Assessment of Optimal Pathways for Power Generation System in Ghana

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Abstract

This study applied 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) to develop optimal generation pathways and dispatch scheduling of selected generating technologies for power generation in Ghana. Simulating conventional and non-conventional energy technologies, the study examines the technological, economic and environmental implications of renewable energy policies from 2010 to 2040. Sensitivity analyses were undertaken to determine the effect of varied development in non-conventional renewable energy technologies investment cost as well as fuel prices. The findings suggest that, with a comprehensive implementation of energy efficiency and other strategies, renewable energy technologies can contribute more than 70% of the generation requirement in Ghana by 2040. This will result in significant economic and environmental benefits as well as sustainability of the energy sector.

Keywords: Ghana, Greenhouse Gases, LEAP, Optimisation, Renewable Energy,

1. Introduction

The expanding Ghanaian economy coupled with increased population has resulted in a rapid demand for energy. Inadequate expansion to meet the growing demand has resulted in a situation where the current generation capacity meets about only 65% of the demand as at March 2014 (Energy Commission Ghana, 2015). The installed electrical power generation capacity of Ghana as at March 2014 was 2851 MW which is made up of 55.4% large Hydro generation, 43.77% Thermal power generation and 0.09% Photovoltaic (PV) generation (Energy Commission Ghana, 2015). The country's grid generation used to be solely from Hydro sources (100% renewable) with the commissioning of the Akosombo hydro dam in 1966. Thermal power generation was introduced in 1983 to supplement the conventional hydro generation due to the severe drought that year (Aryeetey 2005).

An analysis of the trend in expansion shows that Ghana is gradually shifting to a predominantly fossil-fuelled thermal generation. 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 (Sanaeepur et al. 2014). Goal 7 of the United National's Sustainable Development Goals (SDG) which replaces the previous Millennium Development Goals (MDG) stipulated that adopting technology that will ensure provision of clean energy in developing countries will not only encourage growth but will also help the environment (Zhao, Hu and Cai 2016). Ghana is endowed with a number of clean energy technologies that can be exploited to meet its energy requirement. An excellent average solar radiation of 5 kWh/m^2 all year round and in all parts of the country, as well as favourable sites for wind and small-medium hydro power have been identified (Gyamfi, Modjinou and Djordjevic 2015).

Decision-making on sustainable energy is often unique and depends on the circumstances of each planning area. Good decisions concerning the best choice of technologies for future years will avoid expensive changes in later years. This therefore provides a need for energy planning to develope the best generation mix making use of the available technologies, policies drivers as well as challenges. The government of Ghana recognising the role of energy planning established the Energy Commission Ghana (EC) to manage and regulate the utilisation of the country's energy resources. The commission, which is the main agency for strategic energy planning, developed future demand and generation expansion plan of the country from 2006 to 2020. The results of this study which were presented in the strategic energy plan of Ghana (Energy Commission Ghana 2006), is currently the benchmark for generation expansion in the country.

The EC's study examines three pathways for power generation in Ghana from 2006 to 2020. These options include Option1, which is an expansion plan based on thermal and 10% Non-conventional Renewable Energy Technologies[1] (NRET) by 2020, Option 2 based on thermal, Bui hydro and 10% NRET and Option 3, which is based on thermal, nuclear and 10% NRET. The current generation expansion plan of the country is based on option two. However, the NRET dependable capacity as at March 2015 was only 0.03% compared to the targeted 10% (Energy Commission Ghana 2015).

Apart from the EC's study, there is a general lack of research on the future development of the generation system of Ghana. Moreover, the EC's study only projected the energy system up to year 2020 based on year 2000 parameters, which does

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[1] New renewable energy technologies does not include conventional large hydro generation plants.

not fully represent the current situation. The study did not also fully assess the environmental impact of the future generation pathways and hence, did not consider the impact of introducing carbon tax on the future development of the generation system. Also, provisions were not made to identify the optimum cost model for generation expansion in Ghana. This is particularly important when investment decisions are to be made on NRET systems

The LEAP tool was applied in Awopone et al. (2017) 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. The aim of this current study to examine future optimal development of the generation system of Ghana and provide a framework that could lead to discussion for the development of renewable energy technologies in Ghana. The findings in this paper will provide a useful platform for discussions with stakeholders and energy policy planners.

