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# Design of Hybrid Power System with Policy and Regulatory Framework Formulation for Renewable Energy Intervention in Africa, Case Study of Nigeria

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**For the Award of Doctorate Degree in Mechanical Engineering, University of Tlemcen, Algeria**

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## DECLARATION

I, Ismail Abubakar Jumare, a PhD student of the Mechanical Engineering Department of University of Tlemcen, Algeria hereby declare that this dissertation entitled **“Design of Hybrid Power System with Policy and Regulatory Framework Formulation for Renewable Energy Intervention in Africa, Case Study of Nigeria”** is original and written by me in the frame of Water and Energy Security in Africa (WESA) project. It has been written under the supervision of Prof. Abdellatif Zerga of the Pan African University, Institute of Water and Energy Sciences (PAUWES) c/o University of Tlemcen, Algeria and Prof. Ramchandra Bhandari of the Institute for Technology and Resource Management in Tropics and Subtropics (ITT), TH Köln (University of Applied Science), Cologne, Germany. All information obtained from literature have been duly acknowledged and a list of references provided.

______________________ ___________________

Signature Date

## CERTIFICATION

This is to certify that this dissertation entitled **"Design of Hybrid Power System with Policy and Regulatory Framework Formulation for Renewable Energy Intervention in Africa, Case Study of Nigeria"** was conducted by Mr. Ismail Abubakar Jumare, and it meets the requirements for the award of doctorate degree in Mechanical Engineering (Renewable Energy), of the University of Tlemcen, Algeria.

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| ______________________ | ______________________ |
| Prof. Abdellatif Zerga | Date |
| ______________________ | ______________________ |
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## DEDICATION

I dedicate this work to God Almighty, the sustainer of all, for sparing my life and giving me the health, strength and wisdom in working on this research.

## ACKNOWLEDGEMENT

My immense gratitude goes first to God Almighty (Subhanahu Wata'alah) for his guidance, protection and assistance in all my academic pursuit. More thanks to God Almighty whose grace and mercy has brought me this far and shall lead me on while I live in his glory.

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Moreover, my beloved parents: Late Alhaji Abubakar Balarabe Jumare and Hajiya Halima Ahmad deserve a lot of appreciation and continuous prayers for Allah's mercy and forgiveness till the end of my life. I enjoyed their moral upbringing and supports in my academic pursuit and the entire life. May Jannatil Firdaus be their final abode, Ameen. My recognition also goes to our eldest brother in the family, in person of Dr. Jibreel Abubakar Jumare for his guidance and supports. My other elder ones in the family are not skipped also for the generous role they played in their different capacities. May Allah reward them all abundantly.

Mention must be made of a distinguished personality and a role model in my academic field of endeavour, in person of Prof. Engr. Abubakar Sani Sambo, for his supports and guidance during the conduct of the research. Also, I will not forget the support of my Islamic tutors most especially Malam Aminu Adam Ahmad for his sacrifice for the sake of Islamic Ummah. Thank you all so much.

My final thanks extend to other distinguished personalities in which their names are too many to be enlisted here, that have also played a positive role in my life.

## ABSTRACT

Electricity supply is a strong precondition to economic growth and development at all levels. However, the kind of electricity service and the mechanisms involved are of paramount importance in ensuring sustainability. Renewable energy systems integration to grid is considered one of the promising alternatives however, effective policy mechanisms as well as technical infrastructure shaping are necessary elements for such realization. Due to the power of these components, renewable energy technologies have been vigorously promoted in developed countries, hence addressing their energy concerns and improving the living standards of their populace. By contrast, this is not the case in the African context, and more specifically the case study country.

In view of the above background information, this research work is therefore aimed at grid-integration of renewable energy power plants in the African context, looking at the case of Nigeria. This was done by first looking at a general energy landscape and renewable energy market in the global context as a kickstart and driver to the policy task direction of the dissertation. On the technical bit, physical component modelling, optimization, energy management and evaluations, detailed sensitivity analysis, energy efficiency assessment, economic benefits evaluation of systems switching, extrapolation assessment at bigger capacity, and environmental life cycle assessment were conducted by a combination of software packages viz.: Hybrid Optimization Model for Electric Renewables (HOMER), Microsoft Excel, Ganzleitlichen Bilanz (GaBi), and some databases. On the complementary policy bit, in-depth analysis based on defined indicators was conducted of the existing renewable power policy in the global context for a continental cluster of highly performing countries, with narrowing to the case study country existing power policies. The lessons obtained from both the technical and policy aspects with added innovative thoughts were sufficiently applied in the formulation of the appropriate policy instruments for the case study country while also evaluating the risks associated. As a supplementary and final deliverable, grid-infrastructural assessment was conducted in evaluating the appropriate grid-based mechanisms in favour of integrating the renewable energy system to the utility grid of the case study country.

