transmission and distribution (T&D) losses scenario

In 2010, transmission and distribution (T&D) losses accounted for about 23% of the total power generation in Ghana, a reduction from a peak of 29% in 2003. However, between 1970 and 2000, these losses varied from 4–11% [25]. The current high T&D losses are due to large non-technical losses (mainly because of theft and non-payment of bills) [7]. The average value of the technical losses (losses due to current flowing through the network) was about 5% between 2010 and 2014 with a long-term projection of 3% [18].

The T&D scenario therefore assumed improvement in the transmission and distribution networks and billing system resulting in reduction in these losses. This was interpolated to reduce to 15% in 2020 and 10% in 2030 in Low Transmission and Distribution scenario (TD). In the Modest Transmission and Distribution scenario (TD1), the T&D losses were interpolated to reduce to 12% in 2020 and 8% in 2030. While in the High Transmission and Distribution scenario (TD2), it was interpolated to reduce to 10% in 2020 dropping further to 5% by 2030.

3. Results and Discussion

3.1. Technical results

3.1.1. Technical results of baseline scenario

The total electricity demand of Ghana increased by about 6 times between 2010 and 2050 (Figure 1). The results of the energy demand projection for Ghana from 2010 to 2040 using LEAP energy demand model is presented in Figure 1. The results show that demand projection will increase into the future with an average demand growth rate of 7% from 2010 to 2040. This growth rate follows the historical demand growth of the country, and are consistent with official load projections [18]

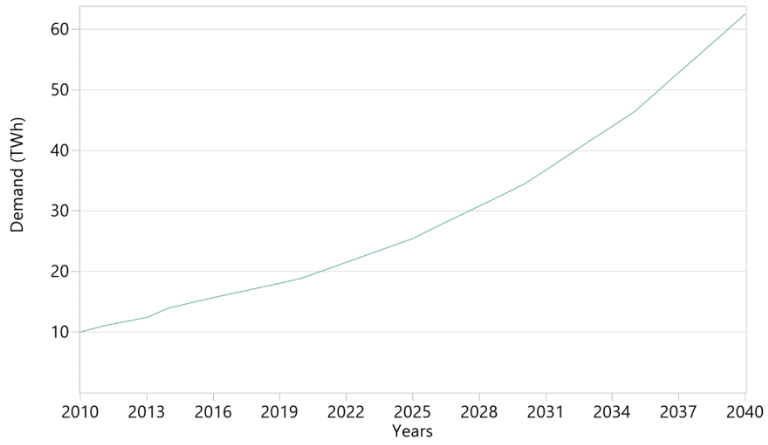

Figure 1. Electricity demand forecast for Ghana.

This implies that without any expansion in capacity, the current generation system will only be able to provide 20% of the demand in 2040. LEAP optimisation algorithm is designed to ensure that supply meets demand requirements. Thus, significant expansion in capacity was predicted in the OPT scenario in order to meet this demand and the 18% reserve margin applied in this study. This value was adopted based on Ghana Grid Company (GRIDCO) [26] recommendation for grid reliability in Ghana.

The Ghana LEAP model predicts a switch from hydropower to thermal generation as illustrated in Figure 2.

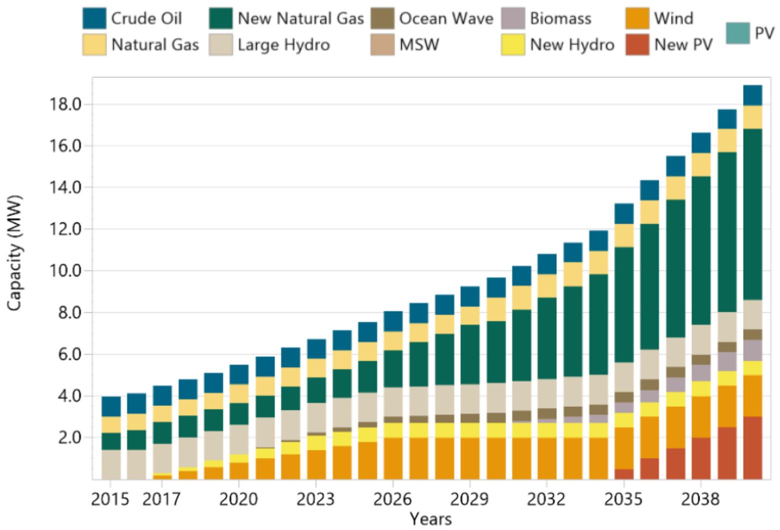

Figure 2. Installed capacity in Ref scenario.