2. Methodology

2.1 LEAP/OSeMOSYS Optimization Model

The Long-range Energy Alternatives Planning (LEAP) system, version 2015.0.27.0 was adopted for this study. The LEAP model developed by Stockholm Environmental Institute (SEI) is a widely used energy modelling tool for energy policy analysis and emission mitigation studies (Heaps 2016). The optimization 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

LEAP interface with OSeMOSYS provides a transparent connection, which enables LEAP automatically write data files needed for OSeMOSYS. This enables

LEAP users to perform optimisation without directly interacting with OSeMOSYS or GLPK. Optimal in this case is defined as the energy system with the lowest total net present value of the social cost of the system over the entire period of the calculation (Heaps 2016).

An optimization model is characterised mainly by its objective function and constraints. The objective function of the LEAP optimization model is to estimate the generation system to meet demand by minimising the total discounted cost (Augutis, Martišauskas and Krikštolaitis 2015):

$$Minimise \sum_y \sum_t \sum_r TC_{ytr} = OC_{y,t,r} + CC_{y,t,r} + TEP_{y,t,r} - SV_{y,t,r}, \forall y,t,r \qquad (1)$$

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, while y, t, r is the year, technology and region indexes respectively.

The fuel constraint is the main driver of the model. Fuel production during each time slice and year must be greater than or equal to its consumption by technologies plus any exogenous demand for that fuel (Howells et al. 2011).

$$\Pr oduction_{y,l.f} \geq Demand_{y,l,f} + Consumption_{y,l,f} \qquad (1)$$

Where:

$$\Pr oduction_{y,l,f} = \sum_t \left(Activity_{y,l,t} \times OtptActivityRatio_{y,t,f} \times YearSplit_{y,l} \right) \qquad (2)$$

$$Consumption_{y,l,f} = \sum_t \left(Activity_{y,l,t} \times InptActvtyRatio_{y,l,f} \times YearSplit_{y,l} \right) \qquad (3)$$

Each technology is able to accommodate an activity that uses or produces or both use and produce energy. The capacity of each technology must be greater than its activity for each load region.

$$Activity_{y,l,t} \leq TotalInstalledCapacity_{y,t} \times CapacityFactor_{y,t} \qquad (4)$$

In the activity constraints, the activity of a technology is limited by its annual availability.

$$\sum_{l}\left(Activity_{y,l,t} \times YearSplit_{y,l}\right) \leq TotCapAnn_{y,t} \times CapacityFactor_{y,t} \qquad (5)$$

2.2. Description of Scenarios

The Base Case Optimum (BCO) scenario is the least cost generation system 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. The maximum capacity addition was assumed based on energy commission recommendation to ensure stability of the grid, while the maximum availability of the NRET were assumed based on the confirmed available resources (Gyamfi, Modjinou and Djordjevic, 2015; Energy Commission, 2006). The Carbon Tax (CT) scenario is similar in scope to the BCO. The only difference being the introduction of carbon tax. This scenario assumed an introduction of 20 \$/kg CO_2 tax in 2020, increasing to 40 \$/kg in 2030. This is to conform to the Bali Road Map which underscores the need for developing countries to also introduce mitigation actions after 2012 (Zhao, Hu and Cai, 2016). The Energy Efficiency (EE) scenario considers strict implementation of energy efficiency strategies in all sectors of demand (Gboney, 2009). The scenario therefore assumes the implementation of various strategies to improve energy efficiency resulting in 20% reduction in demand over the BCO scenario in 2020, improving further to 30% by 2030.

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% to 11% (World Bank 2014). The current high T&D losses are due to large non-technical losses, mainly due to theft and non-payment of bills (Energy Commission 2006). The T&D scenario therefore assumed improvement in the billing system resulting in significant reduction in non-technical losses. This was assumed to be reducing at a rate of 2% per annum starting from 2015 to its lowest value of 7% in 2023.

The Comprehensive (COM) scenario combines constrains of the CT, EE, and T&D scenarios. This scenario therefore assumes a simultaneous implementation of all the policy directions. A variant of the comprehensive scenario (COM1) was developed to combine only the constraints of CT and EE scenarios. This was to enable a further assessment of the effect of carbon tax with lower demand growth.

2.3 Data for the LEAP Model

The population of Ghana in 2010 was 24.7 million people, which is projected to be increasing at a growth rate of 2.4% (Ghana Statistical Service 2013). The GDP growth rate of 8% was adopted 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 energy consumption survey conducted by the Energy Commission of Ghana in 2010 (Energy Commission Ghana 2015).

The Technology Cost data was adopted from International Energy Agency (IEA 2014) and National Renewable Energy Laboratory (NREL 2012). 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 according to projections presented in IEA (2014).