Regarding the obtained results, it is evident on the technical part that the transition from the standalone system to the proposed grid-connected hybrid system led to drastic reduction in the optimized sizing and ultimately 3% increment in overall energy supply, 68% and 85% decrement in net present cost (NPC) and levelized cost of energy (LCOE) respectively, with avoided emissions at the operational level. The energy efficiency incorporation to the proposed grid connected system resulted in more commendable transition based on the further decrease in optimized sizing and ultimately 88% and 81% reduction in overall NPC and LCOE respectively. Regarding the supplementary economic benefits of the system switching from the standalone to the proposed grid-connected system, the observed savings translated to a payback period (PBP), discounted payback period (DPBP) and internal rate of return (IRR) of 6.09 years, 7.18 years, and 16% respectively. Same economic benefit analysis on the adoption of the energy efficiency to the proposed grid-connected system resulted in observed PBP, DPBP, and IRR of 1.78 years, 1.99 years, and 56% respectively. The extrapolation assessment to the proposed grid connected system and its energy efficiency measure over 50 decentralized systems showed clearly the economy of scale benefits. With respect to the environmental impact of the proposed grid-connected system execution on life cycle ground, the analysed impact categories mainly the global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone layer depletion potential (ODP), human toxicity potential (HTP), and the abiotic depletion potential (ADP) after an uncertainty assessment incorporation revealed 21.3 - 33.38 g $CO_2$ – eq./$kWh_{elec.}$, 1.077 – 1.663 g $SO_2$ – eq./$kWh_{elec.}$, 0.134 - 0.197 g phosphate eq./$kWh_{elec.}$, 6.33E-11 – 1.01E-10 g $R_{11}$ – eq./$kWh_{elec.}$, 29.65 – 46.09 g DCB – eq./$kWh_{elec.}$, and 0.246 – 0.383 MJ/$kWh_{elec.}$. respectively. Different possible scenarios considered from the proposed grid-connected system in this regard combined with the grid-only power of conventional system generation path showed clearly the different impacts on the life cycle environmental performance indicators for proper decision.

Further quantitative results of the grid-integration of the hybrid renewable power systems that focussed on the grid-infrastructural concerns has been the utility grid extension measures. The quantified extension distance on average ($D_{av.}$) in ensuring the viability of the whole extrapolated power system grid-integration was 0.5 – 1.6 km, which ultimately gave a total distance ($D_{Total}$) of 25 – 80 km. In line with this foundational case, the capacity of distance ($CoD_1$) in respect of the total extrapolated capacity of the proposed grid-connected system was found to be 32,000 – 102,400 MW.km, whereas, for the extrapolated capacity on energy efficiency incorporation gave a capacity of distance ($CoD_2$) of 18,025 – 57,680 MW.km. In view of these grid-extension quantifications, the equivalent investment costs ($I.C_s$) were determined for both the $CoD_1$ and $CoD_2$ in ranges viz. 43.6 – 526.5 Million Euros and 24.6 – 296.6 Million Euros respectively.

The policy instruments in view of the successful adoption of the renewable power integration to the utility grid have been properly reformulated with the associated risks evaluated as well as the supplementary qualitative measures regarding the utility grid sustainability. Therefore, these overall tasks will greatly be useful to the energy planners and decision makers in favour of improved, sustainable, and high-quality power access for the case study country and the African continent at large.

**Keywords:**

[Renewable Energy; Decentralized Hybrid Power Supply; Power Policy Instruments; Grid Infrastructure; Sustainability; Nigeria]

# RÉSUMÉ

*L'approvisionnement en électricité est une condition préalable solide à la croissance et au développements économiques à tous les niveaux. Cependant, le type de service d'électricité et les mécanismes impliqués sont d'une importance capitale pour garantir la durabilité. L'intégration des systèmes d'énergie renouvelable au réseau est considérée comme l'une des alternatives prometteuses, cependant, des mécanismes politiques efficaces ainsi que la mise en forme des infrastructures techniques sont des éléments nécessaires pour une telle réalisation. En raison de la puissance de ces composants, les technologies des énergies renouvelables ont été vigoureusement promues dans les pays développés, répondant ainsi à leurs préoccupations énergétiques et améliorant le niveau de vie de leur population. En revanche, ce n'est pas le cas dans le contexte africain, et plus précisément le pays de l'étude de cas.*

*Au vu des informations générales ci-dessus, ces travaux de recherche visent donc à l'intégration au réseau des centrales électriques à énergie renouvelable dans le contexte africain, en examinant le cas du Nigéria. Cela a été fait en examinant d'abord un paysage énergétique général et un marché des énergies renouvelables dans le contexte mondial en tant que point de départ et moteur de l'orientation de la tâche politique de la thèse. Sur le plan technique, la modélisation, l'optimisation, la gestion et les évaluations des composants physiques, l'analyse détaillée de la sensibilité, l'évaluation de l'efficacité énergétique, l'évaluation des avantages économiques de la commutation des systèmes, l'évaluation de l'extrapolation à plus grande capacité et l'évaluation du cycle de vie environnemental ont été menées par une combinaison de logiciels à savoir: modèle d'optimisation hybride pour les énergies renouvelables électriques (HOMER), Microsoft Excel, Ganzleitlichen Bilanz (GaBi) et certaines bases de données. En ce qui concerne la politique complémentaire, une analyse approfondie fondée sur des indicateurs définis a été menée sur la politique actuelle en matière d'énergie renouvelable dans le contexte mondial pour un groupe continental de pays hautement performants, avec un rétrécissement à l'étude de cas des politiques énergétiques existantes des pays. Les enseignements tirés à la fois des aspects techniques et politiques avec des idées innovantes supplémentaires ont été suffisamment appliqués dans la formulation des instruments politiques appropriés pour le pays de l'étude de cas tout en évaluant les risques associés. En tant qu'élément livrable supplémentaire et final, une évaluation des infrastructures du réseau a été réalisée pour évaluer les mécanismes appropriés basés sur le réseau en faveur de l'intégration du système d'énergie renouvelable au réseau électrique du pays de l'étude de cas.*