Two main fuel types were considered for the combined cycle thermal generating plants considered in the model. The results show that thermal generation in Ghana will continue to be dominated by natural gas-fuelled systems. Even though the same operating characteristics were modelled for both crude oil and natural gas plants to reflect the co-firing nature of the thermal plants in the country, the model did not consider operating the plants on crude oil as one of the least cost options. This is mainly due to the comparatively higher cost of crude oil. These results give credence to proposals by the Energy Commission Ghana to operate the thermal plants on natural gas when available [7].

Figure 2 also shows the economic competiveness of the Non-Conventional Renewable Energy Technologies (NRET) with the introduction of these systems in much larger quantities from 2016 onwards. The model considered the introduction of wind and small hydro plants in 2016. This means that Wind and Small hydro are the least cost options of the NRET. Wind energy plants capacity increased from 200 MW to its maximum allowable capacity 2025. PV generation plants, which dominated the NRET capacity at the end of the study period, were not considered until 2035, when the model had exhausted the available capacity for wind, hydro and wave generating systems. The model did not however consider Municipal solid waste (MSW) as one of the least cost options for power generation in Ghana due to their extremely high investment cost.

The share of NRET generation in 2010 was 0.059%, which increased to 30% in 2023 because of the introduction of wind and hydro as discussed earlier. This share however, reduced to 25% in 2035, increasing marginally to 27% at the end of the study period with the addition of new PV systems as shown in Figure 3.

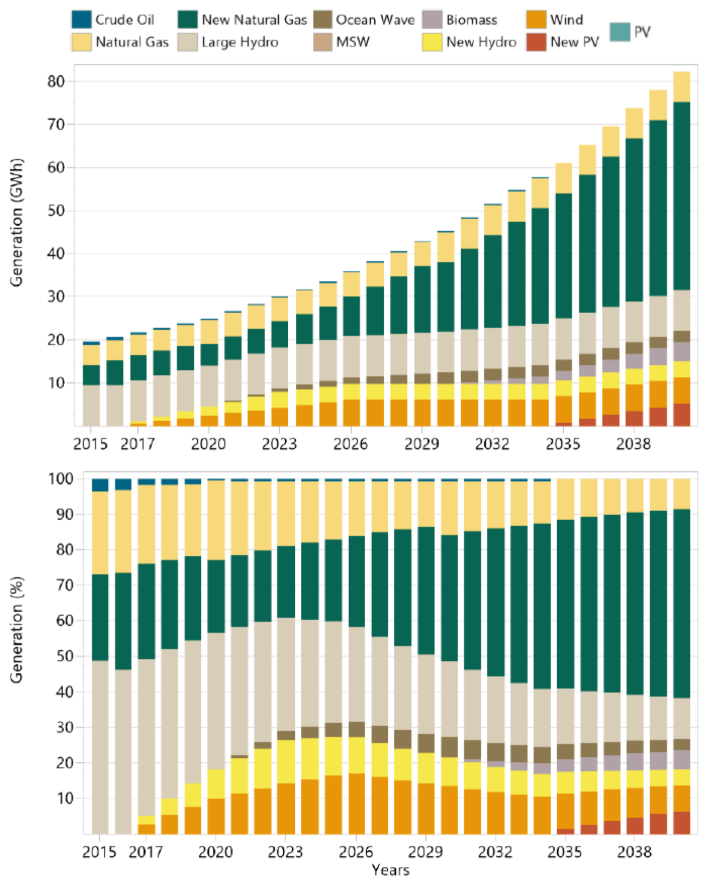

Figure 3. Electricity generation by plant type in Ref scenario.