3 Results and Discussion

This section examines the results of the generation system of Ghana based on the input data and assumptions made in this study for the various scenarios from 2010 to 2040.

3.1 Technical Results of Baseline Scenarios

The total electricity demand of Ghana in 2014 was 14 GWh which is expected to increase to 19 GWh and 63 GWh in 2020 and 2040 respectively at the current average growth rate of 8% per annum (GRIDCO 2011). This implies without any expansion in capacity, the current generation system will only be able to provide 20% of the demand in 2040. Thus significant expansion in capacity is predicted in the BCO scenario in order to meet this demand and the 18% reserve margin applied in this study. The generation outlook of the BCO scenario for selected years is presented in Figure 1.

[Figure 1 near here]

Interestingly, it was observed that the NRET were introduced on their own merit. This clearly illustrates high potential for integration of these technologies into the generation mix of Ghana.

Figure 1 further shows that thermal generation in Ghana will continue to be dominated by natural gas fuelled systems. Even though the same operating characteristics were assumed 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 to be 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 for utility providers to fully operate the thermal plants on natural gas when available (Energy commission Ghana 2006).

The introduction of carbon tax has a direct impact on the development of renewable energy technologies. It is observed from Figure 2 that the total NRET generation increases to 23 TWh in the CT scenario which constitute 28% of the total generation in 2040 compared to 25 in the BCO scenario.

[Figure 2 near here]

This is because RET produces very little to zero GHG. Thus an introduction of carbon tax will affect mainly the cost of production of the thermal plants and thus make the RET more economically viable. This was evidenced with the earlier deployment of PV plants in the CT scenario.

It is widely accepted that improvement in transmission and distribution losses as well as demand side efficiency measures will lead to lower electricity demand. Figure 3 shows the installed capacity capable of meeting the generation requirement by scenario at the end of the study period.

[Figure 3 near here].

Demand side efficiency strategies such as replacement of incandescent bulbs, refrigeration and air conditioning standards and labelling as well as industrial sector efficiency improvement measures at levels implemented in the EE scenario will result in 24% lower demand compared to the reference case (Figure 3). Improvement in the billing system by metering of all government and other public buildings, implementation of smart metering system and other strategies to lower the current technical and non-technical losses in the transmission and distribution system of the country at levels proposed in the TD scenario will also lead to 14% reduction in installed capacity. However, the introduction of carbon tax in Ghana at levels proposed in the CT scenario will lead to slightly higher installed capacity. These findings are consistent with those of McPherson & Karney (2014) which suggest that higher capacities of NRET are needed to meet the demand as compared to Thermal plants because of the relatively lower capacity factors of NRET.

The policy scenarios have similar capacity portfolios as the BCO scenario. However, the percentage share of NRET is much higher with the implementation of policies. It is observed from Figure 4 that the simultaneous implementation of NRET policies (COM scenario) significantly increase the RET share of generation from 0.01% in 2015 to about 40% in 2023 and remaining almost constant until the end of the study period. The high NRET share has resulted in the total renewable generation[2] share of over 80% between 2020 and 2025 and eventually decreasing slightly to 70% in 2040.

[Figure 4 near here].

These results however show that fossil fuel generation will continue to form an integral part of the generation system of Ghana as the renewable energy technologies cannot cater for all the future demand.

3.2 Technical results of scenarios with sensitivities

Figure 5 shows the electricity generation in the BCO system with high investment cost (HC) of NRET and varied fuel prices. The results assess the hypothetical high NRET investment cost with both low (LF) and high fuel price (HF) conditions.

[Figure 5 near here].

The analyses show the introduction of NRET on their own technical and economic merit despite their high investment cost. However, whereas NRET share with high fossil prices was 1% more, that of the system with low fossil prices was 8% less than BCO scenario. These results suggest that fossil fuel prices considerably affect the high integration of renewable energy system in the country. High fossil prices will make NRET more attractive to investors. The Government of Ghana currently subsidies fuel to continue to make electricity affordable. However, the sensitivity analyses show that phasing these subsidies will gradually make NRET economically attractive. There

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[2] This includes the conventional large hydro generation

should however be gradual (Parajuli et al. 2015) and should be link to expansion in NRET.

The results of the sensitivity analysis with Low Investment (LC) of NRET and varied fuel prices are illustrated in Figure 6. As expected, low investment cost of NRET has increased the share of these systems. Wind and PV systems were dispatched in 2015 and 2016 respectively, compared to 2020 and 2034 in the BCO scenario. The NRET share was higher with higher fuel prices (approximately higher than that of low fuel cost) as it was in the case of high investment cost

[Figure 6 near here].