*En ce qui concerne les résultats obtenus, il est évident sur le plan technique que la transition du système autonome au système hybride proposé connecté au réseau a entraîné une réduction drastique du dimensionnement optimisé et finalement une augmentation de 3% de l'approvisionnement énergétique global, 68% et 85% diminution du coût actuel net (NPC) et du coût de l'énergie nivelé (LCOE) respectivement, avec des émissions évitées au niveau opérationnel. L'incorporation de l'efficacité énergétique au système connecté au réseau proposé a entraîné une transition plus louable basée sur une nouvelle diminution du dimensionnement optimisé et, finalement, une réduction de 88% et 81% du NPC global et du LCOE respectivement. En ce qui concerne les avantages économiques supplémentaires du passage du système autonome au système connecté au réseau proposé, les économies observées se sont traduites par une période de récupération (PBP), une période de récupération* *actualisée (DPBP) et un taux de rendement interne (TRI) de 6,09 ans, 7,18 ans et 16% respectivement. La même analyse des avantages économiques sur l'adoption de l'efficacité énergétique du système connecté au réseau proposé a donné des PBP, DPBP et IRR observés de 1,78 ans, 1,99 ans et 56% respectivement. L'évaluation de l'extrapolation au système connecté au réseau proposé et sa mesure d'efficacité énergétique sur 50 systèmes décentralisés ont clairement montré les avantages de l'économie d'échelle. En ce qui concerne l'impact environnemental de l'exécution proposée du système connecté au réseau sur le sol du cycle de vie, les catégories d'impact analysées principalement le potentiel de réchauffement planétaire (GWP), le potentiel d'acidification (AP), le potentiel d'eutrophisation (EP), le potentiel d'appauvrissement de la couche d'ozone (ODP) ), le potentiel de toxicité humaine (HTP) et le potentiel de déplétion abiotique (ADP) après une incorporation d'évaluation de l'incertitude ont révélé 21,3 - 33,38 g CO2 - éq./kWhelec., 1,077 - 1,663 g SO2 - eq./kWhelec., 0,134 - 0,197 g de phosphate éq./kWhelec., 6,33E-11 - 1,01E-10 g R11 - eq./kWhelec., 29,65 - 46,09 g DCB - eq./kWhelec., et 0,246 - 0,383 MJ / kWhelec respectivement. Différents scénarios possibles envisagés à partir du système connecté au réseau proposé à cet égard, combinés à la puissance du réseau uniquement du chemin de génération de système conventionnel, ont clairement montré les différents impacts sur les indicateurs de performance environnementale du cycle de vie pour une décision appropriée.*

*D'autres mesures quantitatives de l'intégration au réseau des systèmes hybrides d'énergie renouvelable, centrées sur les problèmes d'infrastructure du réseau, ont été les mesures d'extension du réseau électrique. La distance d'extension quantifiée en moyenne ($D_{av.}$) Pour assurer la viabilité de l'intégralité de l'intégration du réseau du système électrique extrapolé était de 0,5 à 1,6 km, ce qui a finalement donné une distance totale ($D_{Total}$) de 25 à 80 km. Conformément à ce cas fondamental, la capacité de distance ($CoD_1$) par rapport à la capacité totale extrapolée du système connecté au réseau proposé était de 32 000 à 102 400 MW.km, tandis que pour la capacité extrapolée sur l'incorporation de l'efficacité énergétique, une capacité de distance ($CoD_2$) de 18 025 à 57 680 MW.km. Compte tenu de ces quantifications d'extension du réseau, les coûts d'investissement équivalents ($I.C_s$) ont été déterminés à la fois pour le $CoD_1$ et le $CoD_2$ dans les gammes à savoir 43,6 à 526,5 millions d'euros et 24,6 à 296,6 millions d'euros respectivement.*

*Les instruments politiques en vue de l'adoption réussie de l'intégration des énergies renouvelables au réseau électrique public ont été correctement reformulés avec les risques associés évalués ainsi que les mesures qualitatives supplémentaires concernant la durabilité du réseau électrique public. Par conséquent, ces tâches globales seront grandement utiles aux planificateurs et décideurs énergétiques en faveur d'un accès à l'électricité amélioré, durable et de haute qualité pour le pays de l'étude de cas et le continent africain dans son ensemble.*

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***Mots clés :***
*[Énergie renouvelable ; Alimentation hybride décentralisée ; Instruments de politique énergétique ; Infrastructure de réseau ; Durabilité ; Nigéria]*

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## CHAPTER ONE

# 1. INTRODUCTION

Energy accesses as well as the drive towards effective and efficient utilization are very critical to sustainable development. However, these could not offer a lasting solution except renewable energy resources are harnessed properly and considered equally or more important than the conventional sources. According to the British Petroleum (2018), the global electricity generation during 2017 was recorded as 25,551 TWh, of which the fossil fuels accounted for 65% of the total. Hence, leaving the renewable energy participation far behind despite their huge potentials. The only renewable energy resource said to thrive in the mix was the hydro, of roughly 17%. It must be noted further that global warming translating to climate change and variability is a major consequence of the use of conventional sources; specifically, fossil fuels in offering energy solutions. In the same vein, one of the most crucial challenges of the globe is dealing with global warming with its negative impacts to humanity especially in Africa (Richard and Michael, 2016). Therefore, with increasing global energy demand resulting from continuous increase in population, continuous rise in energy prices, as well as the necessary plans to reinforce the countermeasures to global warming, calls for intervention in a jointly, adequately and timely manner in offering a lasting solution (Goto et al., 2010).