It is very important to note that the introductions of these NRET were based on their own economic merit. This clearly shows the high potential of diversifying the generation system of Ghana with appropriate renewable energy policies.

3.1.2. Technical results of CO_2 emission target scenarios

The introduction of CO_2 emission targets directly affects the development of clean energy technologies. Figure 4 shows the development of the optimum generation system of Ghana under the three CO_2 emissions constraints. The introduction of these targets resulted in much higher deployment of NRET. Compared to OPT scenario, the model predicted additional 1.5 GW, 3.5 GW and 7 GW NRET generation capacities in the ET, ET1 and ET2 scenarios respectively, by 2040.

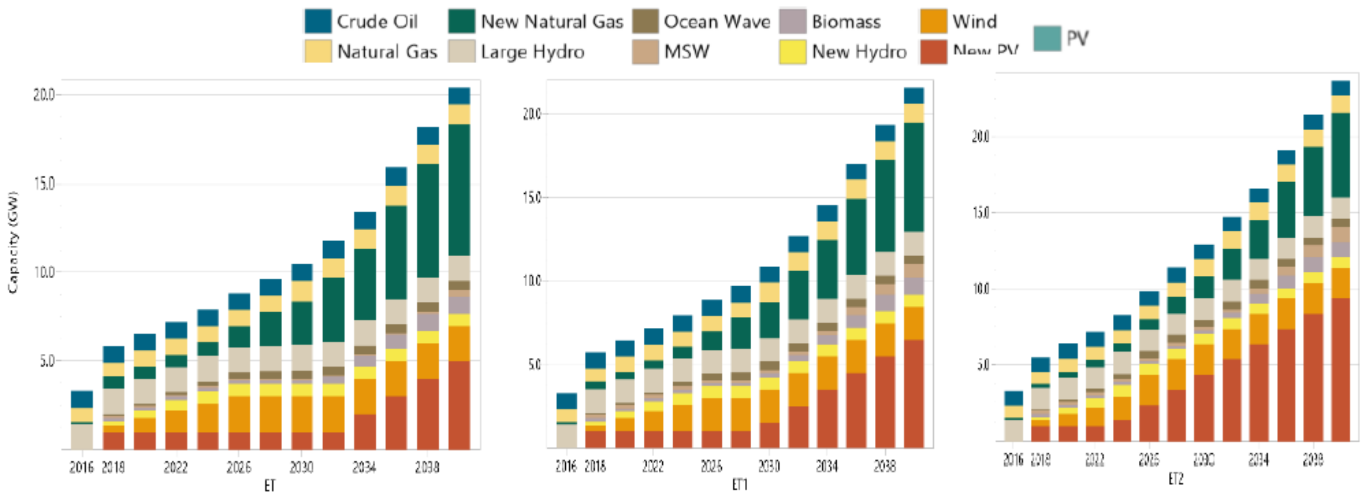

Figure 4. Installed capacity in CO_2 emission target scenarios.

The high NRET have resulted in a total renewable generation capacity share ranging from 54% to 68% with the introduction of 10% to 30% emission reduction targets on the Optimum scenario.

New PV generation plants, which were not considered by the model in the OPT scenario until 2035, are selected at the same time with wind and new hydro plants, with the introduction of carbon emission targets. In the ET scenario, New PV where introduced in 2017 with a capacity of 0.5 GW, increasing to 1 GW in 2018 and remaining constant until 2030, when wind and hydro resources have been fully exploited. The same trend is observed in the ET1 and ET2 scenarios. However, much higher PV capacity addition is achieved with the introduction of high renewable target (ET2 scenario).

MSW plants, which were not selected in the Ref scenario, are forced onto the generation mix with the introduction of carbon tax. MSW generation starts with a capacity of 0.1 GW in 2017, increasing to 0.3 GW in 2040, with a low emission target. Modest and high emission targets will lead to 0.85 GW and 1 GW MSW plants capacity by the end of the study period. The developments of the renewable generation systems have reduced the share of generation from fossil fuel plants. Electricity generation from thermal generation plants in 2040 reduces from 62% in the Ref scenario to between 55% and 42% with the introduction of emission reduction targets as shown in Figure 5.