These results all together show the high potential for integration of renewable energy system in larger capacities into the generation system of Ghana. The analyses suggest that NRET will be part of the generation system of Ghana under all cost sensitivities. It was observed that unfavourable high NRET investment cost as well as low fossil fuel cost did not prevent the introduction of NRET on their own merit.

3.2 Economic Results

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 fuel cost over the period of the study discounted at 10% to the base year.

The results of the cost-benefit analysis of the alternative scenarios compared to BCO scenario is presented in Table 1. The top part of the table shows the cost-benefits in

2010 billion US dollars while the bottom part shows percentage change. A positive value represents how much more each policy scenario costs compared to the base, while a negative number represent benefits.

[Table 1 near here]

It is evident from Table 1 that the demand side energy efficiency as well as transmission and distribution constraints will result in lesser NPC compared to the BCO system. This is due to the lower energy demand with corresponding lower generation requirement. On the contrary, the introduction of carbon tax will lead to a slight increment in cost of about 5%. The least cost system will involve a comprehensive implementation of all policy types considered this study. This means that the implementation of RET will not only lead to higher diversity in the generation sector with higher implementation of RET but will also lead to significant reduction of about 41% in cost within the study period.

Several iterations of the model with varied NRET investment cost (-30 to 10% of base case) and fuel cost (-10 to 30% of base case) were undertaken to determine how future changes in these parameters will affect the optimal configuration. Table 2 shows the economic results of the sensitivity analysis. The top part of the table shows the cumulative NPC in 2010 billion US dollars, while the bottom part shows the percentage change of the sensitivities compared to the baseline optimal scenarios.

[Table 2 near here]

As anticipated, Low fuel price will lead to economic benefits in all scenarios. Whereas the cumulative incremental cost of the BCO with high fuel prices was between 4% and 17% more than the baseline, that of the system with low fuel prices was 5% to 13% less than the baseline situation. These results show that the development of fossil prices in the future directly affect the profitability or otherwise of renewable energy technologies.

Interestingly, higher benefits were obtained in all scenarios with LF + HR sensitivity. This is because high NRET cost will lead to lower NRET contribution, thus increasing thermal generation share. The generation cost of thermal plants largely depends on the cost of fuel; a lower cost of fuel will thus lead to lower overall NPC. Policies that will ensure future lower cost of fossil fuel prices as well as lower NRET investment cost will yield desired benefits with higher deployment of renewable energy technologies. This is evident with comparatively higher savings occurring in the comprehensive scenarios with lower fuel and NRET investment cost sensitivity.

The Government of Ghana currently subsidies fuel to continue to make electricity affordable. However, the sensitivity analyses show that phasing these subsidies will gradually make NRET economically attractive. These should however be gradual (Parajuli et al. 2015) and should be linked to expansion in NRET.

3.3 Environmental Analysis

The greenhouse gas emission (GHG) from the various scenarios is presented in Figure 7.

[Figure 7 near here].

The power system without any policy intervention (BCO) scenario results in about 3.13 million tonnes GHG emissions in 2015. This increases at an annual growth rate of 11.5% to about 18 million tonnes GHG at the end of the study period mainly due to the continuous expansion of thermal generation to meet the increasing demand.

Figure 7 also shows the mitigation potential of the policy scenarios. The comprehensive scenario (COM), which is a combination of policies aimed at promoting high integration of renewable energy technologies, exhibited superior GHG savings compared to the other scenarios. A highly significant GHG emission reduction of about 70% is achieved in the COM scenario in 2040 compared to the baseline BCO scenario. This is because of the lower demand in the COM scenario due to energy efficient strategies and improvement in transmission and distribution losses.

[Table 3 near here]

A highly significant GHG emission reduction potential of about 66% is achieved in the COM scenario in 2040 compared to the baseline BCO scenario. This is because of the lower demand in the COM scenario due to energy efficient strategies and improvement in transmission and distribution losses.

Table 3 further reveals that introduction of carbon tax at levels proposed in this study will not yield significant GHG emission savings compared to the other policies. The cumulative GHG emission savings of the carbon tax scenario compared to BCO scenario was 6%, while that of T&D and EE scenarios resulted in about 27% and 43% cumulative GHG savings respectively. 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. The negative impact of the introduction of carbon tax can be addressed 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 avoided CO_2 emission of the policy scenarios. 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 comprehensive scenario in achieving economically efficient CO_2 emission reduction. It is important to note that, while all the other policy scenarios resulted in benefits in terms of cost of CO_2 avoided, the CT scenario resulted in abatement cost of 54 US$/tonne of $CO_{2.}$ This is because of the higher cost in expanding the generation system to meet the demand.