The major challenges for the deployment of renewable energy technologies worldwide in addressing energy challenges are Size and Risk (Richard and Michael, 2016). Size in the sense that many investors begin to view the deployments of renewable energy systems as capital intensive, which is of course a challenge however, they fail to understand that it's a huge investment in the long run due to the sustainable nature of the solution to be offered. At the same time, risky in the sense that the investors begin to look at the deployment as something neither feasible nor appealing to the masses, hence might result in huge loss. Therefore, cost reduction could be necessary in ensuring proper diffusion of renewable energy systems and efficient decarbonisation of electricity supply (IEA, 2016). It must also be noted that structural changes to the design and operation of renewable energy power systems is also a necessity in ensuring adequate incentives to the deployment of the renewable energy solutions globally (IEA, 2016).

On narrowing down to the African context as the central focus, the situation is even more critical. Statistics of the International Energy Agency (IEA) (2020) revealed the total African electricity generation of 822 TWh during 2017, of which the fossil fuels accounted for about 79.6% of the total. The renewable energy participation is said to be chronically poor if not of the hydro that accounts for about 15.5% of the total supply in the mix. It must be stated that Africa is a continent of paradox. Paradox in the sense that it's blessed with huge energy resources particularly the renewables but the level of harnessing is chronically poor. It is very unfortunate that more than half of the continent's population have no access to modern energy services particularly electricity (Thornley et al., 2015). This is obvious from the share of power supply to the continent as compared with that of the world's total in the 2017 energy statistics shown, despite African population accounting for about 17.2% of world's total (The World

Bank, 2020). With continuous increase in the continent's population and energy demand therefore calls for alternative solutions bearing in mind the huge consequences of the fossil fuel uptake and its depleting nature. Moreover, proper policies and technical infrastructure are needed in place to ensuring the successful implementation of the alternative energy solutions as well as grid integration for addressing the energy deficits at all levels.

In line with the preceding paragraph, it must be stated that for there to be successful implementation of renewable energy systems to national grids, the grid infrastructure and adequate policies or drivers toward its prevalence at all levels are powerful tools as mentioned earlier. Unfortunately, these have been the major challenge to addressing energy deficits of the continent with renewables intervention. It is obvious that the performance of the energy sectors in Africa especially with regards to renewables is quite below expectation not just because of the poor technical infrastructure i.e. grid network, but also as a result of inadequate policy instruments in support of the energy systems and their grid integration. The major reason why developed countries and countries under transition are flourishing greatly in the world is not only due to their huge energy resources, technical infrastructure and the know-how, but also equally due to their favourable policies for implementing the renewable energy systems and grid integration. Although, it is now fortunate that a number of policy interventions have been recorded in some countries of the African continent such as Rural Electrification Support Policies in South Africa, Ghana, and Zimbabwe, Geothermal power support policies in Kenya, Bioenergy Policies in Mozambique and soon (Stephen et al, 2007). Hence, this effort is quite impressive but the diffusion, expansion, strong adoption and diversification of the policies is a high necessity.

In addition to addressing the energy deficits with the alternative sources, i.e. renewable energy supplement to the grid systems and the policy intervention, end use energy efficiency is also of great interest to be set in place. It is quite unfortunate that 10-40% of the continent's total primary energy input is lost in the process of transformation to final energies (Ejigu, 2012). Same problem applies also to transmission and distribution with significant losses in both with that of distribution more severe. This challenge could be viewed as a direct consequence of low technical know-how and inadequate technology transfer and capacity building in the continent.

Furthermore, the incorporation of hybrid-based energy systems solution to energy challenges is considered a key in the African continent. Due to the limited advancement in renewable energy systems in some few countries, hybrid energy systems are gradually being incorporated as standalone power systems for electricity provision in remote areas however, the concept is expected to go beyond that in terms of diffusion, optimization and also integration of the systems to national grids for ensuring improved and efficient access. This by so doing ensures a broader expansion of the economic integration of renewable energy technologies across African countries and will address limitations in terms of fuel flexibility, efficiency, reliability, and balance in energy systems inherent to a single energy system (Susan and Jeffrey, n.d).

Finally, Nigeria being the case study is considered an appropriate choice considering the fact that energy deficit is high. This is owing to the fact that as of 2016, roughly 74 million people do not have access to the national grid and with also no access to off-grid hence are without access to electricity (International Energy Agency, 2017). This makes the country a very uncomfortable place, putting it at risk of economic activities and industrialization challenges. Hence this research initiative is a great opportunity to serve better in flourishing the economic activities and industrialization while also improving standards of living of the population significantly. Another strong point is bearing in mind that Nigeria is a huge oil and gas producing country that so much depend on such for energy services. This was obvious on the fact that according to 2017 statistics, its proven oil reserve was 37.5 Billion Barrels and with proven gas reserve of 5.2 Trillion Cubic Meters (British Petroleum, 2018). This makes the country the leading in proven gas reserve and the second in proven oil reserve in the continent; and then the $10^{th}$ in the proven gas reserve and $11^{th}$ in the oil reserve globally (British Petroleum, 2018). These pose set-back on the uptake of the renewables despite the huge potentials. Hence the research initiative of such nature becomes more necessary in cutting the attention of the decision makers regarding diversification of services considering the environmental threats and the unsustainable nature of the endowed conventional energy sources. Also, the need for joint climate actions in line with the sustainable development initiatives and the intended nationally determined contributions (INDC) is seen to be fundamental at all levels.