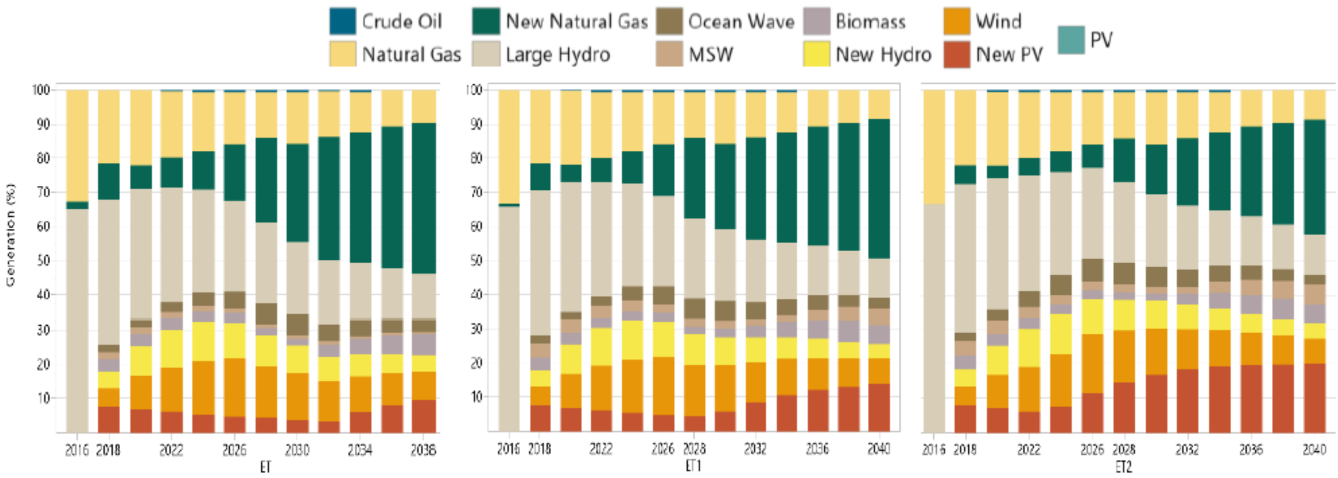

Figure 5. Generation share by plant type in CO_2 emission target scenarios.

This reduction in thermal generation directly reduces the quantity of fuel imports for power generation. This implies that CO_2 targets have a positive impact on energy security of Ghana. The security of the energy system in this case is analysed in terms of self-sufficiency and diversification of energy resources.

3.1.3. Technical results of carbon tax scenarios

The carbon tax scenarios examine the effect of the introduction of carbon tax constraint on the optimum generation system of Ghana developed by the Ghana LEAP model. The study evaluated three tax levels: CT, CT1 and CT2, representing low, modest, and high carbon tax respectively. Figure 6 shows the development of the optimum generation system from 2015 to 2040 under the three carbon taxes constraints.