The analyses suggest that significant economic and environmental benefits are achieved with the implementation of energy efficiency and improvements in transmission and distribution losses in Ghana. This means that if the Government of Ghana intends to achieve reduction in demand and greenhouse emission, strategies to improve demand side efficiency should be pursued. Demand side management strategies such as energy standards for refrigeration and air conditioners, and phasing out of incandescent bulbs have been implemented in countries such as UK, India, china, USA and Canada with high degree of success (Emodi et. al. 2016).

The country should also implement policies to promote the reduction of both technical and non-technical T&D losses. Conventional approaches for improving technical losses with higher benefit/cost that can be pursued to reduce these losses are discussed in Aguero (2012). In 2014, 70% of the transmission and distribution losses in Ghana was due to non-technical losses mainly through electrical thefts, meter tempering and non-payment of bills. Installation of heavy duty locking rings and the use of pre-pay meters can help improve non-technical losses.

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 analyses of the possible least cost generation pathways show that further reduction in GHG is possible in Ghana with the implementation of additional policies. These measures when fully implemented will lead to sustainable low-carbon development of the generation system

4. Conclusions

In this study, alternative least cost generation options for the generation system of Ghana were examined. The analyses show that suitable policies for clean power generation have an important role in CO_2 mitigation in Ghana. A comprehensive adoption of policies aimed at reducing transmission and distribution losses and improving energy efficiency in Ghana will lead to a significant reduction in demand, resulting in over 70% renewable energy generation contribution by the year 2040.

The introduction of these 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 price shocks and unreliable feedstock fuel supply.

The results show that significant greenhouse emissions savings is achieved in the alternative scenarios resulting in net benefits in cost of avoided emissions compared to the base case. The study therefore recommends the strict implementation of strategies to improve demand side efficiency and transmission and distribution losses.

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. Studies are also needed to assess how the grid can accommodate the future generation expansion.

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Table 1 Cumulative discounted cost for optimisation scenarios (discount rate = 10%)

	NPC (Billion 2010 US$)					
	BCO	**EE**	**CT**	**T&D**	**COM**	**COM1**
Transformation	6.16	5.09	6.57	5.28	4.82	4.52
Fuel	9.36	6.06	8.96	7.19	4.12	4.40
Env. Ext			0.69		0.20	
NPC	15.52	11.15	16.22	12.47	9.14	8.92
	Percentage change					
Transformation	0	-17	7	-14	-22	-26
Fuel	0	-35	-4.27	-23	-56	-53
NPC	0	-28	5	-20	-41	-42

Table 2 Economic performance of optimal scenarios fuel and NRET investment cost sensitivities (discount rate = 10%)

	NPC (Billion 2010 US$)				
	BCO	**EE**	**CT**	**T&D**	**COM**
Baseline	15.52	11.15	16.22	12.47	9.14
LF + LR	14.75	10.66	15.50	11.94	8.55
LF + HR	13.48	10.48	14.08	10.76	8.51
HF + LR	16.11	11.01	16.55	12.50	8.61
HF + HR	18.12	12.75	18.76	14.42	10.22
	Percentage change				
LF + LR	-5	-4	-4	-4	-6
LF + HR	-13	-6	-13	-14	-7
HF + LR	4	-1	2	0.2	-6
HF + HR	17	14	16	16	11.81

KEY: LF = low fuel cost, HF = high fuel cost, LR = low NRET capital cost, HR = high NRET capital cost

Table 3 Cumulative emissions and cost of avoided CO_2 emissions

Scenario	Cumulative emission (Million tonnes CO_2e)	CO_2e Savings (%)	Cost of avoiding GHGs ($/tonne CO_2e)
BCO	225.88	-	-
CT	213.05	5.68	-54
T&D	165.37	26.88	-50
EE	128.39	43.16	-45
COM1	84.89	62.41	-47
COM	76.34	66.2	-43

Figure 1 Installed capacity in BCO scenario

Figure 2 Electricity generation by plant type for CT scenario

Figure 3 Installed capacities of scenarios in 2040

Figure 4 Percentage share of generation by source in Comprehensive scenario

Figure 5 Electrical generation of BCO scenario with high NRET investment cost

Figure 6 Electrical generation of BCO scenario with low NRET investment cost

Figure 7 Annual GHG emissions (Million tonnes CO_2e) by scenarios