Scenario Analysis of the Electricity System of The Gambia

Lamin K. Marong

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Sustainable Energy Management
Prince of Songkla University
2018

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Major Program Sustainable Energy Management

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I hereby certify that this work has not been accepted in substance for any degree and is not being currently submitted in candidature for any degree.

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Year 2017

Abstract

Sustainable Energy for All (SE4All) is an Initiative launched in 2012 by the United Nations (UN) Secretary General to achieve three interlinked objectives (i.e. ensuring universal access to modern energy services, double the global rate of improvement in energy efficiency (EE) and double the share renewable energy (RE) in the global energy mix) by year 2030. In The Gambia, the energy (electricity) supply situation is precarious and unsustainable as it currently relies on single imported fuel oil to meet the nation's demand. The dependence on the imported fuel oil cannot meet the hugely growing demand therefore resulting into huge demand-supply gap (more than 150 MW). This situation coupled with the high electricity production cost lead to the conduction of this study using Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE).

The objective of this study is geared towards exploring the optimal national electricity supply mix by employing long-term, bottom-up energy supply system optimisation tool to meet the current and future national electricity demand sustainably (i.e. considering the economic feasibility and environmental concerns).To make gains towards this objective especially diversification via increasing the renewable energy share, The Gambia, made commitments (targets) to increase centralised (grid-connected) renewable energy share in its electricity supply mix by 2020 and 2030. Based on these commitments, prompted the need to explore two possible scenarios, viz: Business As Usual (BAU) and Renewable Energy Target (RET) using Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) for 2030 horizon.

The results showed that the system capacity development, generation as well as generation mix in both scenarios are expected to be dominated by oil (HFO/LFO) based systems up to 2019, after which the system is expected to be diversified with more of renewable energy systems at both centralised and decentralised levels and negligible contribution from alternative sources such as natural gas systems. This increase in the generation after 2019 is as result a result of the commencement of the importation of cheap hydroelectricity from the regional OMVG dams expected to come online by 2020. In addition to OMVG hydroelectricity imports is the generation from committed solar PV, wind and solar thermal projects.

Generally, comparing both scenarios (BAU & RET), the RET scenario is found to be more attractive as well as attainable as a result of its increased rate of renewable energy share (by 9 %), very marginal increase in total system cost (by USD $2 million), and less CO_2 emissions (by 40 %) and carbon intensity (by 30 %) explained by more renewables (solar, wind, import hydro) penetration. However, the BAU scenario could still be attractive as Non-Annex one country, if the government considers that 10 % (2020) and 33 % (2030) renewable penetration rates suffice and not worth additional investments of USD $ 2 million. Regarding the sensitivity analysis, the BAU scenario with 5 % discount rate has led to addition of more renewables energy systems and disfavours that of fossil fuel power plants while the higher discount rate of 15 % favour both renewables and few fossil fuel plants and disfavouring fossil fuel generating plants.

Keywords: *The Gambia, Sustainable energy, Renewable energy, Electricity, Energy policy*

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The accomplishment of this thesis would not have been possible without the valuable contribution assistance and encouragement from wide range of actors. Firstly, I would like to gratefully acknowledge my wonderful supervisors, Dr. Sopin Jirakiattikul, and Asst. Prof. Kua-anan Techato, for their continuous support, encouragement, and invaluable guidance. A special thanks goes to Dr. Sopin for taking me as an advisee and for guidance and encouragement all long the accomplishment of this work. Asst. Prof. Kua-anan as my co-advisor and the Sustainable Energy Management program has been very instrumental in making this study a success and my study life easy. My sincere graduate goes to both supervisors for their timely and constructive feedback on the realisation of this work.

I would also like to recognise the technical and financial supports accorded by the Government of The Gambia (more precisely the staff at the Ministry of Petroleum & Energy – MoPE, National Water & Electricity Company Limited – NAWEC and Public Utilities Regulatory Authority – PURA) and the International Renewable Energy Agency (IRENA) are warmly acknowledged. My overwhelming thanks go to my friends from the Sustainable Energy Management and Environmental Management Groups. Specifically, Luke Makarichi, Alam Surya Wijaya, Saudee Maprasit, Thangrak Veu, Chanwit K., Suttinee Jingjit, to name but a few.

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Lamin K. Marong

Dedication

This thesis is dedicated to my wonderful parents, my amazing brother & sister, my best friend and brother (Alhajie), and my department head who always pushed and encouraged me.

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1 CHAPTER ONE: INTRODUCTION

1.1 Background and Scope

Nowadays, energy policies on the future energy supply options seek to guide the transition to an energy system that is characterised by three goals. These include: a secure supply chain i.e. from energy extraction up to delivery; affordable supply in relation to economic output and; reduced environmental impacts especially GHGs emissions. However, to attain all these three goals is quite difficult if not impossible and therefore requires trade-offs between and among sources of energy as well as technologies taken into account all three dimensions of sustainability (social, economic and environment).

Regarding sustainability, Africa as a continent (within which The Gambia is situated) needs to significantly improve its electricity supply to meet the growing need of its rapidly growing population and economy. The continent, despite being hugely blessed with numerous domestic renewable and nonrenewable energy resources suffers low electricity consumptions (just 3.2 % out of global total of 22 668 TWh in 2012 (International Energy Agency (IEA) 2014) (International Energy Agency (IEA) 2016)) compared to other continents. However, these indigenous energy sources if effectively and efficiently utilised can lead to an energy supply system that is secure as well as affordable, thus contributing to one of the key goals of Sustainable Energy for ALL (SE4ALL) initiative[1] "i.e.: *ensuring universal access to modern energy*" while avoiding negative environmental impacts (SE4ALL Global team 2016).

Like most African countries, The Gambia's energy production particularly electricity is unsustainable due to the heavy reliance on single imported fuel[2] mainly oil (Sahel Invest Management International 2014). The dependence on oil has put immense pressure on Government's efforts for sustainable growth and prosperity. The volatility in international oil prices has plunged the country in long periods of debt and economic recession (Sahel Invest Management International 2014). Consequently, the heavy dependence on imported oil for electricity generation, with the deplorable state of the

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[1] SE4ALL initiative launched in 2012 by the UN to achieve 3 goals by 2030 (see: www.se4all.org).

[2] The capacity of the petroleum storage facility is about 51,000 metric tons (Source: http://www.accessgambia.com/information/gampetroleum.html)

electricity system (Singh, Nouhou and Sokona 2013) have resulted in high electricity generation cost ($ 0.50 US cents per kWh); as a result, the country pays one of the highest electricity costs in West African region which has an electricity cost averaging $ 0.35 US cents per kWh (World Bank Group 2016) (Sahel Invest Management International 2014) (ERERA 2014).

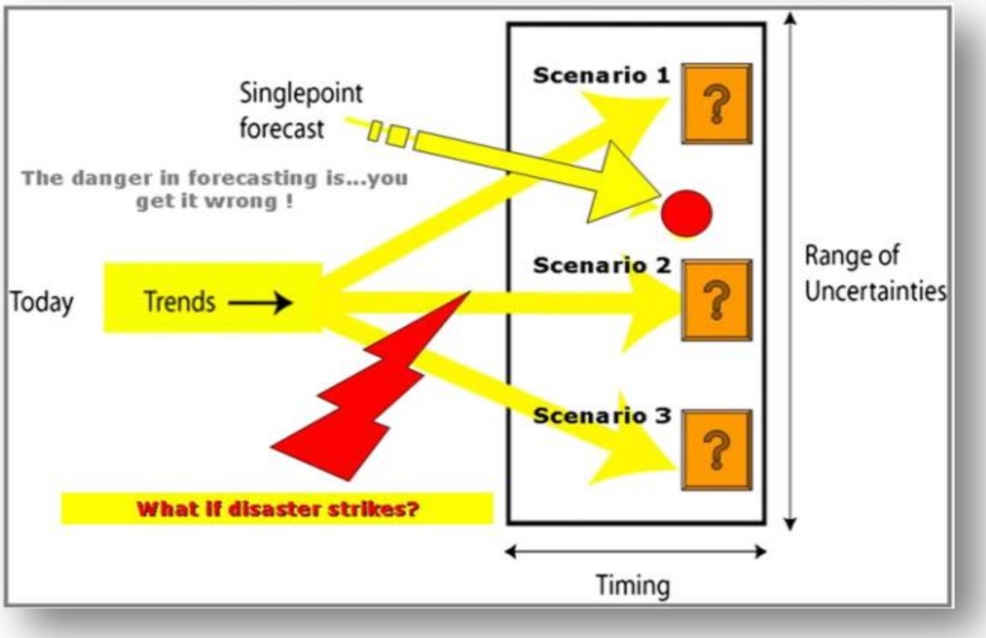
Given this unsustainable state of the electricity supply system with the renewed Government's ambition to increase the penetration of renewable and alternatives energy sources (Particip GmbH 2014) and the country's recent policy directions (Sahel Invest Management International 2014), that seeks to achieve:

- *energy security;*
- *prices stability and;*
- *full access to electricity.*

With these policy directions, there is dire need for one to gain comprehension of the future technology options of supplying electricity at lowest cost to meet the current and expected rapid growth in electricity demand (which was 621 GWh in 2011 and expected to exceed 800 GWh by 2020 (Singh, Nouhou and Sokona 2013)) in The Gambia, these least cost electricity supply options will assist in the identification of key technologies such as hydro (which will be imported from the OMVG[3]), wind and solar to become one of the best generating options for the future electricity supply mix, thus given the objective of the study.

Given the future uncertainty, a scenario based approach is adopted for the long term assessment of the electricity supply options. According to the Intergovernmental Panel on Climate Change (IPPC) *Special Report on Emission Scenarios* (Ogunlade and Ber 2000), "Scenarios are simply alternative images of how the future might unfold and are appropriate tool with which to analyse how driving forces may influence future outcomes and assess the associated uncertainties." It is important to point out that a scenario is not a prediction of the future to come but an internally consistent description of a future state or trajectory that is as comprehensive as needed for analysis purposes as illustrated in Figure 1.1

[3] Organisation pour la mise en valeur du fleuve Gambie (OMVG): Regional intergovernmental organization for the development of The Gambia river basin – it comprises of The Gambia, Senegal, Guinea Bissau and Conakry



Source: R. Weijermars et al., 2011

Figure 1.1: Description of scenario against forecast

It is also vital to distinguish between scenario and forecast, the latter, describes a single future development (with only statistical deviations) of the underlying system being studied while, the former, draws a consistent picture of the consequences of a given set of assumptions.

In any scenario modelling, the planning horizon is quite vital, for this study 2010 to 2030 is the time horizon. This horizon is based on the renewable target set by Government up to 2030 (Particip GmbH 2014) and also the timespan used in the WAPP[4] Masterplan for *planning and prospects of renewable technologies in the West African Region* using the MESSAGE[5] computer model (Miketa and Merven 2013).

1.1.1 Objectives of the study

[4] WAPP: West African Power Pool - Master Plan

[5] MESSAGE: Model for Energy Supply Strategies and their General Environmental Impacts

In view of the national energy poverty and the need/ambition to attain energy supply security in the not too distant future, this study seeks:

- To provide rational basis for decision making i.e. evidence based decision making process, that allows "What-if?" questions, to help analyse and compare the implication of different policy actions regarding electricity system improvement and expansion.

- To assist in the formulation of medium to long term supply strategies to meet the future demand as well as the requirement for sustainability i.e. social (import dependency, reliability of supply, rural electrification, etc.), economic (cost minimisation) and environmental (emissions of greenhouse gases, air pollution etc.) dimensions thereby ensuring security of supply.

- To provide the least cost electricity supply options for The Gambia in medium to long term.

1.1.2 Questions of the study

Taking into account the aforementioned objectives, this study will be very useful in answering the following questions on the future improvement and expansion of the national electricity system:

- *What are the least cost technology options in ensuring security of electricity supply in the medium to long term?*

- *What is the medium to long term energy supply mix?*

- *How does the RE target impact on the electricity system in terms of capacity requirement, technology choice, and fuel consumption?*

- *What is the total installed capacity as well as fuel consumption in the thermal power generation?*

- *How much investment is required (i.e.: economic costs) as well as amount of CO_2 emitted (environmental costs) in the scenarios?*

- *Finally, how uncertain and sensitive are some of the input parametres?*

1.1.3 Approach/Methodology used

The approach used in this study can be summarised into five (5) main phases. The definition of the problem statement is captured in the 1st phase; the 2nd phase looks into past and current literatures on works done using energy system optimisation tools especially MESSAGE. Then in the 3rd and 4th phases of this study will look at data gathered/required as well as development of the mathematical model using MESSAGE. In the final or 5th phase entails scenario development and analysis as illustrated in Figure 1.2.

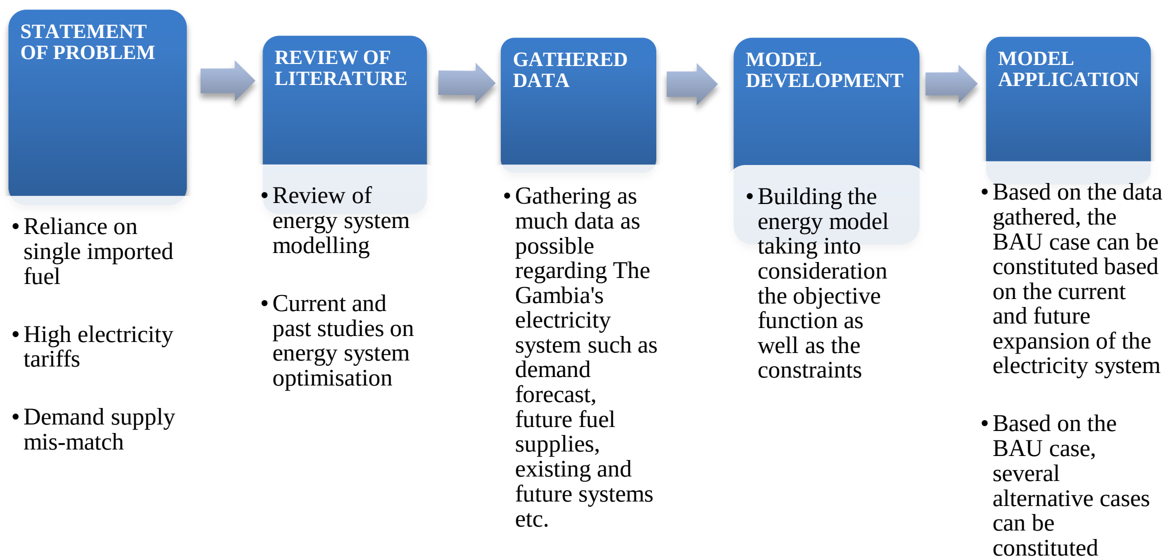


Figure 1.2: Steps adopted in the study

As mentioned previously, the specific approach used in this study is "scenario analysis" which entails using a mathematical (precisely, mixed integer programming) system model called MESSAGE - Model for Energy Supply Strategy Alternatives and General Environmental Impacts. MESSAGE ensures sufficient supply of energy considering the technologies and resources in the model for specific energy demand (Fairuz, et al. 2013). The fundamental features of the MESSAGE Model are represented in Figure 1.3.

MESSAGE is a tool used in the computation of supply-side of energy systems. The development of the future energy demand is an exogenous input to the model which is very vital in the modelling of any electricity system. The whole supply system is represented as network of technologies and energy levels, starting from extraction or supply of primary energy, passing through energy conversion processes to transmission and distribution up to meeting the given demand for final energy.

The decision variable of MESSAGE modelling tool is optimisation of an objective function (e.g. least cost, maximum self-sufficiency, lowest environmental impact). The optimisation is done by comparing the techno-economic performances of a particular technology with its alternatives on life cycle analysis (LCA) basis. When a particular final energy (electricity or heat) can be satisfied by two or more options (example electricity needs can be met by using gas or oil), the optimal solution that will be chosen by MESSAGE will be based on discounted cost applied to the investment cost, operation and maintenance (O&M) costs, fuel cost if non-renewable etc.

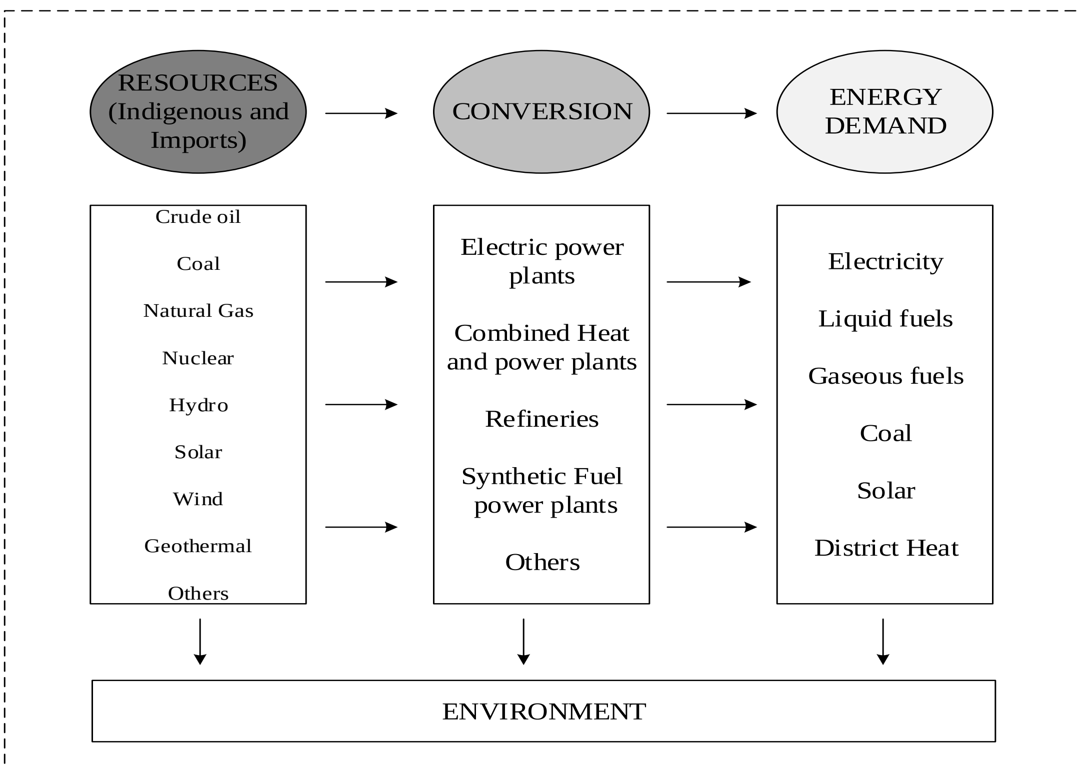


Figure 1.3: Fundamental Features of MESSAGE

1.1.4 Output and Outcome of the study

Using MESSAGE to optimise the national electricity system will give vital output such as the most sustainable expansion path for the country's electricity system (that is the best combination of fuel and technologies in satisfying a given demand of final energy) by considering the economic, social as well as the environment issues, policies, laws and regulations etc. The outcome on the other hand, can lead to formulation and implementation of robust energy supply strategies (such as better informed policies, plans, laws as well as regulations on construction and commissioning of new power plants that will ensure future supply security and less environmental concerns).

1.2 Country Profile

The Gambia is smallest mainland African country, located in West Africa. Its official name is The Republic of The Gambia and gained independence from Britain on 18th February 1965. Since then it has had three (3) Presidents and the third one was just recently voted to office in late 2016 bringing great hope and optimism for the country. The Gambia being Africa's smallest country has seven regions which include: two municipalities – (Banjul City Council - BCC and Kanifing Municipal Council - KMC) and five provincial administrative regions – Western region (WR), North Bank Region (NBR), Lower River Region (LRR), Central River Region (CRR) and Upper River Region (URR). In addition, the country has around a total of forty (40) districts which is unevenly distributed in these regions, with about 1 870 villages, each village having an average of 13 compounds (Malanding and Alieu 2006).

Politically, The Gambia is one of the most stable countries in West Africa. Politics of The Gambia takes place within the framework of a Presidential republic, whereby the President is both the head of the government as well as the state. The country has a multi-party system in which it holds regular presidential as well as parliamentary elections. Legislative powers are vested in both the Cabinet and National Assembly. The revenant units include local government areas, districts, wards, and villages.

Recently, the country has seen rapid internal changes as well as changes in its GDP structure from only agriculture dominant sector towards a more balanced agriculture and service (tourism) dominant sectors (Ministry of Finance and Economic Affairs (MoFEA) 2011
<http://eeas.europa.eu/archives/delegations/gambia/documents/about_us/page_2012_201

5_en.pdf>). These rapid changes are in line with the Government's then long term development strategy called the Vision-2020, whose goal is: *"to transform The Gambia into a financial hub, a tourist paradise, a trading export oriented agricultural as well as manufacturing nations, thriving on free market policy and a vibrant private sector, sustained by a well-trained, skilled, healthy, self-reliant and enterprising population, guaranteeing a well-balanced ecosystem and a decent standard of living for all, under a system of Government based on the consent of its citizenry."*

The Vision – 2020 since its development in 1994 is being executed by series of medium term development plans or strategies such as (Poverty Reduction Strategy Paper) PRSPs I & II, now (Programme for Accelerated Growth and Employment) PAGE I and PAGE II (currently being validated) etc. (Ministry of Finance and Economic Affairs (MOFEA) 2016 <http://www.mofea.gov.gm/downloads-file/national-development-plan>) (Ministry of Finance and Economic Affairs (MoFEA) 2011 <http://eeas.europa.eu/archives/delegations/gambia/documents/about_us/page_2012_2015_en.pdf>), which all sought to achieve a prosperous Gambia in the medium to long term.

1.3 Geography, Location, Climate

The Gambia is located on the West Coast of Africa between 13.79^{o} and 16.82^{o} West longitude and entirely within 13^{o} North latitude. The country stretches about 400 km inland and has a width that varies between 24 – 28 km across the length of the country and as a results, it has a total land area of 11 300 km^2. The Gambia is bordered with only one country – Senegal on all its three sides and on the West side lies the Atlantic Ocean (*see* Figure A 1 *annex map of The Gambia*).

The Gambia is horizontally bisected by the River Gambia that divides the country into north and south banks. This river takes its source from Futa Djallon Highlands in Guinea Conakry (West Africa). The Gambia is classified as one of the Sahelian countries as it is characterised by a long dry season from October to early June and a short rainy season from mid-June to early October. Annually, the average rainfall varies between 850 mm to 1 200 mm while temperatures range between 18^{o} C to 33^{o} C. Relative humidity in The Gambia is about 68 % along the Coast and 41 % inland during the dry season and generally about 70 % throughout the country in the wet season (Rio+20 Report 2012).

1.4 Population

According to the most recent 2013 census, the population (see Table 1.1) of The Gambia was about 1.9 million (The Gambia Bureau of Statistics (GBOS) 2013 <http://www.gbos.gov.gm/uploads/census/The%20Gambia%20Population%20and%20Housing%20Census%202013%20Provisional%20Report.pdf>). During the inter-censual period 2003-2013, the average annual population growth rate of the country has been around 3.3 percent. With this rate (3.3 %), the population is expected to double in less than 18 years. Comparing this current population growth rate with the then observed annual growth rate of 2.7 percent over the inter-censual period 1993-2003, the population growth rate has significantly increased. In addition, this rate of growth is also higher than the West African regional average which currently hangs around 2.6 % per annum (Dieudonné Ouedraogo 2007).

Table 1.1: Population of The Gambia between 1963 to 2013

Years	Urban	Rural	Total
1963	50,478	265,008	**315,486**
1973	103,635	389,864	**493,499**
1983	226,980	460,837	**687,817**
1993	384,114	654,031	**1,038,145**
2003	693,947	666,734	**1,360,681**
2013	1,110,646	771,805	**1,882,450**

Source: GBOS report

During the recent census, the number of people per housing unit averaged 8.2 persons with the number of households estimated at 229 567 (The Gambia Bureau of Statistics (GBOS) 2013 <http://www.gbos.gov.gm/uploads/census/The%20Gambia%20Population%20and%20Housing%20Census%202013%20Provisional%20Report.pdf>). Households in The Gambia are still large given the fact that many people continue to live in traditional household settings in which members of different generations of households live. This kind of living arrangements still predominates in rural settings.

However, in urban areas the size of households is declining due to immigration. The Gambia is currently undergoing a rapid rate of urbanisation with the share of the urban population increasing from 37 % in 1993 to about 55 % today (Particip GmbH 2014). As the urbanisation trend is set forth, the size of households is expected to be reduced in the long term. The population density has also risen from 127 persons per square kilometre (km^2) in 2003 to 176 per km^2 in 2013 (GoTG & EU 2006). As a result of this high population density, the country is ranked 73rd most densely populated in the World, tenth (10th) in Africa and highest in West Africa by the World Bank (GoTG & EU 2006) (Technical Working Groups (TWGs) 2009).

Moreover, The Gambia is secular state comprising mainly Islamic and Christianity religions. It has predominantly six ethnic groups which include the Mandinka (majority), Fula, Jula, Wolof, and Serehuli as well as other minor ethnic groups.

1.5 Macroeconomic Situation

Historically, economic growth performance in The Gambia has been average (see the Table 1.2 and Figure 1.4), mostly characterised by weather related shocks as a result of the reliance on rain fed agriculture and fluctuating tourism. Economic growth (IMF 15272-CR 2015) in The Gambia continues to be predominantly driven by the agriculture and tourism. Between 2003 and 2006 real GDP growth has declined from an average of 5.9 % to about 4.7 % in 2007. Then, it grew by 6.3 % in 2009, explained by strong boost in agriculture, tourism, and the construction industry (Ministry of Finance and Economic Affairs (MoFEA) 2011 <http://eeas.europa.eu/archives/delegations/gambia/documents/about_us/page_2012_2015_en.pdf>).

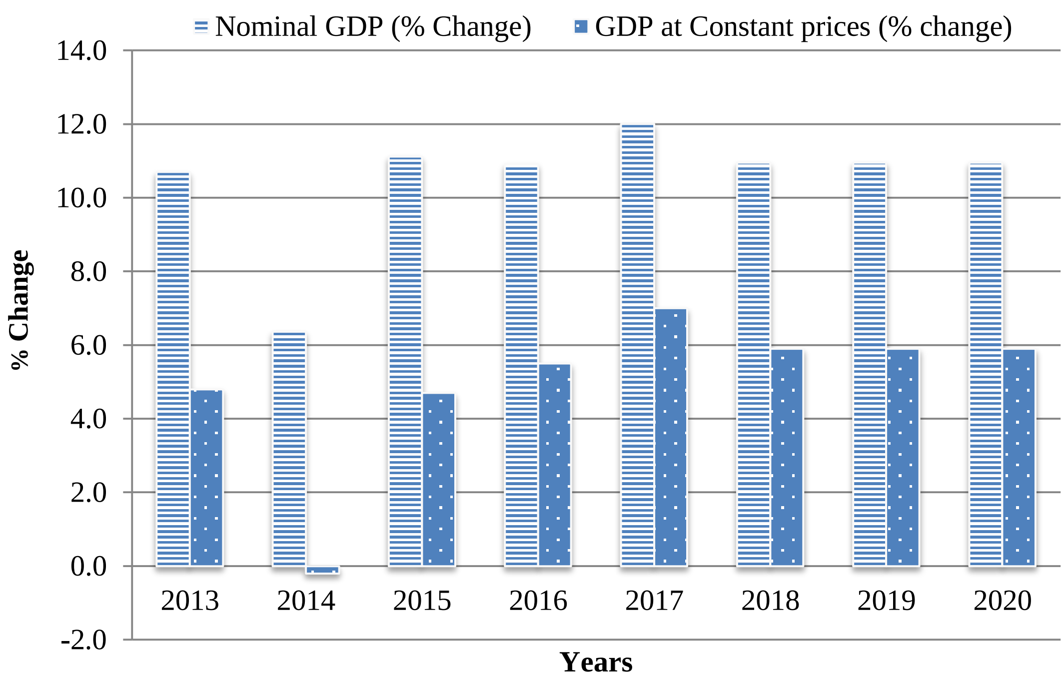
Table 1.2: Actual and Projected Nominal, Nominal GDP Growth as well as Real GDP Growth 2010 – 2020

Year	2010	2012	2014	2016f	2018f	2020f
Nominal GDP (millions of Dalasi[6])	26662.00	29191.00	34380.00	42,372	52,659	64,831
Nominal GDP (% Change)	6.60	10.30	6.37	10.9	11.0	11.0
GDP at Constant prices (% change)	6.50	5.60	-0.20	5.5	5.9	5.9

Source: IMF country report, 2015

[6] Gambian Dalasi (GMD) is the name of the national currency [In February ending 2016:**US$ 1.00 = 40.54 GMD**]

These abrupt changes in real GDP growth can be attributed to the effect of climatic conditions on agricultural output, and as well as the variable growth in key sectors such as industry, tourism, construction, and re-export trade activities, etc. In 2014, the real GDP growth stood at 0.4 % against an estimate of 7 %, this sharp decline reflects exogenous shocks arising from the outbreak of Ebola in the sub-region and low output in the agricultural sector. In 2015 the rate has stepped up to 4.7 %. (Ministry of Finance and Economic Affairs (MOFEA) 2016 <http://www.mofea.gov.gm/downloads-file/national-development-plan>, World Bank Group 2016).



Source: IMF country report, 2015

Figure 1.4: Actual and Projection of Nominal and Real GDP Growth Rates 2013 – 2020

In the medium term, the growth is expected to rebounce to normal and could exceed 5 %, with the backing of strong policy implementation off-course and projected rebound in agricultural output as well as tourism, as these two sectors account for about 40 % of total GDP. Agricultural production is however expected to marginally decline by 8.4 %, which is less severe than 22.7 % declined as previously reported.

Regarding the tourism sector, with the low incidence of new Ebola cases in the region, European Union (EU) economy recovery as well as marketing and investment efforts in this sector should bolster performance. With average expectations of growth in these two sectors, there is chance for the narrowing of the current external deficit in the medium term. In addition, the gross international reserve is expected to be restored, while inflation could return to the targeted 5 %, given the current subdued international prices for food and fuel. In brief, the future is promising economically as shown in Figure 1.4.

Given the high growth rate of population (3.3 %) and urbanisation (55 %) setting forth with the high anticipated economic growth rates, the demand for energy especially electricity is therefore expected to grow rapidly from current existing high growth level. The high level of demand and its expected high growth rate would therefore, require a corresponding increase in the electricity supply to bridge this gap, which is the aim of this study that sought to model the supply side of The Gambia's electricity system using an energy system optimisation tool called MESSAGE. In modelling the national energy system the specifics of The Gambia's energy sector are considered, in terms of both its disposable resources and policies. As the bulk of the energy used in the country is imported, a particular attention was paid to issue like foreign trade, exchange rate as well as the balance of payment

This study is categorised into five chapters including the introduction. In chapter two a literature survey on the modelling of energy systems are reviewed and the other various issues such as national energy resource and policy context, the energy supply technologies. Then in chapter three, the methodology used in the modelling of the electricity system of The Gambia will be documented, it presents mathematical formulation behind the MESSAGE model as well as its input data requirements.

Chapter four, on the other hand, will look at the results (using different scenarios) based on the methodology applied in the previous chapter and as well provide discussions on the results pertaining to the future improvement and expansion paths for the national electricity system and finally in chapter five conclusions and policy recommendations on the main findings of the model as well as recommendations for subsequent scenario studies on the country's electricity systems.

2 CHAPTER TWO: REVIEW OF LITERATURE

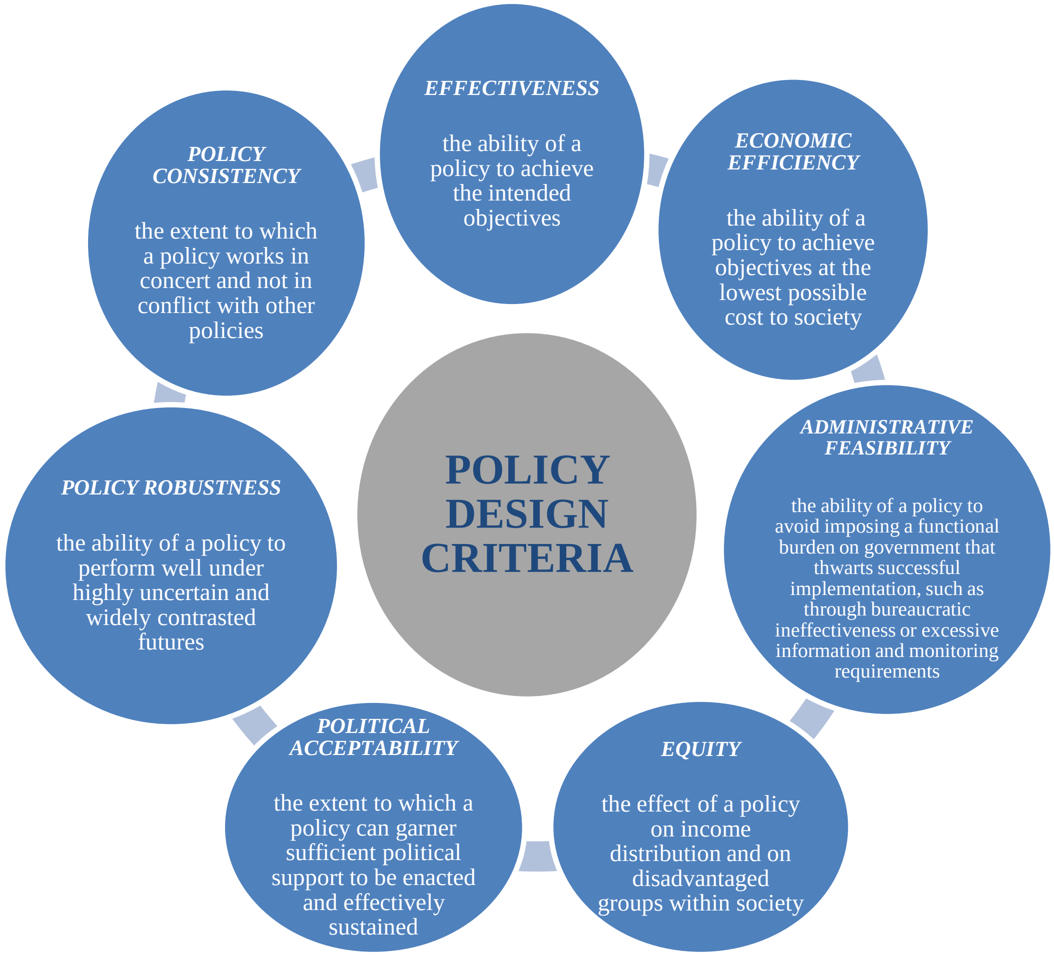
This part of the study covers a wide range of issues from The Gambia's national energy policy context to its energy resources, from energy demand and supply analysis to energy supply technologies. In separate sections, energy system modeling will be reviewed as well as The Gambia's energy system and the stakeholders working in the sector. Therefore, it is vital to review literatures on these issues before proceeding to the methodology in subsequent chapter.

2.1 The Gambia's energy policy and resource contexts

2.1.1 Policy context

It is widely acknowledged globally, the critical role energy plays for the achievement of sustainable development goals (SE4ALL Global team 2016). This means that energy related policies need to be assessed in terms of their performance with respect to the social, economic, and environmental dimensions that are all encompassed within the sustainable development concept. Essentially, energy-related policies frequently seek to make advances with respect to all three of these critical sustainability dimensions. But in reality, policymakers are often faced with difficulties regarding trade-offs between and among these dimensions, as improving one of the dimensions is usually at the expense of the other (Munasinghe 2009).

Thus, the primary goal of energy-related policy design is to seek win-win opportunities for simultaneously advancing social, economic and environmental goals. Provided that this is not possible, which is often the case in reality, the policy goals are determined by applying decision-support tools that integrate diverse economic, social and environmental objectives and values into policy design process, these include seven (7) key evaluative criteria that policy analysts conventionally apply when assessing policies. These criteria (Hahn 1996) illustrated in the Figure 2.1 are used to assess the ability of different policy options to meet their goals.



Source: GEA, 2012

Figure 2.1: Policy Design Criteria

Given these aforementioned key policy design criteria, the current national energy policy (Sahel Invest Management International 2014) was designed considering these criteria and therefore sought to achieve three major goals which are all in line with the country's development agenda i.e. the Vision 2020. These three policy goals are to:

- Improve the energy supply system;
- Improve access as well as affordability of energy services and;
- Enhance the renewable energy potential base of the country.

Scoring all these three goals which is the desired outcome of this study, will not only require a robust and smart energy system but will require financial resources and time. One of the key sub-sectors under the energy sector is the electricity sub-sector which current mode of generation (National Water and Electricity Company (NAWEC) Ltd. 2015) is unsustainable as it entirely relies on imported petroleum products to meet the power need of the country. Therefore, the current energy policy is seeking the deployment of all potential energy supply sources i.e. both *non renewables* (*conventional)* and *renewable energy sources* for the improvement of the country's electricity situation while taken into consideration the indigenous domestic resources as well as the environment (AF - MERCADOS Energy Market International (EMI) 2013).

Under the *non-renewable energy supply sources*, like fossil fuels (oil, gas, coal), the policy seeks the continuous utilisation of these fuels mainly Heavy Fuel Oil (HFO) (AF - MERCADOS Energy Market International (EMI) 2013) (Sahel Invest Management International 2014) in the national electricity supply system as a result of the current high existing level of expertise and experience in the operation and running of these systems as well as the associated not-high investment costs when compared with most renewable energy systems. In addition, the expected continuous utilisation of fossil fuels in the national electricity system is as a result of the old and aging infrastructure of the existing systems which urgently needs improvement as well as replacements. Therefore, in short to medium term, the policy is considering the continuous utilisation of these conventional or non-renewable energy sources such as new and improvement of existing HFO/diesel power plants and also diversify with the integration of more competitive as well as efficient technologies like natural gas, biomass and even efficient coal power plants in the near future to accelerate the country's electricity security goal (Fichtner Studies 2014).

In the medium to long term, the policy direction seeks the penetration of *renewable energy sources* such as Solar PV (<u>P</u>hoto<u>v</u>oltaic), Wind, as well as Hydro power to help in sustaining the electricity supply system and as well reduced the environmental impacts and thereby leading the country to more sustainable energy supply path (Particip GmbH 2014). Besides, The Gambia as a party to <u>U</u>nited <u>N</u>ations <u>F</u>ramework <u>C</u>onvention on <u>C</u>limate <u>C</u>hange (UNFCCC) which means that she is implementing within her own powers the Kyoto protocols and other climate agreements, despite being a non-annex one country – that is – under no obligation to reduced its emissions. Notwithstanding, The Gambia (Climate Analytics Team and INDC Team 2014) based on its national circumstances, particularly to support its development policies and programmes is willingly implementing measures in its own way to curb the increase in emissions by adopting more environmentally friendly energy technologies.

As this study mainly focuses on the national electricity sub-sector, the following electricity objectives have being stipulated in the recently validated national energy policy which are all within the three (3) energy policy goals outlined above (Sahel Invest Management International 2014) i.e.:

To improve the energy supply system by ensuring:

- Addition of generating capacity of heavy fuel oil (HFO) fired generators of higher unit capacity (15 to 25 MW or more) in the short term;
- Promote the development of alternative thermal generation (gas, steam, etc.) as a long term strategy;
- Private sector participation in electricity generation through a regionally competitive set of policies;
- That the Utility, National Water and Electricity Company Ltd – NAWEC and all Independent Power Producers (IPPs) perform their functions efficiently under the effective oversight of Public Utilities Regulatory Authority (PURA);
- That NAWEC is a viable business entity able to meet shareholder's obligations;
- Enforce the renewable energy law, and achieve 20 % at least per cent renewable energy generation capacity by 2018.

Improve access and provide an affordable energy service through:

- Ensuring the rehabilitation of the transmission and distribution system;
- Embarking on the rural electrification project to cover all viable towns and villages identified;
- Encouraging the use of energy efficient generators optimise electricity production costs;
- Sensitisation program for efficient use of energy
- Exploitation of sub-regional and regional initiatives directed at augmenting local capacity to develop energy resources.

Enhance the renewable energy potential base by:

- Encouraging the introduction of wind pumps for water lifting, for energy conservation purposes;

- Introducing solar water heaters in institutional facilities, hotels and private households;
- Popularising the use of Solar PV systems in the provinces to provide power for health and veterinary clinics and telecommunication facilities.

At the moment, the policy, plans and law (National Assemby 2005) on electricity sub-sector are aware of the enormous challenges facing the sub-sector and therefore seek to address the limited and unreliable supply, the high cost (Sahel Invest Management International 2014) as well as underexploit energy potentials and the pursuit of environmentally sound practices. But this can only be achieved with gradual and systematic expansion and improvement of the current supply system.

2.1.2 Resource context

The first step in any energy chain is the resources that are often extracted and processed before being fed into technologies to supply essential energy services[7]. In between the resources and the energy services are several infrastructures, technologies as well as fuels which are hugely dependent on a particular type of resource. Energy resources especially finite resources are defined by many classification systems as concentrations of naturally occurring solid, liquid, or gaseous material in or on the earth crust in such form that economic extraction is potentially feasible (UNESC 1997) or more generally, an energy resource is any matter that can produce heat, power life, move objects or produce electricity (Nelson 2015).

Considering these definitions, the national energy resources in The Gambia can as well be summed into *renewable energy and non-renewable energy resources*. The country’s *renewable energy resources* consist of mainly biomass energy as well as solar and wind. Due to near flatness of the country’s terrain the River Gambia has little or no potential for hydropower development and therefore will essentially rely on a regional dams being constructed in neighbouring countries (Sahel Invest Management International 2014) for electricity import via a regional transmission lines expected in not too distant future.

Biomass as an indigenous renewable energy resource constitutes the largest energy supplied and consumed in The Gambia. It supplies about 90% of the households’ energy requirements and comprises mainly solid biofuels (firewood, charcoal, sawdust,

[7] Energy services (at end users’ side) are often ignorant of the particular resource that ensures their supply and therefore less considerate about the harmful effluents released therefrom.