In offering more clarifications based on specific foundational elements of the research, the other components of the introductory part have been successfully brought forth in a well sequential manner below:

### 1.1 General Motivational Statement

The need to learn energy operational principles from the best practices in the world and also to incorporate the lessons and additional innovative measures for there to be sustainable energy supply in the case study country.

### 1.2 Problem Statement

This research work will be conducted in order to address the following problems / gaps in the Nigerian context:

1. Overdependence on conventional sources mostly oil and gas in developing energy solutions despite their negative consequences counteracting the green and sustainable development targets.
2. Poor utilization of renewable energy resources despite their huge potential and their tremendous impact to addressing the energy deficits of the continent.
3. Lack of grid-integration of renewable energy systems and its hybrid in the country.
4. Inadequacy or inappropriateness of policy mechanisms and technical infrastructure challenge in support of renewable energy power systems to the grid network.
5. Inadequate awareness to the public on the need for a transition regarding the energy operation pattern in the country of study and the African continent at large.

### 1.3 Overall Research Questions

**1.** Is grid-integration of hybrid renewable power systems worthy and realistic based on technical, economic and environmental concerns?
**2.** What measures or mechanisms are necessary in warranting the grid-integration of the renewable power systems to the utility grid of the case study country? (Grid-infrastructural Concerns)
**3.** What appropriate "policy and regulatory framework" is necessary for the grid-integration of the renewable power systems?
**4.** How could the possible risks in the implementation process of the "policy and regulatory framework" be managed effectively?

### 1.4 Research Aim and Objectives

The aim of this research is to design an energy system alongside the policy and regulatory framework in favour of renewable energy integration to the grid, with specific case of Nigeria.

The specific objectives of the research work are out-listed below:

1. To carry out an in-depth decentralised techno-economic and environmental life cycle evaluation of a grid-connected hybrid power system.
2. To formulate appropriate renewable power policy instruments for the case study country based on the power system design lessons and the existing policy gaps.
3. To carry out an extensive risk assessment on the formulated power policy instruments in the case study country.
4. To recommend appropriate grid-based mechanisms in favour of grid-integration of the renewable power systems.

### 1.5 Justification of the Research Problem

The rationale behind this research work is based on the following strong arguments and expectations viz.:

1. This research if well conducted and properly adopted will ensure logical and consistent drive of renewable energy solutions towards active implementation at all levels.
2. It will ensure proper and efficient utilization of renewable energy resources and the energy systems with sustainability.
3. It will assist tremendously in boosting energy supply at low costs and in an environmentally friendly manner.
4. It will assist greatly in overcoming limitations associated with renewable energy systems due to the virtue of resource diversification (Hybrid System) in support of the national grid.
5. It will ensure a better operational strategy and sustainability of the grid infrastructure which has been currently part of the challenges of the power sector.
6. Finally, on a general note, all these aspects mentioned above are pre-requisites to addressing the sustainable development targets based on the technical, economic,

environmental and social pillars, and will drastically revolutionize or change the status quo of the country and the African continent at large.