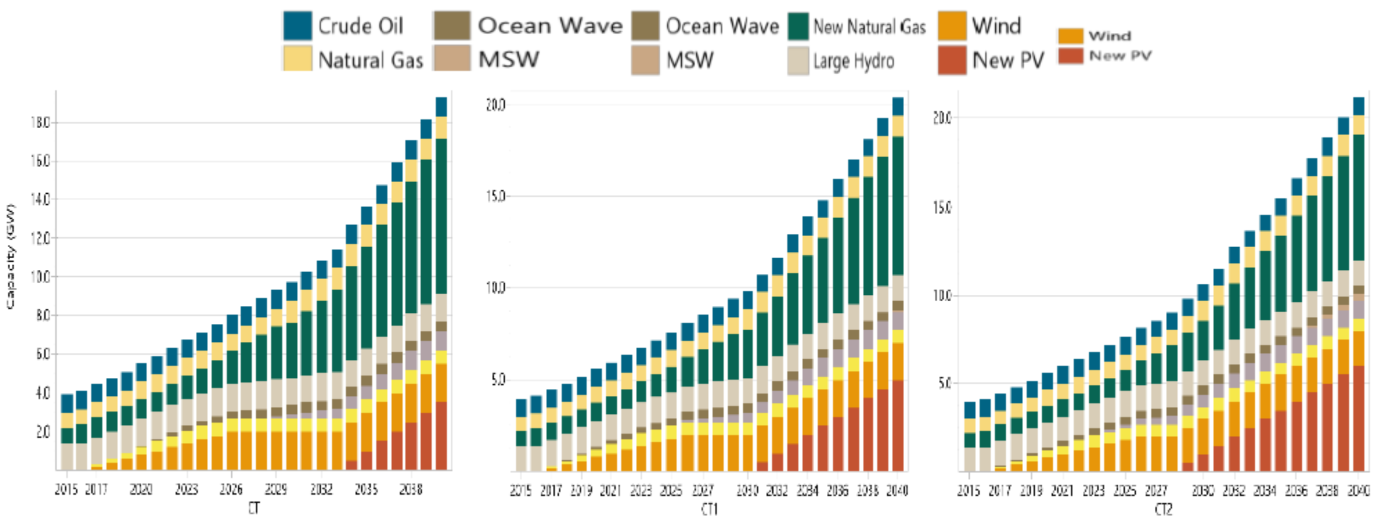

Figure 6. Installed capacity in CO_2 tax scenarios.

It is observed from Figure 6 that the capacity level of the conventional large hydro generation did not change within the study period, however, thermal generation capacity slightly decreases with increase in carbon taxes. The share of thermal plants decreases by about 10% with the introduction high carbon tax (CT2) Scenario. This will result in about 10% savings in fossil fuel requirement for power generation.

Electricity generation from thermal plants reduced by about 17% to 43 TWh in the CT2 scenario compared to the OPT scenario in 2040 as illustrated in Figure 7. On the other hand, generation from renewable sources increased from 32 TWh (38% share of generation) in the BCO to 39 TWh (47% generation share) in CT2 scenario by 2040.

These analyses clearly show that the introduction of carbon tax has direct impact on the development of renewable energy technologies. This is because renewable energy technologies such as wind and PV produce very little to zero GHG emissions. The imposition of carbon tax will affect mainly the cost of production of the thermal plants and thus makes the RET more economically viable.