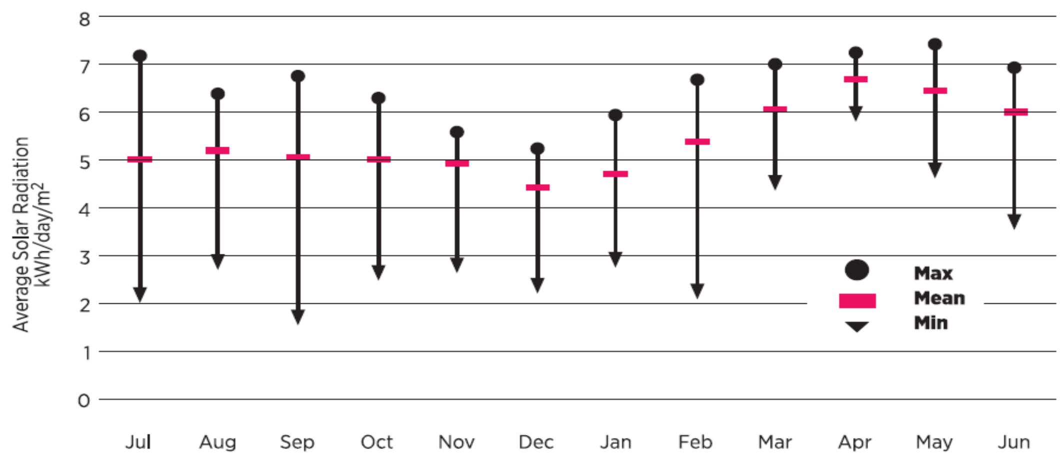
briquettes etc.) while liquid or gaseous biofuels are merely in existence. In 2011, the country's potential for agricultural residue to biomass energy stood at 317 523 mt/year which is quite good even for electricity production, (Singh, Nouhou and Sokona 2013) as depicted in the Table 2.1.

Table 2.1: National Energy resource potential of Agricultural Residues 2011

Crop	Amount (mt/year)	Ratio residue/ kernel	Amount residue (mt/year)	Heating value (GJ/mt)	Physical potential GJ/year
Groundnuts	83 858	0.43	25 157	17	427 676
Millet	87 234	2	174 468	17.6	3 070 637
Maize	23 613	3	70 839	17.5	1 239 683
Sorghum	20 556	2	41 112	17.6	723 571
Rice paddy (straw residue)	51 131	1.50	66 693	15.1	1 007 058
Rice paddy (husk residue)	51 131	0.15	6 669	15.9	106 041

Source: WB 2012, RRA (IRENA)

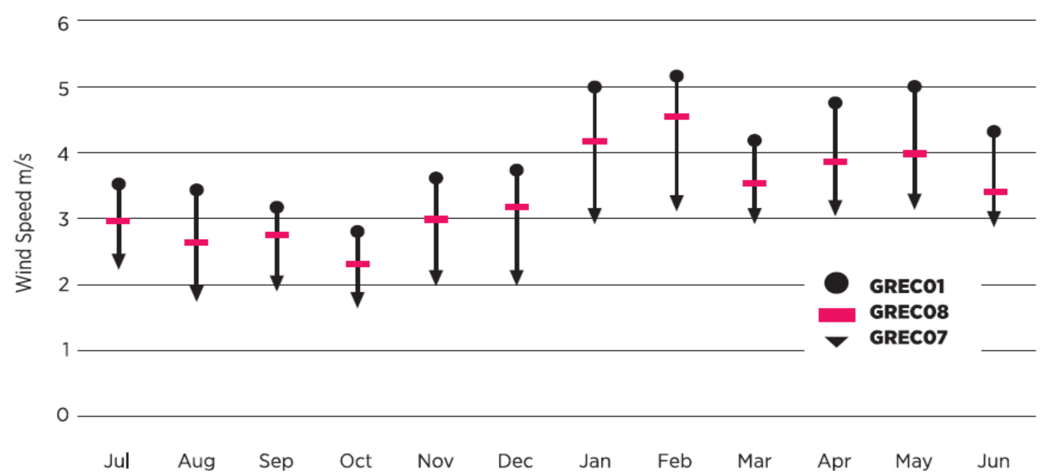
Regarding solar and wind energy resources, the (Lahmeyer GmbH 2005) study on renewable energy potentials (RE Masterplan) in The Gambia, has provided the average solar irradiance throughout the country varying between 4.5 – 6.7 kWh/day/m^2 which is quite good for solar PV as well as solar thermal applications. According to Figure 2.2, the period of high solar insolation was recorded around March to May when the diurnal variation between the maximum and minimum radiation values were small while December and January gave the periods of low insolation.



Source: Renewable Energy Masterplan (REMP) 2005

Figure 2.2: Monthly Solar Radiation data for The Gambia

The wind, however, is very moderate varying between an average 4.0 m/s[8] inland and little over 4.3 m/s on the coastline in coastal areas. Unlike the solar potential, the wind speed was high between January and March while low in July towards September (see Figure 2.3).



Source: REMP 2005

Figure 2.3: Monthly wind speed data at 30 metres height at 3 locations in The Gambia

[8] **m/s:** metre per second , **kWh:** kilowatt-hour

For *non-renewable energy resources* such as petroleum, natural gas or even coal, the country has no indigenous reserve of these fossil fuels which are currently being used in electricity generation or in the automobile sector; therefore all the fossil fuels (petroleum) need of the country are being imported from neighbouring countries as stated earlier. Given this situation, the energy system of the country especially electricity is neither secure nor sustainable in the short to medium term.

Notwithstanding, in the early part of year 2000s, following 2D seismic and 3000 sq. km 3D surveys have revealed with high potential the presence of petroleum resources. These resources are found mainly at off-shore sites in the Atlantic Ocean and work is being done with international exploration and production companies to bring this prospect to fruition (by converting these resources to reserves) (Michael E. Brownfield 2003). However, as it not known when these resources will be potential reserves therefore constituting a limitation which can be taking on board in subsequent studies on the modeling of the national energy system when the country becomes an oil producing nation rather than an importing one.

2.2 Energy demand and supply analyses

The energy demand and supply are crucial components in the optimisation of any electricity system and besides, given the huge mis-match between these symmetrical sides of the national electricity system, necessitated the analysis of these components.

2.2.1 Energy Demand Analysis

Energy is not an end in itself but rather the means for providing energy services. In any energy system, demand for energy services is a key driving force in determining the appropriate supply options available therein. This demand for energy services in turn is hugely influenced by several factors which include but not limited to the following:

- Population
- Economic activity
- Technology performances

Based on these key factors, it is expected that this century would see a major shift in energy demand and economic development from the developed to mainly developing countries like The Gambia (United States (U.S.) Energy Information Administration (EIA) 2016) (International Energy Agency (IEA) 2016).

As this study is mostly concentrated on the electricity aspects of the energy system, the demands for other energy forms such as heat are negligible as the potential demand for the latter is merely available in The Gambia, thus the demand analysis will only take into consideration the electricity demand side of the system. Currently, The Gambia, as will be highlighted in the subsequent section, only meets a proportion of its potential electricity demand which makes the computation of the demand a daunting task as it is not easy to say what the demand will look like if there was to be full access.

Given this situation, there is need to distinguish between key notions of electricity demand i.e.– actual (met) demand, suppressed (unmet) demand, theoretical demand as well as expressed demand.

- *Actual demand:* This is otherwise referred to as the "met demand"; it is the demand that is being served by the Utility – National Water and Electricity Company Limited (NAWEC).
- *Suppressed demand:* Contrary to the actual demand, the "unmet demand" or suppressed demand refers to the demand that NAWEC is currently not able to meet. It includes both connected demand not served (load shedding) as well as the current unconnected demand.
- *Theoretical demand:* It refers to an estimate of the demand that would have been there provided there had been full electricity access. It is a demand that include both currently connected users as well as the currently unconnected users, in brief; it is the sum of the met demand and the unmet demand.
- *Expressed demand*: It is a vital notion of demand for electricity as it is the demand used in modeling of the electricity system. Expressed demand refers to a trajectory that takes consideration of current met demand towards the theoretical demand. According to the revised national energy policy (Sahel Invest Management International 2014), the key factors shaping the expressed electric demand as well as its future trend include in addition to the three aforementioned factors are:

  - ✓ Energy intensity;
  - ✓ Technological innovation and deployment;
  - ✓ Efficiency of electrical goods and use.

The aforementioned demand factors are crucial in the determination of electricity demand using MAED (Model for Analysis of Energy Demand) or other demand side energy modeling tools. Some recent studies using MESSAGE to optimise various energy systems had used MAED to determine and to project the energy demand which was then inputted into MESSAGE to give the optimal expansion of the supply side of the system being modelled.

However, in the determination and projection of the national electricity demand, this study does not use the MAED but made reference to the previous studies on the electricity system. These studies have had detailed study and data (see Table A 1) for computation of expressed demand and its projected annual growth rate. This can be similar to that could be obtained from the MAED which requires high input data in order to be able to accurately determine the expressed demand and its future growth trends.

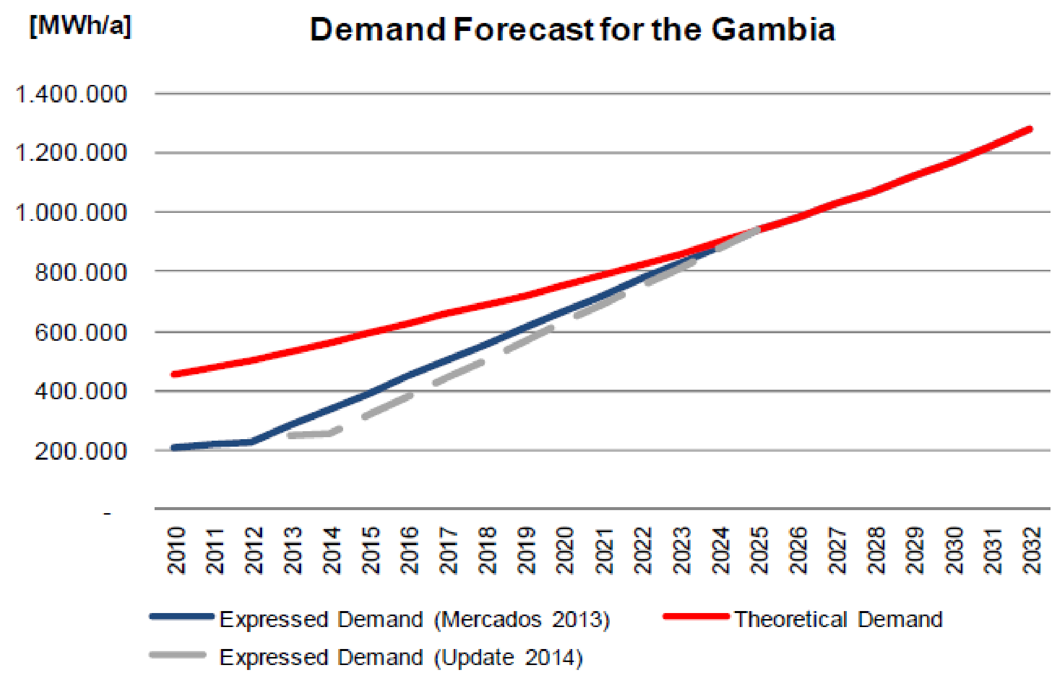
These vital studies include (energy policy (EP), renewable readiness assessment (RRA), public utilities regulatory authority (PURA) report, renewable energy master plan (REMP) etc.) which have all projected different electricity demand growth rates but on average, they have projected an annual growth rate of about 6 % to 7 % (Singh, Nouhou and Sokona 2013) (AF - MERCADOS Energy Market International (EMI) 2013) (Sahel Invest Management International 2014) commencing 2011. Below is national electricity demand (expressed) data from 2005 – 2011.

Table 2.2: The national expressed electricity demand in MWh from 2005 – 2011

Year	Electricity (expressed) demand MWh
2005	310 259
2006	375 692
2007	416 280
2008	473 040
2009	501 420
2010	596 030
2011	621 680

Source: NAWEC, PURA

More details on how these demands are obtained and expected to grow are highlighted in subsequent chapter (methodology) as well as Table A 1 in the annex. In addition, a separate study conducted by the World Bank (WB) on the national electricity system had given forecast of the theoretical demand (which include the suppressed demand), the expressed demand (estimated by a study that was done in 2012) and, the Bank's (WB) consultant's own forecast from 2010 to 2032 (Fichtner Studies 2014) as shown in Figure 2.4.



Source: Fichtner Study 2014

Figure 2.4: Electricity demand projection of The Gambia (MWh/a) 2010 – 2032

In Figure 2.4 above, the theoretical demand is expected to increase from 480 GWh in 2010 to about 1 290 GWh in 2030. The expressed demand, however, done by the Mercados 2013 study (AF - MERCADOS Energy Market International (EMI) 2013) and the updated one by the WB consultant have revealed that the demand will grow from 200 GWh in 2010 to 950 GWh in 2025 which is the year the expressed demand is expected to be tandem with theoretical.

2.2.2 Energy Supply Analysis

In energy supply analysis, both resources and technologies are crucial aspects to take into consideration. The resources with the conversion technologies are quite useful in delivering energy forms (primary, secondary etc.) required for the subsequent steps in the conversion process up to the delivery of final energy to the end use sector. In essence, the energy supply system ensures the transformation of energy resources (fossil fuels, renewables, etc.) to energy carriers (electricity, liquid fuels, heat, hydrogen etc.) then finally to end-use (lighting, appliances, etc.).

In the past and even up till now, human societies have derived useful energy for cooking and heating by the supply and the combustion of traditional solids fuels such as wood, animal dung, and other biomass forms etc., which are mostly in the form of chemically stored energy. Even the energy supplied in the form of manual labour and animal power were indirectly in the form of chemical stores of energy i.e. in the form of food and animal feeds (Jefferson, et al. 2012).

Then in the mid-19th century, coal as another solid fuel became prominent and effective in the energy supply mix, thereby replacing much of the human and animal power that were in predominant used in past millennia. However, in the late 1800s, following the discoveries of the oil fields began the era liquid fuel began to surface, but it was not until after the middle of the 20th century that oil actually commenced to dominate the global energy supply mix (United States (U.S.) Energy Information Administration (EIA) 2016).

Notwithstanding, over the same period, gaseous fuels such as natural gas was also being consumed but at a limited pace, but, it was not until the last two to three decades natural gas as gaseous fuel has begun to displace some of the liquid fuels. This on-going evolution of energy supply trend from solid to liquid to gaseous fuels is being and will continue to be influenced by cost and convenience. The same situation is quite true for most renewable and alternative energy supply options (Jefferson, et al. 2012).

Given this evolution of the energy supply system in the global context, the analysis of the energy supply system in the context of The Gambia can broadly be categorised into existing supply system and candidate (future) supply systems. These systems constitute both resources and technologies.

a. Existing energy supply systems

In this part, the existing national energy system is presented and the discussions here can be grouped into conventional non - renewable energy (RE) supply system, as well as RE supply systems while that of the electricity supply system will be dealt in detail in the next chapter.

I. Conventional non RE supply systems

As mentioned previously, the characteristics of the current energy supply system is unsustainable as it relies totally on imported fossil fuels (mainly petroleum products) to satisfy the need of the consumptions sectors. Apart from biomass (see previous chapter), the dominant primary energy form being supplied is petroleum products which consist of mainly gasoline (premium and regular); diesel oil, heavy fuel oil (HFO), liquefied petroleum gas (LPG) as well as kerosene and/or jet (aviation) fuel (Sahel Invest Management International 2014).

These products are mainly being supplied from nearby Ivory Coast through a contract agreement entered into between Total Oil International and EAGLE. The Subsidiaries of international oil marketing companies such as The Gambia National Petroleum Company (GNPC), GALP, Elton, Total and other local operators such as JAHOIL take the products normally from a depot to meet their individual market demands. In terms of logistics, this system is functioning effectively as most of the operators have their own logistical support arrangements (Sahel Invest Management International 2014).

Currently, the country has two depots, one situated in Banjul with a capacity of about 17 000 m^3 covering an area of about 10 500 m^2 and a new one located in Mandinary, just about 26 km from Banjul the capital. This new facility currently handles petroleum receives, supplies and distribution all over the country:

- Via a submarine pipeline for discharging tankers;
- 51,000 metric tons of storage capacity and;
- Serve about 55 retail stations nationwide.

The supply of these products excluding LPG grew from 114 million metric tons (mmt) in 2006 to about 148.8 mmt in 2012 (Sahel Invest Management International 2014). Table 2.3 shows the annual imported petroleum products from 2006 to 2012. The breakdown of consumptions of each of the fuel supplied is as well given.

Table 2.3: Imported petroleum fuels in metric tons 2005 to 2012

	2006	2007	2008	2009	2010	2011	2012
Petrol (Gasoline)	15,028.00	17,979.00	15,435.16	17,895.57	18,251.23	22,331.45	18,406.23
Kerosene (Jet fuel)	18,554.00	21,751.00	14,959.98	14,975.26	15,952.96	18,526.43	16,177.72
Diesel	42,526.00	42,152.00	44,107.40	50,571.13	67,001.56	67,153.55	63,175.04
LPG	1,500.00	1,500.00	1,500.00	2,500.00	2,250.00	2,235.00	2,288.00
HFO	36,407.98	44,874.00	42,387.71	54,916.40	51,361.30	47,745.17	48,742.41
Total (metric tons)	**114,015.98**	**128,256.00**	**118,390.25**	**140,858.36**	**154,817.05**	**157,991.60**	**148,789.40**

Source: MOPE, MOFEA

i. *Gasoline:* In 2012, gasoline fuel otherwise petrol was the 3rd largest liquid petroleum product supplied in the country. As indicated in Table 2.3, it amounted to about 18,406 mt in 2012 which was lower by 18 % compared to the year before. The sectorial consumption during same period showed that transport sector continues to dominate the gasoline market with about 95 % of the total imported in 2012 (see Figure 2.5), followed by the agriculture and fishing sector about 4 % while the remaining 1 % was shared among the commercial, industrial and residential sectors.

Gasoline (petrol): 18 406 mt

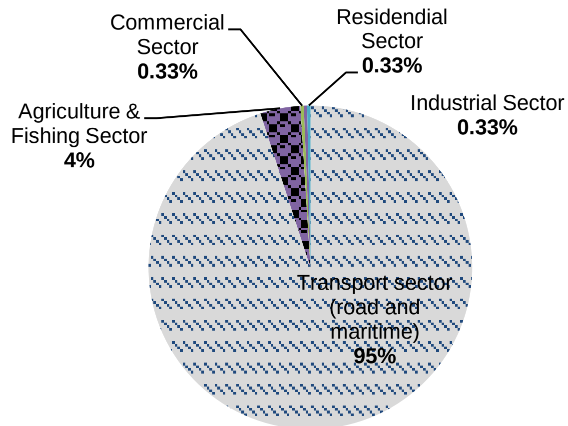


Figure 2.5: Distribution of imported Gasoline (in metric tons - mt) in 2012 by sector

ii. *Kerosene (Aviation/Jet) fuel:* Among the liquid fuel being imported, aviation or jet fuel constitute the lowest. In 2012, the quantity imported was 16,177.72 mt which was a decrease compared to that of 2011. This product can be divided into two namely: kerosene being used in the residential sector for lighting and jet fuel used in the aviation sector. The distribution of imported kerosene fuel by these two consumption sectors is shown in Figure 2.6.

Kerosene (Jet Fuel): 16 178 mt

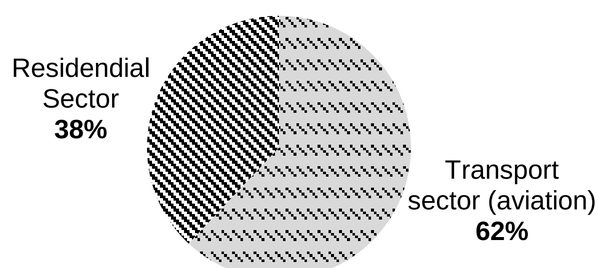


Figure 2.6: Distribution of imported (Jet fuel) Kerosene (in metric tons - mt) in 2012 by sector

iii. *Diesel (Light Fuel Oil - LFO):* The quantity of diesel imported in 2012, stood at 63,175.04 mt which was the highest among the liquid petroleum products being supplied. This total quantity imported was shared among transport sector (81 %), commercial and institutional sectors (9 %), industry (including energy) (8 %), residential (1 %) as well as the agriculture and fishing sectors (1 %). The 8 % of the diesel supplied in the industrial sector about 3% of that sub-amount is used by the Utility – NAWEC, for its operation in the provincial areas as shown in the Figure 2.7. However, currently NAWEC is reducing its diesel consumption by installation of HFO or hybrid renewable energy power plants in these areas (Fichtner Studies 2014).

Diesel: 63 175 mt

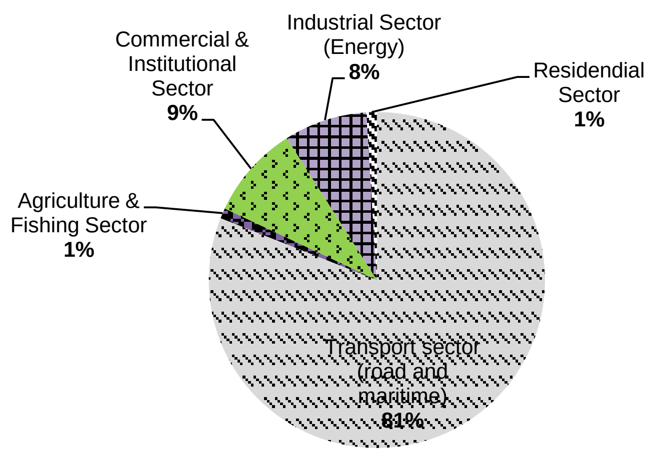


Figure 2.7: Distribution of imported Diesel in 2012 by sector (in metric tons - mt)

iv. *Heavy Fuel Oil (HFO):* It was the 2nd largest liquid petroleum product being supplied in country after diesel. In 2012, the total HFO imported was 48,742.41 mt. Contrary to other liquid petroleum products; the chunk of HFO is being used in the energy industry to generate electricity. This industry consumes about 98 % (see the Figure 2.8) of the total quantity imported, while the remaining 2 % is used by other sectors within the industrial sector such as manufacturing, construction etc.

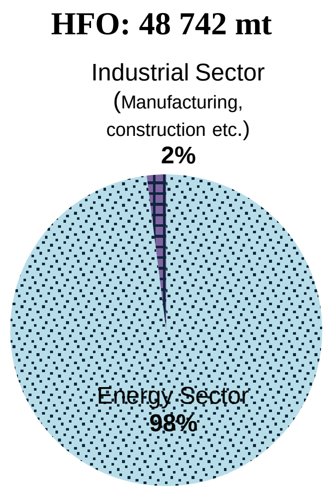


Figure 2.8: Distribution of imported HFO in 2012 by sector (in metric tons - mt)

Among these liquid fuels, two are actually essential for electricity generation in The Gambia i.e. HFO which is predominantly used for electricity production and Diesel (LFO) which is less used due to the relative high operating cost. Therefore the two essential fuels for this study are HFO and LFO which are being considered in subsequent chapters.

Different from the liquid petroleum products, is the gaseous products mainly LPG which is as well imported and sold in different sizes of cylinders to the residential and the commercial (hotel and restaurants) sectors for cooking. The quantity of LPG imported was 1,500 tons in 2006 and grew to 2,288 tons in 2012 (Hagan, Yabo and Ceesay 2012) as indicated in the Table 2.3. Regarding natural gas as a gaseous fuel and coal are not currently being imported and therefore not used in the existing energy supply system but under consideration in the future.

It is vital to note that (Sahel Invest Management International 2014), with the discovery of petroleum resources off the Atlantic coast of The Gambia in the early 2000s, and subsequent exploration activities in the late 2000s (Michael E. Brownfield 2003), has established to a great degree of certainty, the availability of petroleum resources in the country’s sea waters. However, the actual production of this resource or the conversion of these resources to reserves is not known and therefore not actually taken into consideration in this study thereby constituting a limitation. Besides, the availability of petroleum resources can only be confirmed upon drilling and production activities (Banerjee, et al. 2012).

II. Renewable energy (RE) supply systems

Currently, the renewable energy supply system contribution to national energy supply system especially electricity generation is very negligible, as it contributes less than 2 % (Particip GmbH 2014) of total grid connected electricity. The grid connected RE systems comprise solar PhotoVoltaic (PV) and wind energy systems that have proven to be feasible and cost effective options for providing clean energy services in communities in The Gambia, given their excellent to moderate potential. Under the UNIDO-GEF[9] 4 demonstration project, the country has grid-tied wind systems of about 120 kW installed and operated since 2009 and also 2 x 450 kW (0.9 MW) wind turbines installed and operated since 2012. In addition to wind systems, a diesel/PV hybrid system of 60 kW has been installed and being in operation since 2015. Besides these recent developments, a lot more of stand-alone solar PV and wind technologies have been installed all over the country but data on these installations are sparsely available.

Both grid-connected and stand-alone renewable energy based systems have good potentials for addressing the energy supply demand gap in the country and help expand electrification even in remote and inaccessible area. Based on the country's solar and wind resources, and suitable land areas, solar photovoltaic (PV), wind technologies, biomass, hydro (expected to be imported) have the potential of generating more than 675.8 TWh/year of electricity[10]. Table 2.4 shows the technical potential for these technologies (Singh, Nouhou and Sokona 2013).

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[9] United Nations Industrial Development Organisation – Global Environmental Facility (UNIDO-GEF)

[10] IRENA (2014) Estimating the renewable energy potential in Africa: A GIS Approach. Visit: http://www.irena.org/DocumentDownloads/Publications/IRENA_Africa_Resource_Potential_Aug2014.pdf

Table 2.4: Technical Potential of Renewables in The Gambia

Technical potential of selected renewable energy technologies	
Technologies	Potentials (TWh/year)
PV[11]	474
Wind	173
Biomass	1.8
Hydro	Negligible in country, however import possible

Source: IRENA RRA Gambia 2012

III. Existing electricity supply system

Please refer to subsequent sections as well as the next chapter for more detail information.

2.3 Energy supply technologies

Before delving into the energy system modeling it is vital to give run-down descriptions of the energy (more precisely electricity) supply technologies that are being or to be used in modeling national energy system. Energy supply technologies are basically numerous and include technologies that extract, refine, produce, convert and/or even transport energy from the resources level to energy services. Below are brief descriptions of some of these technologies used in this study:

i. *Oil based power plant:* Currently, all electricity generated in The Gambia is being supplied by this form of fossil fuel power plants. Oil based power plants essentially combust oil products to generate steam which then turns a turbine that is connected to a generator to produce electricity. These power plants can be generally grouped into: Heavy Fuel Oil (HFO) power plants and diesel / Light Fuel Oil (LFO) power plants which are based on the type of oil products being used to generate electricity.

ii. *Natural gas based power plant:* This is also another form of fossil fuel power plants, but uses natural gas instead of oil as described above. Unlike oil based

[11] Given this situation the Gambia ‘s energy policy looks forward to build huge solar power plant as well as conventional energy sources and also will rely on the imported hydro power to meets its energy demand

power plant that generally uses steam turbines to generate electricity, natural gas power plant can use steam, gas turbine or even both to produce electricity.

For electricity production, natural gas power plants can be grouped into *Open cycle gas turbine - OCGT* (which combust natural gas with the help of compressed air in the combustion chamber, then the high temperature gas/air mixture expands in a turbine, then drives generator to produce electricity) this is also referred to as simple cycle gas turbine (SCGT), *combined cycle gas turbine – CCGT* (this form of natural gas power generating system combines both gas cycle and steam cycle to produce electricity, the power generation process starts in the same process as described in OCGT and then the heat recovered from the gas cycle is then used to produce steam that is applied to a steam turbine to generate additional electricity) and *cogeneration* (this is similar to the combined cycle, but instead of generating additional electricity, the heat is instead used to supply the heat requirements for consumption sectors). Currently, this form of fossil fuel power plant is not being used in the Gambia's electricity system. CCGT and OCGT are the natural gas systems considered in this study as a result of their practicality in The Gambia.

iii. *Coal based power plant:* As the name suggest, it uses coal as fuel to generate power. The coal is often combusted to generate steam or even gasified to turn a turbine and generating electricity via the generator. There are numerous ways coal is used to generate electricity, one of the ways include the utilisation of the following technologies: *sub-critical coal power plants*, *coal-biomass power plants*, and *super-critical power plants*. These power plants can produce electricity by using steam turbine or gas turbine or even both as in the case of integrated gasification combined cycle. These types of power plants are also not currently in use in the national electricity system.

iv. *Hydropower plant:* This is a renewable energy based power plant that uses the potential energy in water to turn a turbine connected to a generator which produces electricity. The turning of the turbine converts the potential energy stored in water to kinetic energy that rotates the shaft of the turbine which is connected to a generator to produce electricity. Hydropower plants can be grouped into *hydrokinetics* (using natural hydro potential to generate power by submerging devices into potential sites usually of very small size), *run-off river plants* (limited water storage capacity and mostly incorporated with irrigation agriculture), *dams* (large water storage capacity with electricity production the main objective) as well as *pumped storage* (essential in meeting demand during peak demand hours). These technologies are as well not currently in use in the country. In this study, regional dams are being modelled to supply the electricity to country by importation.

v. *Wind farm:* Unlike hydro power plant, wind farm uses the kinetic energy of the wind to rotate the blades of turbine connected to a turbine shaft. This rotating shaft drives the generator to produce electricity. Wind farms can be located on-shore and/or off-shore depending on the site's wind potential. The turbines in the wind farm can be in the form of *horizontal-axis and/or vertical-axis wind turbines* which are based on the position of the turbine blades. In this study, the on shore horizontal-axis wind turbines are considered as a result of their successful applications previously.

vi. *Solar farm:* Solar energy is produced from the sun's electromagnetic radiation, via semi-conducting materials. The basic building block of a solar energy system is the solar module which consists of a number of solar cells. Solar cells and modules comes in many different forms varying greatly in performance and degree of maturity. The different types of solar cells used in solar modules can be in the form of *mono-crystalline (single crystal), poly-crystalline (multi crystals), thin films and amorphous material* etc., that produces electricity or heat by using them in *solar PhotoVoltaic (PV) system* (mainly electricity production), *solar thermal system* (heat production), as well *as concentrated solar power – CSP* (both heat and electricity). This study considered solar PV systems (at centralised and decentralised systems), as well as solar thermal for providing electricity in The Gambia. Table 2.5 gives some of these energy conversion technologies are their status of application and development as at 2014.

Table 2.5: Some modern energy conversion technologies

Technology			Energy output	Status as at 2014
Fossil fuel energy	Oil	Heavy Fuel Oil	Electricity	Commercially applied
		Light Fuel Oil	Electricity	Commercially applied
	Natural gas	Open Cycle Gas turbine	Electricity	Widely &commercially applied
		Combined Cycle Gas Turbine	Electricity & Heat, CHP	Widely & commercially applied
		Cogeneration	Electricity & Heat, CHP	Commercially applied
	Coal	Pulverised Coal	Electricity	Widely & commercially applied
		Integrated Gasification Combined Cycle	Fuels, Heat & Electricity	Applied but potential for improvement
Hydropower energy	Mini-hydro		Movement	Remotely applied & well-known
	Small & large scale hydropower		Electricity	Commercially applied
Wind energy	Small wind machines		Movement, Electricity	Water pumping & battery charging
	On-shore wind turbines		Electricity	Widely applied commercially
	Off-shore wind turbines		Electricity	Demonstrated, and being deployed
Solar energy	Passive solar energy use		Heat, Light, Ventilation	Demonstration and applications
	Low-temperature solar energy use		Heat (space & water heating, cooking), Cold	Solar collectors commercially applied, solar drying and cooking are locally applied
	Photovoltaic solar energy conversion		Electricity	Widely applied, remote & grid connected, high learning rate
	Concentrated solar power		Heat, Steam, Electricity	Demonstrated and being deployed

Source: GEA, 2011

These afore technologies are considered in this study as a result of their maturity as well as their potential to ensure electricity supply security in The Gambia (Sahel Invest Management International 2014). However, considering supply security will require taken into account the following technological parametres:

- Technologies operating characteristics
- Their costs
- Their environmental impacts

For fossil fuels electricity supply technologies such as oil, natural gas and coal power plants which are all being considered in this study based on the national policies and plans (AF - MERCADOS Energy Market International (EMI) 2013). Using the aforementioned parametres, oil based power plants are relatively cheap compared to natural gas but are less efficient in terms of operating conditions and its environmental problems. Natural gas power plants however, are efficient and more environmentally sound compared to coal and oil but economically they are relatively expensive. For coal, it has serious issues with pollutions (provided more advanced technologies are used) despite being cheap in terms of costs as well as operations.

Regarding renewable electricity supply technologies such as solar, wind as well as hydropower are also included based on their potential and feasibility (Lahmeyer GmbH 2005). Solar power operating characteristics and environmental impacts (if LCA is not considered) are quite good despite its current relatively high cost which is actually on a decreasing trend as a result of recent technological improvements. Wind farms are also considered given their low environmental impacts and favorable operating conditions but the cost is still quite high. Hydropower, however, has issues regarding its environmental impacts and even social acceptance but its cost is relatively lower as compared to other RE technologies and has fairly good operating conditions.

In brief, all these characteristics are being taken into consideration in the modeling of the national electricity system.

2.4 Energy system modeling

Energy modeling or **energy system modeling** is the process of building computer models of energy systems in order to analyse them. Such models often employ scenario analysis to investigate different assumptions about the technical and economic conditions at play. Outputs may include the system feasibility, greenhouse gas emissions, cumulative financial costs, natural resource use, as well as energy efficiency energy of the system under investigation (Wikipedia 2017) (M. M. Peter 1993).

Energy modeling (Subhes C. Bhattacharyya 2010) is a new field that commenced proliferating in the 1970s as a result of global oil crises that stroke the world during those periods. Besides the 1970 oil crises, are also the advances in technology and the immense rise of emissions especially in the past decades which have led to considerable increase in the number of energy models being developed and thus making energy system modeling an integral part in policy analysis in order to address the technical, environmental as well as economic impacts of energy systems.

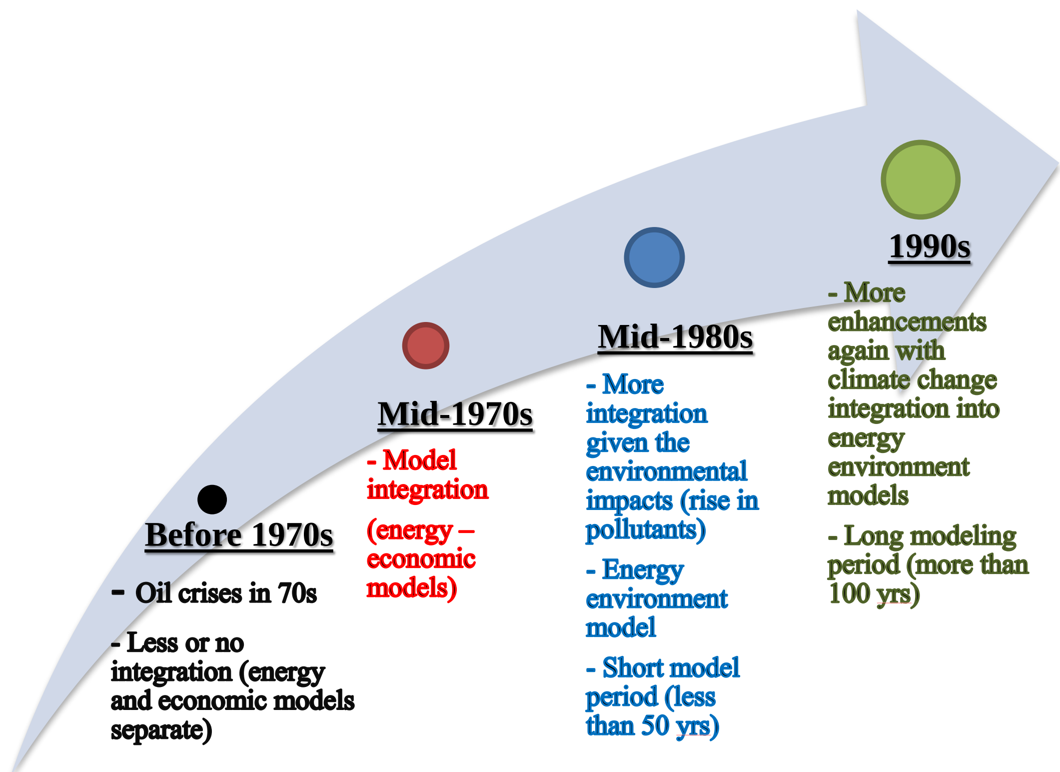


Figure 2.9: Evolution of energy modeling

Historically, the development of energy models has undergone three key phases; which include a phase of model integration which took place in the mid-1970s as result of the oil crises to make energy models more sophisticated and adaptable to then energy-economic conditions, then in the mid-1980s was the shift in which energy-environment interaction models were developed as a result of growing environmental concerns (such as pollutions) from energy system operations or utilisations but these models were not enhanced to cover very long modeling periods and then finally in the 1990s the climate change component was added to the energy-environment interaction model to make them more robust and enhance their modeling capabilities for very long modeling periods (e.g. over 100 years). Up to date, most of the existing models are being regularly enhanced and new sophisticated ones being developed as well (Nicole 1999).

During this evolution of energy system models, numerous studies have been and being conducted to analyse and categorise the different modeling techniques and approaches adopted since the 1970s. Such is the one done by Hoffman and Woods (Hoffman 1976) who classified different modeling techniques based on their approaches to solve energy related problems: i.e. linear programming based approach, input-output approach, econometric methods, process methods etc. In a separate classification, Grubb et al. (Grubb and Robert 1993) used six different criteria to group energy models viz: i) top-down vs bottom-up ii) time horizon iii) sectorial coverage iv) optimisation by simulation techniques v) level of aggregation as well as vi) geographic coverage, trade and leakage. Hourcade et al. (Hourcade 1996) as well have distinguished three ways to differentiate energy models which include model purpose, model structure and their level of external and input assumptions.

However, it was not until 1999 when an instrumental study was conducted by Nicole Van Beeck (Nicole 1999), who basically takes into consideration most of the previous literatures on energy modeling and classification but has added great detail and substance to energy modeling. This study has classified numerous energy models based on nine characteristics, which include i) model purpose (i.e. forecasting, exploratory and backcasting); ii) model structure (degree of endogenisation); iii) methodology (optimisation, econometric, as well as simulation); iv) mathematical approach (linear programming, mixed integer programming, and dynamic programming); v) spatial coverage (global, regional, national and local), vi) time horizon (long term, medium term and short time) and last but not least; vii) data required (quantitative, monetary and disaggregated). These characteristics will be described shortly.

Like Beeck, Pandey (Pandey 2002) has also classified energy-economic models into top-down/simulation; and bottom-up optimisation/accounting, which were then grouped based on different paradigms that include time horizon (long, medium and short terms), sector-wise (energy, and energy & economic), and spatial coverage (which can be global, regional, national and/or local). More recently Nakata (Nakata 2004) (M. M. Peter 1993) in a separate study has also considered top-down and bottom-up models as modeling approaches and the methodologies adopted by these approaches are grouped based on partial equilibrium, general equilibrium as well as hybrid (integrated) models. Nakata then further grouped these models based on modeling technologies (i.e. optimisation, economic and accounting), and as well takes into consideration spatial dimensions (i.e. global, regional, as well as national).

Most of these literatures are extremely vital as they set the basis for which an appropriate model could be chosen for energy system modeling, however, among these literatures reviewed, the most extensive was the classification done by Van Beeck (Nicole 1999), who based her classification on previous studies on energy modeling. As mentioned earlier, Beeck's study had classified energy models in nine ways and these ways as eluded to by Beeck are neither exhaustive nor entirely independent of each other. For instance, if a modeling approach is top-down, most of its assumptions will be internal, while for bottom-up approach most of its assumptions are external (i.e. determined by the model user). Below are the descriptions of the nine ways of model classification by Beeck:

- *Model purpose:* Generally, three model purposes can be distinguished, which are forecasting purposes (i.e.: predicting the near future), exploratory purposes (i.e.: exploring scenarios or long term in the future) and, last but not least, backcasting purposes (i.e.: looking back from the future to the present). But specifically, four model purposes can be distinguished and they include energy demand models, energy supply models, impact models, and appraisal models (see (Nicole 1999)). Currently, some of these models are integrated and therefore serve dual or multi purposes.

- *Model structure:* Different from model classification by purpose, is the classification of model by structure. This classification can help categorise models depending on their degree of endogenisation (i.e.: degree of internal and external assumptions into a model), the extent to which energy supply technologies, non-energy uses or energy end-use are described in a model. These four dimensions can be put on a range from "more" to "less" and any model can be ranked on this range.

- *Methodology:* Model can also be grouped based on the path used in developing them, these include – econometric, macro-economic, economic equilibrium, optimisation, simulation, spreadsheets, backcasting and multi-criteria modeling methodologies. Consequently, energy models categorisation based on methods can have the following features viz: modeling approaches, incorporation of supply and demand modules, input data requirement, flexibility to incorporate new end use, fuel and technology, rural energy specificities, informal sectors, data and skills concerns etc.

- *Mathematical approach:* This explains the mathematical procedures that are applied in various models, they comprise of – linear programming (LP), mixed integer programming (MIP) and dynamic programming (DP). Nowadays, there are models that are equipped with more than one mathematical technique. In LP, the technique is that in any given situation there are activities that can be expressed in the form of linear equalities or inequalities, that is for instance if x_1 and x_2 are the inputs to the model and y is the output, then the linear relationship is defined as:

$$y \leq ax_1 + bx_2$$

In MIP, however, is an extension of the LP and allows for the representation of greater deal of parametre relationship and their properties. For instance, the utilisation of discrete modeling techniques like (zero/one) to represent (no/yes). The last but not least mathematical approach (DP) involves solving the main problem by solving the sub-problems of the main problem.

- *Analytical approach:* It is an approach that is very crucial in grouping energy model. Based on this approach, models can be grouped into two i.e. top-down and bottom-up model. The main distinction between these two approaches or models lies in their ability to adopt technologies, their ability to capture the decision making behavior of the economic agents, and how the market and the economic institutions actually operate over a given period of time. In brief, top-down approach are usually of an aggregated typed model, it has high degree of endogenisation and generally used for predictive purposes, while bottom-up approach on the other hand is of a disaggregated type of model, with minimum degree of endogenisation and useful for exploratory purposes.

Table 2.6: MESSAGE and other Energy models characteristics using Beeck's classification

Model Name	Model Characteristics						
	Purpose	**Structure**	**Methods & Associated costs**[12]	**Mathematical Approach**	**Geographical Coverage**	**Time Horizon**	**Data Required**
MESSAGE	Explore	Detailed description (energy end-uses, technologies	Optimisation Freeware	DP*	Local National	Short Medium Long term	Quantitative Monetary Disaggregated
LEAP	Explore Forecast	DS**: High DOE*** SS**: Low DOE	DS: Econometric / Macroeconomic SS: Simulation Freeware	N/A	Local/National/ Regional/Global	Medium Long term	Quantitative Monetary Aggregated Disaggregated
ENERGY PLAN	Forecast Explore	Depends on mode	Econometric and Simulation Free Software	N/A	National	Short Medium	Quantitative
RETscreen	Explore	Detailed description (energy supply technologies)	Spreadsheet/Toolbox Freeware	N/A	Local National	N/A	Quantitative Monetary Disaggregated
MARKAL	Explore	Low DOE***	Optimisation Not freeware	LP*/DP*	Local National	Medium Long term	Qualitative, Monetary, Disaggregated

Source: Adapted from N.V. Beeck

:** Linear programming/Dynamic programming, *:** Demand-side/Supply-side, *****:** Degree of endogenisation

- *Geographical coverage:* It implies whether the modeling tool can be applied globally, regionally, nationally, locally or even to a project. Aside the geographical coverage, sectorial coverage of model can also be used to classify models. This classification is usually based on different sector of an economy. It can be multi-sectorial (many sectors) models or single-sectorial (one sector) model.