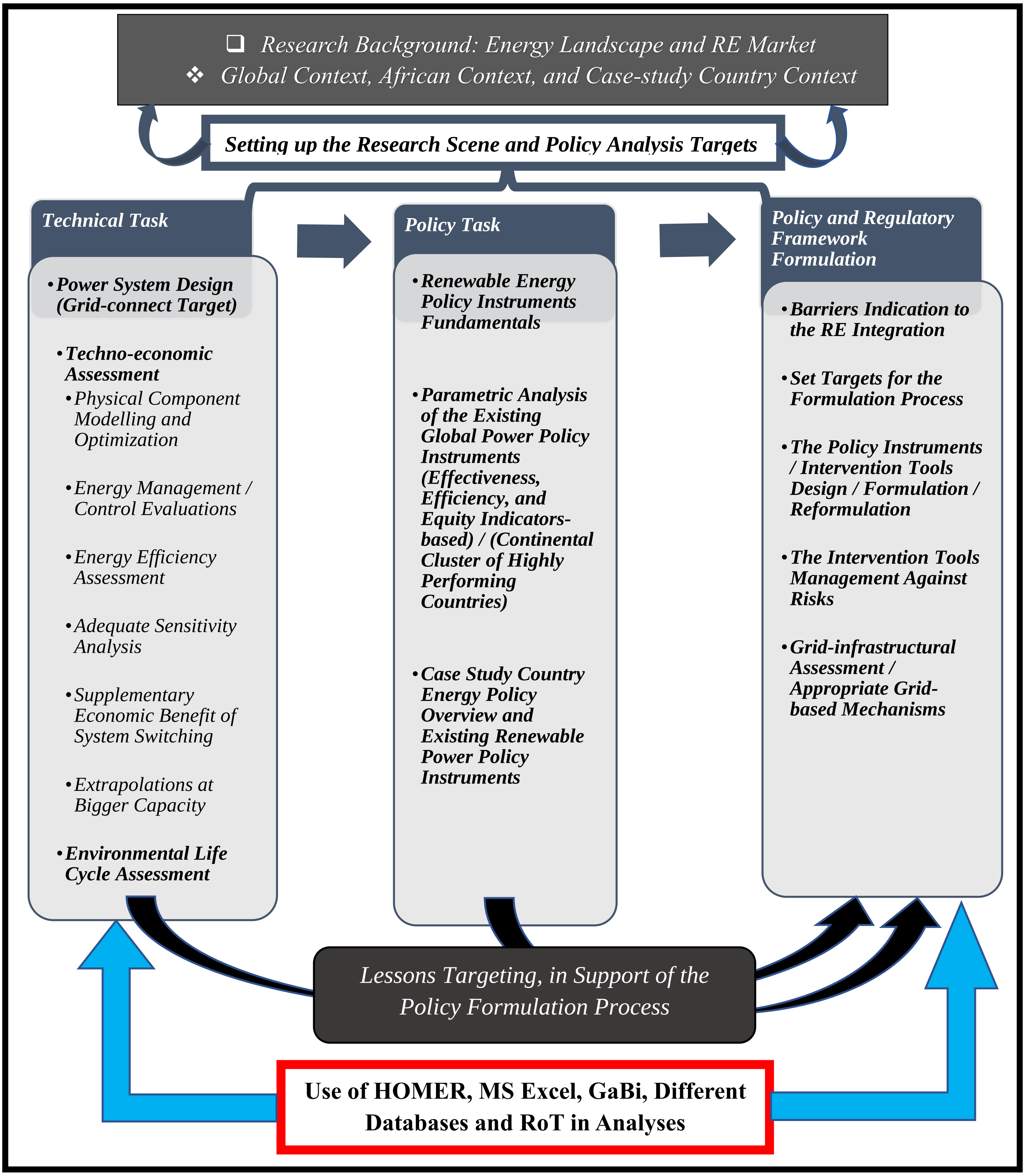
### 1.6 Scope of the Research

Within the limit of this research, the aspects of power were considered solely. Data collections, evaluations and curations were all necessary and helpful for the power system design. In line of the design, extrapolations and environmental life cycle assessment in predicting performance and obtaining lessons useful in the policies formulation being another aspect of critical concern were all covered. These aspects get finalised with risk assessment on the formulated renewable power policies as well as the grid-infrastructural evaluations. These areas of focus will serve better in addressing the power challenges facing the case study country.

### 1.7 Research Limitations

The research work has been limited on the fact that experimental validation was not conducted on the power system design. This has been due to time constrain and considering the fact that It has no direct linkage to the very fundamental policy part hence, of low priority. Also, the data collection for the power system design part has been based on databases application (i.e. space / climate-related and others with averaged past data applied for the location), without measurements on site. This was due to the bulk nature of the data needed and the lack of equipment for such measurements, and being that the databases are appropriate, reliable, and widely applied in different researches in the domain. Hence the results obtained may slightly vary from the results of the actual or measured data on site. Lastly has been on incorporation of set of data with large spectrum of application for the environmental life cycle assessment task. However, a data curation approach was employed in addressing this limitation, which was the uncertainty analysis.

## SUMMARISED RESEARCH DESIGN



# CHAPTER TWO

## 2. RESEARCH BACKGROUND - STATE OF ART (ENERGY LANDSCAPE)

### 2.1 Global Energy Overview

The globe is a spherical entity of 196 countries, comprising a total land area of 148,940,000km$^2$ and a population of 7.4 billion in 2016 (Population Reference Bureau, 2016; CIA World Fact Book, 2017). The globe is with no doubt endowed with huge energy resources ranging from conventional (i.e. Coal, Oil, Gas, and Uranium / Nuclear) to renewables (i.e. Solar, Wind, Biomass, Geothermal, and Hydro). It might interest reader to also have the information regarding specifically the available reserves for the resources. Hence, for that, the table below should be referred to, based on data obtained from the British Petroleum (BP) (2018), World Energy Council (WEC) (2016), and Bauer (2015):

***Table 1:*** *Global Energy Resources Reserve*

| **Conventional Sources** | | |
|---|---|---|
| Energy Type | Reserves Specification | Year |
| Oil | 1,696.6 Billion Barrels / 10,349.26 EJ | 2017 |
| | 239.3 Billion Tonnes / 10,349.26 EJ | |
| Gas | 193.5 Trillion Cubic Meters / 7,042.47 EJ | 2017 |
| | 6,831.7 Trillion Cubic Feet / 7,042.47 EJ | |
| Coal | 1,035,012 Million Tonnes / 26,910.31 EJ | 2017 |
| Nuclear / Uranium | 3.6989 Million Tones / 298,205.32 EJ | 2014 |
| **Renewable Sources** | | |
| Energy Type | Reserves Specification | Year |
| Solar | Input Power to the Outer Atmosphere: 175,000 TW<br>Theoretical Potential Power to Surface: 89,000 TW | N/A |
| Hydro | Theoretical Potential: 5 TW | N/A |
| Biomass | Theoretical Potential: 100 TW | N/A |
| Wind | Theoretical Potential: 400 TW | N/A |
| Geothermal | Huge Potential (Un-quantified) | N/A |