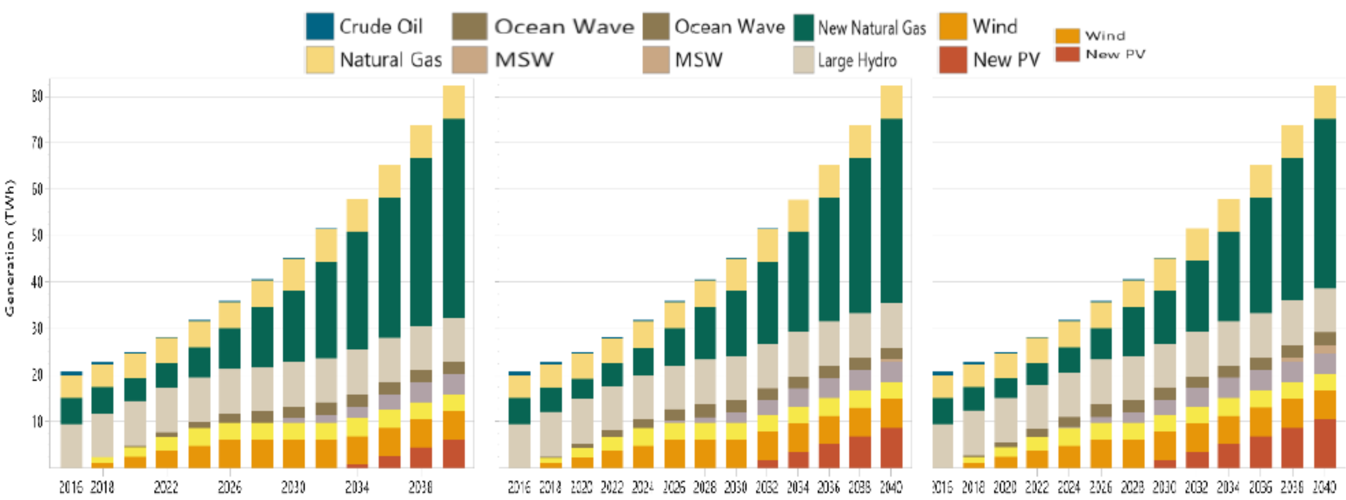

Figure 7. Electricity generation by plant type in CO_2 tax scenarios.

Comparing Figures 2, 4 and 6 shows that both carbon tax and CO_2 emission target scenarios resulted in higher capacities compared to Ref scenario. This is because of their higher renewable energy penetration. The cumulative installed capacities of the CT2 and ET2 scenarios in 2040 are 11% and 26% respectively more than the Ref scenario. These findings are consistent with those of McPherson & Karney [27], which suggest that higher capacities of NRET are required to meet the same demand as thermal plants because of the relatively lower capacity factors of NRET.

3.1.4. Technical results of transmission and distribution losses scenarios

Transmission and distribution scenarios examine the development of the optimum system with the implementation of strategies to improve transmission and distribution losses. As anticipated, improvement in transmission and distribution losses will lead to lower generation requirements. Figure 8 show the development in generation technologies from 2015 to 2040 with improvement in transmission and distribution losses.

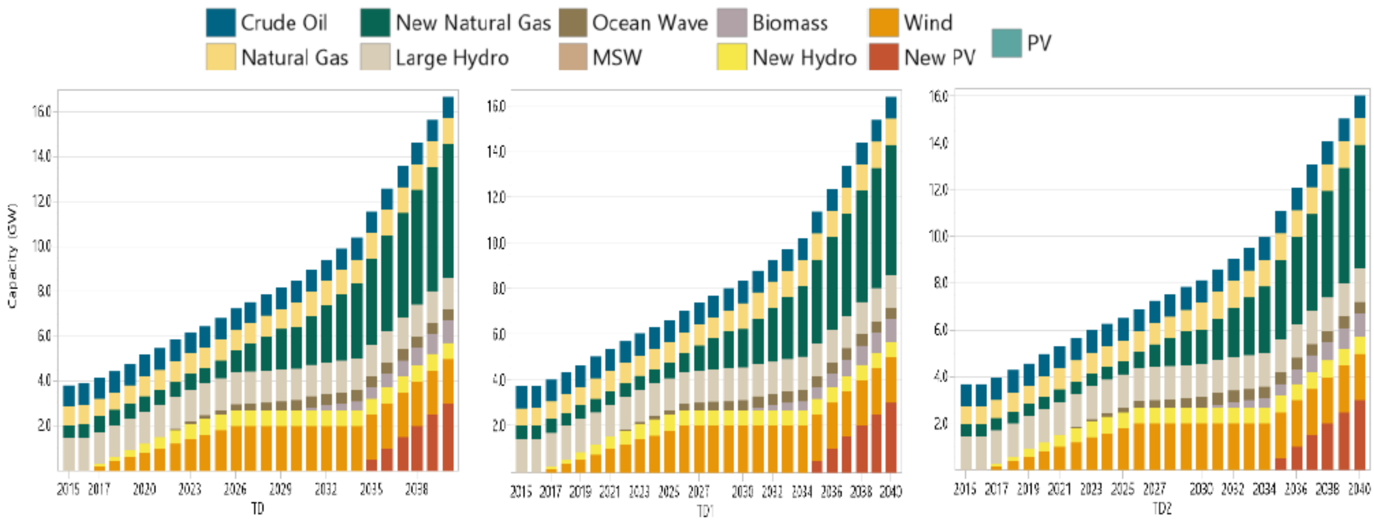

Figure 8. Installed capacity in transmission and distribution losses scenarios.