- *Time Horizon:* It depends on the context but can be short, medium and/or long term energy modeling tools. It is vital to note that there is no standard definition of short, medium or long terms, however, in 1993; Grubb et al. did a notice-based

[12] Source: **Energy Toolkit:** ***An Overview of LEDS Planning Instruments Version1.0, 2015***

time definition. They defined short term (≤ 5 Years), medium term (3 – 15 years) and long term (≥ 10 years) depending on modeling circumstances and framework.

- *Data[13] required:* The data can be aggregated, disaggregated, monetary, quantitative and/or qualitative depending on the model type.

Given the aforementioned classification and the important role energy models play in solving complicated problems, the choice of choosing the right tool to model a particular energy system is quite crucial, as inappropriate energy model can lead to an inaccurate decision and thus poor formulation of policies, plans or strategies. As this work seeks to optimise the energy system of The Gambia using a scenario based approach, MESSAGE as an energy system optimisation, multi-year tool can be an appropriate model to find the least cost energy supply options for The Gambia as tabulated in Table 2.6. Following a thorough comparison between the five aforementioned models, the MESSAGE model have been selected for running the simulation in this research due to the many reasons below.

MESSAGE is recommended by the International Atomic Energy Agency (IAEA) as a handy tool to optimise energy system. It is also ranked as the most multi-purpose and sophisticated simulation model of all programs available at the IAEA, and could principally fulfill the targeted objectives of all the IAEA software family of energy planning tools. Therefore, the model gains high credits to be used as recommended simulation model in this study. Also, the MESSAGE model is recognised by IAEA as a superlative model that is designed to evaluate alternatives energy supply scenarios consonant with user-defined constraints (capacity, production, investments as well as emissions etc.) and has been the subject and object of numerous studies which are analysed in the subsequent section.

Historically, it is a tool that was originally developed at the International Institute for Applied Systems Analysis (IIASA) in 1970s. In the early 70s, MESSAGE being the last in series of the linear programming models was first developed by Hafele and Manne in 1974, called the Hafele – Manne Model, and then evolved to the Suzuki's model in 1975.

[13] Most of the Data required for this study will be obtained from The Gambia's Ministry of Energy, the Utility, IRENA database and other international energy organization generating data.

In the late 70s, numerous versions of the model known as MESSAGE were developed and more recently it has been adopted and enhanced by IAEA who added a user interface.

2.5 Previous Studies

Below are some of the studies done using MESSAGE or other optimisation tools for The Gambia and elsewhere:

Table 2.7: Summary of studies on energy system modeling using optimisation tools

Sn	Title and Authors	Year	Optimisation Tool used	Results
1	Energy in a Finite World (path to sustainable future) – *Wolf Häfele et al* (Wolf Hafele 1981)	1981	MESSAGE, MEDEE, IMPACT, MACRO	They used MESSAGE with other complex system modeling tools to conduct a global energy system analysis. The utilisation of MESSAGE in the study was just complementary as it optimally determines the cost-supply ratio of the required global energy from 1975 – 2030.
2	Economic and Sensitivity Analysis of Non-Large Nuclear Reactors With Cogeneration Option In Lithuania – *Egidijus Norvaisa and Robertas Alzbutas* (Egidijus and Robertas 2009)	2009	MAED, MESSAGE	The analysis was done in two parts i.e. modeling of future Lithuanian energy system development options (in which they used MAED to project the energy demand data then supplied that output into MESSAGE to see the future development of the energy supply systems) and the analysis of the influence of main initial model parameters to the calculation results (sensitivity and uncertainty analysis). In the economic analysis, they concentrated on evaluation of possibilities to construct small and medium nuclear reactors in Lithuania while

				the sensitivity analysis analysed the main contributors to the possible variations of modeling results.
3	Formulating an optimal long-term energy supply strategy for Syria using MESSAGE model – *A. Hainoun et al.* (A.Hainoun, Aldin and S.Almoustafa, Formulating an optimal long term energy supply strategy for Syria using the MESSAGE 2009)	2009	MESSAGE	They modelled the national energy chain covering all energy level and conversion technologies for the period 2003 to 2030. They concluded that for future security of electricity supply, the national (Syrian) energy system will have to rely on oil and natural gas with limited renewable energy penetration and nuclear.
4	A methodology for the assessment of nuclear power development scenario – *D.K. Mohapatra and P. Mohanakrishnan* (Mohanakrishnan 2010)	2010	DESAE, MESSAGE	They used MESSAGE and DESAE (Dynamic of Energy System—Atomic Energy) models to depict the overall growth of energy and electricity particularly in India, considering the vigorous utilisation of nuclear power to meet its growing energy demand. In their study, MESSAGE was first used to depict the overall energy and electricity supply taking into consideration energy demands from various sectors of the economy. Then energy supply options, including the nuclear power technologies, are represented by their technical and economic parameters in MESSAGE. DESAE then takes the MESSAGE aggregated results on nuclear growth and computes the nuclear material flows, spent generated and the detailed information on nuclear infrastructure needs. These outputs

				from DESAE are finally fed back to MESSAGE to establish consistent assumptions on nuclear power development.
5	The potential role of nuclear energy in mitigating CO_2 emissions in the United Arab Emirates – *Hasan Jamil AlFarra*, *Bassam Abu-Hijleh* (AlFarra and Abu-Hijleh 2011)	2011	MESSAGE	Using MESSAGE, they estimate the energy demand and CO_2 emission in the UAE up to 2050. They modelled numerous scenarios and found that to mitigate CO_2 emission, UAE has to depend on nuclear energy which is economically viable.
6	Electricity Strategy and Action Plan – *AF Mercardos EMI* (AF - MERCADOS Energy Market International (EMI) 2013)	2012	ORDENA plus®	Several scenarios were modelled and they found that The Gambia's electricity system should rely on import of electricity (Hydroelectricity) and in-house conventional generation sources
7	WAPP – Planning and Prospects for Renewable Energy – *IRENA* (Miketa and Merven 2013)	2012	MESSAGE	RE (hydro, solar, wind) technologies can contribute to least cost solutions under favourable conditions.
8	Long term strategy for electricity generation in Peninsular Malaysia – Analysis of cost and carbon foot print using MESSAGE – *Fairuz et al.* (Fairuz, et al. 2013)	2013	MESSAGE	In their study, they have examined the cost and the relative carbon foot print of energy expansion for *twelve energy scenes or cases for the production of electricity for Peninsula Malaysia for the period 2009 to 2030.* They concluded by coming up with best strategy which comprises of accumulated percentages of energy resources in the fuel mix, as well as minimum cost of expanding this strategy and the CO_2 emissions during the study period.
9	Future nuclear perspectives based on MESSAGE integrated assessment Modeling – *Mathis Rogner*	2013	MESSAGE	They modelled numerous scenarios and compare with the BAU case. They remarked that under a comprehensive and global

	and Keywan Riahi (Rogner and Riahi 2013)			mitigation effort, the stabilisation of the GHGs concentration at low levels (450 ppm[14] CO_2) would be technically achievable even with an increase in energy demand and with the nuclear phase out, and thus suggested that with huge investments in energy efficiency improvements and demand reduction could offer an energy supply options that can include or not nuclear power.
10	The impacts of considering electric sector variability and reliability in the MESSAGE model – *P. Sullivan et al.* (Sullivan, Krey and Riahi 2013).	2013	MESSAGE	In this paper, they remarked that renewables although being a sustainable solution but may require adjustments in investment and generation decisions in order for the utilities to maintain reliability in their service areas as opposed to conventional generating technologies that have high degree of reliability and can be adjusted any how to match load. They demonstrated how carefully chosen model constraints can allow a flexible approach to treating integrations concerns of variable renewable technologies into the electric sector in a high level energy model.
11	Estonian Energy Supply Strategy Assessment for 2035 and Its Vulnerability to Climate Driven Shocks – *Mariliis Lehtveer et al.* (Lehtveer, et al. 2015)	2015	MESSAGE	In their work, they described MESSAGE as a useful tool for simulating the Estonian energy infrastructure and assists in making related decisions. They have also affirmed that moving forward Estonian energy system has to rely on wind and nuclear energy to

[14] ppm: parts per million

				solve problems related with CO_2 emissions, however, in the near term they recommend that for energy security purposes and practicality, Estonia has to construct new oil shale power plants but with efficiencies (CHPs)and emission reduction measures to be taken onboard.
12	Energy policy for low carbon development in Nigeria: A LEAP model Application – Nnaemeka Vincent Emodi et al. (Nnaemeka Vincent Emodia 2016)	2016	LEAP	The Long Range Energy Alternative Planning (LEAP) model was used to explore Nigeria's future energy demand, supply as well as theirs associated GHGs emissions from 2010 – 2030. They studied 4 scenarios including the BAU case and found that in order to decrease energy demand and emission of GHGs by 2040, the Government of Nigeria will require more aggressive energy policies.
13	Exploring scenarios for more sustainable heating: The case of Niš, Serbia. – Zivkovic Marija et al. (Marija Zivkovic 2016)	2016	LEAP	Using LEAP, the study modelled 5 scenarios excluding the BAU case to help analyse different these different scenarios that were developed by local stakeholders for the city of Nis by 2030. Based on the decarbonisation, energy security (ES) as well as energy efficiency (EE) strategies, the study concluded that for Nis heating system the final scenario proved to give Nis a desirable future with substantial improvement in EE. ES and reduction in emission when compared to BAU case.

14	The potential for peat to power usage in Rwandan power system and its associated implications – *Jean de Dieu K. Hakizimana et al* (Hakizimana, et al. 2016)	2016	MAED, MESSAGE	The study was conducted in 2015 and pointed-out that low level of access to modern energy services in Rwanda is largely attributed to lack of investment in energy sector. They found that the introduction of peat-fired power plants for electricity generation can actually phased out oil based thermal power plant thereby being a cost effective option for power supply during the model period of 2013 to 2045.
15	Electricity generation technology options under the greenhouse gases mitigation scenario: Case study of Cameroon – *Pierre Meukam et al* (Meukam, et al. 2016)	2016	MAED, MESSAGE	In their study as in other studies, MAED was used for energy demand assessment. While, the MESSAGE model was used to optimise the supply system and as well as quantify GHGs emitted. They found that by 2035, electricity demand could reach 35 TWh, 19 TWh and 17 TWh for High, Intermediate and Low scenario respectively. Hydro, Thermal (Gas, HFO, LFO), Biomass, Solar and Wind power plant projects have been considered in the study, with different implications based on country policy. Results showed that GHG emissions constraints can be met if appropriate investments are made.

16	The Gambia Electricity Sector Roadmap – High Level Update – *The Government of The Gambia* (National Water and Electricity Company (NAWEC) Ltd. 2017)	2017	Least-cost model	This study presented several scenarios for 2025 horizon commencing 2017 using a least cost supply model. It provides the strategies to be considered by Government of The Gambia in the short to medium term. It suggests strategies to be adopted in order to avert the discrepancies between the demand and supply in the Gambia. The chosen scenario is found to increase renewable penetration by 40 %. Solar PV and hydroelectricity imports constitute the chunk of this percentage.

Source: LKM, 2017

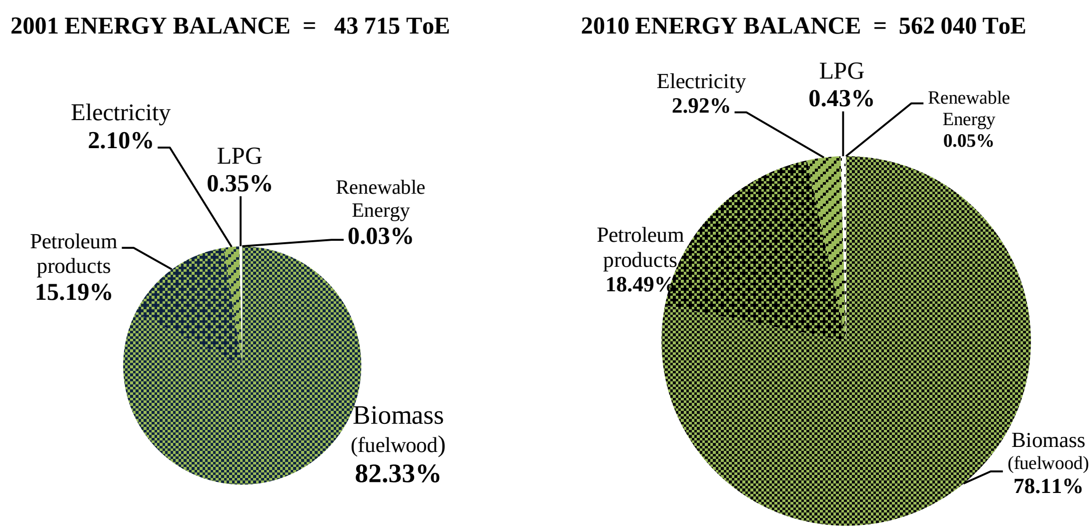
All these aforementioned studies have used in one way or the other used MESSAGE or other energy modeling tools to optimise the energy systems of various systems they analysed. In brief, all their analysis revolves mainly on technical, economic and /or environmental aspects of energy systems.

The conclusion of this section cannot be without a quote from a famous statistician, George E.P. Box, 1976 (Boekel 2008) eluded that "*essentially all models are wrong, but some are useful*" what this statement affirms is all models are by default wrong and by this definition, it implies that no model is correct. Therefore, it recognises that all models are merely a manifestation of reality and by definition makes all models incorrect in one respect or the other. However, it is to note that the quote went further to add that despite all models being wrong that does not imply that they are useless.

In view of this quote by Box, energy models are therefore useful mathematical tools based on system approach and the choice of the best model can be determined based on problem that the decision makers sought to solve. Complex energy system modeling can lead to better decision making by providing the decision maker with more information about the possible consequences of the choices being or to be made.

2.6 The Gambia's energy system

The energy system in The Gambia is dual in nature, on the one hand, is where the utilisation of traditional and inefficient energy forms or devices dominate all consumption sectors especially in the household sector. On the other, is where modern energy system such as electricity as well as modern fuels and appliances are being used. The 2001 and 2010 energy balances of The Gambia are shown in Figure 2.10. In this figure, it can be seen that the amount of energy supplied between these two periods has significantly increased (more than 100%); however, in terms of structure of the national energy supply sources, there was merely a change.



Source: SE4ALL (The Gambia) 2014

Figure 2.10: 2001 and 2010 National Energy Balances

Below are the descriptions of each of the energy forms supplied in The Gambia over the years:

- *Biomass:* Since 2010 up to date, the biomass energy especially fuel wood continues to constitute the largest proportion of the total national energy supplied. In 2010, biomass energy constituted about 78 % of the total energy supplied (562 040 tons of oil equivalent (ToE)), making it the largest energy source consumed. In addition, about 90 % of household energy consumption (Sahel Invest Management International 2014) comes from fuelwood (firewood, charcoal, sawdust, and agricultural wastes etc.) and if this consumption pattern remains in the medium to long term, it could pose serious social as well as environmental consequences. According to the AES[15]-2012 document (Hagan, Yabo and Ceesay 2012), the country has lost more than 50 % of its forest cover in the last six decades due to the heavy dependence on the forest resources to meet the domestic energy requirements.

Table 2.8: Forest Resources of The Gambia 1946 to 2015

Forest Type	% of total land area						
	1946	**1968**	**1980**	**1993**	**1998**	**2005**	**2015p[16]**
Closed Woodland	60.1	8.0	1.3	1.1	0.7	1.5	2.8
Open Woodland	13.3	14.6	10.7	7.8	6.2	12.0	12.2
Savannah	7.8	31.6	24.8	31.8	34.6	31.5	25.0
Total Forest Cover	81.2	57.3	36.8	40.7	41.5	45.0	40.0

Source: DCMI, Household Energy Survey

However, In the future, provided more aggressive policies are in place the rate of forest degradation would likely continue and the activities that can be attributed to this lost in forest cover are mainly agriculture (land clearing, overgrazing as well as bush fires etc.) and other anthropogenic activities (such as human settlements, timber as well as fuelwood harvesting). Therefore, the need for sustainable utilisation of forest resources is vital for continued biomass energy utilisation in the country. Besides, according to the RRA report (Singh, Nouhou and Sokona 2013), the country has very good bio-energy (from agricultural residues) potentials as depicted in Table 2.4.

- *Fossil Fuels (Petroleum):* This is the second largest energy form supplied in 2010. All petroleum fuel need of the country is sourced from neighbouring countries like Cote d'ivoire or Port Gentil in Gabon. The imported petroleum products consist of petrol, diesel, jet-A1, LPG, HFO as well as LFO etc. as illustrated in Table 2.3 which are used in various economic activities such as electricity generation, cooking (LPG) as well as transportation fuels for vehicles.

[15] Access to Energy Services (AES)
[16] P: projection

The Gambia being a non-oil producing nation, imports all of its fossil fuel requirements from other countries as stated previously, thereby making it susceptible to any exogenous shocks such as price increase of oil in the international market. Any increases in world oil price will often lead to an erosion of the gains in the country's development efforts. However, it is believed with high chances that The Gambia has good prospects for hydrocarbons resources. So far these resources are found in the Atlantic Ocean and extent north of Casamance-Bissau sub-basin which forms part of four West African countries including Mauritania – Senegal – The Gambia – Guinea Bissau coastal basin.

The area is characterised by prominent halokinetic strata deformation and also has proven petroleum systems. With these prospects, the petroleum importation nightmare will hopefully ceased to stop thereby making the country more energy independent and secure in the future. For electricity generation from other fossil fuels sources such as coal and natural gas are also being considered in the electricity strategy (AF - MERCADOS Energy Market International (EMI) 2013) especially their contribution in diversifying the national electricity production system.

- *Electricity:* In the total national energy supply chart in Figure 2.10, electricity constituted about 3% of the total supplied in 2010. Electricity in The Gambia is produced by thermal means i.e. mainly Heavy Fuel Oil (HFO) utilisation in the Greater Banjul Area (GBA) and diesel oil in the provincial stations. Figure 2.11 provides the evolution of the national electricity supply capacity since 1981. Between 1981 and 2014, the total national electric installed capacity grew from 6 MW (1981) to 104 MW (2014) representing a 17.3 fold increase. The generation as well grew by 13.5 folds i.e. 20 GWh in 1981 to 270 GWh in 2014. The reliance on these petroleum fuels for electricity production is not only inefficient and inadequate but became economic burden as a result high national electricity tariffs (Particip GmbH 2014) compared to countries in the sub-region.

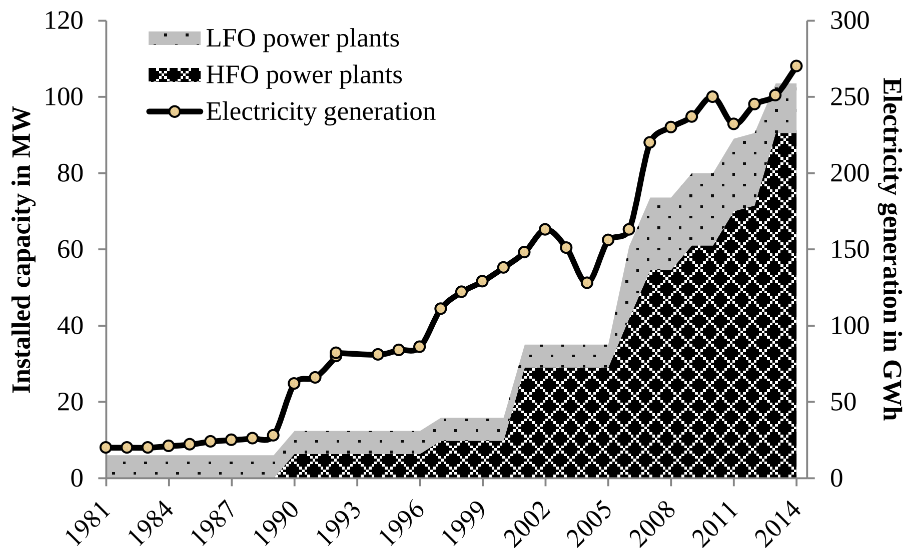


Figure 2.11: Evolution of national electricity supply capacity 1981-2014

Currently, The Gambia's electricity production, transmission as well as distribution are being managed and operated by a single public utility company called National Water and Electricity Company Ltd. (NAWEC). NAWEC operates two power plants in GBA and six isolated smaller stations in the provinces. The two power plants in the GBA are located Kotu and Brikama, while the six small isolated stations are spread in the regional towns of Essau, Kerewan, Farefenni, Bansang and Basse.

In the revised 2014 National Energy Policy, under the electricity sub-sector, the government seeks to improve the electricity supply system, improve access as well as provide affordable energy services. All these goals are being reinforced by the National Electricity Act (National Assemby 2005) that seeks to promote cost effective generation, transmission and distribution of electricity, set standards for electricity services, determine appropriate tariffs, as well as enable a transition to a private investor controlled and operated electricity sector. However, so far, the role of the private sector in the electricity sub-sector is quite limited.

In 2014, the electricity generation capacity was about 104 MW of which only 62 MW was available (see Table 2.9). This discrepancy between the installed and available capacities is partially constrained by the Utility's financial position to either replace the ageing generation infrastructure and the difficulty in carrying out its maintenances adequately. Most of the generation capacity is met from two HFO based power plants: i.e. Kotu (41 MW installed and only 19 MW available) and Brikama (47 MW installed and only 36 MW available). Besides these two big power plants, the utility – NAWEC also delivers electricity via six small isolated grids with a total of 13 MW of installed capacity of which only 7 MW is available and using high speed, LFO plants as baseload.

Table 2.9: National Electricity Installed and Production capacities and peak demand as at 2014

Location	Power Stations & Description		Installed Capacity (MW)	Production (MWh)	Peak demand (MWh)[2014]
Greater Banjul Area (GBA)[17]	Kotu	Thermal	41.4	99 977	535 360
	Brikama	Thermal	47.4	162 429	
	Batokunku/ Tanji	Wind	1.5	119	
Provincial Towns/Regional Towns	Essau	Thermal	0.8	483.79	24 640
	Farefenni	Thermal	4.5	2 721.33	
	Kerewan	Thermal	0.9	544.27	
	Kaur	Thermal	0.66	399.13	
	Bansang	Thermal	1.9	1 149.01	
	Basse	Thermal	4.32	2 612.48	
Total			**103.65**	**270 435.01**	**560 000**

Source: NAWEC 2015 report

According to the 2010 estimates the electricity access rate was estimated at 40 %, in the GBA the rate was about 60% while in the provinces the rate was only 6 %. Also about 66 % of Gambian electricity demand is estimated to be suppressed (National Water and Electricity Company (NAWEC) Ltd. 2015). During the last decade, the demand for electricity demand has grown at an average of 5.5 % per annum (Singh, Nouhou and Sokona 2013). This low access rate and the high level of suppressed demand are mainly attributed to insufficient generation capacity, inadequate transmission and distribution network, over reliance on import of expensive fuel for generation, poor performance of the power utility as well as

[17] GBA (Greater Banjul Area): it is the whole south western part of The Gambia.

weak sector regulation etc. In 2009, the latest Investment Climate Assessment (Ministry of Finance and Economic Affairs (MoFEA) 2011 <http://eeas.europa.eu/archives/delegations/gambia/documents/about_us/page_2012_2015_en.pdf>) reports that about 80 % of firms in The Gambia mentioned electricity as a major or very severe constraint to their operations.

Like the generation, the T&D system is as well underperforming as the loss encountered recently stood at 25 % (comprising both technical and non-technical losses) (Sahel Invest Management International 2014). The Gambia has two 33 kV transmission lines with a length of about 125 km conveying electricity from the Kotu and Brikama thermal power plants to 33/11 kV transmission substations and 33/0.4 kV distribution sub-stations.

Electricity from these sub-stations are conveyed by 181 km 11 kV lines with various 11/0.4 kV transformer stations at various sites in the GBA and Brikama. Then low voltage lines distribute electricity to three phase and single phase consumers at 400 V and 230 V respectively. The high T&D losses can be attributed to the limited and inadequacies in the network, overloading of transformation capacity, and high reactive power flows (Fichtner Studies 2014).

- *Renewable Energy:* Apart from biomass which is described above, the other indigenous proven renewable energy resources of The Gambia consist of solar and wind. Given the location of the country, it enjoys a favourable tropical weather thus for most part of the year solar irradiation is quite high and wind speeds are quite moderate. The Gambia’s current renewable energy supply is very negligible (about 0.05 % of total energy supply, 2010). In 2006, studies on the renewable energy potentials (especially solar and wind) were conducted and based on these studies, the average solar radiation of The Gambia was at 4.4 – 6.7 kWh/m^2/day while the wind conditions at 30 m height were moderate in the interior part of country (less than 4.0 m/s), but rise to an average wind speeds of about 4.3 m/s on the coast line in the western part of the country (Lahmeyer GmbH 2005) as shown in Figure 2.2 and Figure 2.3.

  With very good solar radiation all over the country, several energy supply options especially electricity can be explored such as photovoltaic (PV) farms, Solar Home Systems (SHSs), as well as Hybrid Systems with PV etc. Currently there are numerous small solar PV systems (especially SHSs) installed all over the country but data on these systems are not available due to their scale. Also there are growing number of solar renewable energy companies that design, and install small scale solar PV systems for both public and private sectors.

Wind energy, as potential is moderately good especially along the coast line, thus, in last decade, there are few installed wind firms that are providing electricity to some communities (Batokunku[18], Tanji) along the coastline and sometimes even sell the excess to the grid under power purchase agreements (PPAs).

Previously (since the 1990s), wind power has being used in The Gambia, but was mainly limited to water pumping projects such as irrigation and other water supply purposes. In recent years, wind power has gathered so much interest within multilateral institutions, donors as well as the Government mostly owed to technological advancement. The Batokunku wind project was the first project confirming these growing interests in The Gambia. Batokunku (0.90 MW) wind firm generates electricity for local community use and also supply any surplus power generated to the Utility. The annual electricity generation in 2012 of the wind firm was at 120 MWh, another site besides Batokunku is Tanji which has also installed wind power of capacity of about 120 kW (Dodou S. and Peter D. 2014).

In the future, both solar and wind firms are being considered as vital renewable energy sources that could improve or increase the RE mix of the country which is in line with one of the goals of the SE4ALL initiative launched by the UN in 2012 (SE4ALL Global team 2016).

In addition to solar and wind, hydropower is also another potential renewable energy resource that The Gambia can benefit from. Due to the near flat terrain and the fact that no part of the country rises 75 m above sea level, hydropower potential of the country is extremely limited according to several private studies done on the river Gambia (Sahel Invest Management International 2014). However, it is vital to state that further upstream of the river Gambia, in Guinea and in Senegal there are very good potential for the hydroelectricity production. For this reason, a regional energy project called the OMVG (among The Gambia,

[18] a community located at the south western part of the country as well as Tanji

Senegal, Guinea Conakry, Guinea Bissau) is currently being implemented in Senegal and Guinea to build a dam of a total installed capacity of 368 MW.

As a regional project, all the dams that are being built are located outside of The Gambian territory, thus the need to build a regional transmission line of 225 kV to cover a total distance 1600 km (AF - MERCADOS Energy Market International (EMI) 2013) that will be connecting all four countries. Upon construction of the regional interconnection line and the completion of the dams, The Gambia is expected to import about a total of 50 MW (30 MW and 20 MW) from Sambangalou and Kaleta hydropower plants respectively. Regarding policies on RE in The Gambia, there is no specific policy on RE, however RE policies are being covered under the National Energy Policy (Sahel Invest Management International 2014) and the latter has had sub-sections on the different RE resources of the country.

In 2013, the government enacted an RE law (Ministry of Petroleum and Energy 2013 <http://extwprlegs1.fao.org/docs/pdf/gam134879.pdf>) which put in-place the legal frameworks surrounding RE deployment and implementation in The Gambia. The main objectives of the Act are to: promote RE development; incentives and support for grid connected RE systems; installers registration and promotion of standards on RE equipment and appliances; feed-in tariff (FiT) development and implementation; RE fund establishment amongst other things. The enactment of this law is quite vital as it set the pace for the deployment and penetration of RE technologies in The Gambia.

2.7 Energy Sector Stakeholders

In The Gambia, institutions involve in the planning as well as execution of energy sector policies, strategies and plans can be grouped as follows: the National Assembly (Parliament), the Government (excluding the NA), the Parastatal as well as other institutions. The National Assembly is the highest legislative body of the country. The government, however, comprises of several institutions and the highest body involves in the formulation and execution of policies related to energy. The parastatals comprise of numerous energy institutions that are mandated with the implementation of energy sector programmes and plans such as ensuring the supply of energy. Other institutions include various MDAs (Ministries, Departments as well as Agencies); NGOs, Private sector, Associations etc. that also play a crucial role in the execution of specific aspects pertaining to energy supply and consumption.

The Government institutions such as the *Office of the President (OP)* and the *Ministry of Petroleum and Energy (MoPE)* are the key institutions responsible for addressing matters pertaining to energy sector planning, management as well as the development and implementation of the national energy policy and strategies with the support from other government institutions (such as *Ministry of Finance and Economic Affairs – MoFEA, Ministry of Environment, Climate Change, Water Resources and Wildlife – MoECCWRW* etc.) and parastatals (*National Water and Electricity Company – NAWEC, Public Utilities Regulatory Authority – PURA, Gambia National Petroleum Company – GNPC, The Gambia Standard Bureau – TGSB, The Gambia Renewable Energy Centre – GREC etc.*). These parastatals are responsible for the preparation and implementation of specific energy related issue linked to energy standards, regulation, energy projects privatisation, decentralisation, and commercialisation of energy entreprises, planning of energy production and consumption, management of research studies etc.

Specific to the electricity sub-sector, the key stakeholder institutions include OP, MoPE, MoFEA, NAWEC, MoECCWRW as well as PURA. In Gambia, electricity and water related services are provided by one Utility – NAWEC. NAWEC is vertically integrated electricity utility that handles electricity generation, transmission, as well as distribution. Water production and distribution as well as sewerage are also its intervention areas. The MoPE is responsible for the implementation of government policies related to electricity supply, and distribution including renewable energy. PURA on the other hand, conduct tariff reviews and recommend tariff adjustment to MoFEA which then evaluate financial implications and provide advice to OP for final decision. Depending on the magnitude of the issue on the table will necessitate if the issue needs to be tabled before the national assembly or OP can make the decision.

3 CHAPTER THREE: METHODOLOGY

The principal approach applied in this study is “scenario analysis” which involves using a mathematical (precisely, mixed integer programming) system model called MESSAGE – Model for Energy Supply Strategy Alternatives and its General Environmental impacts. MESSAGE ensures sufficient (future) supply of energy (electricity, heat, etc.) considering the technologies and resources in the model for specific energy demand (Fairuz, et al. 2013).

Given the future uncertainty, a scenario based approach is quite vital in long term assessment of energy (more precisely electricity) supply options. According to the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Emission Scenarios* (Ogunlade and Ber 2000), “Scenarios are simply alternative images of how the future might unfold and are appropriate tool with which to analyse how driving forces may influence future outcomes and assess the associated uncertainties.” It is important to mention that a scenario is not a prediction of the future to come but an internally consistent description of a future state or trajectory that is as comprehensive as needed for analysis purposes.

It is also vital to distinguish between scenarios and forecasts, the latter, describes a single future development (with only statistical deviations) of the underlying system being studied while, the former, draws a consistent picture of the consequences of a given set of assumptions.

MESSAGE as a scenario analysis tool was originally developed in the 1970s but it was not until the 1980s when a remarkable advancement was made (EnergyPlan n.d.) at the IIASA - International Institute for Applied Systems Analysis. However, the current version has been adopted and enhanced by the International Atomic Energy Agency (IAEA), who added a user interface, in order to facilitate its usage.

As highlighted in the previous chapter, MESSAGE is a dynamic, bottom-up, multi-year energy modeling framework that applies linear as well as mixed-integer optimisation techniques (International Atomic Energy Agency (IAEA) 2007). It is a tool used in the computation of supply-side of energy systems. The whole supply system is represented as network of technologies and energy levels, starting from extraction or supply of primary energy, passing via energy conversion processes to transmission and distribution up to meeting the given demand for final energy. The development of the future energy demand is an exogenous scenario input to the model which is very vital in the modeling of any electricity system (International Atomic Energy Agency (IAEA) 2007).

The basic principle of MESSAGE is optimisation of an objective function (e.g. least cost, maximum self-sufficiency, lowest environmental impact). The optimisation is done by comparing the techno-economic performances of a certain technology and/or resource with its alternatives on life cycle analysis (LCA) basis. When a particular final energy (electricity or heat) can be satisfied by two or more options (example electricity needs can be met by using gas or oil), the optimal solution that will be chosen by MESSAGE will be based on discounted cost applied to the investment cost, O&M (operation and maintenance) costs, fuel cost if non-renewable energy etc. The objective function is described in the equation below:

$$\sum_t \Bigg[\beta_m^t \Delta t \Bigg\{\sum_{svd}\sum_l zsvd..lt * \epsilon_{svd} * \Big[ccur(svd,t) + \sum_i \sum_m ro_{svd}^{mlt} * cari(ml,t)\Big]$$
$$+ \sum_{svd} \epsilon_{svd}$$
$$* \sum_{e=0}^{e^d} Usvd.e.t * \epsilon_{svd}$$
$$* \Big[ccur(svd,t) + \sum_m ro_{svd}^{mt} * car2(m,t) + \sum_m ro_{svd}^{mt} * car1(m,t)\Big]$$
$$+ \sum_{svd} \sum_{\tau=t-\tau_{svd}}^{t} \Delta\tau * Yzsvd..\tau * cfix(svd,\tau)$$
$$+ \sum_r \Bigg[\sum_g \sum_l \sum_p Rzrgp.lt * cres(rgpl,t) + \sum_c \sum_l \sum_p Izrcp.lt$$
$$* cimp(rcpl,t) - \sum_\epsilon \sum_l \sum_p Ezrcp.lt * cexp(rcpl,t)\Bigg]\Bigg\} + \beta_b^t$$
$$* \Bigg\{\sum_{svd} \sum_{\tau=t}^{t+t_d} \Delta(t-1) * Yzsvd..\tau$$
$$* \Big[ccap(svd,\tau) * fri_{svd}^{t_d-\tau} + \sum_i \sum_m rc_{svd}^{mt} * cari(m,t) * fri_{svd}^{t_d-\tau}\Big]\Bigg\}\Bigg]$$

Where:

$\Delta \boldsymbol{t}$**:** *length of time period t in years*
$\boldsymbol{dr}(\boldsymbol{i})$**:** *discount rate at period* i *in percent*

$\boldsymbol{\beta_b^t} = \prod_{t=1}^{t-1}\left[\frac{1}{1+\frac{dr(i)}{100}})\right]^{\Delta_i}$

$\boldsymbol{\beta_m^t} = \boldsymbol{\beta_b^t} * \left[\frac{1}{1+\frac{dr(t)}{100}}\right]^{\frac{\Delta_t}{2}}$

$\boldsymbol{zsvd..lt}$**:** *annual consumption of technology* v *of fuel* s *load region* l *and period* t*, if* v *has no load region , l=".."*
$\boldsymbol{\epsilon_{svd}}$**:** *efficiency of technology* v *in converting* s *to* d $ccur(svd,t)$**:** *variable operation and*

maintenance costs of technology v (per unit of main output in period t)
$\boldsymbol{ro_{svd}^{mt}}$***:*** *the relative factor per unit of output of technology v for relational constraints m in period t, load region l*
$\boldsymbol{car1(m,t)}$ ***and*** $\boldsymbol{car2(m,t)}$***:*** *coefficients for the objective function, that are related to the user defined relation m in period t.*
$\boldsymbol{cari(ml,t)}$***:*** *the same for load region l, if relation m has load region*
$\boldsymbol{Usvd.e.t}$***:*** *the annual consumption of fuel s of end-use technology v in period t and elasticity class e.*
$\boldsymbol{\kappa_e}$***:*** *the factor giving the relation of total demand for d to the demand reduced due to the elasticity to level e*
$\boldsymbol{ro_{svd}^{mt}}$***:*** *the relative factor per unit of output of technology v for relational constraints m in period t $cred\ (d,e)$* ***:*** *the cost associated with reducing the demand for d to elasticity level e*
$\boldsymbol{Yzsvd..\tau}$***:*** *the annual new built capacity of technology v in period t*
$\boldsymbol{cfix(svd,\tau)}$***:*** *the fix operation and maintenance costs of technology v that was built in period t*
$\boldsymbol{ccap(svd,\tau)}$***:*** *specific investment of technology v in period t (given per unit of main output)*
$\boldsymbol{fri_{svd}^{n}}$***:*** *the share of this investment that has to be paid n periods before the first year of operation*
$\boldsymbol{rc_{svd}^{mt}}$***:*** *the relative factor per unit of new built capacity of technology v for user defined relation m in period t*
$\boldsymbol{fra_{svd,m}^{n}}$***:*** *the share of the relative amount of the user defined relation m that occurs in n periods before the first year of operation (this can, e.g., be used to account for the use of steel in the construction of solar towers over the time of construction)*
$\boldsymbol{Rzrgp.lt}$***:*** *the annual consumption of resource r, grade g, elasticity class p, in load region l and period t*
$\boldsymbol{cres(rgpl,t)}$***:*** *the cost of extracting resource r, grade g, elasticity class p, in load region l (this should only be given, if the extraction is not modelled explicitly)*
$\boldsymbol{Izrcp.lt}$***:*** *the annual import of fuel resource r from country c in load region l, period t and elasticity class p, if r has no load region l = "."*
$\boldsymbol{cimp(rcpl,t)}$***:*** *the cost of importing resource r in period t from country c in load region l, and elasticity class p*
$\boldsymbol{Ezrcp.lt}$***:*** *the annual export of fuel resource r to country c in load region l, period t, and elasticity class p, if r has no load region l = "."*
$\boldsymbol{cexp(rcpl,t)}$***:*** *the gain for exporting resource r in period t to country c in load region l, and elasticity class p*

What this objective function does is to compute the present values of different energy supply options by discounting all costs occurring at later points in time to the base year, and the sum of the discounted costs is used to find the optimal solution. By bringing all cost to their present values facilitate comparison between options; basically, the discount rate ($\mathbf{dr}(\mathbf{i})$) defines the weights different periods are accorded in the optimisation. In principle, a low discount rate gives more weight to future expenditures than the present ones and thus favours technologies that have high initial investment cost but low operation costs, while a high rate tends to give more weight or importance to present expenditures than the future ones (A.Hainoun, Aldin and S.Almoustafa 2009) (International Atomic Energy Agency (IAEA) 2007)(see chapter 5 on sensitivity analysis).

MESSAGE being a tool that optimises a given energy system can help in optimally bridging the gap between the demand and supply sides of energy systems. It simply assures sufficient energy supply for given technologies and resources according to the specified energy demand. Therefore, the main characteristic of MESSAGE is to model the supply side of the energy system; and this study in particular seeks to model this side of The Gambia's electricity system.

3.1 National energy supply system

Like any supply system, The Gambia's energy supply system consists of both resources and technologies which are crucial in meeting the country's demand. The resources with the conversion technologies are quite useful in delivering energy forms (primary, secondary etc.) required for the subsequent steps in the conversion process up to the delivery of final energy to the end-use sector. In essence, the energy supply system ensures the transformation of energy resources (fossil fuels, renewables, etc.) to energy carriers (electricity, liquid fuels, heat, hydrogen etc.) before final delivery for end-use (lighting, appliances, etc.).

In the previous chapter the whole supply side of the energy system was analysed including the existing energy supply system which was grouped into conventional non-renewable energy supply system and the renewable energy supply system. However, in those analyses, the electricity side of things was not thoroughly dealt into and therefore; require detail look into the system to shed light on the issues.

In subsequent sub-sections we will look into existing electricity supply system, then the future or candidate electricity supply options for The Gambia, based on its national policies, studies and plans.

3.1.1 Existing electricity supply system

This portion of the energy supply system considers the national electricity supply system as a whole, which includes the existing resources and technologies used in electricity generation as well as the transmission and distribution technologies that provide the electricity needs of various consumption sectors of the economy.

I. Generation systems

As eluded to already, the current national electricity system is completely dependent on single imported liquid fuel (i.e. HFO/LFO) to supply the economy. This imported liquid fuel is used in different power plants across the country. Presently, the total power plants installed capacity is about 104 MW (88 MW in the Greater Banjul Area (GBA)) of which only 61 MW are available (55 MW in GBA) as described in Table 2.9 in the previous chapter. National Water and Electricity Company (NAWEC) being the sole Utility Company in The Gambia is struggling technically and financially and as result, carrying out its routine activities or operations is hugely challenging, as only 61 % of installed generation capacity is available (National Water and Electricity Company (NAWEC) Ltd. 2015).

Most of this capacity comes from two heavy fuel oil (HFO) thermal power plants in Kotu (41 MW of which 19 MW is on average available) and Brikama (47 MW of which 36 MW is on average available). Aside from the GBA and Brikama, NAWEC also operates six isolated minigrids with 13 MW of installed capacity (7 MW is available) using Light Fuel Oil (LFO) as baseload power station with very high operational costs (National Water and Electricity Company (NAWEC) Ltd. 2015).

In Table 2.9, the only substantial grid renewable energy power plant is the wind farms in Batokunku and Tanji, at the West Coast region. As at 2012, these wind farms have installed capacities of 2 x 450 kW (about 1 MW) in Batokunku and 120 kW in Tanji. These mini wind farms have horizontal-axis wind turbines that serve these communities with electric energy at reduced price and the excess is often supplied to the grid on the basis of power purchase agreement (PPA) with the Utility. In addition, the Utility as well recently has installed very small solar PV – diesel hybrid system (60 kW) in one of the small provincial sub-station (Kaur), however, this capacity is very negligible as it is just demonstration project and upon successful monitoring, it could be scaled up.