Source(s): British Petroleum, 2018; WEC (2013); Bauer, 2015

Having seen the energy resources overview, the predominant primary energy conventionally used over centuries is the fossil fuels (Oil, Gas and Coal) and traditional wood for final energy generation in form of heat, electricity and transport fuels. These were considerably supplemented by nuclear fuels i.e. the use of Uranium within a couple of decades due to increase in global energy needs (Bauer, 2015). The global primary energy demand continues to rise due to drastic increase in population and the need to meet up the population growth while also improving standards of living. In addition, the global total primary energy production in the year 2017 was estimated as $163.23 \times 10^3$ TWh, of which Asia is the leading with its supply valued at $46.18 \times 10^3$ TWh, and the least goes to Central and South America with value of $9.37 \times 10^3$ TWh (International Energy Agency, 2020). The global primary energy consumption for the same year i.e. 2017 was analysed according to the British Petroleum (2018) to be $157.14 \times 10^3$ TWh. This consumption value was broken into the different fuel mix viz.: oil ($53.75 \times 10^3$ TWh), natural gas ($36.70 \times 10^3$ TWh), coal

$(43.40 \times 10^3$ TWh), nuclear energy $(6.94 \times 10^3$ TWh), hydro and other renewables $(16.34 \times 10^3$ TWh) (British Petroleum, 2018).

On moving to electricity as a central and most critical concern, it is considered a driver of economic growth and development in all final energies. Therefore, the power sector is where more attention is needed due to the multiplying effect it has on the rest of the economy. Electricity is anticipated to be the fastest growing final energy with consumption at an exponential growth at all regions from 2012 to 2040 (International Energy Agency, 2015). This is in view of the fact that population growth continues to rise exponentially and hence more increase in energy demand and pressure to improve the power sector status quo for there to be improved living standards. The growth in electricity demand is dominated by the Eastern part of the globe particularly Asia-Pacific which during the past i.e. in 1990 produces only nearly one-fifth of the global electricity with continues rapid increase up to the recent time (International Energy Agency, 2015).

The global installed power capacity on efforts to address demands, serving as baseline for generation was obtained of 2017 as 7.69 TW (Statistica, 2020). This was of course dominated by the fossil fuels as usual, of which the fossil fuels' share of the total value was obviously 53.95%. On proceeding to power generation, report according to British Petroleum (2018) shows a global generation of 25,551.3 TWh during 2017, of which Asia Pacific was found to be the leading in the statistics, with a generation of 11,462.9 TWh, and of course Africa the least with a generation of 830.7 TWh. This is obvious on how power supply in the African continent is chronically poor in comparing with its population of nearly 16% of the global total in 2016 (Population Reference Bureau, 2016). Noting also the huge energy resource endowed with in the continent but chronically poor access: Paradoxical Africa. The power generation mix in the global context has also been obtained according to the British Petroleum (2018) for the same 2017 generation above as: oil (883 TWh), natural gas (5915.3 TWh), coal (9723.4 TWh), nuclear energy (2635.6 TWh), hydro and other renewables (6211.4 TWh), others (182.6 TWh).

Finally, wrapping up the global power discussion could be done by giving clear overview of the global electrification rate. Having said earlier that energy is a precondition to development, this could be realised fundamentally based on the level of electricity access for the population on global and regional / continental basis. Further details to show breakdown for urban and rural areas might be of great interest as well. This information is closely associated with the level of living standards for the population. Below table shows the breakdown of electrification rates for the globe and regions / continents of the globe secured from the International Energy Agency (IEA) (2017).

***Table 2:*** *Global and Regional Aggregates Electrification Rate in 2016*

| Region | Population Without Electricity (Millions) | Electrification Rate (%) | Urban Electrification Rate (%) | Rural Electrification Rate (%) |
|---|---|---|---|---|
| Developing Countries | 1,060 | 82 | 94 | 70 |
| Africa | 588 | 52 | 77 | 32 |
| North Africa | > 1 | 100 | 100 | 99 |

| | | | | |
|---|---|---|---|---|
| Sub-Saharan Africa | 588 | 43 | 71 | 23 |
| Developing Asia | 439 | 89 | 97 | 81 |
| China | 0 | 100 | 100 | 100 |
| India | 239 | 82 | 97 | 74 |
| Central and South America | 17 | 97 | 98 | 86 |
| Middle East | 17 | 93 | 98 | 79 |
| World | 10,60 | 86 | 96 | 73 |

Source: International Energy Agency, 2017.

From the table above, it is obvious that the problem is more to African continent specifically Sub-Saharan Africa of which strong intervention is needed jointly, adequately and timely in changing its status quo.

### 2.1.1 Global Renewable Energy Market

The market for Renewable Energy has been doing great in the global perspective due to the strong deployment by some highly distinguished countries in the globe like US, China, Germany, and so on. Starting with power capacities, the following information were obtained from the REN21 (2018) for the globe, BRICS (i.e. association of five major emerging national economies viz.: Brazil, Russia, India, China and South Africa), EU, and some other countries during 2017. This was based on the total and breakdown by technology.