A reduction of 2000 MW to 3000 MW capacities is achieved depending on the level of transmission and distribution losses improvements, compared to the BCO scenario. This capacity savings is approximately equal to the current (2015) total generation capacity of the country. The development of the generation technologies remains almost the same as that of the BCO scenario. However, much higher renewable generation share of generation is achieve with improvement in transmission and distribution losses.

Ghana electricity generation system has relied greatly on hydropower, and most recently, thermal generation plants. This has resulted in serious power outages and load shedding each time there is insufficient rainfall or inadequate supply of fuel. Introduction of renewable energy policies have resulted in higher diversification of the generation system. The level of energy security of an energy system is improved with higher diversity in energy technologies [14]. These results therefore show that implementation of appropriate renewable strategies will improve the security of the generation system of the country.

3.2. Cost-benefit analysis

The objective of the LEAP/OseMOSYS optimisation is to develop a least cost model of the generation system. Cost-benefits analysis technique was adopted for the economic evaluation of the various scenarios in this study. Cost-benefit analysis is an analytical tool which is used to determine the best possible approach by comparing the cost and benefits of alternatives. In this study, the cost of the system is expressed in terms of Net Present Value of cost of transformation (Investment and Operation and Maintenance cost) as well as resources (fuel cost) over the period of the study discounted at 10% to the base year. Transmission and distribution cost, land use and potential cost of affecting local livelihoods were not considered in this study. This was not only due to lack of reliable data, but also on the scope of this study, which focuses on how the various supply side constraints will influence the development of generation options.

Table 2 presents the results of the cost-benefit analysis provided by the LEAP model. The results compare the cost-benefits of alternative scenarios to Ref scenario. A positive value represents how much more each policy scenario cost compared to the Ref scenario, while a negative number represent benefits.

Table 2. Cumulative costs & benefits: 2010-2040 relative to OPT scenario discounted at 10.0% to year 2010 (billion 2010 USD).

	ET	ET1	ET2	CT	CT1	CT2	TD	TD1	TD2
Transformation	2.2	3	4.3	0.2	0.7	1.2	- 0.6	- 0.7	- 0.8
Resources	- 1.7	- 2.2	- 3.1	- 0.2	- 0.7	- 1.1	- 2	- 2.4	- 2.7
Emission cost				0.3	1	1.5			
NPV	0.5	0.8	1.2	0.3	1	1.6	- 2.7	- 3	- 3.6

It is observed from Table 2 that the cumulative costs of implementing the emission targets and carbon tax scenarios are 0.5 to 1.2 billion USD and 0.3 to 1.6 billion USD respectively, compared to the OPT scenario. This is largely due to the higher capital investment (transformation cost) of RET, which are deployed in much higher capacities. Even though, the constraints on the optimum generation system resulted in savings in the use of resources, these savings were not sufficient to offset the high capital investment.

The introduction of policies to improve transmission and distribution losses to levels proposed in this section will lead to 2.7 to 3.6 billion USD cumulative cost savings over the study period. This significant cost savings is due to the reduction in generation requirement (Figure 7). It should be noted that financial cost in the implementation of measures to reduce transmission and distribution losses were not quantified in this study. This is mainly due to unavailability of reliable information on the topic in Ghana. However, the high savings suggest the need for the country to adopt strategies to reduce these losses. Greater premium should be placed on reducing the non-technical losses, which constitute the bulk of the transmission and distribution losses in Ghana [1]. According to [28], only 50% of the electricity generated in sub-Sahara Africa is paid for. This is attributed to a combination of low percentage of billing electricity injected in distribution networks and low collection of billed amounts. The country should therefore consider the implementation of Advanced metering infrastructure (AMI) for monitoring consumers, the use of temper proof meters and replacement of old meters with accurate electronic meters and frequent energy audits up to the distribution transformer [29]. These measures have proven to be very effective in reducing non-technical losses in North Delhi from 53% in 2002 to 15% in 2009 [29].