In addition, as the chunk of the generation engines in both the GBA and the provinces will have to be retired within the next few years due to the planned expiration of their useful life span (Fichtner Studies 2014) (AF - MERCADOS Energy Market International (EMI) 2013). This would therefore necessitate substantial investments in rehabilitation of some moderately old engines and off-course new generating capacity to address the growing need for electricity. Additional details are provided in subsequent section.

II. Transmission and Distribution (T&D) systems

Besides the generation facilities, T&D system as well required attention pertaining to its upgrading and expansion in both the GBA and provinces. It is to note that like many generation facilities, the T&D system is solely operated and maintained by NAWEC. The main goal for the T&D system in the national energy policy (Sahel Invest Management International 2014) is to ensure one national grid in the medium to long term instead of the current separate isolated grids.

Today, there are two transmission lines linking the two major thermal power plants (Kotu and Brikama) with a total length of about 260 km that convene power to six primary substations of 33/11 kV as shown in Table 3.1. The secondary substations (11/0.4 kV) at various locations sourced by 11 kV lines (252.5 km) departing from primary substations cannot adequately offload the power.

Table 3.1: National T & D assets infrastructure as at 2014

Type		Units	Installations
Lines	33 kV	km	260
	11 kV	km	250
	0.4 kV	km	940
Transformers	33/11 kV	Piece	6
	CCS[a]	Piece	149
	PMT[b]	Piece	90
Switchgears	33 kV	Piece	22

Source: Fichtner 2014

[a] Compact Sub-Stations [b] Pole Mount Transformers

Despite these installations, there exist numerous challenges to surmount in the network which include rehabilitating the low and medium networks and as well reduce losses (which currently stood at 23 %) (Sahel Invest Management International 2014) to industry standards, improved network stability, upgrade transmission network and improve load flow. Until now 33 kV is the highest voltage level in the Gambia but for power transmission over larger distances higher voltage (HV) levels (132 kV or more) would be needed to avoid losses. This HV would allow for interconnection with Senegal that would bring better stability and also offer the benefits of interconnection such as exporting to a larger market. All these aspects are taken on board in the modeling of the national electricity system.

3.1.2 Future or candidate electricity supply options

Beside the existing electricity system are the future or candidate choices for electricity supply in The Gambia which are basically options that have potential to supply electricity in the future; these can be grouped into conventional non RE and renewable energy options.

I. Conventional non RE

As mentioned in the previous chapter the conventional non-renewable technologies are vital in the power system as they allow the stability of the grid and without these easily controllable technologies, the integration of more variable renewable technologies into the grid would be a daunting task if not infeasible. These conventional technologies consist of alternative fossil fuel technologies to oil like coal, natural gas etc. which are being modelled as they can provide low cost and efficient forms of power generation, taken off course into consideration their environmental implications.

a) *Fuel oil:* Currently, The Gambia’s power sector is totally (almost 100%) reliant on petroleum fuel. Therefore, given this huge reliance, oil-fired technologies are unlikely to be displaced any time soon as they play an important role in the power supply system. They are also relatively quick to build, the fuel oil as well is relatively easy to transport and the generation plants have low capital cost compared to other conventional systems. In the near future, the continuous use of HFO in the urban areas and LFO/HFO in provinces are likely to be continued, despite their potential environmental concerns as explained in the previous chapter.

b) *Coal:* Among the future options of conventional power generation used in this study is coal, which is likely to provide the most appropriate scale of plants, with low cost and its ease of import as a result of port availability. The possibility to cofire with biomass is also an added opportunity for coal utilisation in power generation. However, given the high environmental impacts of this technology, it is likely to face some negative reactions from the populace, provided a cleaner coal fired technologies are considered. Despite being a huge treat to the environment, it is being considered given the energy security issue in hand.

c) *Natural gas:* Given its less carbon intensity compared to coal or oil, it is greatly considered as a potential power generation source. Currently there is no gas pipeline connecting the country to gas supplies but in the long-run there are possibilities to connect to the West African gas pipeline project or the drilling of prospective wells situated off the coast of The Gambia to be sources of supply for this system.

II. Renewable energy supply systems

These include hydro, solar PhotoVoltaic (PV) as well as wind power generation technologies:

a) *Hydro:* Geographically, The Gambia is famous for its river that divides the country into two. Given the near flat terrain and the fact that no part of the country rises 75 m above sea level, the hydropower potential of the country is extremely limited according to several private studies (Sahel Invest Management International 2014). However, it is vital to state that further upstream of the river Gambia, in Guinea and in Senegal there is excellent potential for hydroelectricity production. For this reason, a regional hydro-energy project under the Organisation pour la Mise en Valeur du fleuve Gambie (OMVG) (among The Gambia, Senegal, Guinea Conakry, Guinea Bissau) is currently being implemented in Senegal and Guinea to build dams of a total installed capacity of 750 MW (National Water and Electricity Company (NAWEC) Ltd. 2017).

   The OMVG (Gambia River Basin Development Organisation) is responsible for joint exploitation of the river Gambia of which the hydro project is one component. This power would be shared between the four member countries (Guinea Bissau, Guinea Conakry, The Gambia and Senegal). It must be noted that the project has yet to reach financial close and there has been significant delay in its implementation.

As a regional project, all the dams are situated outside of The Gambian territory, thus the need to build a regional transmission line of 225 kV to cover a total distance 1600 km (AF - MERCADOS Energy Market International (EMI) 2013) that will connect all four countries. The hydropower plant in Guinea Conakry (Kaleta dam) has a capacity of about 250 MW of which 20 MW is The Gambia's share. The Sambangalou dam (in Senegal) has a total of 500 MW of which 30 MW is reserved for The Gambia. Upon completion of the regional interconnection line (expected by 2020) and the running of the dams, The Gambia is expected to import a total of 50 MW (30 MW and 20 MW) from the Sambangalou and the Kaleta hydropower plants respectively.

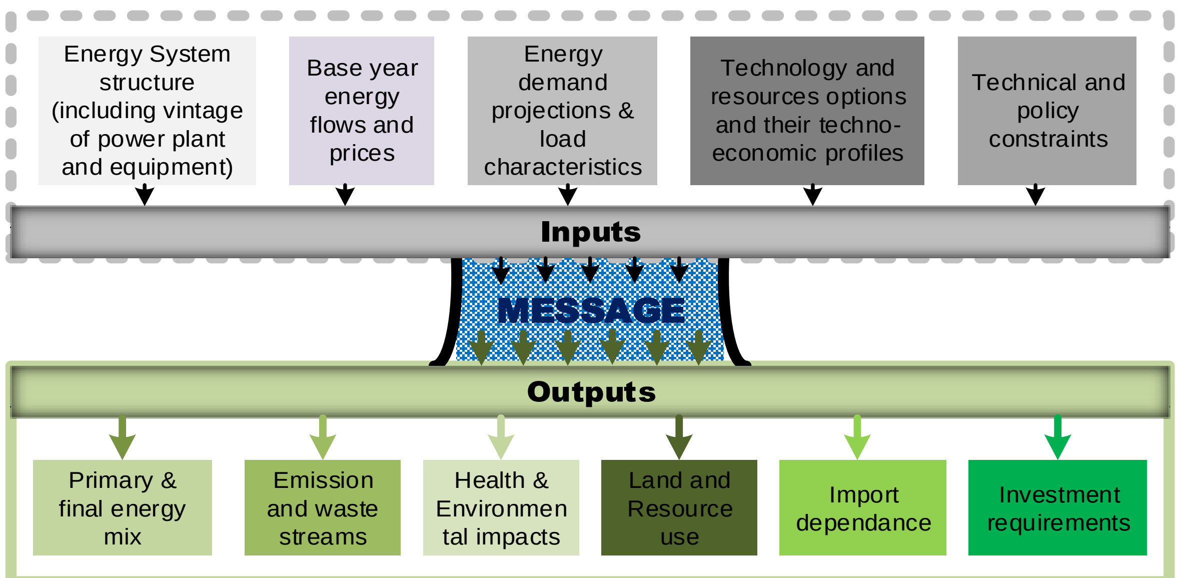
b) *Solar PV:* As earlier stated, The Gambia is blessed with a very good solar regime (see previous chapter) which is available throughout the country and throughout the year. Given the low environmental impact of solar (not considering LCA); it's a very good option for future energy supply in The Gambia. However, the high capital cost (which has drastically decreased in recent and the trend expects to continue) and its competition with other land use patterns might likely hinder its development expect for non-utility scale solar systems.

c) *Wind:* Unlike solar, the wind regime is quite moderate (see also previous chapter) and primarily more available off and along the shore and this has been manifested by successful implementation of few wind farms along the coast line. Further inside the country, the wind regime is relatively weak, however, it is worth mentioning the development of small scale wind farms are possible in some provincial towns like Kerewan. Environmentally, The Gambia is also blessed with a variety of bird species which may be threaten by wind power installation. Another issue that needs to be addressed is grid stability concerns, which can be caused by wind variability.

It is vital to mentioned that emerging technologies such as off-shore wind, ocean and wave energy as well as alternatives energy systems such as nuclear are not considered in this study due to the infeasibility or practicality of these technologies taking into account the time frame of this study. Also the characteristics of both the existing as well the future energy supply options described above are taken on board in the modeling of the national electricity system.

3.2 Modeling of the National Electricity System

Given the afore sub-sections on the existing national electricity supply system and the potential future (candidate) electricity supply system. The modeling of the national electricity system using MESSAGE was done by taking into consideration a variety of these electricity supply options that are required as essential model input to help deliver desired output (i.e. future electricity supply options). Figure 3.1 illustrated the inputs and outputs of the MESSAGE model.



Source: Adapted from MESSAGE user manual

Figure 3.1: General input and output of MESSAGE

In order to model the electricity system of The Gambia, the following vital inputs are taken on board: the energy system structure, the projection of the electricity demand, the load profile or region, capacity and investment of technologies, fuel price development, T&D as well as the limits, bounds, and constraints on both existing and/or planned technologies and resources etc. indicated in Figure 3.1. Descriptions of these input data in relation to The Gambia's electricity system are as follows:

a) Energy system structure: The system structure basically looks at the vintages of power plants i.e. installation of existing power generating system, as well as their planned date of retirement and the commencement of future or new investment on power generating plant. The table below gives the existing power generating units as at 2016 with their installed date and planned retirement date.

Table 3.2: Existing power plant vintages as at 2016

Location	Power Stations & Unit name		Installed capacity (MW)	Installation / commissioning date	Planned retirement date
		G1	3	1981	2018
		G2	3	1981	2015
		G3	3.4	1997	2021
Greater Banjul Area (GBA)[19]	**Kotu**	**G4R[a]**	6.4	2001	2019
		G6	6.4	1990	2021
		G7	6.4	2002	2019
		G8	6.4	2001	2019
		G9	6.4	2009	2018
		G1	6.4	2006	2018
		G2	6.4	2006	2018
	Brikama	**G3**	6.4	2007	2018
		G4	6.4	2006	2019
		G5	6.4	2013	2019
		G6	6.4	2013	2019
		Wartsila	8.9	2011	2031
	Batokunku/	**BWF[b]**	2 x 0.45	2012	2042
	Tanji	**TWF[c]**	0.120	2012	2037
Provincial Towns/Regional Towns	**Essau**	**G1**	0.2	2006	2020
		G2	0.6	2006	2020
		G1	0.6	2006	2020
	Farefenni	**G2**	0.6	2006	2020
		G3	1.8	2006	2020
		G4	1.5	2006	2020
			4	2014	2030
	Kerewan	**G1**	0.4	2006	2020
		G2	0.5	2006	2020
		G1	0.06	2006	2020

[19] GBA (Greater Banjul Area): it includes Banjul the capital, Kanifing Municipality and Brikama Area.

	G2	0.06	2006	2020
Kaur	**G3**	0.06	2006	2020
	G4	0.1	2006	2020
	G5	0.38	2006	2020
	PV/DHs[d]	0.06	2014	2039
	G1	0.2	2006	2020
Bansang	**G2**	0.2	2006	2020
	G3	0.2	2006	2020
	G4	0.5	2006	2020
	G5	0.8	2006	2020
	G1	0.6	2006	2020
Basse	**G2**	0.6	2006	2020
	G3	2	2007	2021
	G4	1.12	2007	2021
		4	2014	2030
Total		**103.65**		

Source: NAWEC Annual Reports

[a] Generator 4 retired [b] Batokunku wind farm [c] Tanji wind farm [d] Solar photovoltaic and diesel hybrid system

Given that most of the existing generating facilities in Table 3.2 are on the verge of retirement with the next two (2) years or so, therefore it is a necessity for the country to increase the current installed capacity now by investing in new capacity in the future especially after the planned retirement dates and as well increase the capacity and the length of the T&D system from the levels shown in Table 3.1. In modeling these power plants those power plants in grey cells are considered to be commissioned plants as their installation dates was beyond 2009 as base year while the normal cells in Table 3.2 are considered existing ones (before and including 2009).

Table 3.3 gives the candidate (future) power plants for increasing the generation capacity and T&D networks capacity and distance. These future supply options can be categorised into committed (planned) and non-committed (generic) options. Table 3.3 just presented the committed or planned projects while the generic or non-committed options are being shown under the sub-section on technologies.

Table 3.3: Committed and Planned Generation and T&D system in the emergency-short-medium-long term

Location	Generation and T&D		Emergency	Short – medium term	Medium – long term
Greater Banjul Area (GBA)[20]	Kotu	FF[a]	15 MW	30 – 50 MW	30 – 50 MW
		RE[b]		1 – 5 MW	
		T&D[c]		132 kV	
	Brikama	FF	80 MW		30 – 50 MW
		RE	10 MW	10 – 20 MW	10 – 20 MW
		T&D	33 kV	132 kV	225 kV
	Batokunku/ Tanji	RE		600 kW	
Provincial Towns/Regional Towns	Essau			600 kW	
	Farefenni	OMVG[d]		20 MW	30 MW
	Kerewan			3 MW	10 MW
	Kaur				
	Bansang			1 MW	10 MW
	Basse			500 kW	10 MW

[a] fossil fuel [b] renewable energy [c] transmission & distribution [d] organisation pour la mise en valeur de la fleuve Gambie

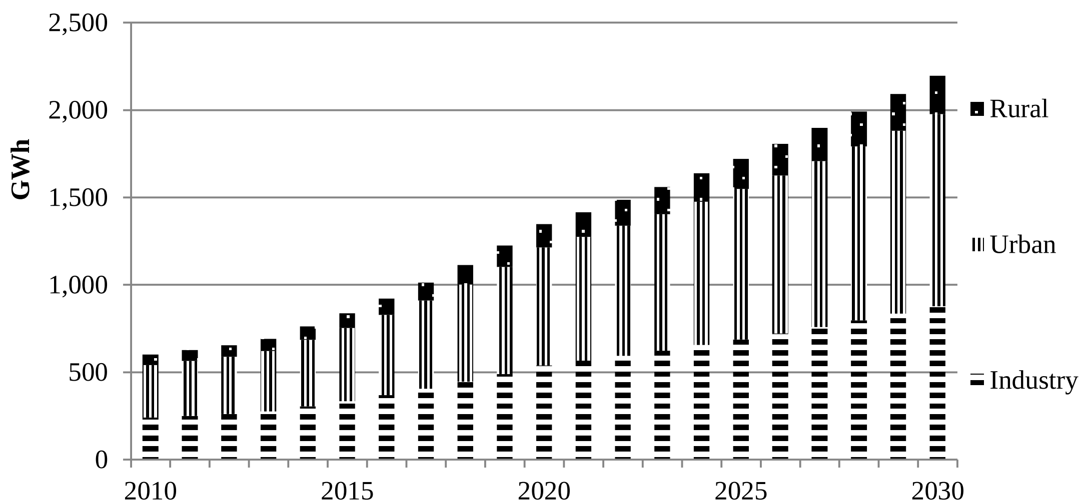
b) *Electricity demand projections:* As earlier stated, MESSAGE formulates the future electricity supply options from a given demand that is exogenous to the model. The electricity demand data of The Gambia is provided for the period 2010 to 2030, based on the study plan, and is disaggregated into industrial electricity demand, urban electricity demand and rural electricity demand.

The industrial demand represents the electricity demand for the industry (manufacturing and service – hotel), construction as well as mining etc. In brief it includes huge electricity consumption sectors. The urban and rural electricity demand as the name suggest represent the demand of households in these two set-ups but they also include the demand of the commercial sectors that are not large scale electric consumers.

[20] GBA (Greater Banjul Area): it includes Banjul the capital, Kanifing Municipality and Brikama Area.

The demand projections of these consumption sectors (see Figure 3.2) are based on the demand data provided by the Utility as well as the data reported by the Gambia's RRA (Singh, Nouhou and Sokona 2013) for the first four modeling period (i.e.: 2010 to 2014) then projections are made for the rest of the period by using the annual percentage increase reported in the WAPP report and other studies (Miketa and Merven 2013).

The electricity demand for the 1st four modeling period is obtained by subtracting the losses (T&D losses) from the electricity generations in gigawatt-hours (GWhs) for each year. However, in MESSAGE demand data are expressed in MWyr or GWyr[21] rather than MWh or GWh, therefore the GWh obtained are converted to MWyr[22] for input into the model.



In GWh	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
Industry	240.9	261.9	304.8	368.8	445.9	539.6	594.8	656.1	722.7	797.2	878.6
Urban	301.3	326.7	381.1	460.8	557.1	674.5	743.7	819.9	904.0	996.0	1098.5
Rural	60.4	65.7	76.2	92.0	111.3	134.9	148.9	163.8	180.5	198.9	219.9
Total	**602.7**	**654.4**	**762.1**	**921.6**	**1114.3**	**1349.0**	**1487.4**	**1639.9**	**1807.2**	**1992.0**	**2197.0**

Source: WAPP report, 2012

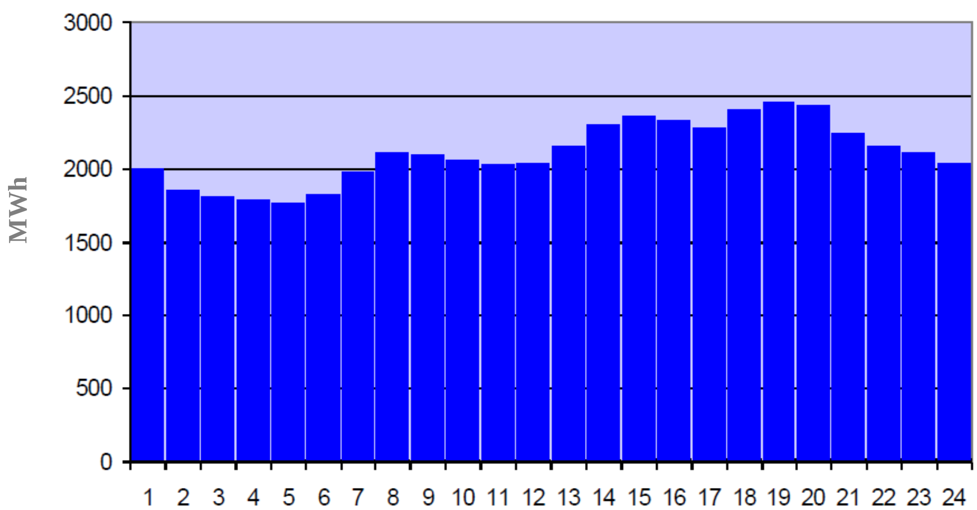
Figure 3.2: Projected Electricity demand in MESSAGE in GWh

[21] MWyr or GWyr: megawatt-year or gigawatt-year

[22] 1 MWyr = 8760 MWh = 8.76 GWh

As shown in Figure 3.2, the total electricity demand is expected to grow from 603 GWh in 2010 to 2197 GWh in 2030, an average growth rate of 6.7% per annum. Urban electricity consumption dominates the total electricity demand followed by industry and then rural demand. It is important to note that the urban and rural electricity demand include the household as well as commercial sectors' demand.

c) *Load profile/region:* In order to accurately model the electricity demand data in MESSAGE, load profile or region are employed into the model. The load profile shows the variation of electricity demand at a given point in time, as the demand for electricity varies with time, depending on the season, type or time of day etc. Electricity as an energy carrier generally has to be provided by the utility at exactly the same time it is consumed and MESSAGE tries to simulate this situation by splitting each year into an optimal number of load profiles. As depicted in Figure 3.3 the national hourly load pattern is higher between 08:00 hrs to 24:00 hrs and experiencing the highest load in 19:00 hrs with about 2500 MWh, while the lowest load pattern is observed between the hours of 1:00 to 7:00 with the lowest load recorded at the 5:00 hrs with about 2750 MWh.



Source: NAWEC report, 2014

Figure 3.3: Hourly Load Pattern for the electricity demand in MWh 2012

In this study, a year is divided into three seasons: pre-summer (January–April); summer (May–August); and post-summer (September–December). The pre-summer and summer days in the model are characterised by three blocks of equal demand: day (6 a.m.–6 p.m.), evening (6 p.m.–11 p.m.) and night (11 p.m.–6 a.m.). While the post-summer days include an additional block (7 p.m.) to capture the daily demand peak.

d) *Technology:* As shown Figure 3.6, technologies in MESSAGE link two energy levels or forms together by producing, converting, transmitting or distributing the energy form(s) from primary level up to meeting the final demand. In the Gambia's electricity system both existing and planned (committed, candidate or future) technologies as well as resources are being modeled. The technologies in the model are defined by their activity and capacity variables.

The activity variable considers the operation of a particular technology and it is characterised by the technology's input and output, its efficiency as well as the operation and maintenance (O&M) costs etc. While, the capacity variable considers elements like the plant's factor, fixed operation cost, life time of the plant, its capacity, as well as investment cost etc.

Like the electricity demand projections, data on technologies' (existing and planned) capacity and activity variables are obtained from the National energy policy, plans, technical and feasibilities studies on the electricity system as well as West African Power Pool (WAPP) report (Miketa and Merven 2013) (AF - MERCADOS Energy Market International (EMI) 2013) (Fichtner Studies 2014). These variables are basically the techno-economic parameters/assumptions (*see* Table 3.4: Techno-economic parametres of generic technologies in MESSAGE) of various technologies being modelled. In this study the technologies can be broadly grouped into two:

Thermal Power Generation Technologies consisting small diesel system for peri-urban and rural uses, heavy fuel oil feeding the grid, centralised diesel feeding the grid, combined cycle gas turbine (CCGT) feeding the grid, open-cycle gas turbine (OCGT) feeding the grid, and supercritical coal also feeding the grid etc.

For renewable energy generation technologies, they consist of: On-shore wind feeding the grid, Utility scale solar photovoltaic (PV) feeding the grid only during day time, Distributed or rooftop solar PV, Medium to large scale concentrated solar power (CSP) with or without storage feeding the grid etc.

Table 3.4: Techno-economic parametres of generic technologies in MESSAGE

Technology	Fuel /Type	Energy conversion efficiency[23]	Start year	Plant Factor	Plant Life[24]	Construction time	Investment cost	Fixed O&M cost	Variable O&M cost	Technology status
					years	*years*	*2010US $/kW*	*2010US $/kW*	*2010US $/MWh*	
Thermal Generations										
Diesel Gensets	Diesel	0.35		0.9	25	1	1070		17	Existing
HFO Gensets	HFO	0.35		0.9	25	2	1350		15	Existing
Diesel Genset	Diesel	0.35	2013	0.9	25	1	1070		17	Committed
Diesel 100kW system industry	Diesel	0.35	2010	0.9	20	<1	659		55.35	Committed
Diesel 1kW system urban	Diesel	0.16	2010	0.9	10	<1	692		33.21	Committed
HFO Genset	HFO	0.35	2014	0.9	25	2	1350		15	Committed
OCGT	Gas	0.3	2014	0.935	25	2	603		19.92	Committed
CCGT	Gas	0.48	2015	0.935	30	3	1069		2.90	Committed
Supercritical Coal	Coal	0.37	2018	0.94	30	4	2403		14.26	Committed
Renewable Generation										
Hydro	Large	1	2026	0.95	50	5	2000		5.99	Committed
	Small	1	2014	0.5	30	2	4000		5.42	Future
Biomass		0.38	2014	0.93	30	4	2500		20.02	Future
Wind farm	Large	1	2014	0.275	25	2	2740	87		Committed
	Small	1	2014	0.3	25	2	2375	87		Committed
Utility solar PV		1	2013	0.34	25	1	3325	43		Committed
Urban roof top PV	No storage	1	2013	0.41	20	<1	3491	70		
	Storage	1	2013	0.37	20	<1	4655	931		
Rural roof	No storag	1	2013	0.41	20	<1	5558	333		

[23] **Energy conversion efficiency:** the ratio of energy input to energy output

[24] **Plant factor:** is a value used to express the average percentage of full capacity used over a given period of time. Capacity factor can apply to an individual generating unit or any collection of generating units. Plant factor refers to the capacity factor of an entire generating facility including all available generating units.

top PV	e							
	Storage	1	2013	0.37	20	<1	7410	1482
	No storage	1	2015	0.76	25	4	6318	63
Solar Thermal								
	Storage	1	2015	0.95	25	4	9025	90

Source: WAPP report

Another important classification that can be deduced from Table 3.4 is using the status of the technology, which can also help to distinguish among technologies that already exist (before and during 2009), those that are committed (after 2009) and those that are not committed (after 2009) but possible options for supply of electricity in The Gambia.

This classification is vital because in the modeling of the Gambia's electricity system, 2009 has been taken as the base year, meaning in modeling term that, all power plants that were built before and including 2009 are considered existing technologies. Power plants that started operation between 2010 and 2016 are, in reality, existing technologies, but in modeling terms, we model them as committed projects. Beyond 2016 are considered as planned (committed, non-committed or future) technologies.

e) *Fuel price development:* Fuel prices (Miketa and Merven 2013) are as well another important scenario parametres, as they are determinants of future technology choices. According to the WAPP report (Miketa and Merven 2013), the assumptions on the availability of fuel in the West African region are presented in Table 3.5. This fuel availability covers biomass fuels, coal, oil as well as gas (mainly natural gas).

Table 3.5: Generic assumptions about fuel supply availability in West African Region

Country	Coal	Gas	Oil	Biomass
Burkina Faso	NA	NA	Inland	Scarce
Cote d'Ivoire	Import	Domestic	Coastal	Moderate
The Gambia	Import	LNG	Coastal	Moderate
Ghana	Import	Domestic/Pipeline	Coastal	Moderate
Guinea	Import	LNG	Coastal	Moderate
Guinea-Bissau	Import	LNG	Coastal	Moderate
Liberia	Import	LNG	Coastal	Moderate
Mali	NA	NAe	Inland	Scarce
Niger	Domestic	NA	Inland	Scarce
Nigeria	Domestic	Domestic	Coastal	Moderate
Senegal	Import	LNG	Coastal	Moderate
Sierra Leone	Import	LNG	Coastal	Moderate
Togo/Benin	Import	Pipeline	Coastal	Moderate

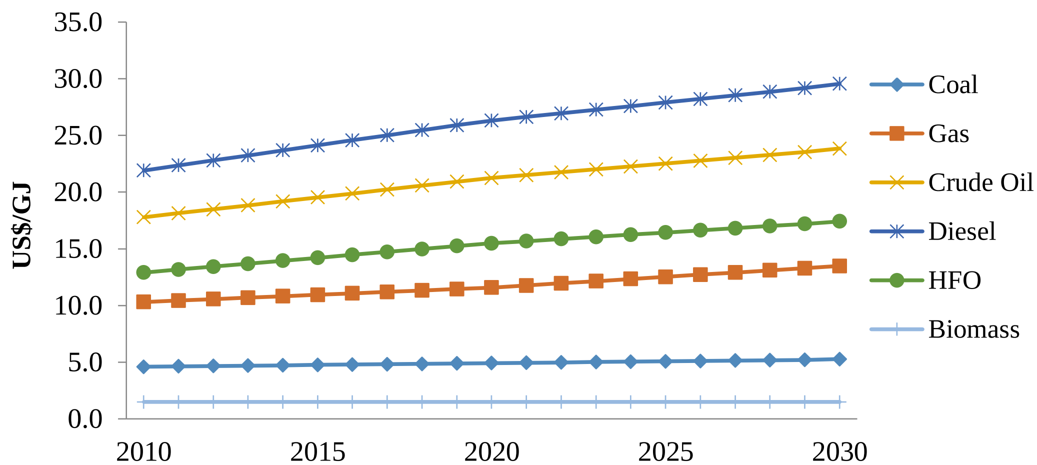
Source: WAPP Report 2013

In Table 3.5: Generic assumptions about fuel supply availability in West African Region, The Gambia as most of the West African countries has the same assumptions about the availability of fuels in the region. For coal fuel it is expected to be imported from neighbouring Nigeria or Niger which are having some quantity of this resource. For natural gas the country as a coastal country has the potential to import liquefied natural gas (LNG) to feed its future natural gas power plant.

The gas can be imported from Nigeria, Cote d'Ivoire, or Ghana or even later in the future once the country is connected to the West African Gas Pipeline (WAGP) project. Oil however, can be easily imported by coastal means into The Gambia as contrary to an inland country where additional transportation logistics would be required. Biomass availability is assumed to be moderate as the country has the potential to produce biomass for the power sector at a reasonable price which is contrary to those countries with scarce biomass potential, as they have high cost associated with power generation.

In Figure 3.4, the fuel price assumptions have been summarised. These price assumptions are affected by numerous factors especially in the case of a country that has no fossil fuel reserve and entirely rely on import to quench its energy needs. These factors include demand growth, productive capacity and the type of supply sources. The future prices of these fuels are highly uncertain as they can vary depending on global economic situation, the availability of conventional as well as non-conventional sources of supply and ease of accessing the markets.

These future prices of fuels are based on the price projection by the several energy institutions that generate fuel price data such as the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), Energy Information Administration (EIA) (Miketa and Merven 2013) etc. In the data published by these institutions assuming a moderate case of economic development the price of biomass (use traditionally or untreated), is assumed to be constant at USD $ 1.5 /GJ for the entire planning horizon, a marginal growth rate is expected for coal price that varies from USD $ 4.6 / GJ in 2010 to about USD $ 5.3 / GJ in 2030.The prices of the oil products and gas are assumed to grow at the rate of 1.5% and 1.3% per annum respectively over the planning horizon. The oil price (HFO, crude oil, and diesel oil) in 2010 is USD $ 12.9, 17.8, and 21.9 per GJ for HFO, crude and diesel, It can reach USD $ 17.4, 23.8, and 29.6 per GJ respectively by 2030, for gas it is also expected to grow from USD $ 10.3 / GJ in 2010 to USD $ 13.5 / GJ in 2030.



In US$/GJ	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
Coal	4.6	4.7	4.7	4.8	4.9	4.9	5.0	5.0	5.1	5.2	5.3
Gas	10.3	10.6	10.8	11.1	11.3	11.6	12.0	12.3	12.7	13.1	13.5
Domestic gas	8.5	8.7	8.9	9.1	9.3	9.4	9.8	10.1	10.4	10.7	11.0

Crude Oil	17.8	18.5	19.2	19.9	20.6	21.2	21.8	22.3	22.8	23.3	23.8
Diesel	21.9	22.8	23.7	24.6	25.5	26.3	27.0	27.6	28.2	28.9	29.6
HFO	12.9	13.4	13.9	14.5	15.0	15.5	15.9	16.2	16.6	17.0	17.4
Biomass	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Source: IEA, WAPP reports

Figure 3.4: Fuel Price Assumptions in US$ per GJ of fuel 2010 – 2030

f) Limits, bounds and constraints: These are amongst the most powerful features of MESSAGE, the limits, bounds and constraints are either imposed on resources or technologies based on several factors such as the reliability of the system, utilisation of resources, technology development, energy availability, financing capacity as well as policy and regulatory issues, emissions etc. to help depict the reality of the national energy system.

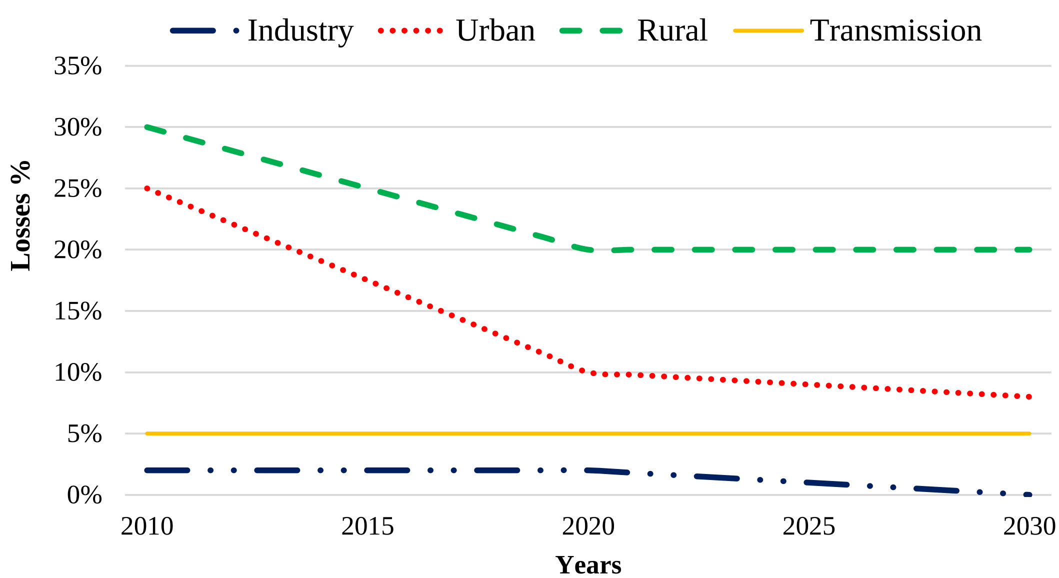
In this study, constraints are put on certain technologies like solar PV, wind as well as coal due to system reliability, cost and emissions concerns. Wind as a Renewable Energy technology, has been limited on the basis of its capacity factor due to their intermittent nature, land availability etc. Constraint is also made on total capacity of solar PV even though the country has vast resources and potential for solar applications; this constraint is put considering the technical and economic feasibility of solar PV farms.

Coal and CCGT plants are also limited by capacity addition which is explained by the economic feasibility, maturity and environmental regulations regarding emissions from coal. It is vital to note that before imposing any constraints on a particular technology or resource, a great deal of thoughts and reflexions are made based on the national energy policy direction and other national strategic documents. Below are the few constraints imposed in this study and in Table A 2 in annex:

- The capacity of wind despite having potential of generating 178 TWh per year was de-rated by the availability factor (i.e., a 165 MW wind plant with 30% capacity factor is constrained to only deliver about 50 MW at any given point in time). The firm capacity for every megawatt of installed capacity was set to half the availability factor (in this example, 15 %).
- Centralised PV plants and Concentrated Solar Power (CSP) were given a 5 % and 30 % capacity credit respectively with an imposed overall upper limit of about 1000 MW.

- Technologies like natural gas plants capacity are being limited to 500 MW upper limit and coal capacity as well as were limited given the environmental consideration.
- Technologies can also be de-rated by their availability factor. i.e. a 100 MW coal plant with 85 % availability can only produce up to 85 MW at any given point in time.

g) *Transmission and Distribution system:* Due to expected high penetration of RE into the future electricity system which can cause instability in the current grid especially the import from the OMVG hydro project, thus the model has taken into consideration the techno-economic parameters of the T&D system to cater for future increase in supply. As illustrated in Table 3.1 the T&D infrastructure has been modelled taking into account the current and future developments while assuming a decrease in both transmission & distribution losses.



	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
Industry	2%	2%	2%	2%	2%	2%	2%	1%	1%	0%	0%
Urban	25%	22%	19%	16%	13%	10%	10%	9%	9%	8%	8%
Rural	30%	28%	26%	24%	22%	20%	20%	20%	20%	20%	20%

Transmission	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%

Source: WAPP report, 2012

Figure 3.5: T&D Losses during the study period

In the study, the transmission losses for all consumption sectors are assumed to be 5 % of generation throughout the study period while that of the distribution losses varies from 2 % in 2010 to 0 % in 2030 for industry, the urban household distribution is assumed to 25 % in 2010 and then decrease to 8 % by 2030.

In the rural setting the distribution losses are quite high as it will be reduced to 20 % by 2030 compared to current level of about 30 % as illustrated in Figure 3.5: T&D Losses during the study period. These reductions in the losses by 2030 can be explained the committed and future T&D improvement and expansion starting 2020. It is also vital to mentioned that the reserve margin (which is the capacity in excess which seek to increase the reliability of the power system) assumed in this study was 15 % and renewable energy such as wind and solar are expected to provide about 10 to 15 % of the installed reserved capacity.

3.3 The Gambia’s electricity chains

Before delving into the description of the scenarios analysed in this study, it is essential to present the Gambia’s electricity supply chain in MESSAGE. The chain (see Figure 3.6) has represented the whole supply system (see previous sub-sections) as network of technologies and energy levels, starting from extraction or supply of primary energy, passing through energy conversion processes to transmission and distribution up to meeting the given demand for final energy.

Based on existing energy supply system and future or candidate energy supply options lamented in previous sub-sections, the representation of the national electricity system in MESSAGE has considered four energy levels which include the resources and imports of primary energy (primary energy level), conversion technologies (secondary energy level), carrier (tertiary level) and the electricity demand (final energy level). In modeling the national electricity system, the only resource being included is biomass as it is the only available indigenous resource in use at the time of this study in addition to the solar and wind resource. The primary energy forms considered include fuel oil (HFO/LFO), natural gas and coal (which are all imported) have been modelled to ensure the supply of secondary energy. These primary energy forms are fed into conversion technologies (such as power plants) to generate energy. Aside the fossil fuel power plants, renewable technologies (such as solar, wind) are also been included to diversify the generation technologies

As depicted in Figure 3.6, the only secondary energy form being modelled is electricity which is being transmitted at the secondary level before being distributed at the tertiary level. At this level, hydroelectricity imports (electricity trade) from regional OMVG project are also included to increase the national electricity supply capacity. As mentioned previously, at the final energy level three consumption sectors are being considered viz: Industry, Urban and Rural as depicted in Figure 3.6. Depending on the size of the consumption sector, they can either be supplied with electricity via transmission or distribution lines.

It is to note that in Figure 3.6 broken-rectangle lines represent the future or possible resources or technologies for the supply of electricity while the non-broken ones represent the existing resources and technologies.

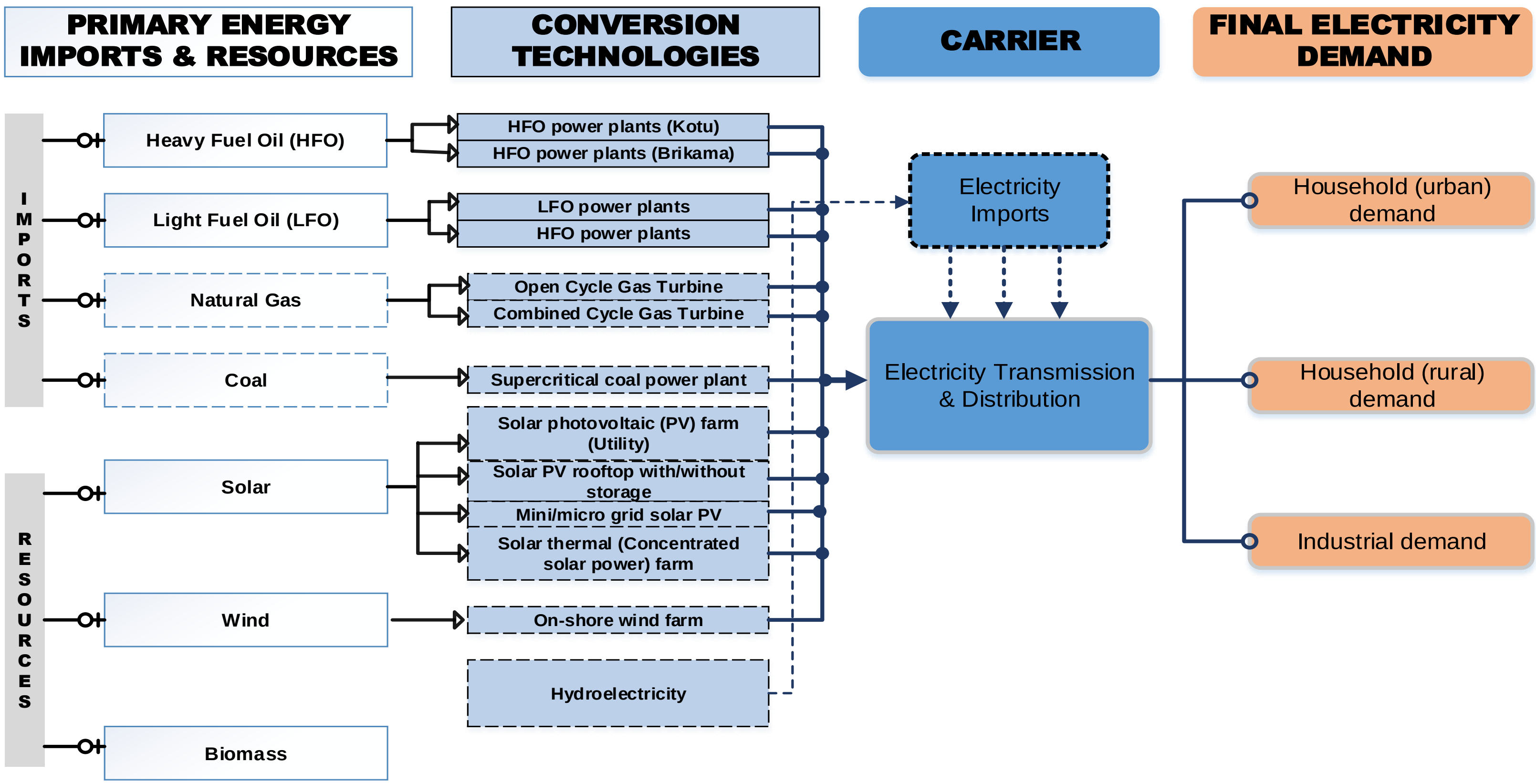


Figure 3.6: Schematic representation of The Gambia's Electricity Chain in MESSAGE

3.4 Scenario Description

Considering the aforementioned electricity chain and the vital input databases, scenarios are modeled to depict how the future electricity supply system might looked like, thus given the main output/purpose of this study, which seek to model two scenarios consisting of the Business-As-Usual (BAU) Scenario and the Renewable Energy Target (RET) Scenario.

3.4.1 BAU (Business-As-Usual) Scenario

This is also referred to as reference scenario, as it assumed a medium growth of electricity demand about 6.7 % per year over the entire study period as illustrated in sub-section 3.2.1 (a) on the demand projection and this rate is based on previous studies on the electricity system which is in turn is mainly based on medium economic and population growth rates of The Gambia over the medium to long term. This scenario also assumed the continued implementation of past as well as current and future trends and policies on the national electricity system (AF - MERCADOS Energy Market International (EMI) 2013) (Fichtner Studies 2014) (Sahel Invest Management International 2014). In the BAU scenario, it is assumed that the country will continue on the present path by pursuing current policies, programmes and projects. As described earlier, the looming insecurity of the current electricity supply system to meet the overwhelming demand, this scenario has taken into consideration numerous energy supply systems including natural gas, coal, hydro, wind, solar etc. to help diversify and ensure security of supply of electricity. In addition to the vital inputs ascribed above, the BAU scenario has also considered the following assumptions and parametres that were crucial for the modeling of the BAU energy system.

- The applied real discount rate (interest rate) is 10%, consistent with the assumption in the WAPP Master Plan and other previous studies such as the National Electricity Strategy and Action Plan (AF - MERCADOS Energy Market International (EMI) 2013).

- US dollar (USD) at 2010 rates is used throughout as the monetary unit, with adjustments made for monetary data from other years using the World Bank’s gross domestic product (GDP) deflator for the United States (World Bank, 2011).

- The study focuses on 2010 – 2030 (This period is based on the target set by Government for RE penetration as well as the study conducted by International Renewable Energy Agency (IRENA) for West African Electricity system).

- As mentioned earlier, in order to capture the key features of electricity demand load patterns, a year is characterised by three seasons: pre-summer (January–April); summer (May–August); and post-summer (September–December). Pre-summer and summer days are characterised by three blocks of equal demand: day (6 a.m.–6 p.m.), evening (6 p.m.–11 p.m.) and night (11 p.m.–6 a.m.). Post-summer days include an additional block (7 p.m.) to capture the daily demand peak.

- In order to ensure reliability of system especially the grid, penetration of intermittent renewables is limited, to 10% of total generation for solar and 20% for wind.

Based on these assumptions and parametres, the model, using actual data on the operation of existing power plants provided by the Utility; all costs data are in constant 2010 US$.

Apart from the existing projects, a detailed view of all the committed projects (hydro and non-hydro) was modeled into MESSAGE. In addition to the committed projects, various generic technologies are considered to expand the electricity system at centralised and decentralised mode such as centralised diesel (LFO) and HFO system, small diesel system for urban and rural uses, combined cycle turbine and supercritical coal all feeding into the grid are also being modelled.

For renewable energy technologies, options such as on-shore wind feeding the grid, utility scale solar PV (PV Farms), and different distributed solar PV in both urban and rural areas are all included in the modelled as generic technologies.

Furthermore, several limits, constraints as well as bounds are imposed on technologies based on the system reliability, resource utilisation, technology development, energy availability, financing capacity as well as regulatory approvals to depict as real as possible the national electricity system.

These assumptions are quite useful as they ensure effective and consistent modeling of the electricity system of The Gambia. Most of the assumptions and parametres were outlined in the West African Power Pool (WAPP) report (Miketa and Merven 2013) which was based on the database generated by West African Electricity system.

3.4.2 Renewable Energy Target (RET) Scenario

This is otherwise referred to as the alternative scenario as it built upon the BAU case by increasing the penetration of grid connected RE into the national electricity system. The RET scenario expects to increase the share of renewable energy in the country's energy mix by 35 % and 48 % in 2020 and 2030 respectively as stated in the national Sustainable Energy for All (SE4ALL) Action Agenda [25] (Particip GmbH 2014). See the subsequent chapter for more description of this scenario.

Table 3.6 provides a summary of the scenario description between the two modelled scenarios. The only different is the addition of renewable energy target to the BAU scenario to obtained the RET scenario.

Table 3.6: Summary of scenario description

Scenarios	Energy policy and strategies	Renewable incentives	National renewable targets
BAU Scenario	✓	✓	–
RET Scenario	✓	✓	✓

[25] The Gambia sustainable energy for all (SE4ALL) action agenda validated in 2014 with renewable energy targets

4 CHAPTER FOUR: RESULTS & DISCUSSION

The methodology and scenarios described in the previous chapter are used in determining the optimal medium to long term development path of The Gambia's electricity system for 20 year period commencing 2010. The two scenarios implemented in this study seeks to examine the structural (technical), economic as well as environmental impacts of the national electricity supply system development considering the national policies, strategies and targets (Particip GmbH 2014).

Before delving into analysis of the results, it is vital to note that the scenarios being modelled have taken into account numerous supply sources in order to address the current and future demand for electricity. The supply sources considered are thermal power supply sources (such as oil, natural gas, coal, biomass) and renewable supply sources (which include hydro, wind, solar). These power supply sources are considered based on existing policies and new strategies by the Government and the Utility (Sahel Invest Management International 2014) (Particip GmbH 2014).

Optimising the supply system various characteristics of the different supply sources were considered such as their economic, operating characteristics as well as environmental concerns (see previous chapter for more details) in order to determine the optimal mix of the energy supply sources in the medium to long term. Below are the results and discussion of the scenarios.

4.1 BAU (Business-As-Usual) Scenario

This scenario is based on assumptions and parametres outlined in the preceding chapter and analysis of this scenario can be categorised into technical (structural), economical as well as environmental analysis for the medium to long term. These analyses are provided below:

4.1.1 Technical Analysis

Technically, the developments of the electricity system's capacity, its generation, fuel consumption, the renewable energy penetration as well as generation mix for the entire study period i.e. from 2010 to 2030 are presented. Figure 4.1 gives the medium to long term expansion of the national ***electricity system capacity*** under this scenario. The total system capacity (consisting of both centralised and decentralised systems) is expected to grow from total of 167 MW in 2010 to about 864 MW by 2030 representing a fivefold increase in the total supply capacity in order to be in tandem with the expected growth in demand. The supply capacity is constituted by the capacities of existing, upgraded as well new oil (HFO/LFO) based power supply systems, new natural gas systems, Utility solar photovoltaic (PV), wind, and distributed (decentralised) solar PV systems including mini-grids.

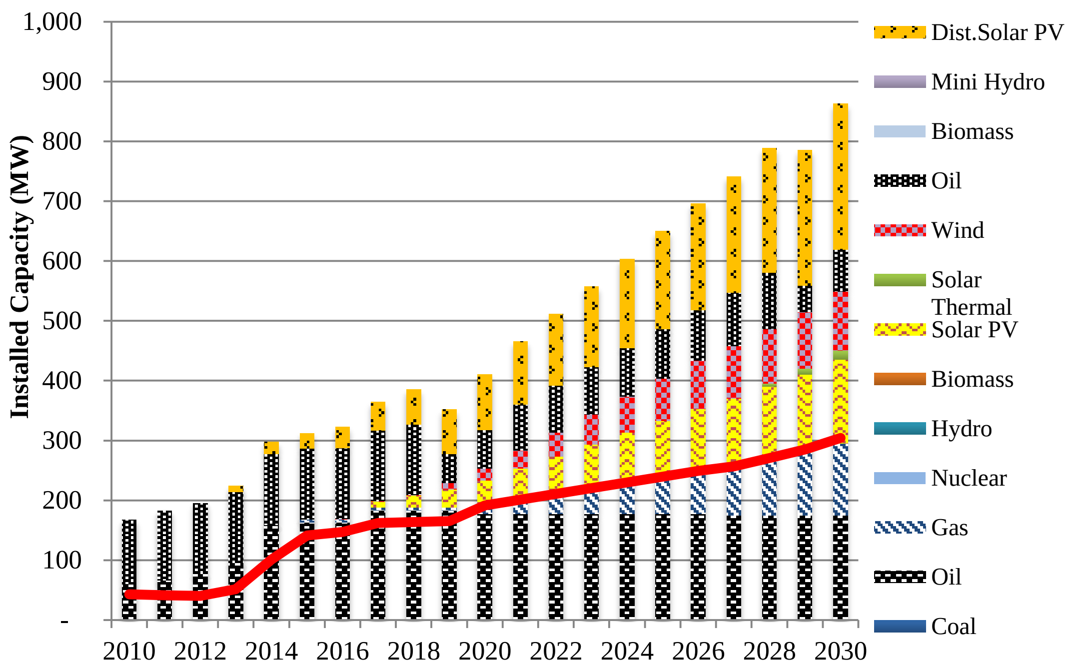


Figure 4.1: Capacity Development (MW) in BAU scenario 2010 – 2030

Between 2010 and 2014, the optimal system capacity is expected to grow from a total of 167 MW to 298 MW. These capacities as illustrated in the Figure 4.1 are dominated by oil (mainly HFO/LFO) based power plants with very negligible distributed (decentralised) solar PV that began proliferating in 2013. In 2015 towards 2019, the dominance of oil based power plants continue to be prominent in the total supply capacity with the system capacity increasing from 312 MW in 2015 to just 351 MW by 2019.

However, compared to 2018, the system capacity in 2019 is less by 34 MW (i.e. 385 MW minus 351 MW). This reduction in the installed capacity is as a result of the retiring (decommissioning) of some oil based systems and the beginning of electricity import from the regional OMVG project that is expected to commence by 2020 to the end of the study period. Thereby limiting or avoiding more capacity installations. Also, during this period (2015 – 2019) there has been the picking up of renewable energy systems mostly solar PV systems in the total annual installed capacity; but, its total capacity is marginal compared to that of oil based systems.

Between 2020 – 2025, however, presents even greater diversity with the penetration of more solar PV systems, natural gas systems, as well as wind in addition to the reducing oil (HFO/LFO) capacity. The system capacity within this period increases from 410 MW in 2020 to about 603 MW by 2024. Beyond 2024 to the end of the study period the system capacity is expected to grow again from 650 MW in 2025 to 864 MW by 2030. In these total system capacities, decentralised as well as centralised (Utility) solar PV systems are expected to play a key role in outpacing oil based systems.

Table 4.1: Total capacity development (MW) in BAU scenario

MW	Oil	Natural Gas	Solar PV	Solar Thermal	Wind	Decentralised Oil	Decentralised solar PV	Coal, Biomass & Hydro	Total
2010	60	-	-	-	-	107	-	-	**167**
2015	163	6	-	-	-	119	25	-	**312**
2020	177	16	40	-	21	64	92	-	**410**
2025	177	66	90	-	71	82	164	-	**650**
2030	175	121	140	15	99	70	244	-	**864**

Solar PV (both centralised and decentralised options), wind onshore (centralised) technologies, natural gas (centralised) are chosen under this scenario given their competitiveness which is a consequence of the reducing cost of installation as well as the associated very low operation and maintenance costs of these systems. Besides, these systems (natural gas, solar PV and wind) are as well among the committed projects ascribed in the national plans, and programmes (Sahel Invest Management International 2014) (Particip GmbH 2014) but also their environmental benefits gave this scenario greater flexibility to choose them against the oil based systems.

Moreover, the decreasing part of oil based systems in the total capacity development is as a result of replacement of most of the old and aging capacity rather than capacity addition. The replacement of these old and aging oil systems is basically done by the installation of new oil based units, but these new installations are mostly replacements and merely additional to the existing oil supply capacity.

Figure 4.2 presents the distribution of ***overall system capacity*** for year 2010 (inner donut circle), 2020 (middle donut circle) and 2030 (outer donut circle). In 2010, the 167 MW of total system capacity is 100 % dominated by oil (i.e. centralised and decentralised) based systems. In 2020 as well, oil based system still continues to be dominant with 59 % of the total system capacity of 410 MW while solar PV systems takes about 32 % and wind and natural gas systems constituted just 5 % and 4 % respectively. 2030, however, has seen less oil based systems (with 28 %) in the total system capacity of 864 MW and more of solar PV systems (44 %), wind (12 %), natural gas (14 %) as well as solar thermal systems (2 %) as illustrated below.

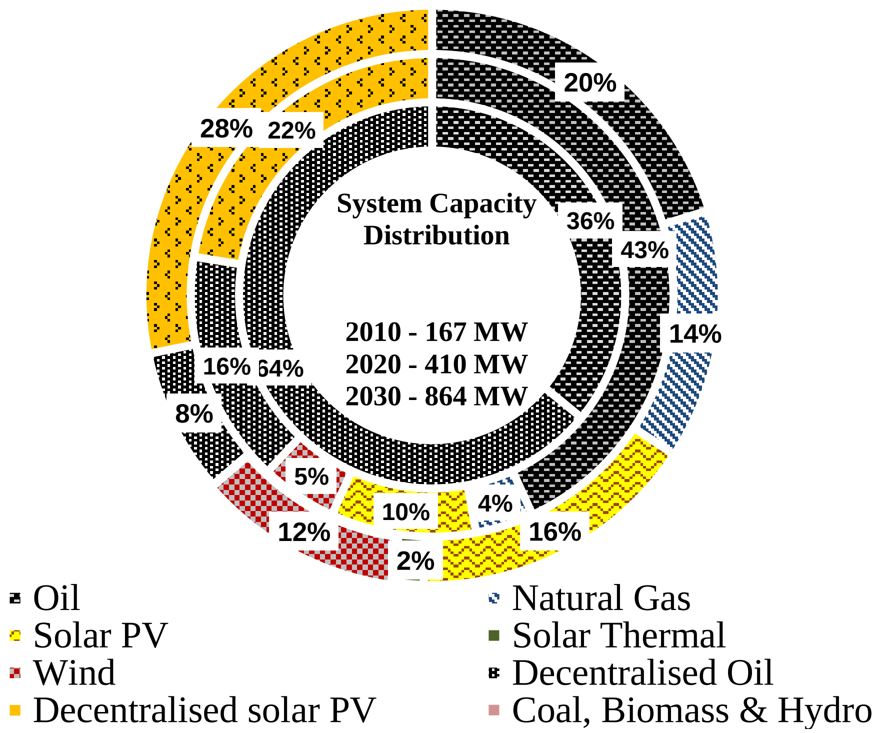


Figure 4.2: Distribution of overall installed capacities in BAU scenario 2010, 2020 & 2030

It is vital to note that, the electricity supply options that were modelled under this scenario but did not surfaced in the capacity development include: coal, hydro, and biomass based power plants. These options did not surfaced in the total capacity development because of their infeasibility to implement as well as environmental considerations and economic related reasons (examples for import coal, consideration the logistics related issues and the environmental concerns makes it infeasible to be selected by the model as future technology supply option, while biomass and small hydro technologies are constrained by lack of comprehensive assessment and infeasibility).

Another aspect of the technical analysis under the BAU scenario pertains to the evolution of the ***electricity production/generation capacity*** from the systems described above. For the entire study period, The Gambia's electricity generation is expected to grow from 673 GWh in 2010 to about 2378 GWh by 2030 in order to address/meet the expected growth in demand. Like the system capacity, the generation from the start of the study period up to 2015, is dominated by generation from oil based systems. This dominance of oil based system in the total electricity generation is expected to continue even beyond 2015 up to 2019, with just marginal contribution from renewables (especially solar PV, and wind).

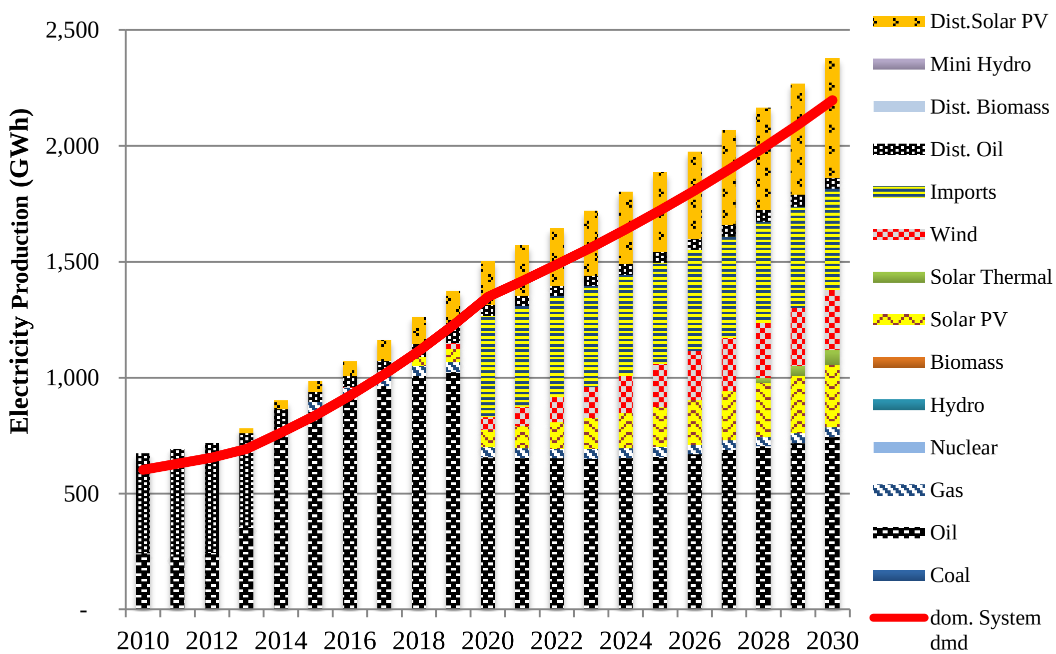


Figure 4.3: Electricity generation (GWh) in BAU scenario 2010 – 2030

However, in 2020 and beyond, the dominance of oil (centralised) based systems in the generation decrease significantly from 1092 GWh in 2019 to just about 790 GWh at the end of the study period. This allows more efficient and cost effective generation technologies such as solar PV, wind, natural gas and more importantly import of hydroelectricity from the OMVG (import of about 438 GWh commencing 2020) regional project that is being implemented in neighbouring Senegal and Guinea Conakry. The OMVG as shown in Figure 4.3 is expected to bring greater diversity into national electricity generation in the medium to long term as it delays or avoids the construction of more systems especially oil in meeting the country's electricity needs.

Figure 4.4 gives the ***generation mix*** in the BAU scenario which has shown a decrease of oil based systems from 100 % in 2010 to less than 40 % by 2030. Renewables (including solar PV, wind as well as import of hydroelectricity) share is expected to be 21 % by 2020 and further to 47 % renewables by 2030 with hydroelectricity imports as well as increase in both centralised and decentralised solar PV and centralised wind supply systems dominating the renewable part of the electricity generation mix.

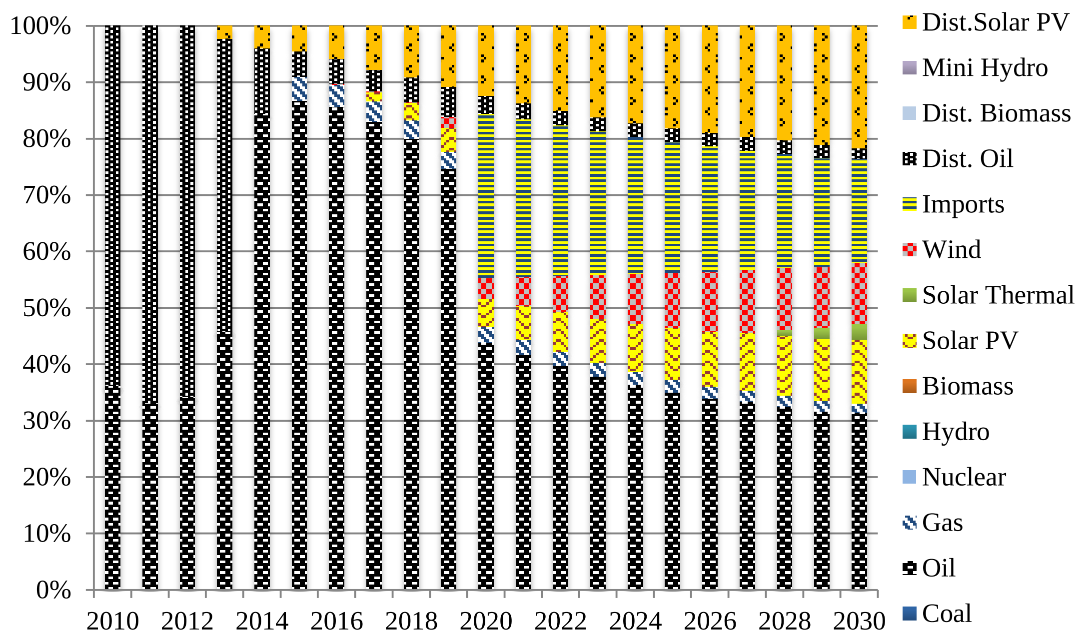


Figure 4.4: Generation mix in BAU scenario 2010 – 2030

However, considering only centralised electricity generation, the share of renewable energy is expected to grow from nil in 2010 to about 10 % in 2020 before reaching 33 % rather than the total RE penetration of 47 % (which include both centralised and decentralised systems) by the end of the study period as depicted in Figure 4.4.

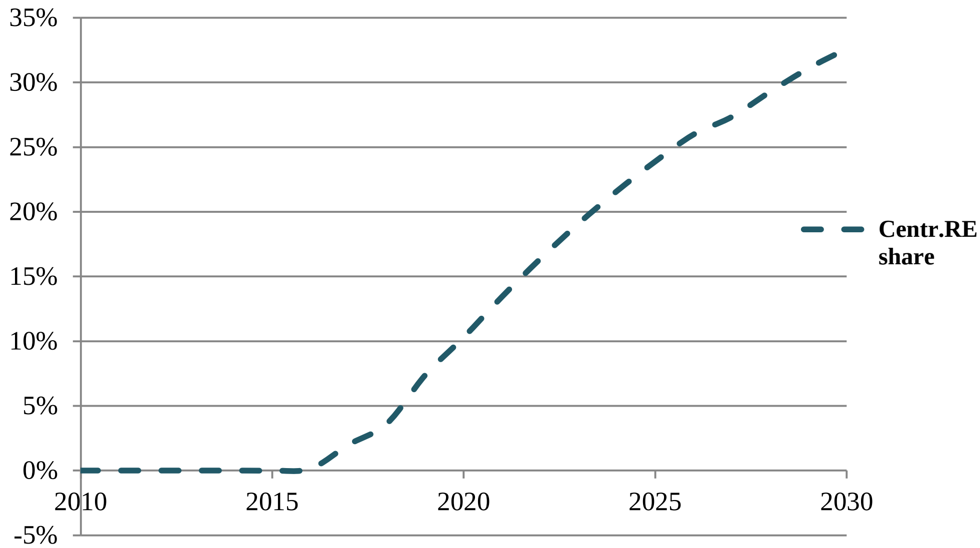


Figure 4.5: Centralised (grid) renewable energy penetration rate in BAU scenario

At the moment, the country does not have any renewables in its power system. However, optimizing the system, the BAU scenario has projected significance penetration of renewables over the planning horizon as least costs electricity supply options. Figure 4.5 presents the share of renewables (hydroelectricity imports, solar PV and wind) in grid supply, which increases rapidly over time reaching 33% by 2030.

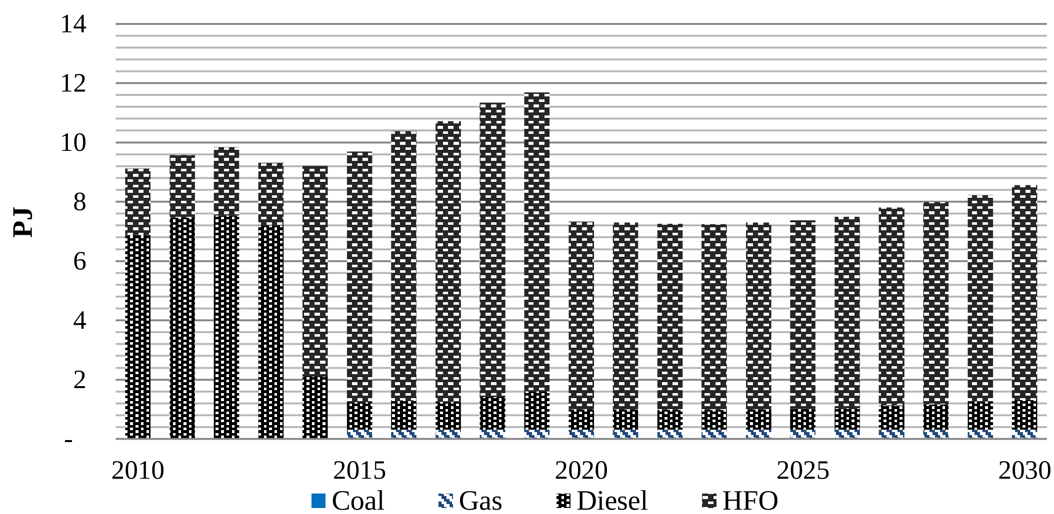


Figure 4.6: Annual primary fuel consumption (PJ) in BAU scenario

Another vital aspect to look at is how the ***fuel consumption*** evolves in the BAU scenario. In this scenario, the fuel requirement has significantly decrease from the complete dependence on oil mainly HFO and LFO (diesel) used in power generation for the first five modelling period. However, from 2020 and beyond, the fuel requirement for power generation is expected to reduce from an average of 10 PJ (peta-joule) to less than 6 PJ between 2020 and 2030 (see Figure 4.6). This reduction can be explained by the introduction of renewable and hydroelectricity imports starting 2020 to 2030.

4.1.2 Economic Analysis

As stated earlier in previous chapter on methodology, the main feature of the MESSAGE is the optimisation of energy system, by discounting all costs occurring in later point in time to the base year of the model. This is important as it makes it possible to compare cost occurring at different periods to the base year. When a particular final energy (electricity or heat) can be satisfied by two or more options (example electricity needs can be met by using gas or oil), the optimal solution that will be chosen by the model will be based on discounted cost applied to the investment cost, operation and maintenance (O&M) costs, fuel cost if non-renewable etc. Under the BAU scenario, ***total system cost*** comprises fuel cost, transmission and distribution costs, centralised as well as decentralised investments and operation & maintenance costs. As mentioned initially, all these costs is in United States Dollar (USD$) using 2010 value.

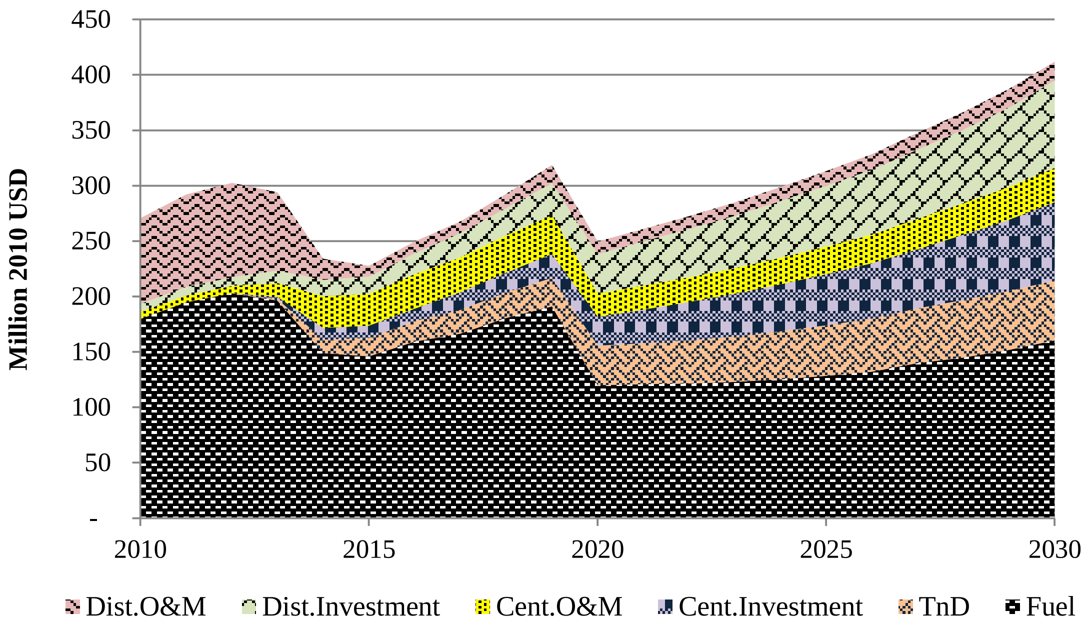


Figure 4.7: Components of total system cost (USD$ millions) in BAU scenario

The total system cost for the entire study period is depicted in Figure 4.7, in this figure the total discounted system costs increase from USD$ 271 million in 2010 to about USD$ 457 million by 2030, given it a two fold increase.

The fuel cost as shown in Figure 4.7 and detailed in Table 4.2, constitutes the burden of the total discounted system cost. However, its part has continue to decrease from an amount of USD$ 180 million to just about USD$ 160 million in 2010 and 2030 respectively, resulting in USD$ 20 million decrease of the amount in 2010. This reduction in fuel cost can be explained by the penetration of more renewable energy systems. More especially the OMVG hydroelectricity imports which delays and/or even avoids to some extent the construction of fuel consuming power plants, thereby leading to a reduce cost of fuel by 2020 (USD$ 120 million) tallying with the commencement year of the OMVG imports.

Table 4.2: Breakdown of the total system cost in the BAU scenario

USD$ in million	Fuel cost	CO_2 cost	T&D costs	Centralised Investment	Centralised O&M costs	Decentralised Investment	Decentralised O&M costs	Total
2010	180	-	-	-	7	7	77.3	**271**
2015	146	-	17	11	29	16	9.8	**228**
2020	120	-	36	26	21	36	11.4	**250**
2025	128	-	46	46	25	55	13.5	**313**
2030	160	-	59	71	31	79	17	**412**

CO_2: Carbon dioxide; **T&D:** Transmission & Distribution; **O&M:** Operation & Maintenance

Second to the dominating fuel cost in total system cost (BAU scenario) is the investment on decentralised systems which include both oil (HFO/LFO) based power system as well as renewable energy systems comprising mainly distributed solar PV systems. The decentralised investment cost is expected to grow from USD$ 7 million in 2010 to USD$ 79 million by 2030. The reason for the rise in decentralised investments is as a result of the growth in electricity demand that need to be addressed by efficient and sustainable supply sources to help attain complete access by 2030.

The cost of transmission & distribution (T&D) system, also has a fairly large part in the total system cost as it constitutes about USD$ 617 million of total cumulated (undiscounted) system cost of USD$ 6,273 million. The T&D cost has grown from USD$ 17 million in 2015 to USD$ 59 million by 2030. It is vital to note that before 2012, the expenditure on the T&D system is not high, but 2012 and beyond, the expenditure on T&D has increase year by year, mainly as a result of upgrading as well as rehabilitation of the existing system to prepare for the imports of hydroelectricity from the regional project – OMVG by 2020.

Other parts of the total discounted system cost in 2030 include centralised investment (USD$ 607 million), decentralised O&M costs (USD$ 549 million), centralised O&M costs (USD$ 498 million) and CO_2 cost. But the latter has been nil over the entire study period explained by the status of The Gambia as a non-annex one country under the Kyoto protocol and therefore under no obligation to curb its CO_2 emissions despite her keen interest in the deployment of carbon cutting technologies.

Another vital cost parametre under the BAU scenario is the ***unitary electricity production cost***, which is obtained as quotient of the total discounted system cost for each period and the annual electricity production/generation for each period as shown below.

Table 4.3: Annual electricity production cost per unit estimation in BAU scenario

	Total discounted system cost (in USD$ millions)	Electricity Generation (in GWh)	Electricity Generation (in kWh)	Electricity production cost (in USD$ per kWh)
2010	271	673	673 000 000	**0.403**
2015	228	984	984 000 000	**0.232**
2020	250	1503	1 503 000 000	**0.166**
2025	313	1885	1 885 000 000	**0.166**
2030	412	2378	2 378 000 000	**0.173**
Overall	6273	30 584	30 584 000 000	**0.205**

In Table 4.3, it is observed that the unitary production cost is highest when electricity generation emanates from oil based systems which is at the beginning of the modelling year (2010), having a production cost of USD$ 0.403 /kWh in 2010. This cost then declines to USD$ 0.166 /kWh in 2020 as consequence of the renewable energy penetration especially the cheap hydroelectricity imports from the regional OMVG project. The cheap import of hydroelectricity can be explained by the reduced total discounted cost in 2020 and its total investment cost which thereby results in low unitary electricity production cost (USD$ 0.166 /kWh). However, for the entire study horizon, the average electricity production cost stands at about USD$ 0.205 /kWh. This amount is two times less than the actual NAWEC's production costs of USD$ 0.52 /kWh.

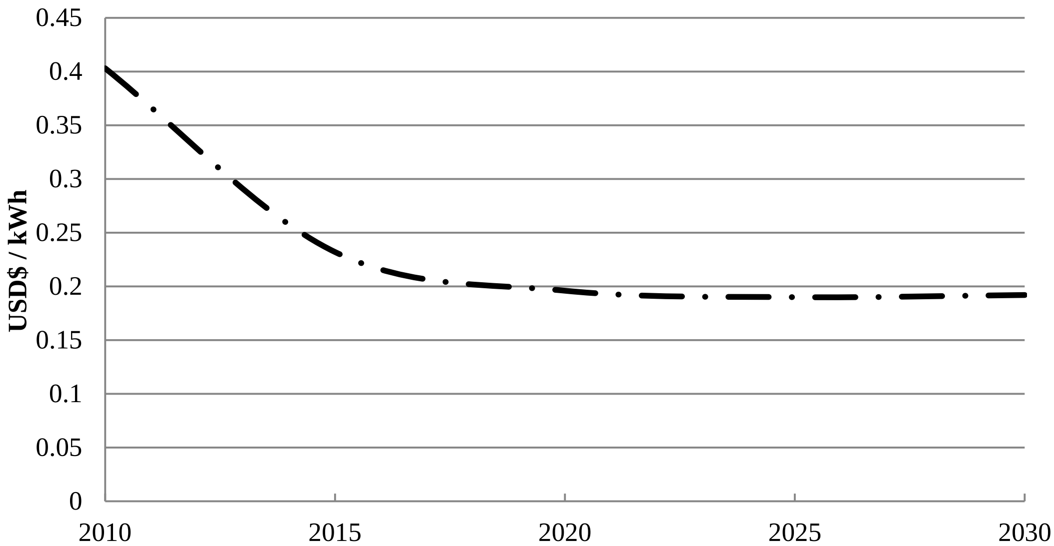


Figure 4.8: Electricity production cost per units in BAU scenario

4.1.3 Environmental Analysis

In this study, particularly the BAU scenario, the ***carbon dioxide (CO_2) emission*** is the only environmental concern taking into consideration. The CO_2 emission are basically emitted by the fossil fuel based systems which in this study include oil based systems (mainly HFO/LFO) as well as natural gas power systems having emission factors of 80.67, 74.07, 56.13 kT / PJ[26] of fuel for HFO, LFO, and natural gas respectively. Figure 4.9 presents the CO_2 emissions from these technologies over the entire study period.

[26] Peta-joule(PJ) = 10^{15} joules

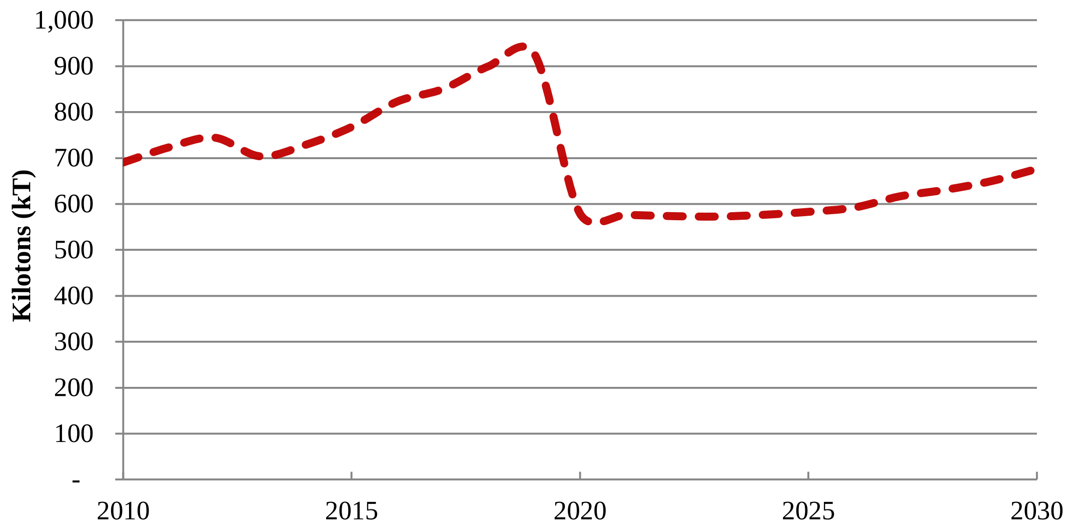


Figure 4.9: CO_2 emission (kT) in BAU scenario 2010 – 2030

The CO_2 emission in this scenario is as high as 690 kT / PJ (kiloton per peta-joule) of fuel in 2010 but then reduces to 579 kT / PJ by 2020 and then increase to just about 676 kT / PJ by end of the study period. The reduction by 2020 can be explained by the less development and utilisation of fossil fuel power plants with more development of renewable energy supply sources and importation of hydroelectricity. Another environmental aspect to shed light on is the ***carbon intensity*** of national electricity system expansion. The carbon intensity is defined as CO_2 emission per unit of electricity produced (often expressed in terms of grams of CO_2 per kWh). Figure 4.10 shows the carbon intensity under this scenario. For the entire horizon, the intensity of carbon would decline by (78.5 %). This reduction is attributed to the increasing share of less or no carbon intensive technologies replacing the chunk of the fossil fuel power plants.

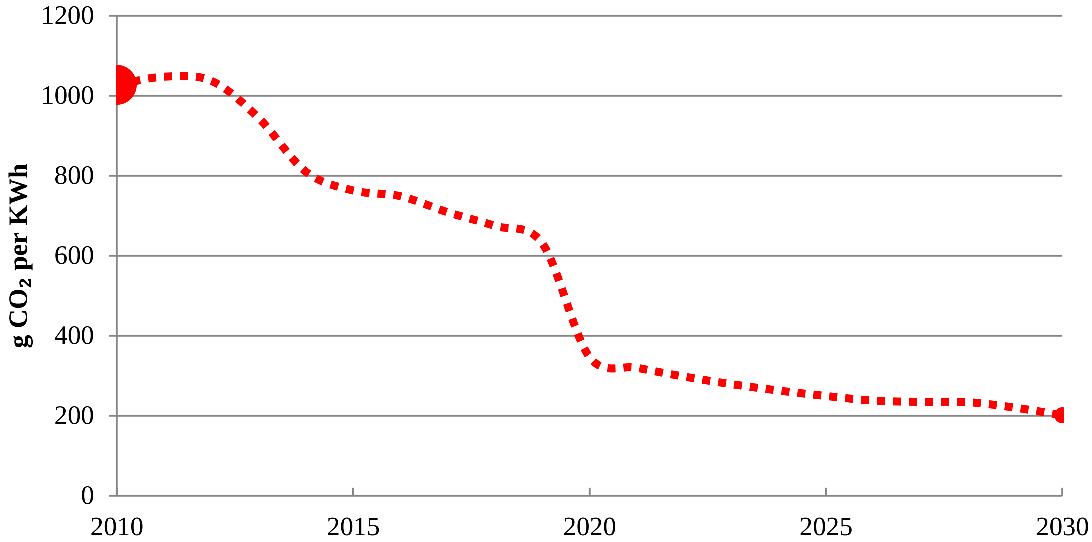


Figure 4.10: Carbon intensity (g CO_2 / kWh) in BAU scenario for the entire horizon

4.2 RET (Renewable Energy Target) Scenario

This scenario is derived from the BAU scenario which was based on assumptions and parametres outlined in the preceding chapter. The basis for analysis in this scenario is the centralised renewable energy penetration obtained in the BAU scenario (see Figure 4.5). These centralised renewable energy penetration rates are then modified to achieve 35 % and 48 % (see Table 4.4) penetration rates 2020 and 2030 respectively in line national targets (Particip GmbH 2014).

Table 4.4: Grid renewable energy penetration data for both scenarios

%	2010	2012	2014	2016	2018	2020	2022	2024	2026	2028	2030
RE Cent. share (BAU)	0	0	0	0	4	10	16	22	26	29	33
RE Cent. share (RET)	0	2	2	2	5	35	38	40	43	45	48

Before 2020, the RE share targets were obtained from the current level of RE share in the centralised grid connected electricity. However, the RE share targets between 2020 to 2030 are computed using the formula below.

$$(Target_{2030} - Target_{2020})/10 + Target_{n-1}$$

These RE share targets obtained were then divided by the efficiency (0.95) of the transmission line (see previous chapter) to obtain new parametres/coefficients which were then fed into the BAU scenario to obtain the renewable energy target (RET) scenario. This process calculation allows the grid to absorb more variable renewable energy systems into the electricity grid.

Like the BAU scenario, analysis in this scenario can as well be categorised into technical (structural), economical as well as environmental analyses in the medium to long term as described hereunder:

4.2.1 Technical Analysis

Under this scenario, the analysis of expansion of the electricity system capacity, its generation, fuel consumption, the RE share penetration as well as generation mix for the entire study period i.e. from 2010 to 2030 are presented. To start with, the ***total system capacity*** depicted in Figure 4.11 is more or less the same as that obtained in BAU scenario in Figure 4.1. The capacity installed increased from 167 MW in 2010 to about 892 MW by 2030.

Basing on the BAU scenario, the supply capacity development in this scenario constitutes the capacities of existing, upgraded as well new oil (HFO/LFO) based power supply systems, new natural gas systems, utility solar PV, wind, solar thermal as well as distributed (decentralised) solar PV systems including mini-grids.