3.3. Environmental analysis

The LEAP model contains all Global Warming Potential (GWP) factors, required for environmental assessment. The Forth Assessment Report (AR4) factors were applied in this study in line with Intergovernmental Panel on Climate Change (IPCC) recommendations [30]. Table 3 shows cumulative GHG emissions at points of emissions in the various scenarios.

Table 3 confirms the mitigation potential of the policies evaluated in this study. Significant GHG emission reduction potential of 16 – 37% is achieved with the introduction of CO_2 emission targets. This is because of the relatively higher share renewable generation. The emission targets compelled higher deployment of renewable energy technologies, since they emit low to zero emissions.

Table 3. Cumulative emissions and cost of avoided CO_2 emissions.

Scenario	Cumulative emission (Mt CO_2e)	CO_2e savings (%)	Cost of avoiding GHG (($/tonne CO_2e)
Ref	223		
ET	187	16	13.9
ET1	170	24	15.1
ET2	141	37	14.4
CT	217	3	53.8
CT1	202	9	48.1
CT2	190	15	48.5
TD	168	25	- 48.3
TD1	160	28	- 49.3
TD2	150	33	- 49.1

Table 3 further reveals that introduction of carbon tax at levels proposed in this study will not yield significant GHG emission savings. The cumulative GHG emission savings in the high carbon tax scenario (CT2) compared to OPT scenario was 15%, while that of ET2 and TD2 scenarios were 37% and 33% respectively. These results show that even though costing emissions will increase the operational cost of thermal generation, it does not automatically lead to adoption of renewable energy technologies. There is a tendency by utility providers to transfer this extra cost to consumers. This negative impact of carbon tax can be address with the investment of tax revenue in the development of renewable technologies.

The cost effectiveness of GHG emission was analysed by calculating the cost of avoiding CO_2 emission. Cost of CO_2 avoided is the cost of reducing CO_2 emission to the atmosphere expressed as $/tonne of CO_2 not emitted with respect to the base case scenario. The decision criterion is to identify the least cost alternative in reducing a tonne of CO_2. The results show superior performance of the transmission and distribution losses scenarios in achieving economically efficient CO_2 emission reduction. While all the other policy scenarios resulted in abatement cost, the transmission and distribution losses scenarios resulted in benefits. This is because of the relatively lower demand achieved with the implementation of policies to reduce transmission and distribution losses. The country can therefore benefit immensely from the global market with the implementation of appropriate energy policies.

4. Conclusion

In this study, LEAP energy tool was used to develop a model of the generation system of Ghana (Ghana LEAP) based on the operational characteristics of the generation of Ghana in 2010. The LEAP model of Ghana was used to determine the optimum development of the country's generation system up to 2040. Three policy constraints were applied to determine their effect on the optimum generation system.

The analyses show that suitable policies for clean power generation have an important role in CO_2 mitigation in Ghana. This was confirmed with the introduction of non-conventional renewable technologies on their own merit in the OPT scenario. Further analysis show that introduction of carbon minimisation policies will promote diversification of the generation mix with higher penetration of renewable energy technologies. This will reduce the overall fossil fuel generation in Ghana, which is characterised by unreliable feedstock fuel supply, as well as price shocks, leading to improved energy reliability.

The results further show that significant greenhouse emissions savings is achieved with improvement in transmission and distribution losses resulting in net benefits in cost of avoided emissions compared to the base case. Ghana being a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) has an obligation to report periodically on measures taken to reduce greenhouse gases. The analysis of the possible least cost generation pathways show that further reduction in GHG is possible in Ghana with the implementation of additional policies. The study therefore recommends the implementation of strategies to reduce transmission and distribution losses as well as carbon minimisation policies such as emission targets and carbon tax. These measures will promote the development of more efficient, reliable and environmentally acceptable energy system in Ghana.

Further studies need to be carried out to assess the impact of high penetration of renewable energy generation technologies on the stability of the grid as well as grid expansion studies to accommodate the potential future generation expansion.

Conflict of Interest

All authors declare no conflicts of interest in this paper.

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