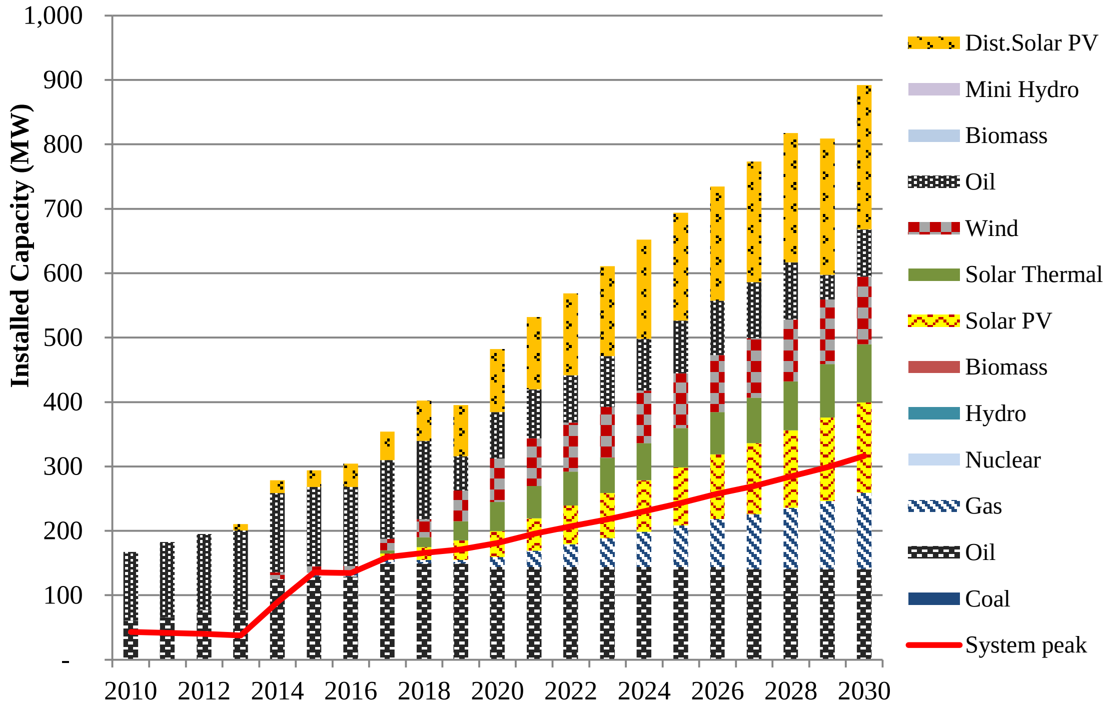


Figure 4.11: Capacity development (MW) in RET scenario 2010 – 2030

The system capacity development given in Figure 4.11 shows that oil based systems dominates the total system capacity before and till 2018 having a total system capacity of 402 MW (2018). However, beyond 2018 shows more and more diversity in the capacity installed with 202 MW and 188 MW of oil (HFO/LFO) based system and renewable energy system respectively in 2019. By 2030, the total system capacities of oil and renewables have both increased to 214 MW and 560 MW respectively. With the capacities of renewables far outweighing the oil based system towards end of the period. It is vital to note that, under the RET scenario, wind based systems have commenced surfacing earlier (since 2014) while natural gas systems are delayed to 2020 and beyond (see Table 4.5) which is bit in contrast to case in BAU scenario.

Table 4.5: Total capacity development (MW) in RET scenario

MW	Oil	Natural Gas	Solar PV	Solar Thermal	Wind	Decentralised Oil	Decentralised solar PV	Coal, Biomass & Hydro	Total
2010	60	-	-	-	-	107	-	-	**167**
2015	129	6	-	-	10	123	26	-	**294**
2020	144	16	40	45	68	72	98	-	**482**
2025	144	65	90	61	85	82	168	-	**694**
2030	141	118	140	91	105	73	224	-	**892**

Solar PV (both centralised and decentralised options), wind on-shore (centralised), natural gas (centralised) are favoured given their competitiveness, reducing cost of installation as well as the associated very low operation and maintenance costs. It is essential to mentioned that, these systems are as well consistent with committed options ascribed in the national electricity plans, and programmes (Sahel Invest Management International 2014) (Particip GmbH 2014). These include improvement of capacity of transmission system to handle high renewable energy (RE) penetrations and associated environmental benefits give this scenario greater flexibility and diversity.

Under this scenario, the distribution of ***overall system capacity*** for the year 2010, 2020 and 2030 is presented in Figure 4.12. In 2010 (inner donut circle), the 167 MW of total system capacity is totally dominated by oil based systems (centralised and decentralised). By 2020 (middle donut circle), the oil based system still continues be dominant with 45 % of the total capacity of 482 MW while solar PV systems, wind, solar thermal and natural gas systems constituted about 28 %, 14 %, 10 % and 3 % respectively. 2030 (outer donut circle), however, has seen less oil based systems (24 %) in the total system capacity of 892 MW and more of solar PV (41 %), wind (12 %), natural gas (13 %) as well as solar thermal systems (10 %) as illustrated below.

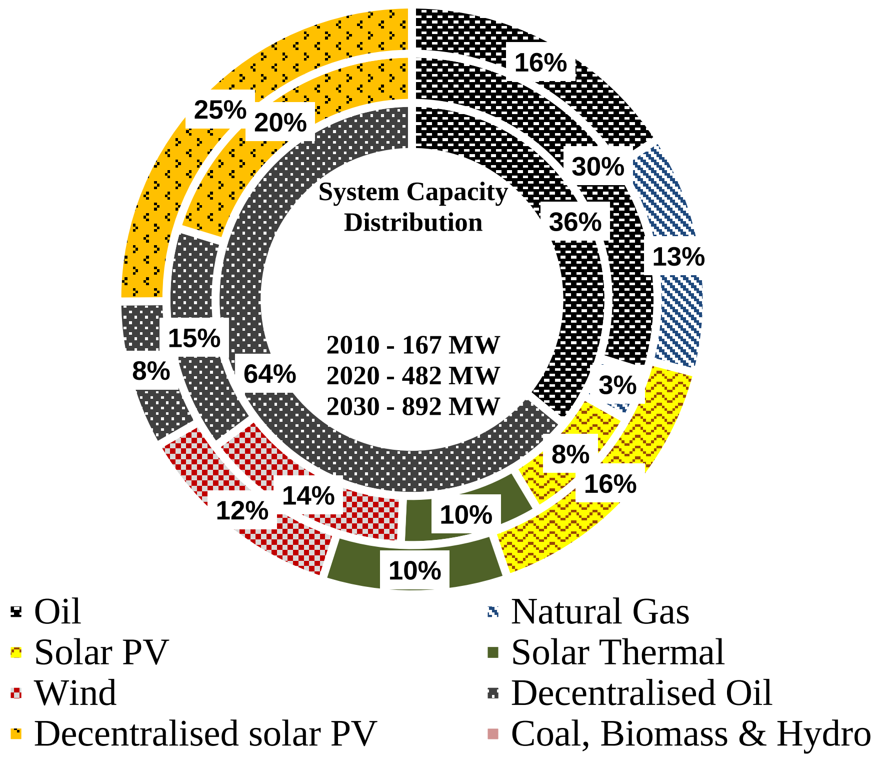


Figure 4.12: Distribution of overall installed capacities in RET scenario 2010, 2020 & 2030

Like the BAU scenario, coal, biomass, and hydro based power plants did not surfaced in the capacity development under this scenario. This is attributed to the environmental concerns (coal), lack of comprehensive assessment (biomass) environmental and infeasibility (hydro).

In the RET scenario, an analysis of the evolution of the generation from the installed systems' is described. In this scenario, The Gambia's ***electricity generation***, is expected to grow from 673 GWh in 2010 to 1495 GWh in 2020 and then to 2384 GWh in 2030 in order to address the growth in demand as depicted in Figure 4.13

In this figure, the generation in 2010 is totally and fully dominated by oil based systems, by 2020 the generation from oil based power plants reduces to 402 GWh, while the renewable generation increases to 1047 GWh with more and more penetration of hydroelectricity imports (438 GWh), solar PV (275 GWh), wind (167 GWh) as well as solar thermal (167 GWh). Oil based generation produced about 533 GWh in 2030 while that of renewables total to 1330 GWh (consisting: hydroelectricity import, solar PV, wind).

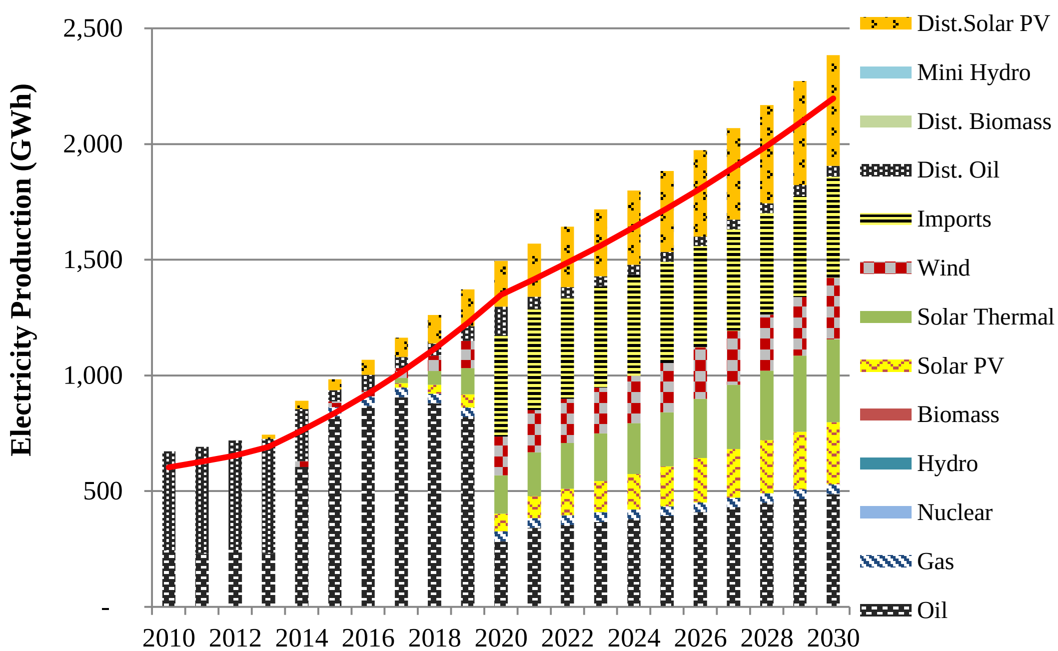


Figure 4.13: Electricity generation (GWh) in RET scenario 2010 – 2030

The hydroelectricity imports (OMVG) as depicted in Figure 4.13 is expected to bring about greater diversity into electricity generation in the medium to long term as it disallows the construction of more systems like oil and natural gas systems.

The ***generation mix*** for the RET scenario is depicted in Figure 4.14. In this figure a decrease from 100 % dependence on oil based systems in 2010 to 69 % (i.e. 31 % oil) of renewables (solar PV, wind as well as import of hydroelectricity) by 2020 and further to 75 % renewables by 2030 is observed. These increases in RE share is dominated by an increase in both centralised and decentralised solar PV and centralised wind supply systems, and more importantly hydroelectricity imports.

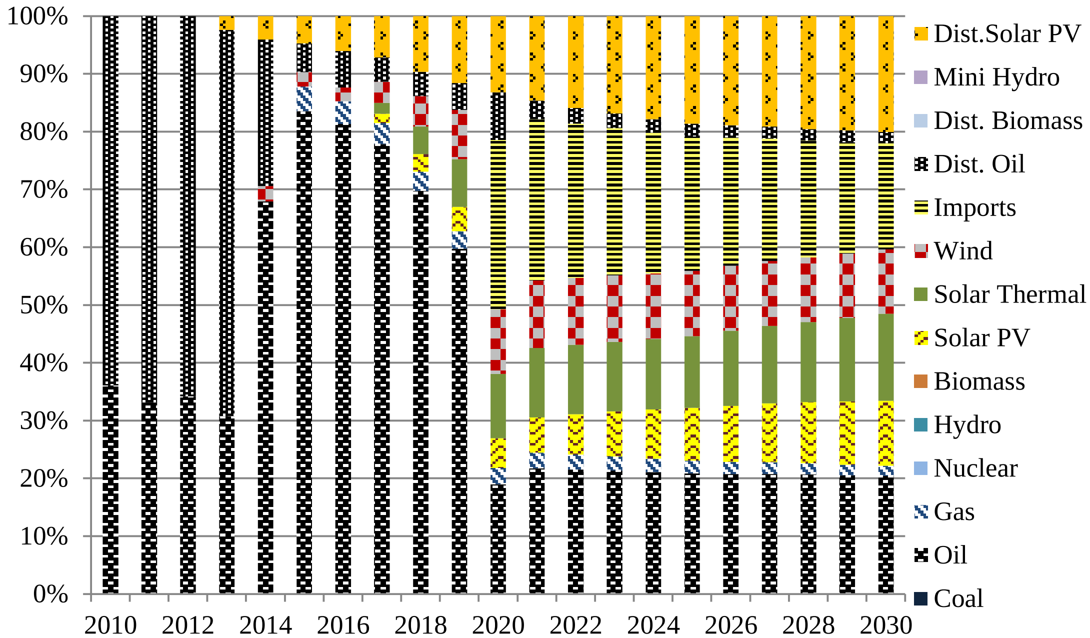


Figure 4.14: Generation mix in RET scenario 2010 – 2030

However, disintegrating the centralised from the decentralised renewable generation, the centralised renewable electricity generation grows from 0 % in 2010 to about 45 % in 2020 and then reduces to 40 % by the end of the study period as depicted in Figure 4.5. However, under the RET scenario, this share in centralised electricity generation increases from 0 % in 2010 to about 35 % in 2020 and then to 48 % by 2030 as depicted in Figure 4.15 and Table 4.4.

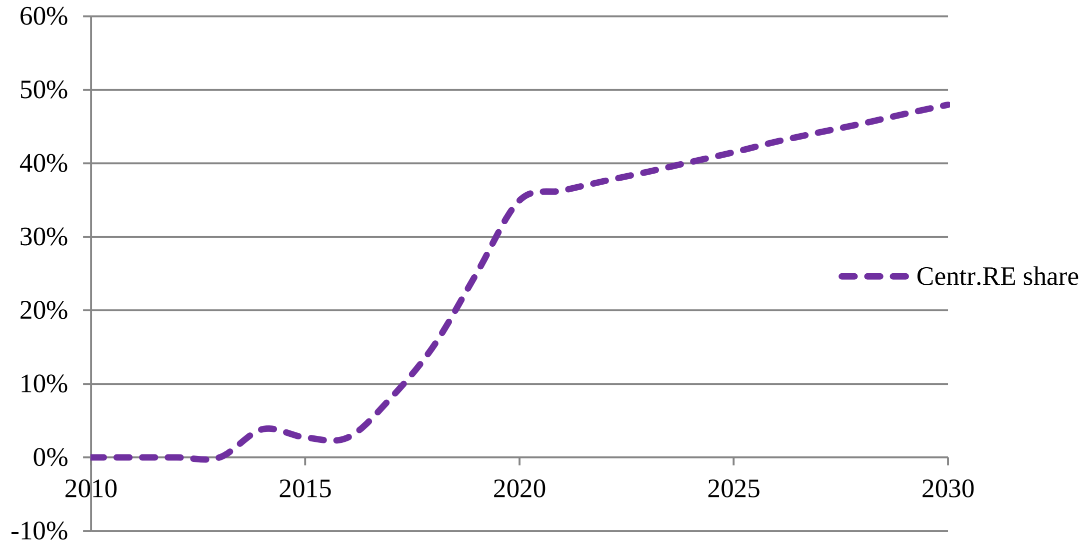


Figure 4.15: Centralised (grid) renewable energy penetration rate in RET scenario

Similar to the BAU scenario, the share of centralised RE generation share in the RET scenario comprises mainly hydroelectricity imports, solar PV, solar thermal as well as wind in the grid supply system.

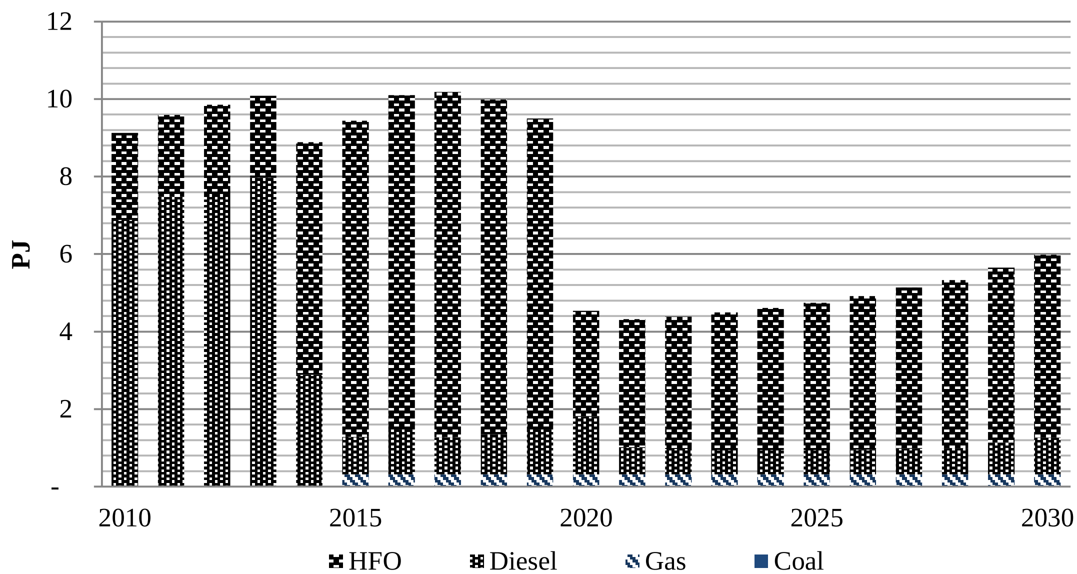


Figure 4.16: Annual primary fuel consumption (PJ) in RET scenario

The ***fuel consumption*** as captured in Figure 4.16, is a crucial scenario result to look into as it influences the expected environmental (GHGs emissions) impacts of electricity generation systems. Under the RET scenario, the fuel requirement has significantly decreased from the complete dependence on oil mainly HFO and LFO for power generation in the 1st five modelling period. However, by 2020 and beyond, the fuel requirement for power generation reduces from an average of 10 PJ to less than 5 PJ between 2020 and 2030 (see Figure 4.16). This reduction can be explained by the introduction of renewable and hydroelectricity imports from 2020 to 2030. In addition, it can be remarked that before 2014 diesel (LFO) has dominated the total fuel consumption while beyond this year the consumption of HFO has taken dominance with natural gas remaining insignificant.

4.2.2 Economic Analysis

Like the BAU scenario, the RET scenario's ***total system cost*** also include components like fuel cost, transmission and distribution costs, centralised as well as decentralised investments and operation costs.

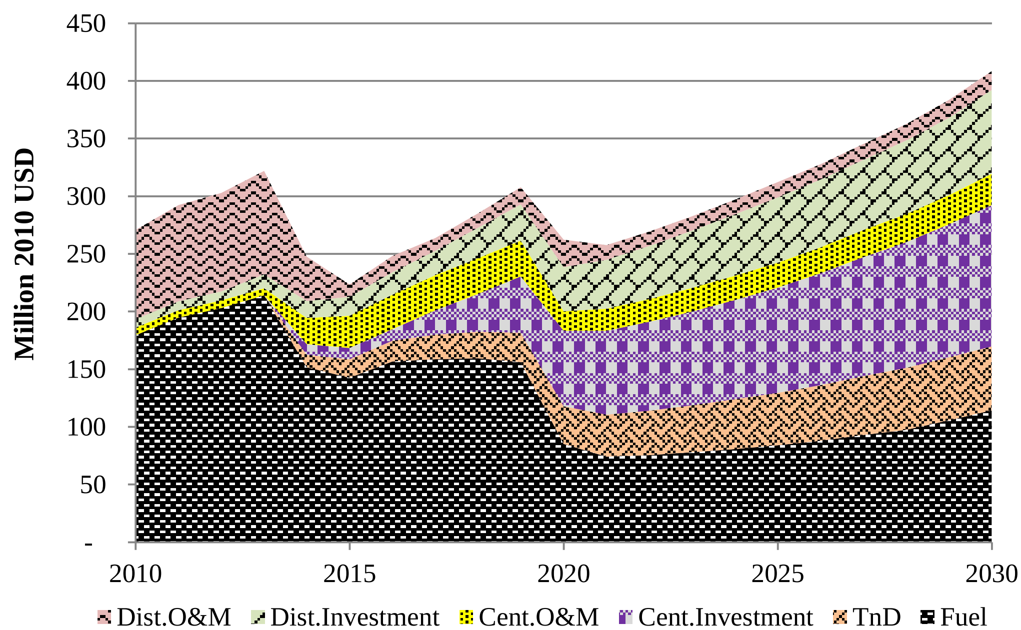


Figure 4.17: Components of total system cost (USD$ million) in RET scenario

The system cost depicted in Figure 4.17, presents an increase of about USD$ 138 million (USD$ 271 million in 2010 minus USD$ 409 million by 2030) of the system cost for the entire study horizon. Overall, the system cost shows an increasing trend at the start of the study period to a reducing trend between 2013 and 2015 then increases again before peaking in 2019 and significant reduction in 2020. After 2020, it commenced to marginally rise again up to the end of the period. In the total system cost, fuel cost constituted the highest portion, however, despite constituting a chunk of system cost, it has shown a decreasing trend from USD$ 180 million in 2010 to just USD$ 85 million in 2020 and then increases a bit to USD$ 115 million by 2030. The drop in the fuel cost in 2020 is explained by the commencement of the hydroelectricity import from the OMVG project, while the increasing trend towards 2030 is as a result of installation of new HFO thermal power plant in the national electricity system.

All other cost parametres except for decentralised O&M costs have indicated an increasing trend while that of decentralised O&M costs reduce from USD$ 77 million (2010) to USD$ 16 million (2010). These reductions in decentralised O&M costs are explained by the replacement of the decentralised thermal system with centralised based systems.

Table 4.6: Breakdown of total system cost in RET scenario

USD$ in million	Fuel cost	CO_2 cost	T&D cost	Centralised Investment	Centralised O&M cost	Decentralised Investment	Decentralised O&M costs	Total
2010	180	-	-	-	7	7	77.3	**271**
2015	143	-	16	10	28	16	10.7	**224**
2020	85	-	33	65	17	38	23.9	**262**
2025	84	-	46	91	22	57	13.2	**312**
2030	115	-	55	122	27	73	16.4	**408.4**

CO_2: Carbon dioxide; **T&D:** Transmission & Distribution; **O&M:** Operation & Maintenance

Given the importance of fuel cost in the whole system cost, it has been separated from the O&M costs which just include other variable and fixed costs for both centralised and decentralised non-renewable systems.

The ***unitary electricity production cost*** under RET scenario is presented in the Table 4.7. This production cost can be obtained as mentioned under the BAU scenario.

Table 4.7: Annual electricity production cost per unit estimation in RET scenario

	Total discounted system cost (in USD$ millions)	**Electricity Generation (in GWh)**	**Electricity Generation (in kWh)**	**Electricity production cost (in USD$ per kWh)**
2010	271	673	673 000 000	**0.403**
2015	224	983	983 000 000	**0.230**
2020	262	1495	1 495 000 000	**0.175**
2025	312	1884	1 884 000 000	**0.165**
2030	409	2384	2 384 000 000	**0.171**
Overall	6276	30 541	30 541 000 000	**0.205**

In Table 4.7 and Figure 4.18, the electricity production cost per unit is highest when oil based systems generated the chuck of the electricity i.e. the beginning of the modelling period (2010), with a unit cost of about USD$ 0.403 /kWh. This cost later declines to USD$ 0.175 /kWh in 2020 as a result of the penetration of more renewable energy especially cheap hydro imports from the regional OMVG project. This hydroelectricity import has led to reduction in the total discounted cost in 2020 with reduced total investment cost and thereby given lowest production cost. However, for the entire study horizon, the average cost of production is expected to be about USD$ 0.205 /kWh (see Table 4.7).

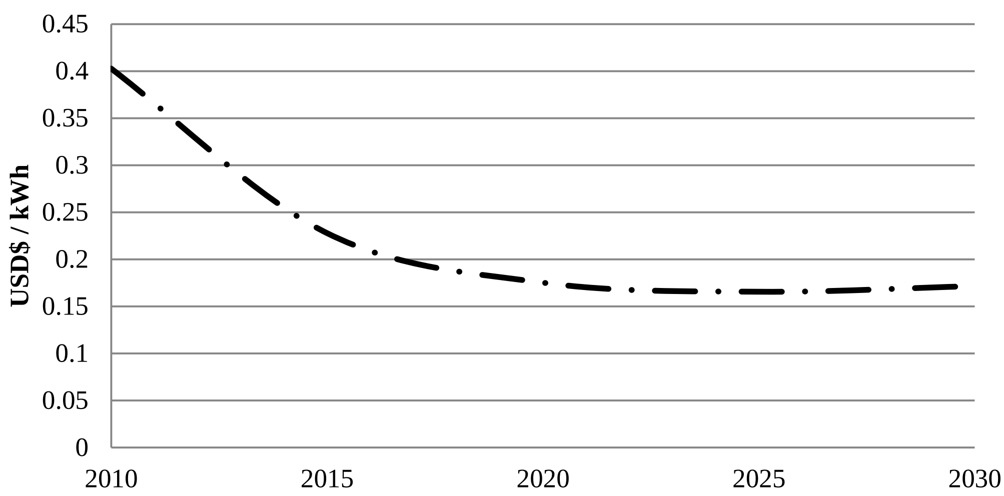


Figure 4.18: Electricity production cost per unit in RET scenario

4.2.3 Environmental Analysis

In the RET scenario, the ***carbon dioxide (CO_2) emission*** emanates from the utilisation of oil based systems (mainly HFO/LFO) as well as limited natural gas power systems having emission factors as mentioned in the BAU scenario. Figure 4.19 presents the CO_2 emissions from these systems over the entire study period.

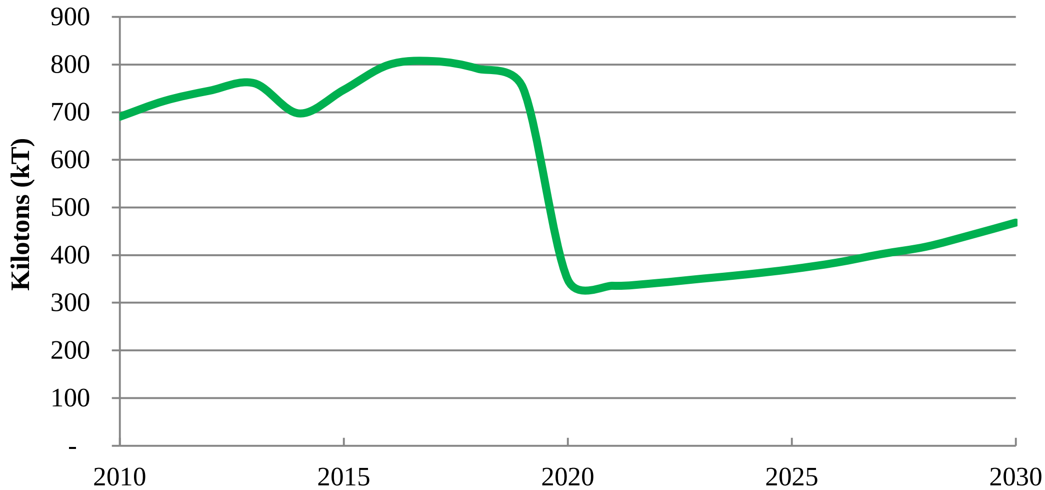


Figure 4.19: CO_2 emission (kT) in RET scenario 2010 – 2030

The CO_2 emission is highest in 2017 with about 807 kT / PJ (kiloton per peta-joule) of fuel but lowest in 2022 with 342 kT / PJ of fuel. It can be deduced from Figure 4.19 that before 2020 the CO_2 emissions were on average about 600 kT / PJ of fuel, while in 2020 and beyond, the average emissions stood at 350 kT / PJ of fuel. This reduction as described in the BAU scenario is as a result of more variable renewable energy especially with the RE target set by the government.

Figure 4.20, provides the ***carbon intensity*** under the RET scenario. The carbon intensity is influence by two main factors i.e. the rate of renewable penetration as well as the import of hydroelectricity. The carbon intensity is expected to decline by more than (80 %) i.e. from 1047.25 g CO_2 / kWh in 2010 to 199.68 g CO_2 / kWh by 2030.

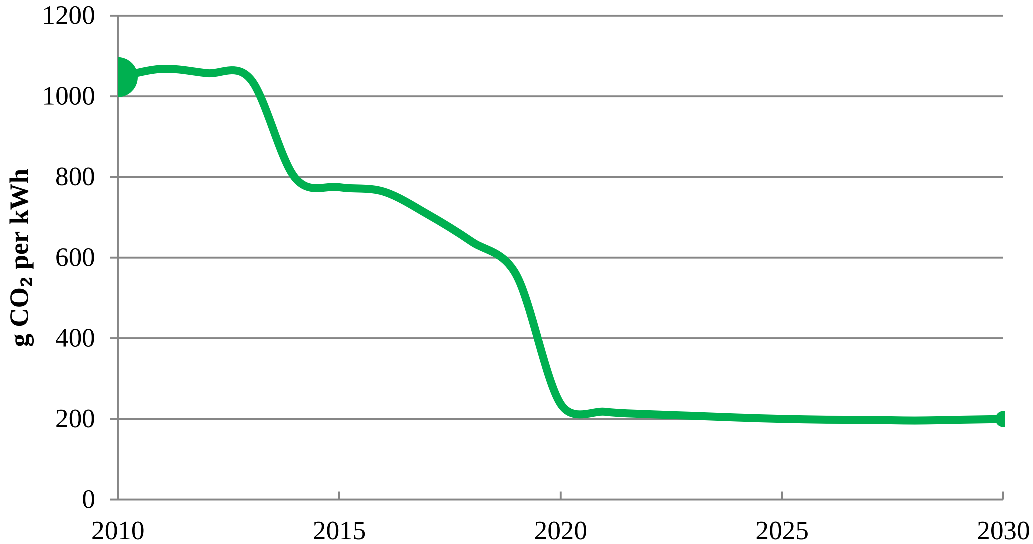


Figure 4.20: Carbon intensity (g CO_2 / kWh) in RET scenario for entire horizon

4.3 Comparison of BAU & RET scenarios

Under this subsection, comparative analysis of the afore described scenarios are delved into. Hereunder are discussions on the technical, economic as well as environmental comparisons of both scenarios.

4.3.1 Technical Analysis

Under this analysis the development of system capacity, generation, and generation mix of both scenarios are analysed.

As given in Figure 4.21, the ***total system capacity*** for the BAU and RET scenario barely differ but their constitution especially in the medium to long term is quite different. In the medium to long term all other system capacities remained virtually the same except for solar thermal and wind that have seen an increase in their installed capacities. Solar thermal capacity grows from nil to 15 MW (2030) in BAU scenario, while in the RET its capacity is expected to be 45 MW (2020) and reached 91 MW by 2030.

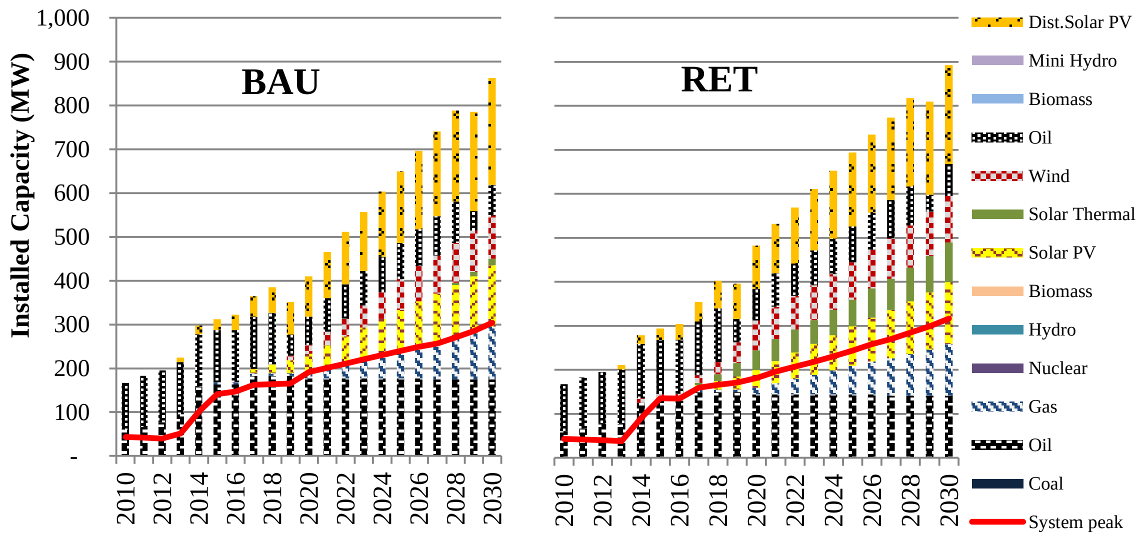
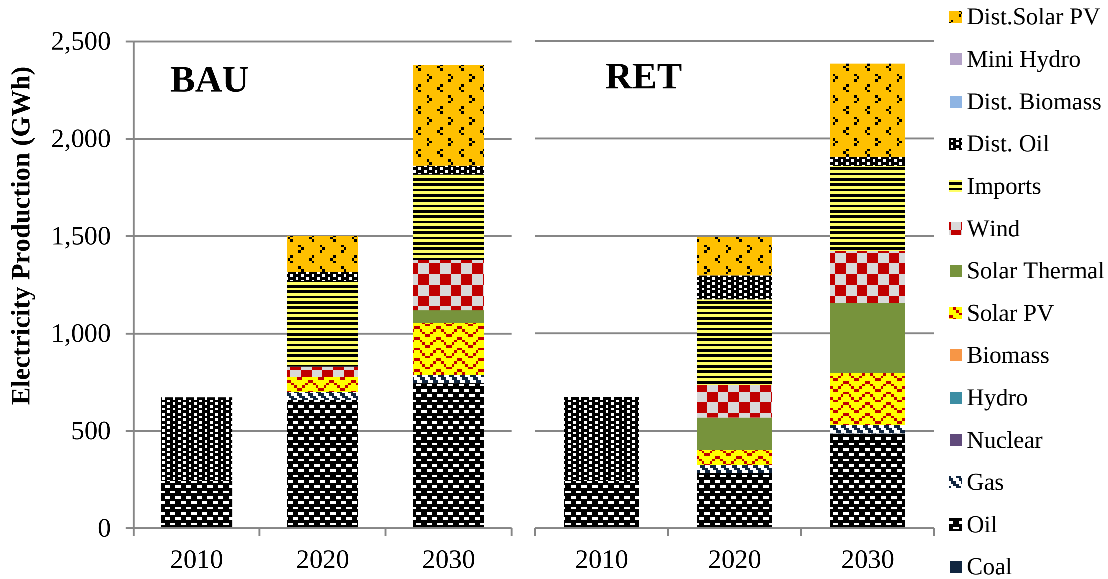


Figure 4.21: Capacity Development (MW) of the BAU & RET scenarios 2010 – 2030

Another aspect of the technical comparative discussions is ***total electricity generation***. Like the total system capacity, the total generations in both scenarios are invariably different for the entire study period. However, the composition of the scenarios quite different with the RET scenario having lesser oil based power system than the BAU scenario. In 2020, the composition of centralised oil generation in the total generation has significantly reduced from 658 GWh (BAU) to just 284 GWh (RET). In contrast, generations from wind and solar thermal have increased greatly with wind increasing from 54 GWh in BAU to 167 GWh in RET and solar thermal generating nothing in BAU to about 167 GWh in RET scenario. Other generations such as OMVG – hydroelectricity imports (438 GWh), solar PV, natural gas (42 GWh) remain virtually the same between the two scenarios.

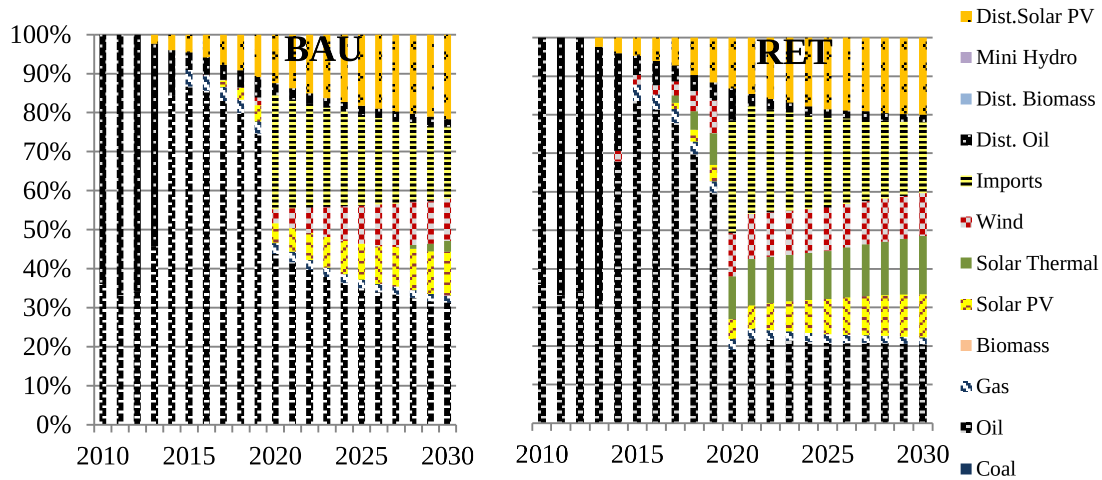
By 2030, the generation from centralised oil still continues to decrease from 745 GWh (BAU) to just 486 GWh (RET), this reduction in oil based generation is displaced by solar thermal systems increasing from 65 GWh in BAU to 359 GWh in RET. While the generation from other sources (such as OMVG – hydroelectricity imports (438 GWh), solar, wind, natural gas (43 GWh)) change marginally between the two scenarios as depicted in Figure 4.22.



Dist.: Distributed/Decentralised; **PV:** Photovoltaic

Figure 4.22: Generation (GWh) from BAU and RET Scenarios 2010 – 2030

Regarding the ***generation mix***, in both scenarios, 2020 has seen significant penetration of renewable generation into the system which can be attributed to many factors such as the OMVG hydroelectricity imports as well as more new wind and solar installations. However, the rate of generation from grid connected RE sources are more robust in the RET scenario (with 35 % and 48 % penetrations) than BAU scenario (with just 10 % and 33 % penetrations) for 2020 and 2030 respectively as shown in Figure 4.23.



Dist.: Distributed/Decentralised; **PV:** Photovoltaic

Figure 4.23: Electricity Generation Mixes in BAU and RET for 2010 – 2030

For both scenarios, the share of hydroelectricity imports in the total generation has decreased from 29 % in 2020 to 18 % by 2030 as a result of constant hydroelectricity imports (438 GWh) while total generation increases to meet demand. Utility solar PV share, however, grows from 5 % of total generation in 2020 to 11 % at the end of the period in both scenarios. The government's commitment to increase the renewable targets can have the following differences between the scenarios: An earlier introduction of wind generation (2 % in 2014 to 11 % by 2030) is observed compared to the BAU scenario which commences in 2019 with 2 % and 11 % by 2030. In addition, generation from solar thermal also commences as early as 2017 with 2 % to about 15 % by 2030 (RET scenario). While in the BAU scenario, its generation did not surfaced up till 2028 (1 %) and then increases to 3 % by 2030.

Figure 4.24 gives the ***grid renewable penetration rates*** in both scenarios. Between both scenarios, the share of grid renewable electricity commenced as early as 2014 with 4 % share in the RET scenario. While that of BAU scenario was delayed to 2017 with 3 % share. This is as a result of the more robust policies to meet the national renewable targets. By 2020, the centralised (grid) renewable share in the RET scenario is more than double relative to same period in BAU case. However, towards 2030, this relative share decline less than one in comparison to BAU case.

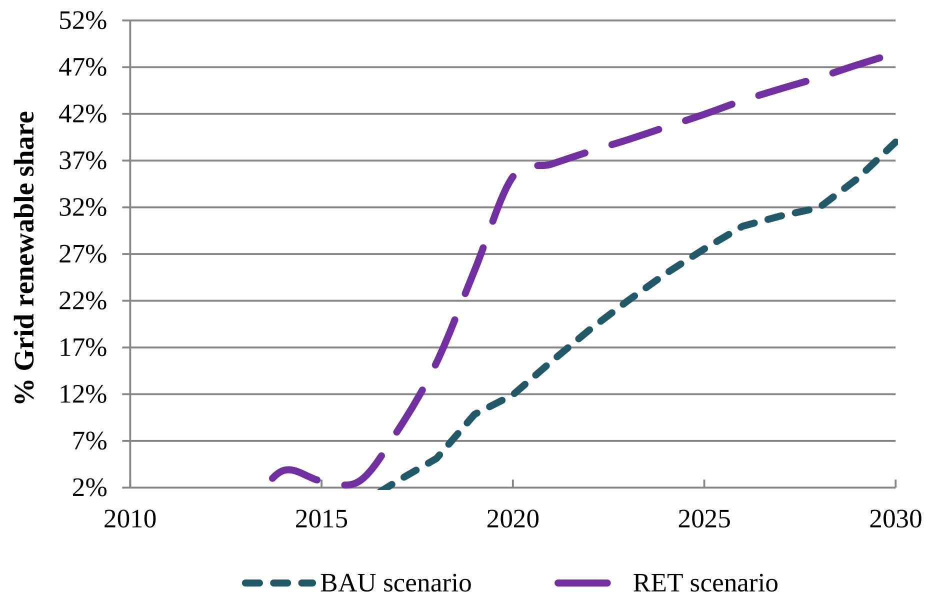
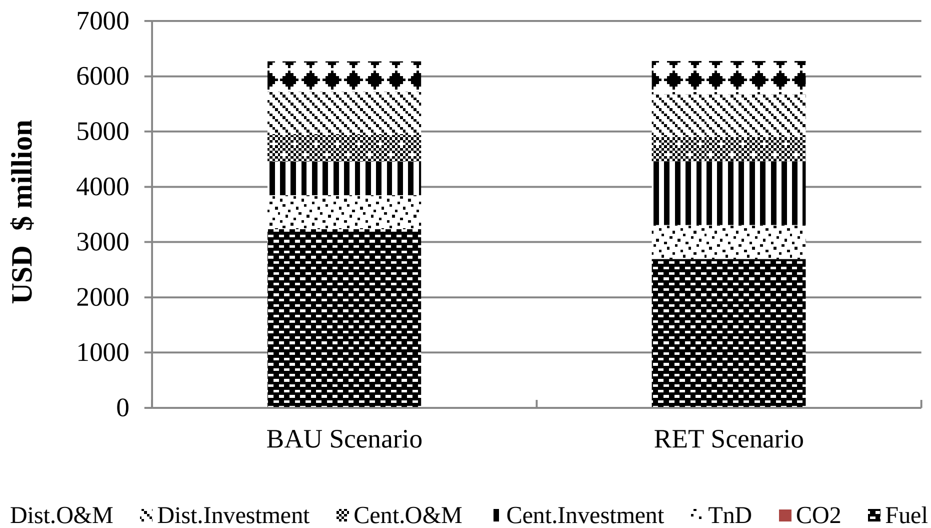


Figure 4.24: Centralised (grid) renewable share in both scenarios for entire horizon

4.3.2 Economic Analysis

In the BAU scenario, ***total system costs*** (undiscounted) amount to about USD $ 6,273 million with fuel cost constituting the highest share (51%). Remaining costs components are more or less equally distributed. During the planning period, The Gambia needs an investment to a tune of USD $ 606 million to build centralised capacity and another USD $ 768 million for building capacity infrastructure in decentralised generation. Total investment needed in generation capacity expansion is USD $ 1376 million, which can be translated to USD $ 69 million annually. Additional USD $ 617 million is needed for T&D infrastructure as shown in Figure 4.25.



Dist.: Distributed/Decentralised; **Cent.:** Centralised; **O&M:** Operation & maintenance; **TnD:** Transmission & Distribution; **CO_2:** Carbon dioxide

Figure 4.25: Economic Costs (USD $ Million) of the BAU and RET Scenarios 2010 – 2030

In same Figure 4.25 displays the undiscounted total system cost for the RET scenario as well. A total system cost in this scenario is negligibly higher than in BAU scenario. However, the cost components are significantly different with fuel costs and centralised investment having important impacts on total system cost. As renewables replace petroleum products for power generation, fuel costs decline considerably, its share is just 42 % of the total costs in RET scenario, as compared to 51 % in the BAU scenario for the entire horizon. Given that renewables are more expensive to build, there investment requirements almost double in RET scenario with USD $ 1,152 million from just USD $ 606 million in BAU scenario.

Despite, these high investment requirements, renewable systems can still play a crucial role in abating greenhouse gases (GHGs) and can as well be more suitable for less developed countries like The Gambia given their low capital demand (except for large hydropower plants) and their adaptability for small scale decentralised (distributed) options. Notwithstanding, for large scale development, renewables still grapple with economic as well as technical feasibility despite the large availability of potential reserves in the country.

4.3.3 Environmental Analysis

Considering the environmental impacts of the studied scenarios, Figure 4.26 gives the ***CO_2 emissions*** corresponding to each scenario. The rate of CO_2 emission from oil and coal being 0.039 and 0.089 MW per year respectively consistent with the IEA and IRENA publications (Miketa and Merven, West African Power Pool (WAPP) - Planning and Prospects for Renewables 2013). In Figure 4.26, it is clear that in the BAU scenario, which has more heavy oil fuel (HFO) operated power plants presented the highest emissions of CO_2 compared to the RET scenario with emissions peaking in around 2020 with more than 800 kT of CO_2 released. The RET scenario produces less CO_2 as shown from Figure 4.26.

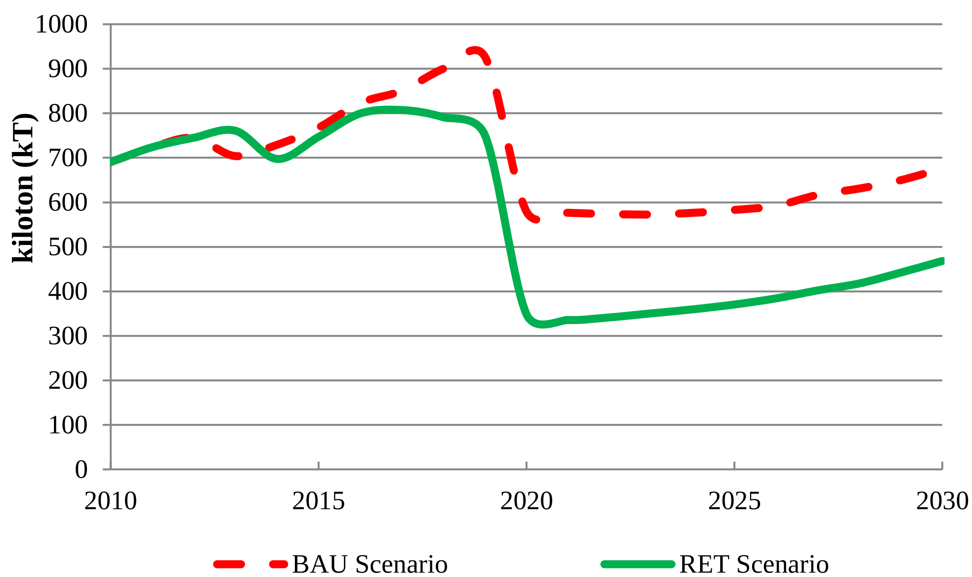


Figure 4.26: CO_2 Emissions (kT) for both scenarios 2010 – 2030

From the period 2020 to 2030, the total CO_2 emitted doesn't exceed 400 kT annually whilst the same period in the BAU scenario the emissions have surpassed that level. This shows that up to 40 % reduction in annual CO_2 emissions is possible with the government's new renewable target. This is an important ancillary benefit, in addition to the energy security. The ***carbon intensity*** in both scenarios is presented in Figure 4.27. Given that the carbon intensity in this study is hugely depended on the renewable energy share as well as the hydroelectricity imports. It is quite obvious for the RET scenario to be less carbon intensive than the BAU scenario. In the 1st five modelling period (i.e. between 2010 - 2015), the total carbon intensity was higher in the RET scenario than the BAU scenario. However, beyond 2015, the relative carbon intensity in the RET scenario declined by more than (30 %) 2020 compared to the BAU scenario.

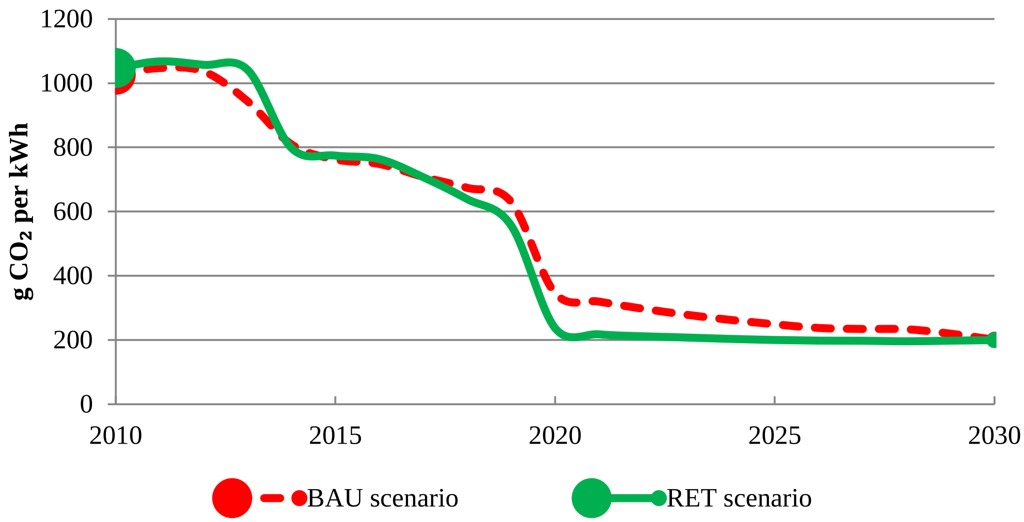


Figure 4.27: Carbon intensity (g CO_2 / kWh) in both scenarios for entire horizon

4.4 Comparison of Thailand and The Gambia's Renewable Ambitions

In Thailand, according to the power development plan (PDP) 2015 (Ministry of Energy - Thailand 2015 <https://www.egat.co.th/en/images/about-egat/PDP2015_Eng.pdf>), there has been several revisions of the power sector development plan as a result of been short or highly ambitious of the targeted goals and plans. The time horizon of the current 2015 PDP is 2036 commencing 2015. This timespan has been divided into two time steps of 10 year periods i.e. 2015 – 2026 with a total project capacity of 36 804 MW and 2027 – 2036 (20 655 MW). Overall the total capacity at end period is 70 335 MW including 37 612 MW of existing capacity as at 2014. Thereby given the expected new capacity addition of about 57 459 MW. Table 4.8 gives the share of grid renewable electricity in Thailand (2015-2036) and The Gambia (2010 - 2030) in new capacity addition.

Table 4.8: Comparison of The Thailand's and The Gambia's renewable ambitions

Year	Thailand (*based on the PDP*)				Year	The Gambia (*this study – based on RET scenario)*			
	Total capacity (MW)	Grid renewable capacity (MW)	Grid renewable share (%)	CO_2 emission (kT)		Total capacity (MW)	Grid renewable capacity (MW)	Grid renewable share (%)	CO_2 emission (kT)
As at 2014	37 612	8 476	22	86 998$^{(2015)}$	**As at 2014**	103	2	< 1	747$^{(2015)}$
Between 2015 – 2026	36 804	10 644	28	87 337$^{(2020)}$	**Between 2015 – 2020**	429	201	38	349$^{(2020)}$
Between 2027 – 2036	20 655	11 004	53	99 822$^{(2030)}$	**Between 2021 – 2030**	513	386	41	468$^{(2030)}$
Overall capacity as at 2036	70 335	30 124	43	–	**Overall capacity as at 2030**	942	384	48	–

For both countries, the targeted time horizon is quite different with Thailand's PDP spans 2015 to 2036 while the current study on The Gambia's electricity spans from 2010 to 2030 based on the national renewable target. Based on PDP2015, Thailand hopes to achieve 28 % of grid renewable penetration between 2015 – 2026, and up to 53 % renewable penetration between 2027 – 2036. These increase in renewable capacity is based on Thailand's energy policy especially electricity which seek to focus on transparency, environmental concerns, cooperation among neighbouring countries (electricity trade) as well as long term economic effectiveness by encouraging public and private sector investments on power generating facilities.

In The Gambia, some of the electricity policy options are valid including electricity trade where the country seeks to be interconnected with neighbouring countries commencing 2020. Environmental issues are also additional current policy option to reduce environmental degradation from power generating facilities. The Gambia also seeks the participation of both public and private sector investment in power generation sector to support economic development. Based on the RET scenario of this study, The Gambia hopes to achieve a total grid renewable penetration of 38 % by 2020 and 41 % by 2030.

In addition, with these renewable penetrations it can save 40 % CO_2 emission by 2030 compared to 2015 level of 747 Kt. This is attributed increase renewable capacity and imports of hydroelectricity which avoids or delays the construction of more fossil fuel power plants. While the Thailand's PDP2015 will contribute 15 % additional emissions compared to 2015 levels of 86 998 kT.

5 CHAPTER FIVE: SENSITIVITY ANALYSIS

As mentioned previously, the objective of MESSAGE – Model for Energy Supply Strategy Alternatives and their General Environmental Impacts is determination of an optimal allocation of energy technologies and associated resources to satisfy the projected final energy demand under several constraints. The mathematical method applied in this operation is dynamic linear programming, which means that all technical and economic relations describing the energy system are expressed in terms of linear as well as non – linear functions (Schrattenholzer 1981). The optimisation of the objective function is done by minimising the total cumulated energy system costs for the period under study in this case 2010 to 2030 (see chapter 3 on methodology – objective function).

This function computes the present values of different energy supply options by discounting all costs occurring later in the modelling period to the base year, and the sum of the discounted costs is used to find the optimal solution. Usually, when modelling and/or analysing energy systems using mathematical models, there are a lot of different initial parametres and calculation results. Practically, it is not possible to perform sensitivity study for every uncertain parametre in the MESSAGE modelling tool. So, considering uncertain parametres we analyse the influence of mainly one important initial parametre (i.e. discount rate) and additional two other parametres (i.e. fuel price and electricity demand) on the main model results.

In determining the optimal solution or result, the discount rate is an essential input parametre as it defines the weights different periods are accorded in the optimisation and facilitates comparison between options by bringing all cost to their present values with the help of the function or equation described below:

$$C_t = \frac{C_t^r}{\prod_{k=1}^{t-1}\left(1 + \frac{\boldsymbol{dr_k}}{\mathbf{100}}\right)^{\Delta k} * f_i}$$

Where:

$\boldsymbol{C_t^r}$**:** *the cost figure to be discounted*
$\boldsymbol{C_t}$**:** *the objective function coefficient in period t*

$$\boldsymbol{f_i} = \begin{cases} 1 & for\ costs\ connected\ to\ investments \\ \left(1 + \frac{dr_t}{100}\right)^{\frac{\Delta t}{2}}, else \end{cases}$$

$\boldsymbol{dr_k}$**:** *the discount rate in period k*

It can be vividly noted that the afore equation is hugely dependent on the discount rate which in most cases is the real interest rate (i.e. excluding inflation rate). This rate in reality is difficult to ascertain especially in the medium to long term, and therefore, requires the conduction of sensitivity analysis to demonstrate how variations in this rate would have on the whole optimisation process.

Using MESSAGE, several studies have conducted sensitivity analysis including the one by *International Atomic Energy Agency (IAEA)* (International Atomic Energy Agency (IAEA) 2004), *Robertas Alzbutas and Egidijus Norvaisa* (Alzbutas and Norvaisa 2012) and *A. Hainoun et al.* (A.Hainoun, Aldin and S.Almoustafa 2009) etc., who in one way or the other have conducted an uncertainty and/or sensitivity analyses for economic optimisation of new energy sources. In their analyses, they found that among the numerous uncertain parametres (such as investment cost of small nuclear facility, fixed O&M costs, nuclear fuel costs, fuel prices, demand, discount rate etc.), discount rate have proven to be most uncertain parametre and therefore seemed to have more impact on the model results including the discounted system cost, installed capacity, generation etc.).

Therefore, in this study the discount rate and two additional parametres (fuel price and electricity demand) have been chosen among the numerous other parametres to ascertain their impact on the development of The Gambia's electricity supply system. Table 5.1 gives the applied discount rate parametres used in this study as reported by the Central Bank of The Gambia and the World Bank database. The original value of 10 % applied in the two scenarios (BAU & RET) analysed above is assumed to have a minimum and maximum values. These values of discount rate (long term real interest rate) are represented in MESSAGE as uniform type distribution or variable (i.e. remain constant year after year up till the end of study period).

Table 5.1: Possible parametres for the discount rate

Parametre	Original Value	Minimum Value	Maximum Value
		In percent	
Discount rate (uniform distribution)	10	5	15

The possible variation of this parametre is only our assumption which is based on the observed real interest rate variations by The Gambia's Central Bank (Central Bank of The Gambia 2011) and confirmed by the World Bank database (World Bank 2015). As depicted in Table 5.1, we assumed that the discount rate for the entire horizon could be as low as 5 % and as high as 15 %. According to the MESSAGE user manual (International Atomic Energy Agency (IAEA) 2007), a low discount rate (in this case 5 %) usually favours future expenditures (such as renewable systems with low operation and maintenance costs) than current ones (such as oil/gas based systems with high operation and maintenance costs) while high discount rate (in this case 15 %) gives greater importance to current expenditures than future ones.

It is essential to note that the outcome of sensitivity analysis is quite crucial in decision making process (precisely policy formulation), as it assists in the identification of importance of various technical, economic, as well as environmental parametres used in the model and their possible implications on future policy formulation process. Basically, it determines how sensitive the formulation of policy can be, given the uncertainty of the employed parametres (in this case discount rate).

In order to estimate discount rate impacts on the future structure of electricity system capacity, electricity production or economic effectiveness of various power plants, additional scenarios were analysed. These scenarios have the same inputs as BAU scenario except for the discount rate (DR), which is set to 5 % (BAU scenario with 5 %) and 15 % (BAU scenario with 15 %).

5.1 BAU with 5 % DR scenario

Under this scenario, all input parametres are kept the same as in the BAU scenario for the entire study horizon except for the discount rate which is varied from 10 % (BAU scenario) to 5 %. As stated initially, a lower discount rate accords great importance to technologies and resources with high investment costs but with low operation and maintenance costs such as renewable systems.

Hereunder is the technical (structural), economic as well as environmental discussions of the impacts of reduced discount rate on the national electricity supply development.

5.1.1 Technical Analysis

Figure 5.1 provides the ***net differences in installed capacity*** between the BAU scenario and BAU scenario with 5 % DR. It can be deduced from the Figure 5.1 that the reduction of discount rate from 10 % to 5 % would lead to an increase in the installed capacity of renewables like solar thermal, wind, and with a minimal increase in distributed or decentralised oil power plants.

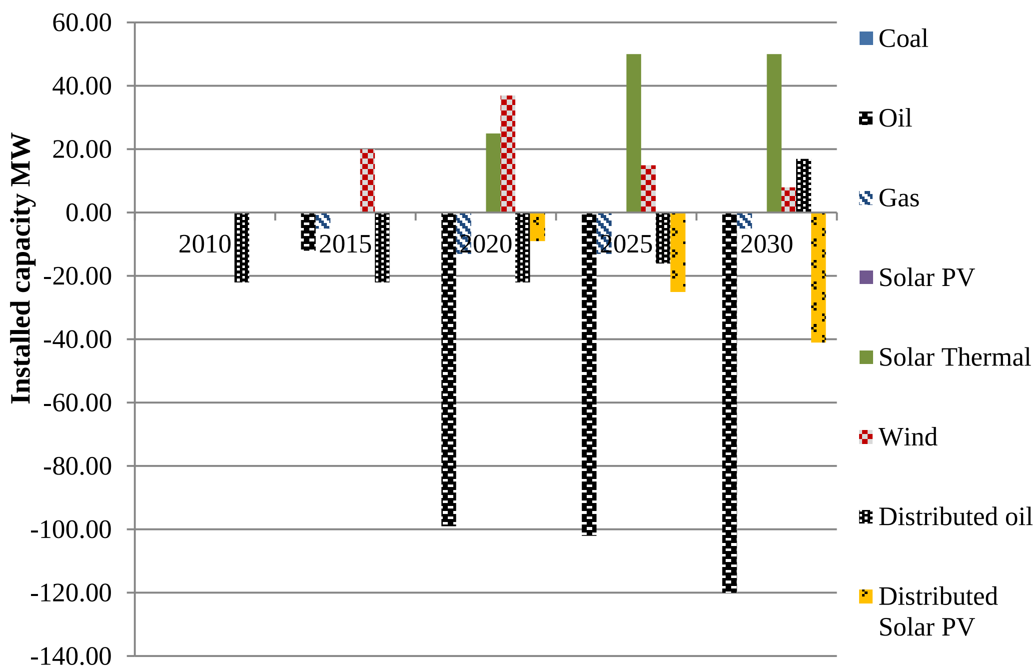


Figure 5.1: Comparison of total installed capacity in BAU and BAU with 5 % DR scenarios

In Figure 5.1 the net capacity addition of solar thermal systems is 25 MW (2020) and further increase by 50 MW at the end of the study period (2030) against the BAU scenario. The wind (on shore) supply capacity has also grown by 20 MW (2015) to about 37 MW (2020) and then lessen to net positive value of about 8 MW by 2030. In addition, distributed or decentralised oil is expected to have net capacity reduction except for 2030 where a positive net increase of about 17 MW more capacity is added comparing to BAU scenario. It can be deduced that a reduced discount rate allows an increment in the installed capacities of renewables than the fossil fuels counterparts.

It is also observed that technologies like centralised oil, distributed or decentralised oil, natural gas as well as distributed or decentralised solar PV have seen their net capacities decreased with a reduced discount. Centralised oil installed capacity dropped by (12) MW in 2015 to (120) at 2030. While that of distributed or decentralised oil has a negative capacity increment of (22) MW in 2010 to just about (16) MW by 2025 and then increased by positive 17 MW by 2030.

Natural gas systems capacity has also decreased by (5) MW in 2020 to about (13) MW in 2025 and then increase but still negative by 2030 with (5) MW of installed capacity. Distributed or decentralised solar PV installed capacity declines by (9) MW in 2015 and by 2030 it declined further to (41) MW. The reductions in installed capacities of these non-renewable technologies are as a result low discount rate which accords less importance to these technologies.

Other technologies like Utility solar PV did not show any changes in its installed capacity with the decrease of DR to 5 % because the same annual installed capacities recorded in both scenarios. In brief, a low discount rate favours renewable technologies like solar thermal, wind and less favorable to centralised oil, distributed or decentralised oil, natural gas etc.

In Figure 5.2 the impacts of reduced discount rate on ***electricity generation*** in the BAU scenario is presented. A reduced discount rate has favoured generation from solar thermal systems, which generated about 109 GWh in 2020 to 228 GWh (2030) as well as generation from wind, which attains its highest in 2020 with 88 GWh to less but positive net generation of 16 GWh by 2030. Again for electricity generation, it is observed that a reduced discount rate is quite favourable to renewables technologies as opposed to the fossil fuel counterparts.

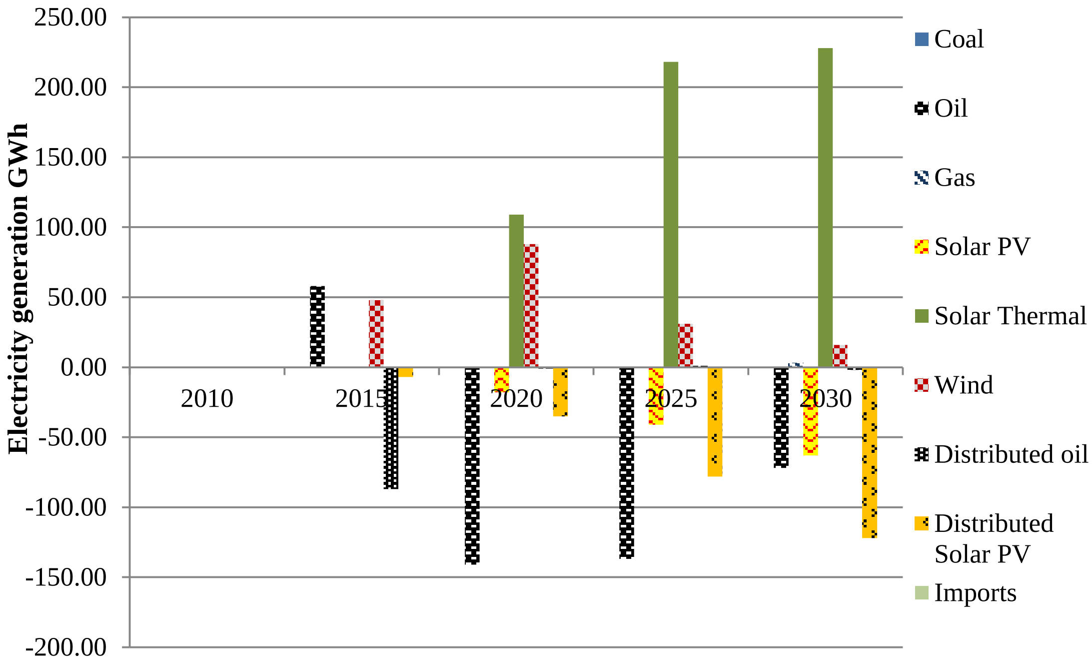


Figure 5.2: Differences in Electricity generation in BAU and BAU with 5 % DR scenarios

However, fossil fuel generation especially from centralised oil systems has declined by (141) GWh in 2020 to about (72) GWh by 2030, despite having positive net increase in 2015 with 58 GWh compared to the BAU scenario. In addition, electricity generation from distributed or decentralised oil systems falls by (87) GWh in 2015 and indifferent in the rest of the period. Utility and distributed/decentralised solar PV, generations have dropped by (18) GWh in 2020 and (63) GWh by 2030; and by (7) GWh in 2015 and (122) GWh by 2030 respectively.

5.1.2 Economic Analysis

Under this analysis, we looked at how different components of ***the system cost*** vary with a reduction in the discount rate to 5 %. Figure 5.3 gives the net variation in these components in the total system capacity of the BAU scenario. The economic impact of reduced discount rate can lead to an increase in centralised investments from USD $ 3 million (2015) to about USD $ 35 million by 2030. These positive net increases in centralised investments can be attributed to the increase in installation of solar thermal, and wind as the discount rate reduces. Centralised operation and maintenance (O&M) costs also grow by USD $ 4 million in 2015 to USD $ by million by end of period. In 2025 and 2030, transmission and distribution (T&D) costs have showed positive net increase of USD $ 1 million and USD $ 6 million respectively. While in 2015 and 2020 T&D costs have a negative net increase in its cost.

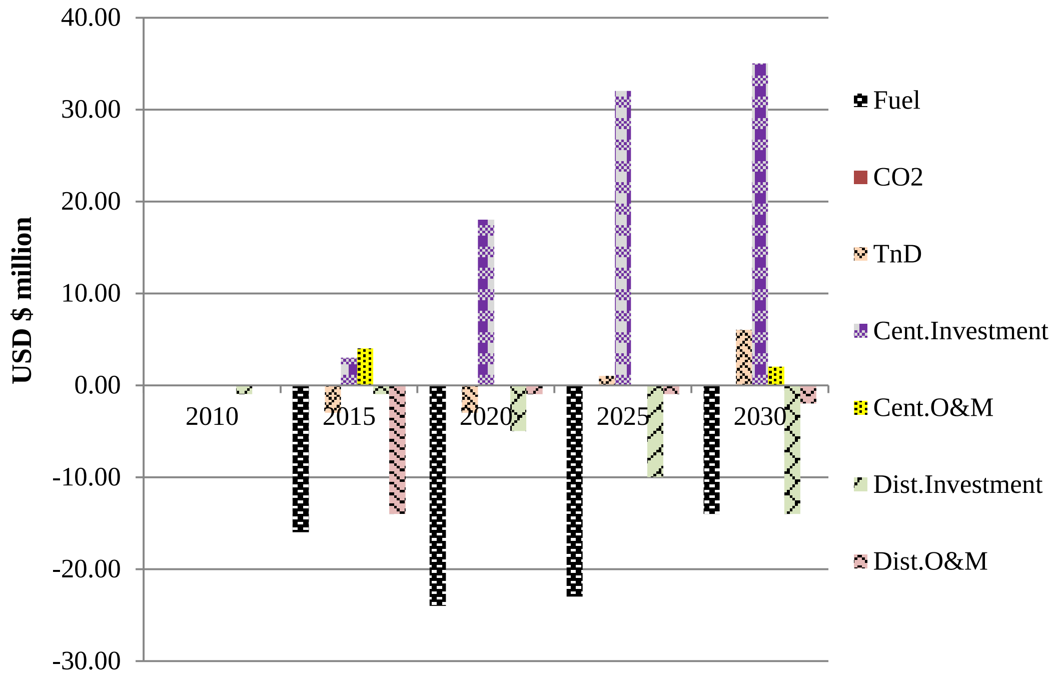


Figure 5.3: Variation in components of total system cost in BAU and BAU with 5% scenarios

In Figure 5.3 also shows a decrease in part of the following components in the total system cost. Fuel cost has the largest reduction with a reduced discount rate. It has declined by USD $ (16) million in 2015 to USD $ (23) million in 2025 before decreasing to USD $ (14) million by 2030. Another component of the total system cost that showed a negative net increase is the distributed or decentralised investments declined by USD $ (1) million in 2010 to USD $ (14) million by 2030. These declines in distributed or decentralised investments can be attributed to the reduction in the capacity and generation of distributed or decentralised oil and solar PV.

The T&D costs as mentioned previously, declined by USD $ (3) million in 2015 and 2020, before having a positive net increase in 2025 and beyond. For distributed or decentralised operation and maintenance (O&M) costs have significantly reduced to USD $ (14) million in 2015 before marginally declining in 2020 and beyond with USD $ (2) million. These O&M costs (centralised or decentralised) include all related cost except the fuel cost and manpower costs of the national electric utility (NAWEC).

5.1.3 Environmental analysis

Figure 5.4 provides the ***CO_2 emission*** from electricity generating power plants especially fossil fuel power plants (mainly oil and natural gas). The impact of reduced discount rate of 5 % has led to negative net increase in emission from 1 kT in 2010 to (111) kT by 2020 and further to (53) kT by the end of the period. The reduction in the CO_2 emissions compared to the BAU scenario is as result of increase in the capacity and generation from renewables and a decrease in oil and gas based generation especially between 2015 and 2023. However, beyond 2025, the reduction in CO_2 emissions still decreases but at a decreasing rate compared to prior years.

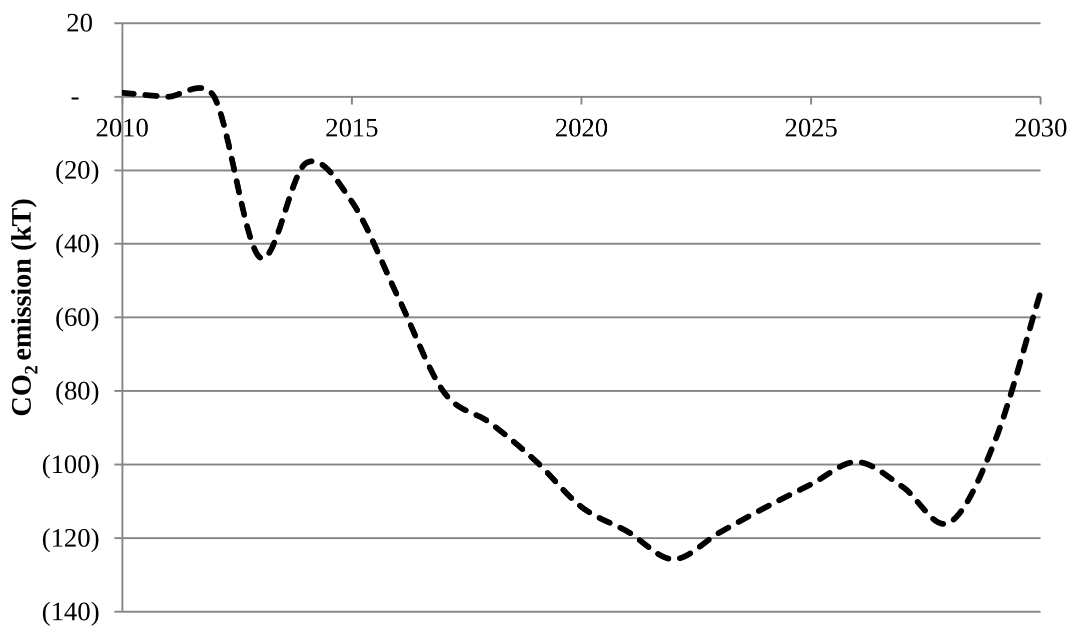


Figure 5.4: CO_2 emissions variation between BAU and BAU with 5 % DR scenario

5.2 BAU with 15 % DR scenario

This scenario has as well the same input data as the BAU scenario, except for discount rate which in this case has been reviewed upwards to 15 % as opposed to 10 % discount rate in the BAU scenario. By varying the discount rate upwards to 15 %, the technical (structural), economic as well as environmental aspects of The Gambia's electricity supply system have been analysed based on the BAU scenario. As stated initially, a higher discount rate (from 10 % to 15 %) gives value to technologies and resources that have high operation and maintenance (O&M) costs but with low investment costs such as fossil fuel power plants.

Below is presented, the discussion of the impacts of high discount rate of 15 % on the national electricity supply development.

5.2.1 Technical Analysis

Technically, the impacts of high discount rate of 15 % on ***the total installed*** is given in Figure 5.5, the installed capacities of centralised oil based power plants have increased by 23 MW in 2015 to 131 MW by 2030 when compared to the BAU scenario. Distributed or decentralised solar PV systems have also had positive net capacity increase of 30 MW (2015) to 122 MW by 2030 compared to the BAU scenario. Natural gas as well has negligible increase in its installed capacity with high discount rate. Its capacity attain highest in 2020 and 2025 with 13 MW of installed capacity in each of the year while decreasing marginally by 11 MW in 2030. Solar thermal and distributed or decentralised oil also had an additional capacity of about 25 MW (in 2030) and 22 MW (in 2010 and 2030) respectively.

With a higher discount rate of 15 %, the installed capacity of distributed or decentalised oil based systems is the only technology that has shown a negative net increase in its capacity. This technology initially has a positive capacity addition of 22 MW in both 2010 and 2015 but in 2020 and beyond its capacity has decreased by (40) MW in 2020 to (104) MW by 2030. Another vital but insignificant reduction in installed capacity is observed with wind whose capacity dropped by just (8) MW in 2030 compared to the BAU scenario. These reductions in capacity of wind and distributed or decentralised oil is as result of 15 % discount rate while increase in the addition of centralised oil and distributed or decentralised solar PV is observed with marginal increase in natural gas and solar thermal.

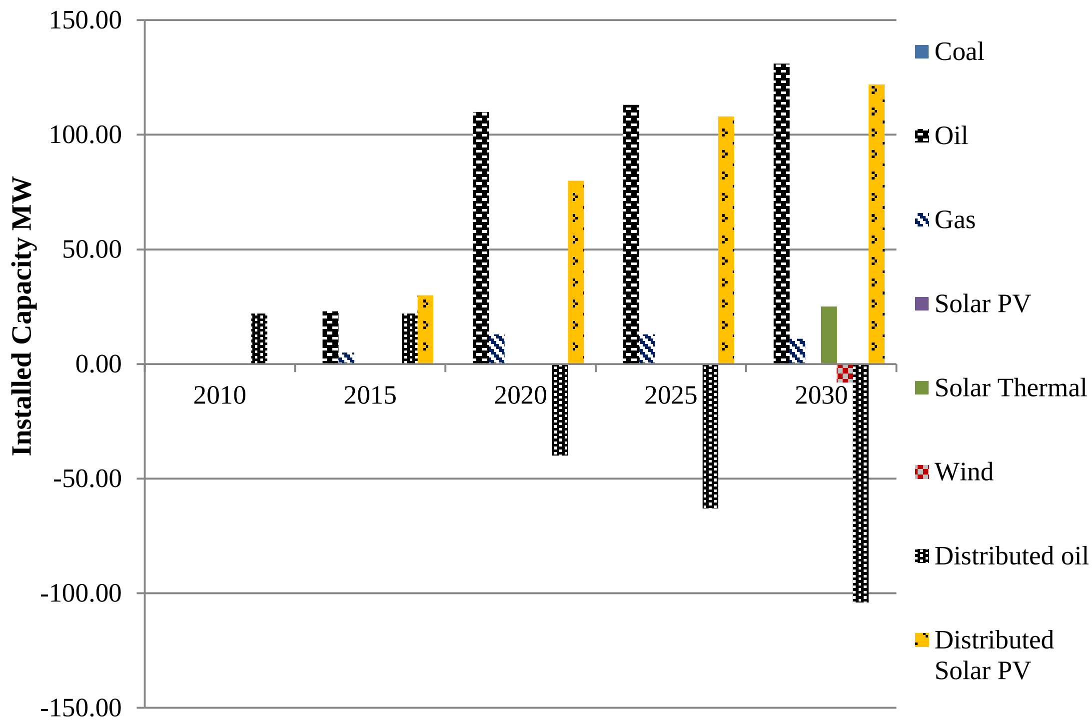


Figure 5.5: Comparison of total installed capacity in BAU and BAU with 15 % DR scenarios

Other technologies like Utility solar PV did not show any changes in its installed capacity with an upward increase in DR of 15 %. Therefore, the a high discount rate has given preference to centralised oil based as well as distributed or decentralised solar PV while given less preference to distributed or decentralised oil and wind.

An aspect of the technical analysis includes generation from the electricity generating plants in the national energy system. Figure 5.5 presents the impacts of a high discount rate (in this case 15 %) on ***electricity generation*** of the BAU scenario. A 15 % discount rate has led to an increase in generation from the following electricity supply systems i.e. Utility or centralised and distributed or decentralised solar PV, decentralised or distributed oil, as well as solar thermal systems compared to the BAU scenario. Generation from decentralised or distributed solar PV has increased by 61 GWh in 2015 to about 267 GWh by 2030. Utility solar PV also realised a positive net increase in generation from 18 GWh in 2020 to 63 GWh by 2030. In addition, decentralised or distributed oil and solar thermal generation grow by 70 GWh in 2015 and 99 MW by 2030 respectively.

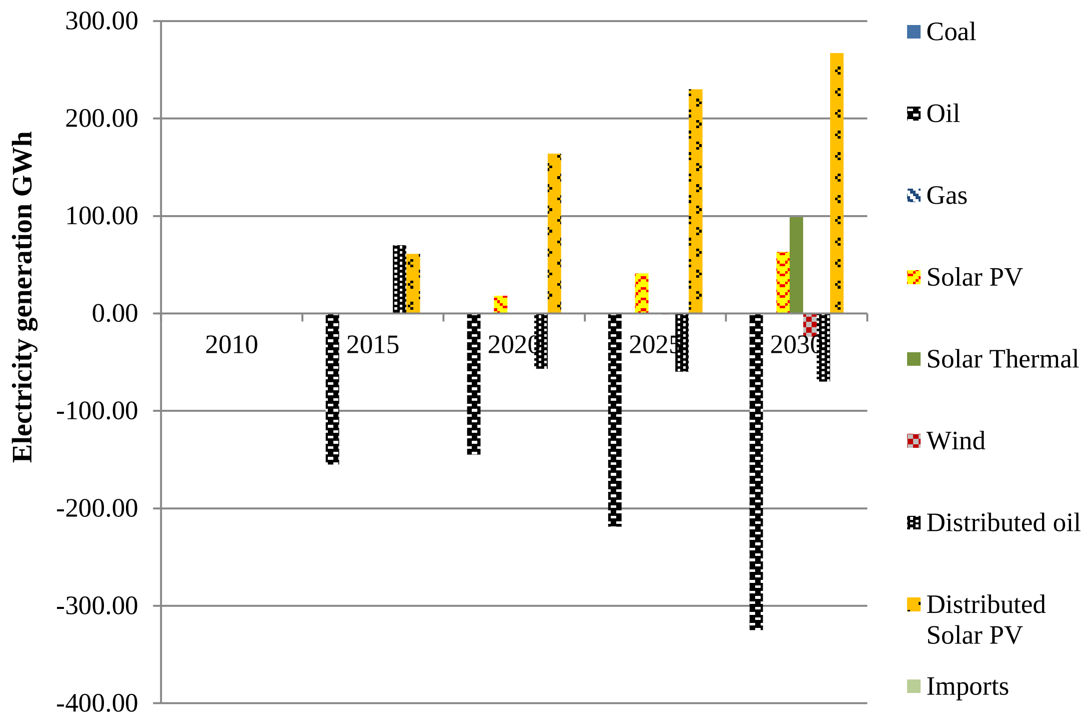


Figure 5.6: Differences in Electricity generation in BAU and BAU with 15 % DR scenarios

However, the generation from centralised oil systems declined by (155) GWh in 2015 to (219) GWh by 2025 and even further reducing to (325) GWh by 2030, against the BAU scenario with 10 % discount rate. Generation from decentralised or distributed oil systems despite having positive net increase in 2015, have declined by (57) GWh in 2020 to about (70) GWh by 2030. Wind generation has also marginally declined by (24) GWh in its total generation in 2030 for the BAU scenario.

5.2.2 Economic Analysis

Economically, we viewed the impacts of higher discount rate on the cost components in the total annual system cost. Figure 5.7 provides the net variation in these components in ***the total system costs*** using the BAU scenario as basis. A rise in the discount rate to 15 % has led to a net increase in investment costs (at both centralised and decentralised levels), and transmission and distribution (T&D) costs. Centralised investments grow by USD $ 4 million (2015) to about USD $ 26 million by 2030. Decentralised investments also have a net positive growth of USD $ 1 million in 2010 to USD $ 32 million in 2030. In addition, T&D costs increase by USD $ 6 million (2015) to USD $ 16 million by 2030, comparing with cost centres attained in the BAU scenario.

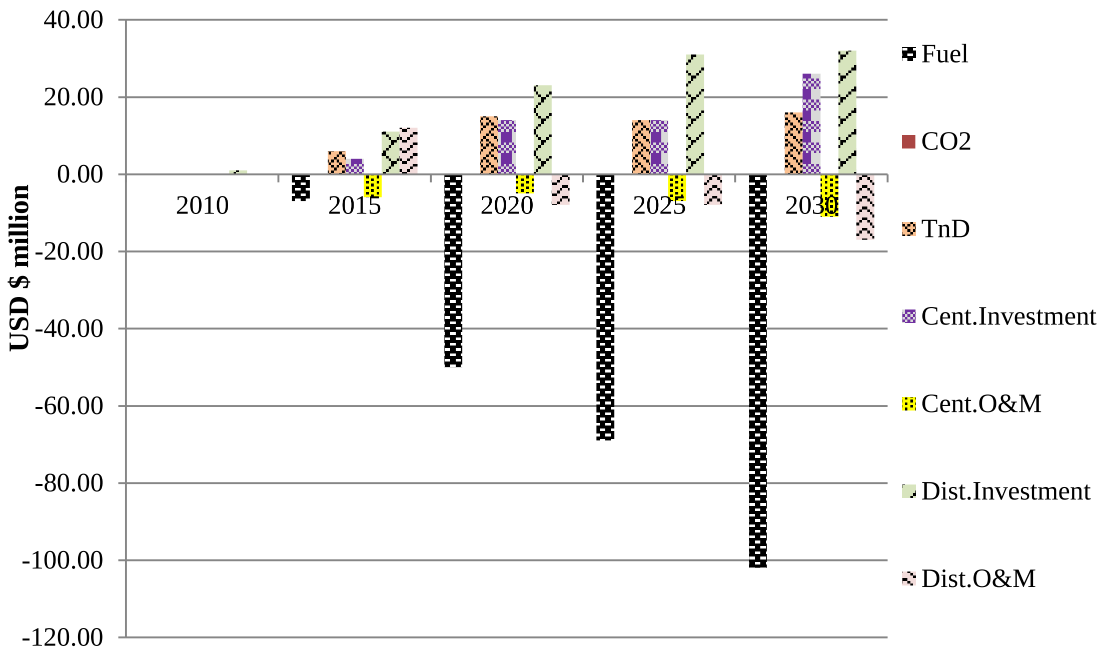


Figure 5.7: Variation in components of total system cost in BAU and BAU with 15% scenarios

Other cost components such as operation and maintenance (O&M) (at both centralised and decentralised options) as well as fuel cost have showed a reduction in their costs with 15 % increase in discount rate. Fuel cost which has showcased the most significant reduction, cost reduces from USD $ (7) million in 2020 to about USD $ (102) million by 2030. Centralised and distributed or decentralised O&M costs, despite having a negative net increase, but its reduction is quite marginal compared to fuel cost. Centralised O&M costs have reduced by USD $ (6) million in 2015 to about USD $ (11) million by end of the study period. In addition, distributed or decentralised O&M costs which initially had positive net increase of about USD $ 12 million in 2015, have however in 2020 and 2030, viewed its costs decreased by USD $ (8) million and USD $ (17) million respectively.

5.2.3 Environmental analysis

A high discount rate of 15 % is expected to have the following CO_2 emissions development from the national electricity generation systems. Figure 5.8 provides the net ***CO_2 emission*** for the entire study period especially from fossil fuel power plants (mainly oil and natural gas). A higher discount rate has initially led to a negative increase in CO_2 emission in 2013 of about 34 kT (kilotons) before significantly reducing by (202) kT by 2020 and further by (387) kT at the end of the period (2030). These reductions can be attributed to generation and capacity increase in solar PV and solar thermal systems.

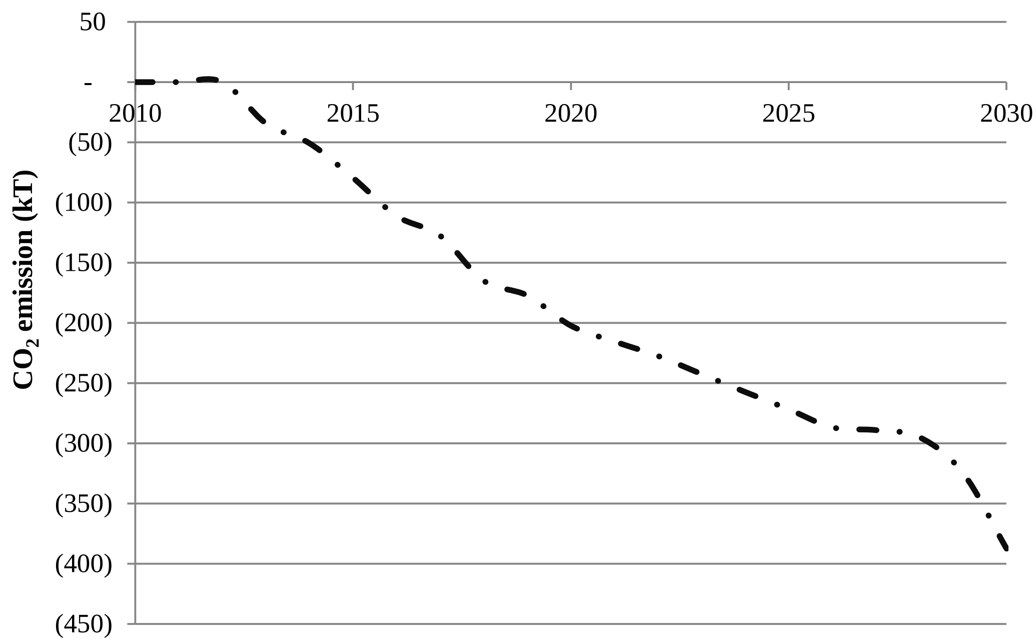


Figure 5.8: CO_2 emissions variation between BAU and BAU with 15 % DR scenario

As mentioned previously, in addition to the discount rate this study also explores the possible impacts of fuel prices and electricity demand on the BAU scenario.

5.3 Impacts of fuel prices on the BAU scenario

Under this sub-section, we attempt to examine the possible impacts of increase in the price of fossil fuels on the main results of the BAU scenario precisely the grid renewable penetration. In order to conduct sensitivity analysis of fossil price increase, we considered the IEA's current policies scenario (CPS) instead of new policies scenario (NPS). Based on the nominal price of CPS (International Energy Agency (IEA) 2013 <https://www.iea.org/publications/freepublications/publication/WEO2013.pdf>), an average 4.5 %[27] annual increase in the fuel price is assumed (see Table 5.2).

Table 5.2: Possible variation of fuel prices

In USD $_{2010}$ / GJ	Biomass[a]	Coal[b]	Natural Gas[c]	Crude Oil[c]	Fuel Oil[d]	
					Light (LFO)	Heavy (HFO)
2010	1.5	3.3	10.9	18.3	23.3	14.0
2012	1.5	3.3	10.9	18.3	23.3	14.0
2014	1.6	5.1	9.5	9.5	11.7	6.9
2016	1.6	5.1	9.5	11.0	13.0	7.2
2018	1.6	5.2	9.2	13.4	16.7	9.3
2020	1.6	5.3	9.0	14.8	18.1	10.7
2022	1.6	5.3	9.4	15.6	19.1	12.1
2024	1.6	5.5	10.4	18.1	20.5	13.5
2026	1.6	5.6	10.9	18.9	23.5	14.1
2028	1.6	5.6	11.3	19.7	23.9	14.7
2030	1.6	5.7	11.4	20.7	25.5	15.0

As shown in Figure 5.9 the impacts of fossil fuel price increase on the possible developments of the BAU scenario is explored. The increase in fuel prices impacted positively on the ***installed and generation*** from renewables such as solar PV (both centralised and distributed), wind onshore and concentrated solar power which surfaced at the end of the horizon. On the other hand, oil (HFO/LFO) technologies are disfavoured as their cost of operation becomes expensive making renewables even more competitive. In 2020, renewables capacity addition reaches 115 MW compared to BAU case, generating about 220 GWh. These generations increase from renewables displaces about (240) GWh of oil generation. By the end of the period, renewables especially solar PV produce 200 GWh displacing the same quantity of oil based generation.

[27] 4.5 % is the annual average price increase with HFO, LFO, and Crude oil each having 4.8% increase in its price, Coal (4.4%), and NG (3.9%)

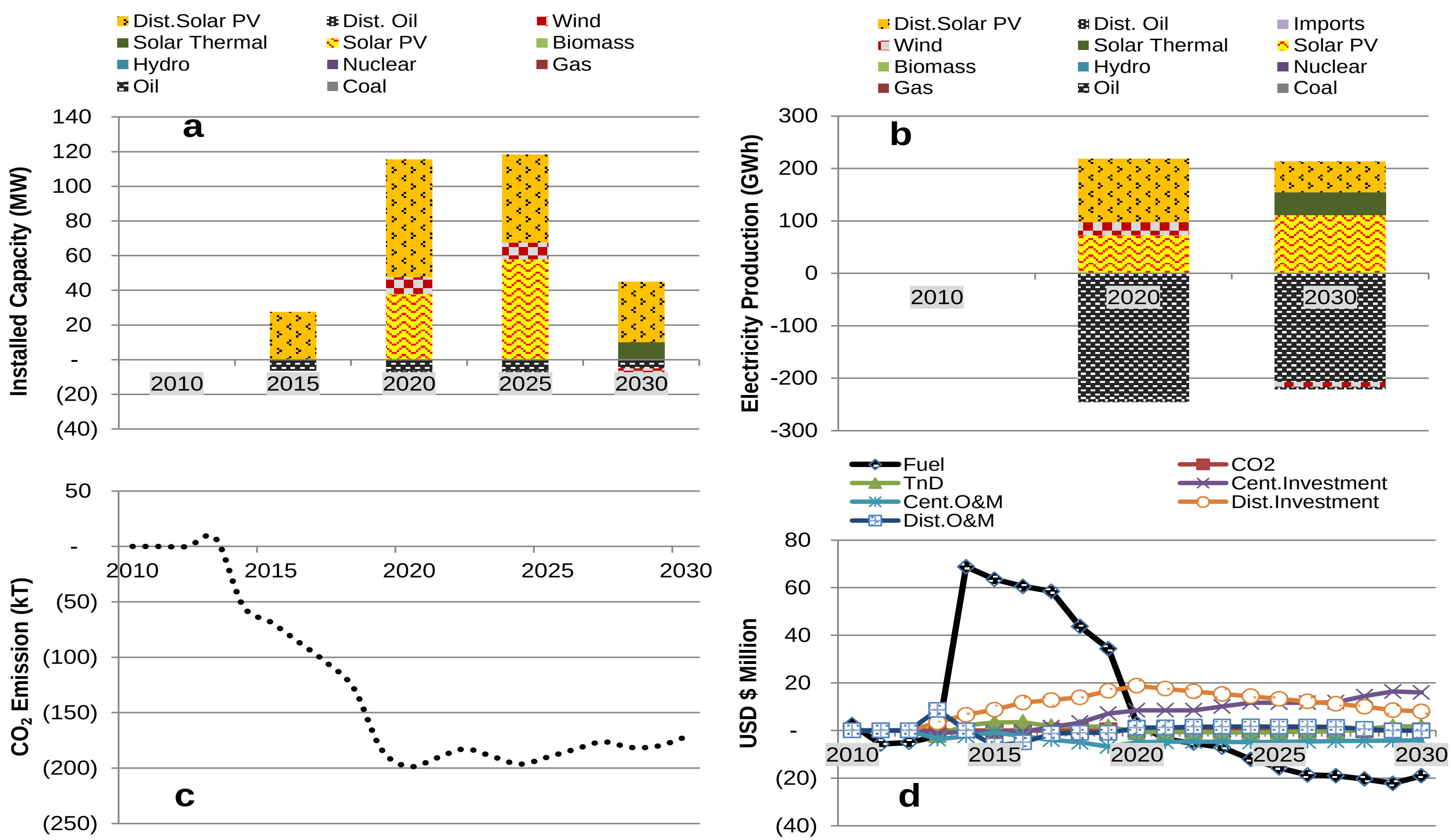


Figure 5.9: Impacts of fuel price increase on installed (a), generation (b), emissions (c), and discounted costs (d)

Given the increase in renewable generation capacities and the decline of oil based generation, the ***CO_2 emissions*** also decline commencing 2013 to (200) kT reduction in CO_2 emission in 2020 and then stabalises around (175) kT by end period compared to the BAU scenario. ***Economically***, the fuel price increase impacts on only fuel and investment (centralised and decentralised) costs while the other components of total system cost stay relatively insensitive. The results showed that expenditure on fuel was as high as USD $ 70.2 million in 2014 before declining to USD ($ 0.6) million in 2020 and continue to decline to USD ($ 20) million by end of the period compared to BAU scenario. The increase in renewables generation have led to an increase but marginal in both decentralised (off-grid) and centralised investment costs. This can be attributed to increase in solar PV installation, generation and the decreasing oil capacity as it becomes costly relative to BAU scenario.

It is crucial to note that the increase in fossil fuel price have led to increase in grid renewable penetration compared to BAU scenario. The share renewable electricity rises from 10 % in the BAU scenario to 34 % by 2020 and 33 % in BAU scenario to 35 % by 2030.

5.4 Impacts of lower demand on the BAU scenario

Any given energy system can only be optimised provided the demand is given. The demand given in Figure 3.2 is based on a very optimistic scenario, however, on a more pessimistic scenario; the national electricity demand is expected to be lower as given in Table 5.3 below.

Table 5.3: Pessimistic development of electricity demand

In GWh	Households Demand		Industrial Demand	Total
	Urban	Rural		
2010	356	7	52	416
2012	363	10	118	491
2014	368	14	198	580
2016	402	20	255	677
2018	486	28	275	789
2020	586	40	294	920
2022	674	55	344	1073
2024	774	76	401	1252
2026	891	100	468	1460
2028	1023	132	548	1703
2030	1176	171	640	1987

This lower demand for electricity is explained by the possible low (pessimistic) economic growth than more optimistic growth rate of above 5 % annually.

Figure 5.10 provides the impacts of low electricity demand on the possible developments of the BAU scenario. A projected low electricity demand impacted negatively on the ***installed and generation*** from both renewables and oil based technologies. The renewables technologies affected by low demand include solar PV, hydroelectricity imports and onshore wind. In 2020, the total installed capacity reduced by (85) MW and reduction in generation by (480) GWh constituting mainly oil technologies. By 2030, the reduction in installed and generation capacities is not significant compared to 2020. Installed capacity reduces by just (55) MW with generation just little over (200) GWh compared to BAU scenario.

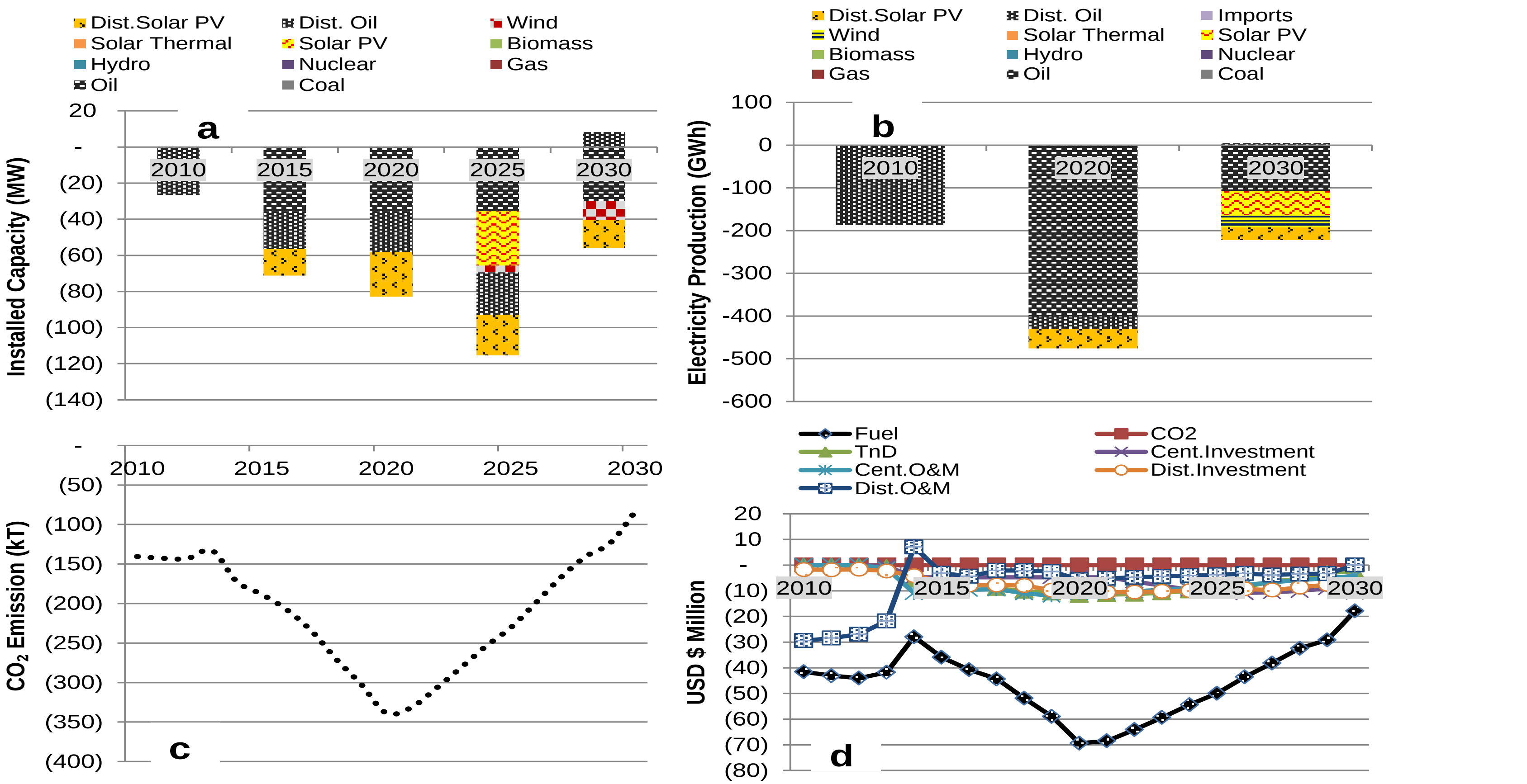


Figure 5.10: Impacts of low demand on the capacity installed (a), generation (b), emission (c), and discounted costs (d)

Given the reduction in total installed and generation capacities compared to the BAU scenario, the ***CO_2 emissions*** also decline reaching (390) kT reduction in CO_2 emission in 2020 and then increases but still negative to (95) kT by end period compared to the BAU scenario. This sharp reduction to 2020 is explained by the significant proportion of fossil fuel in the total generation while beyond 2020 more renewable penetration reducing the gap.

Economically, a low electricity demand impacts mainly on three components of the discounted cost i.e. fuel cost, decentralised O&M and decentralised investments. A low electricity demand generally impacted negatively on the fuel cost. The expenditure on fuel was as high as USD ($ 30.2) million in 2014 before declining to USD ($ 70) million in 2020 and rise but still negative to USD ($ 19) million by end of the period compared to BAU scenario. These reductions in fuel cost (up to 2020) is attributed to significant increase in oil generation while beyond 2020 more generation from renewable explained the less expenditure on fuel. Decentralised investment is also less sensitive compared to fuel cost; the same is true for decentralised O&M. This can be attributed to unattractiveness of several technologies including distributed renewable systems as the demand for electricity is low relative to BAU scenario.

It is crucial to note that the increase in fossil fuel price have led to increase in grid renewable penetration compared to BAU scenario. The share renewable electricity rises from 10 % in the BAU scenario to 23 % by 2020 and 33 % in BAU scenario to 44 % by 2030.

6 CHAPTER SIX: CONCLUSIONS & POLICY RECOMMENDATION

In this study, an analysis of The Gambia's electricity supply system was explored for 2030 horizon starting 2010.Within this horizon; two scenarios were constituted including the Business as Usual (BAU) scenario (which is based on the current national policies and strategies) and Renewable Energy Target (RET) scenario (where the country targets higher renewable penetration by 2020 and 2030 basing on the BAU scenario). In order to represent these scenarios, an energy system optimisation tool called Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) has been employed to bring about adequate, secure and sustainable supply of electricity to meet demand. Addressing this demand several technologies have been deployed into MESSAGE including the current existing heavy/light fuel oil (HFO/LFO), solar photovoltaic (PV), wind, OMVG (Organisation pour la Mise en Valeur de la fleuve Gambie) hydroelectricity imports, solar thermal, as well as natural gas, biomass and coal technologies. These deployed technologies are in line with the government's policy [3], strategies as well as feasibility studies [18] on the national electricity system.

Using MESSAGE, the system capacity development, generation as well as generation mix in both scenarios are expected to be dominated by oil (HFO/LFO) based systems up to 2019, after which the system is expected to be diversified with more of renewable energy systems at both centralised and decentralised levels and negligible contribution from alternative sources such as natural gas systems. This increase in the generation after 2019 is as a result of the commencement of the importation of cheap hydroelectricity from the regional OMVG dams expected to come online by 2020. In addition to OMVG hydroelectricity imports is the generation from committed solar PV, wind and solar thermal projects.

Technically, the system capacity and generation in the two scenarios analysed are presented in Table 6.1. It gives the summary of capacity and generation from centralised as well decentralised fossil fuels based systems and renewable based systems for 2010 and 2030. The total capacity in this period is expected to grow from 167 MW (2010) to 864 MW by 2030 in the BAU scenario. The generation in this scenario is as well expected to rise from 673 GWh in 2010 to about 2,378 GWh by 2030. Both the system capacity and generation in 2010 are totally dominated by fossil fuel based systems mainly HFO/LFO power plants.

Table 6.1: Summary of capacity development and generation in BAU and RET scenario

Capacity & Generation in both scenarios		Centralised & decentralised fossil fuel based systems		Centralised & decentralised renewable based systems		Total	
		MW	**GWh**	**MW**	**GWh**	**MW**	**GWh**
BAU Scenario	**2010**	167	673	-	-	167	673
	2030	366	832	498	1546	846	2378
RET Scenario	**2010**	167	673	-	-	167	673
	2030	332	576	560	1808	892	2384

However, in 2030, the renewable based systems dominated both the installed capacity (498 MW) and generation (1,546 GWh), dominated by solar PV and hydroelectricity imports as well as wind based systems. The total share of renewable energy (both centralised and decentralised) in this capacity has grown from nil in 2010 to 37 % by 2020 before increasing further to 58 % by 2030. The generation develops from 100 % oil (HFO/LFO) based system dominance to 21 % of RE penetration by 2020 and further to 47 % by the end of the study period.

In the RET scenario, the total installed capacity and generation are instrinctly similar to that observed in the BAU scenario. The total installed capacity (for both centralised and decentralised based systems) is expected to increase from 167 MW in 2010 to 892 MW by 2030 while the generation grows from 673 GWh in 2010 to about 2,384 GWh by 2030. The total installed capacity in 2010 is totally dominated by oil based system while by 2030, the total centralised and decentralised fossil fuel and renewables based systems are 332 MW and 560 MW respectively. Share of renewable energy (both centralised and decentralised) capacity under this scenario grows by 0 % in 2010 to 52 % by 2020 and then to 63 % by 2030. In addition, the total generation of 2,384 GWh in 2030 is 75 % of renewables systems and the rest is fossil fuel based systems.

In both scenarios, fossil fuel (HFO/LFO) dominates the future expansion capacities before 2020 while in 2020 and beyond have seen the penetration of renewable energy (RE) systems especially the import (438 GWh) of OMVG hydroelectricity from the regional project expected to come online starting 2020.

Considering the economic aspects, the BAU scenario has a total system cost of about USD $ 271 million in 2010 to about USD $ 412 million by 2030. In this amount the fuel cost constituted the chuck of the total discounted cost but its part has dropped significantly in the medium to long term as a result of high renewables penetration (solar PV, wind, hydroelectricity etc.) which do not require any fuel cost. In addition, the unitary electricity production costs under this scenario, has decreased from USD $ 0.402 / kWh in 2010 to just about USD $ 0.166 / kWh by 2030.

Under the RET scenario, the annual total system cost rises from USD $ 271 million in 2010 to about USD $ 409 million in 2030, thereby representing an increase of about USD $ 138 million between this period. Like the BAU scenario, fuel cost constituted the largest chuck of the total discounted system cost especially between 2010 to 2020 but beyond 2020 these share has significantly decline given way to investment on centralised and decentralised systems (such as solar PV, solar thermal, wind etc.) as well as transmission and distribution (T&D) costs. In addition, the unitary electricity production cost also decline from USD $ 0.403 / kWh in 2010 to about USD $ 0.177 / kWh by 2030, this latter amount is just insignificantly higher than the amount recorded in the BAU scenario.

For both scenarios, the total system costs are insignificantly different, with RET scenario just USD $ 2 million more costly than the BAU scenario (USD $ 6,273 million). However, the relative composition of these total system costs are quite different, with the RET scenario (42 %) having less share of fuel cost than BAU scenario (51 %). This lower share of fuel cost (42 %) in the RET scenario has resulted in an increased in the share of centralised investments to 18.4 % of total system cost compared to just 9.7 % in BAU scenario, thereby increasing centralised renewable installations. Other components (decentralised investment, T&D costs, and O&M costs) of the total system costs are invariably the same between the scenarios.

Environmentally, the CO_2 emissions from the electricity generating system is significant when oil based systems dominated the supply capacity and dropped sharply in 2020 which was the start of the OMVG –hydroelectricity imports and other renewable energy technologies such as wind and solar PV that will avoid/shift the building of more fossil fuel power plants that could contribute to rise in the emissions. The BAU scenario, which has more heavy oil fuel (HFO) operated power plants presented the highest emissions of CO_2 compared to the RET scenario with emissions peaking in around 2020 with more than 800 kT of CO_2 released. From the period 2020 to 2030, the total CO_2 emitted doesn't exceed 400 kT annually whilst for the same period in the BAU scenario the emissions have surpassed that level. This shows that up to 40 % reduction in annual CO_2 emissions is possible with the government's new renewable target. This is an important ancillary benefit, in addition to the energy security.

In this study, the discount rate has been used as a possible uncertain parametre on the output of BAU scenario, which is chosen based on previous studies on The Gambia's electricity system and elsewhere. Under this study, the discount rate applied in the BAU scenario has been varied upward and downward to keep track of changes in BAU scenario.

Aside the 10 % discount rate applied in the BAU scenario, two extra scenarios were modeled by varying the 10 % discount rate downwards and upward by 5 %. With a discount rate as low as 5 %, renewable technologies like wind, solar PV, solar thermal have seen their capacities and generations increased with low discount rate. While centralised oil, distributed or decentralised oil, natural gas as well as distributed or decentralised solar PV capacities decreased compared to the BAU scenario. Given these increase in renewable energy capacity and generation have resulted in an increase in investment cost especially centralised investment, centralised operation and maintenances (O&M) and transmission and distribution (T&D). On the other hand, given the drop in the capacity of oil based systems, the fuel cost and distributed or decentralised investments in the total discounted system cost have declined enormously for the entire time horizon comparing with the BAU scenario. Additionally, the CO_2 emission from fossil fuel power plants decrease sharply between 2010 to 2020, however, beyond 2020, the total annual emissions increases but remains to be in negative quantity compared to the BAU scenario.

Table 6.2: Impacts of discount rate variations on the capacity and generation in 2030

Capacity & Generation in both scenarios		Centralised & decentralised													
		Fossil fuel based systems						Renewable based systems							
		Cent. Oil		Dist. Oil		Natural gas		Solar PV		Wind		Dist. Solar PV		Solar Thermal	
		MW	GWh	MW	GWh	MW	GWh	MW	GWh	MW	GWh	MW	GWh	MW	GWh
BAU Scenario with 5 %	**2030**	(120)	(72)	17	(2)	(5)	3	-	(63)	8	16	41	(122)	50	228
BAU Scenario with 15 %	**2030**	131	(325)	(104)	(70)	11	-	-	13	(8)	(24)	(122)	267	25	99

A higher discount rate of about 15 % has led to increase in the capacities and generation of oil, natural gas as well as distributed or decentralised solar PV system, while a significant drop in the capacity and generation from wind as well as distributed or decentralised oil based systems (as shown in Figure 5.6). As a result of increase in the generation from oil based systems, natural gas as well as distributed or decentralised solar PV have led to an increment in both centralised as well as decentralised investments and transmission and distribution (T&D) cost compared to the BAU scenario. Fuel cost, centralised and decentralised operation and maintenance (O&M) cost have seen their part in the system cost declined compared to the BAU scenario. Environmentally, between the BAU scenario and the BAU scenario with 15 % discount rate have resulted in the continues reduction in the CO_2 emissions from 2010 to 2030 as opposed to the scenario with 5 % discount rate.

The Impacts of fuel price increase and low electricity demand is also explored to see their impacts on installed and generation capacities as well as on CO_2 emission and the discounted costs. Fuel price increase favours more generation and installation of renewable systems such as solar PV, wind onshore, while low demand impacts on all the generation technologies with reduced installed and generation capacities.

Generally, comparing both scenarios (BAU & RET), the RET scenario is found to be more attractive as well as attainable as a result of its increased rate of renewable energy share, very marginal increase in total system cost, and less CO_2 emissions explained by more renewables (solar, wind, import hydro) penetration. However, the BAU scenario could still be attractive as Non-Annex one country, if the government considers that 10 % (2020) and 33 % (2030) grid renewable penetration rates suffice and not worth additional investments of USD $ 2 million. Regarding the sensitivity analysis, the BAU scenario with 5 % discount rate has led to addition of more renewables energy systems and disfavours that of fossil fuel power plants while the higher discount rate of 15 % favour both renewables and few fossil fuel plants and disfavouring fossil fuel generating plants.

It is also vital to point out that, technologies like coal, biomass as well as mini-hydro are being modelled but due to social and environmental concerns for coal, lack of comprehensive assessment for biomass utilisation as a potential electricity generation source, and infeasibility of mini-hydro in the country have unfavoured these technologies, despite their low economic costs.

However, in order to achieve these results in the medium to long term will not be an easy task as the overnight cost of renewable systems are still high relative to fossil fuel counterparts, therefore The Government of The Gambia should heed to the following policy recommendations:

6.1 Recommendations based on study results

Given the results analysed above, the following recommendations are quite crucial to achieve a secure and sustained supply of electricity in The Gambia:

I. The political will to support renewable energy deployment.

II. Priority should be given to the swift and timely implementation of the regional OMVG hydroelectricity project which amounts an imported annual capacity of 438 GWh starting 2020.

III. However, the OMVG hydroelectricity imports will require the construction of transmission line of 225 kV capacity and about 1600 km distance connecting The Gambia to these hydroelectric dams scheduled to be operational by 2020.

IV. For other renewable energy systems (solar, wind etc.), more attractive incentives such as tax breaks and/or rebates, operational feed-in-tariff systems etc.

V. Solar PV technologies for both centralised as well as decentralised (such as roof tops mini/macro grids) options will play an instrumental role in addressing the electricity security challenges facing the country. And on shore centralised wind energy technologies are also interesting electricity supply option for the country.

VI. It should also make provisions for the development and implementation of alternatives energy sources to oil.

VII. Despite the need to develop alternatives to oil and renewable technologies attractiveness in the medium to long term, fossil fuel technologies (such as oil (HFO/LFO), natural gas) will still be very crucial in supplementing these variable renewable supply systems.

In brief, as the focus of study is diversification of the national electricity system considering the current national policies and strategies to obtain secure and sustainable means of addressing the country's electricity challenges. Therefore to ensure security and sustainable supply of electricity in The Gambia, the continued utilisation of fossil fuel (mainly oil) is required in the short to medium term while a balance mix between renewable energy (hydroelectricity imports, solar PV, wind) and fossil fuels is needed for medium and long term to ensure security of supply and sustainability.

6.2 Possible implementation measures

In order to achieve the grid renewable target of 35 % in 2020 and 48 % by 2030 in the RET scenario, technologies like OMVG hydroelectricity imports, centralised solar PV and wind onshore are crucial. The following implementation measures for these key technologies are given below.

I. *OMVG hydroelectricity imports*: This will require the government to reduce transmission and distribution (T&D) losses from its current high level of 25 % by upgrading and expanding the T&D system. This is crucial for hydroelectricity imports, especially before 2020.

II. *Grid Solar PV*: Given its expansive and excellent availability all over the country and all year round will require the implementation and enhancement of schemes outlined in the renewable energy law such as investment incentives (waivers for all direct inputs of all renewable technologies), and the establishment of a renewable energy fund are crucial intervention areas for the government. This will not only encourage households' but motivate independent power producers (IPPs) to increase renewable investments. This technology policy is crucial in providing grid (Utility) as well as off-grid (mini/micro grids/stand -alone) solutions.

III. *Wind Onshore*: This technology can contribute to meeting a portion of the industrial demand especially hotels. Most of The Gambia's on shore wind potentials are available along its coastline and where most hotels are situated. Therefore, wind can be optimally utilized to provide electricity to the hotel industry at low transmission cost. However, the construction of these farms should adhere to the national environmental laws and regulations such as sound disturbances, birds' migratory routes as well as aesthetics concerns from the turbines. The identification and reservation of potential site for wind farm development is also crucial.

Overall, The Gambian government should focus on developing on these three main electricity generation sources beyond oil based systems (including mainly new and existing HFO power plants). These sources include solar PV (grid and off-grid systems), wind onshore, and more importantly hydroelectricity imports. These technologies can help attain a secure, low cost and environmentally acceptable national electricity supply system. In addition, from now and toward 2020, The Gambian government should rely on oil (H/LFO) power plants while beyond 2020 technologies such as hydroelectricity imports, solar PV and wind are crucial in addition to the diminishing oil capacity to optimally address future national electricity demand.

6.3 Recommendations for future study

For improvement and subsequent works on modelling of national electricity system should adhere to the following:

I. The utilisation of system dynamics approach to showcase the potential impacts of the regional hydroelectricity imports on the fishing, tourism and in general agriculture in the Gambia will be essential for subsequent studies. This will provide the possible downside of the OMVG hydroelectricity imports

II. Given the highly susceptibility of fluctuation in demand for electricity as well as the prices of fuel. It is vital for further studies to take into consideration the utilisation of stochastic models (to capture more accurately the variability in these parametres) than optimisation (deterministic) models. Notwithstanding, the utilisation of stochastic models would lead to considerable computational complexity as well as time consuming.

III. Most input information deployed in this current study are obtained from the database of IRENA, however, subsequent studies should take into account up-to-date database from both national and international institutions.

IV. In this current study, the imports of electricity (OMVG hydroelectricity imports) from neighbouring countries were modelled. However, in the future when the country becomes more electricity secure and independent, an export of electricity can as well as be modelled to neighboring countries.

V. The current study assumed that The Gambia will continue to be an oil importing country for the entire study horizon, despite the recently discovered petroleum resources in off the coast of The Gambia. It is vital that, once it is known when these potential resources can be converted to reserves, a study can be conducted considering this novel aspect of the national energy (electricity) supply system.

VI. The CO_2 emission was the only environmental concern considered in this current study, however, future ones should consider other environmental problems (such as SO_X, NO_X etc.) especially when the country becomes the oil producing country.

In the future it would be interesting to constitute another BAU scenario when The Gambia becomes a petroleum producing nation and also conduct a thorough demand analysis of the electricity supply system, which are all beyond the scope of this study. Moreover, further studies could as well explore demand side analysis and even the modeling of different policy scenarios on the supply-side of the electricity system.

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ANNEX – A

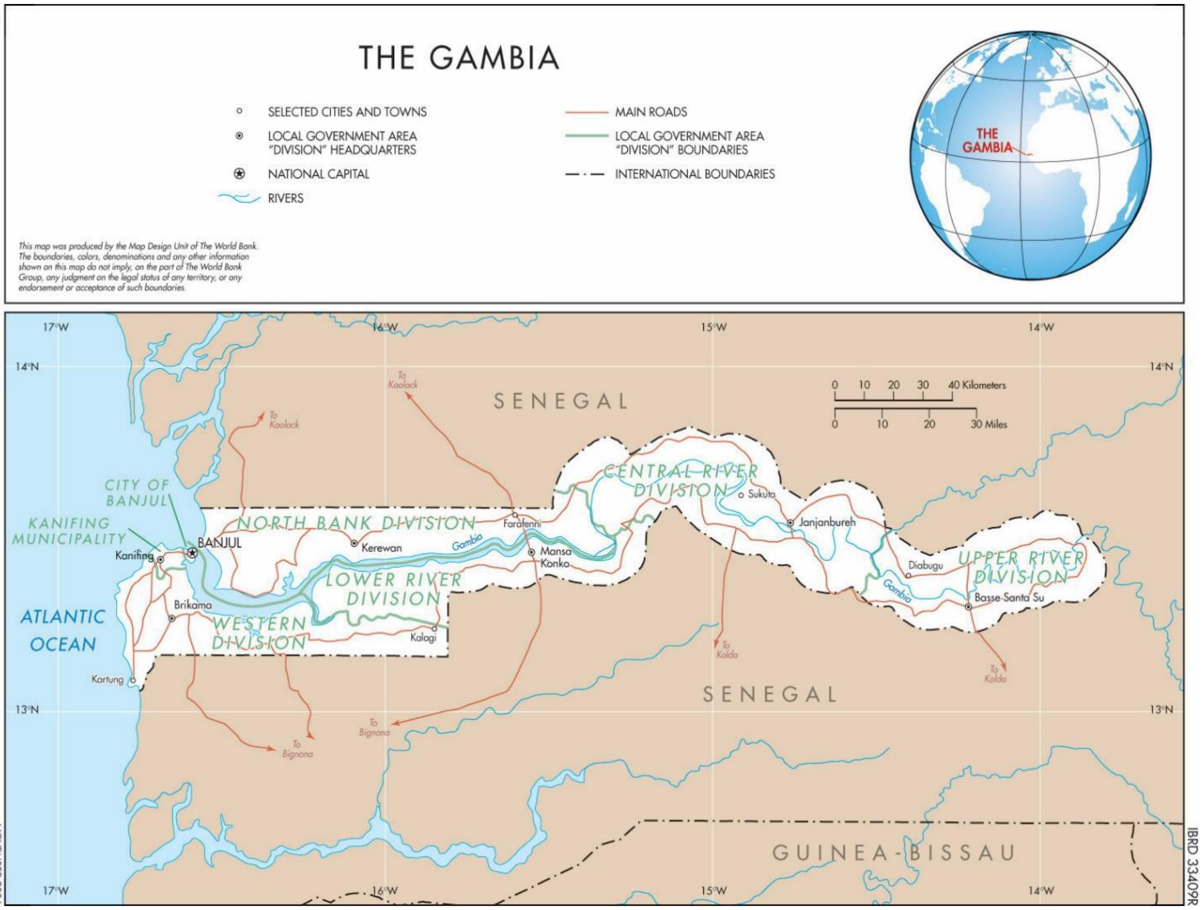

Figure A 1: GEOGRAPHIC AND ADMINISTRATIVE MAP OF THE GAMBIA

Table A 1: DETAILED DEMAND DATA REPORTED BY VARIOUS STUDIEES

GWh	WAPP Masterplan Report		IRENA Report	IAEA report		Recent Study	This study
	Base case	Low case		REF[a]	UAS[b]		
2010	-	-	219	214	214		603
2011	239	219	239				628
2012	337	268	337				654
2013	414	317	414				692
2014	496	385	496				762
2015	586	414	586	326	346	604	837
2016	747	455	747				921
2017	771	496	771				1013
2018	796	609	796				1114
2019	921	658	921				1226
2020	847	703	847	494	555	1296	1349
2021	879	722	879				1416
2022	912	742	912				1487
2023	945	763	945				1561
2024	980	784	980				1639
2025	1017	806	1017	741	884	1728	1722
2026			1055				1807
2027			1094				1898
2028			1134				1992
2029			1176				2091
2030			1219	1103	1396		2197
2031			1264				2306
2040			1751				3579
2050			2514				5828

[a] reference scenario

[b] universal access scenario

Table A 2: MODEL APPLIED CONSTRAINTS/LIMITS/BOUNDS

Scenario	Technology		Limits, bounds and constraints	Explanation
Both Scenarios	New Oil PP	HFO	Capacity limits/bounds up to 2000 MW new capacity addition	
		LFO	Capacity limits/bounds up to 500 MW new capacity addition	
	New Biomass PP		No new capacity addition	Unavailability of assessment on national biomass utilization
	New Natural Gas PP	OCGT	Up to 10 MW new capacity addition starting 2020	Lack of financial resources and improvement of existing natural gas import infrastructure
		CCGT	Up to 50 MW new capacity addition starting 2015	
	New Coal PP		No new capacity addition	Environment and social acceptance, building of new coal import infrastructure
	New Solar Photovoltaic (PV) Farm	Utility (grid)	- Up to 10 MW new capacity addition 2017 - Fix new capacity additions: 2019 (10 MW), 2020 (20 MW), 2022 (30 MW) - 270 000 MW max. of total installed capacity - Reserve margin contribution: 0.05	-
		Off-grid	- Up to 3-5 MW new capacity addition 2013 - Fix new capacity additions: 2018 (3	-

			MW), - 270 000 MW max. of total installed capacity - No reserve margin
	New Wind Farm		- Up to 10 MW new capacity addition 2015 - Fix new capacity additions: 2016 (0.6 MW) - 165 MW max. of total installed capacity - Reserve margin contribution: 0.05
	New CSP Farm		- Up to 5-10 MW new capacity addition 2015 - 103 000 MW max. of total installed capacity - Reserve margin contribution: 0.1
Business-as-Usual (BAU) Scenario only	Transmission Lines	PV	-0.40 of PV generated cannot be transmitted
		Wind	-0.15 of wind generated cannot be transmitted
	Hydroelectricity imports		50 MW limits/bounds on annual activity on imports (2020)
Renewable Energy Target (RET) Scenario only	Transmission Lines	RE Share	35 % (2020) and 48 % (2030)
		PV	-0.40 of PV generated cannot be transmitted
		Wind	-0.15 of wind generated cannot be transmitted
	Hydroelectricity imports		50 MW limits/bounds on annual activity on imports (2020)

ANNEX – B

Message Modelling Guidelines

As a bottom-up optimisation model, MESSAGE requires huge amount of input information in order to simulate energy system so detailed. The main MESSAGE input information is the techno-economic description of the modelled technologies (example: their investment costs, efficiency, capacity, emission factors, fuel types etc.), energy demand and their development, discount rate, fuel costs and their development.

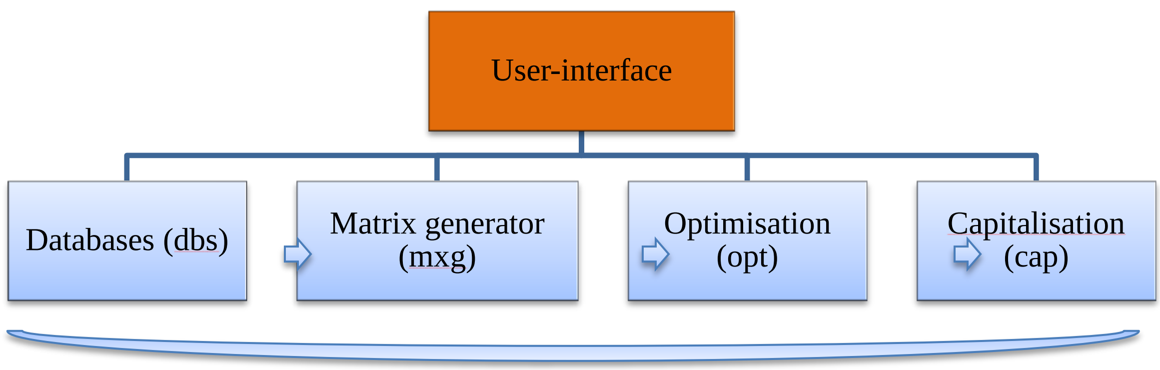

Figure B 1: MESSAGE Components and their interrelationship

Figure B 1 provides the main components of MESSAGE and their interrelationship. The MESSAGE user-interface (for developing the model) comprises of four main components including *databases* (*dbs*) for inputting data, after data input, MESSAGE provides windows to run the *matrix generator (mxg) program* that uses the *dbs* to generate the matrix model, which then is used by program solver called *optimisation (opt)* that solves the matrix generated and finally a program for extraction of results called *capitalisation (cap).*

The cap program takes the solution generated by the opt program and present the result in a standard format. The user interface allows windows for result extraction. It also provides windows with the selection of one part of the solution or the other parts as preferred by the user. In one of these windows the user can further process the extracted results to get the final output in the desired form.

Among these components, the *dbs* component is very crucial as it constitute eight sections requiring detailed data input. These sections include General, Load regions, Energy forms, Demands, Constrains, Technologies, Storages and Resources. Figure 3.1 provides various input information in each of the section of the *dbs* component.

Table B 1: Summarised data inputs in each of the 8 sections of the *dbs* component

Sn	**General**		**Load regions**	**Energy forms**	**Demands**	**Constrains**	**Technologies**		**Storages**	**Resources**
	Key Data	*Default Data*					*Activity*	*Capacity*		
1	Discount rate (%)	Currency	Number and type of seasons in a year	Energy levels defined	Different demand sectors	Cumulative Cumulative per period	Their inputs and outputs	New capacity or historical capacity	Unit capacity and life span	Resource and fuel costs
2	Study Horizon (years)	Energy	Number and type of days in each season	Energy forms defined	Inputting their values	Undefined constrains: emission factors, costs and limits.	Their variable O&M costs	Plant life	Investment costs as well as construction time	Imports or extraction costs
3		Power	Part of each day type	Energy forms include power plants, fuel and demand types		Defining upper and lower limits for resources and technologies	constraints	Technology availability		Constraints or limits
4								Investment costs/unit, construction time, fixed o&m costs		
5								Constraints		

Upon satisfactory completion of the sections in the *dbs*, the MESSAGE model takes this information to generate a metrix (*mxg*) before optimising (*opt*) using the objective function. The result then can be extracted by the capitalisation (*cap*).

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List of Publication and Proceeding

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- Lamin K. Marong[a], Sopin Jirakiattikul[b], Kua-anan Techato[c]: "The Role of Diversification in the Optimisation of Electricity System in The Gambia" (International conference proceeding: Assuring Sustainability via University with Research (ASSURE) Conference, Thailand – 2018)

- Lamin K. Marong[a], Sopin Jirakiattikul[b], Kua-anan Techato[c]: "Future Expansion Path of the National Electricity System Using MESSAGE" (International conference proceeding: Global Warming Mitigation and Adaptation by Sustainable Energy Management (GSEM) Conference, Thailand – 2017)

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