***Table 3:*** *Renewable Global Power Capacities, Top Regions and Countries During 2017*

| Item | Capacity (GW) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Global | BRICS | EU | China | US | Germany | India | Japan | UK |
| Total Renewable Power (Incl. Hydro) | 2195 | 936 | 443 | 647 | 241 | 112 | 106 | 79 | 39 |
| Total Renewable Power (Excl. Hydro) | 1081 | 429 | 320 | 334 | 161 | 107 | 61 | 57 | 38 |
| Total Renewable per Capita | 0.1 | 0.1 | 0.6 | 0.2 | 0.5 | 1.3 | 0.05 | 0.4 | 0.6 |
| Bio-power | 122 | 40 | 40 | 14.9 | 16.7 | 8 | 9.5 | 3.6 | 6 |
| Geothermal Power | 12.8 | 0.1 | 0.8 | ~ 0 | 2.5 | ~ 0 | 0 | 0.5 | 0 |
| Hydropower | 1,114 | 507 | 124 | 313 | 80 | 5.6 | 45 | 23 | 1.9 |
| Ocean Power | 0.5 | ~ 0 | 0.2 | ~ 0 | ~ 0 | 0 | 0 | 0 | ~ 0 |
| Solar PV | 402 | 152 | 108 | 131 | 51 | 42 | 18.3 | 49 | 12.7 |
| Conc. Solar Power: CSP | 4.9 | 0.5 | 2.3 | ~ 0 | 1.7 | ~ 0 | 0.2 | 0 | 0 |
| Wind Power | 539 | 236 | 169 | 188 | 89 | 56 | 33 | 3.4 | |

NB: BRICS: Association of Brazil, Russia, India, China, and South Africa
Source: REN21, 2018

In terms of leading countries by installed renewable power capacities it became obvious that China has been dominating in so many of the technologies hence have really and successfully gone a greater mile as far as renewable energy is concern than the other highly performing countries in the globe. The following information has been reported also REN21 (2018) as could be useful as well:

***Table 4:*** *Top Five Leading Countries in Renewable Power Technology Capacity or generation as of End of 2017*

| Specification | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Renewable Power (Incl. Hydro) | China | United States | Brazil | Germany | India |
| Renewable Power (Excl. Hydro) | China | United States | Germany | India | Japan |
| Renewable Power Per Capita (Excl. Hydro) | Iceland | Denmark | Sweden / Germany | | Finland |
| Bio-power Generation | China | US | Brazil | Germany | Japan |
| Geothermal Power Capacity | US | Philippines | Indonesia | Turkey | New Zealand |
| Hydropower Capacity | China | Brazil | Canada | US | Russia |
| Hydropower Generation | China | Brazil | Canada | US | Russia |
| Solar PV Capacity | China | US | Japan | Germany | Italy |
| CSP | Spain | US | S. Africa | India | Morocco |
| Wind Power Capacity | China | US | Germany | India | Spain |
| Solar Water Heating Capacity | China | US | Turkey | Germany | Brazil |
| Geothermal Heat Capacity | China | Turkey | Iceland | Japan | Hungary |

Source: REN21, 2018

Moreover, with regards to the investments overview, further information was obtained from FS-UNEP Collaborating Centre for Climate and Sustainable Energy Finance (2016) on total investments trend ranging from 2004 to 2015 for the global total and for the different renewable energy technologies. This is as shown from the below table:

***Table 5:*** *Global Trend in Renewable Energy Technology Investment (2004-2015)*

| **Item** | **Total Investments (Billion Dollars)** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
| Global Total | 112.0 | 154.0 | 182.2 | 178.7 | 239.2 | 278.5 | 257.3 | 234.0 | 273.0 | 285.9 |
| Wind | 39.8 | 61.2 | 75.4 | 79.8 | 98.7 | 84.2 | 81.9 | 90.6 | 105.7 | 109.6 |
| Solar | 22.2 | 38.9 | 61.6 | 64.4 | 103.7 | 154.8 | 146.2 | 119.1 | 143.8 | 161.0 |
| Biofuels | 28.2 | 28.3 | 18.5 | 10.4 | 10.1 | 10.3 | 7.2 | 5.7 | 4.7 | 3.1 |
| Bio & Waste | 11.9 | 16.2 | 17.1 | 14.7 | 15.7 | 18.0 | 13.5 | 10.5 | 10.4 | 6.0 |
| Small Hydro | 7.6 | 6.7 | 7.6 | 6.2 | 7.9 | 7.2 | 6.4 | 5.5 | 5.5 | 3.9 |
| Geothermal | 1.5 | 1.9 | 1.7 | 2.9 | 2.8 | 3.7 | 1.8 | 2.4 | 2.6 | 2.0 |
| Marine | 0.9 | 0.8 | 0.2 | 0.3 | 0.30 | 0.3 | 0.3 | 0.2 | 0.4 | 0.2 |

Source: FS-UNEP Collaborating Centre for Climate and Sustainable Energy Finance (2016)

Finally, the investment / net capacity additions / production by top leading countries in the globe during 2016 based on the below information obtained from the REN21 (2017) could be shown below:

***Table 6:*** *RE Annual Investment / Net Capacity Additions / Production in 2016*

| Specification | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Investment in Renewable Power and Fuels (Excl. Hydro > 50MW) | China | US | UK | Japan | Germany |
| Investments in Renewable Power and Fuels Per Unit GDP | Bolivia | Senegal | Jordan | Honduras | Iceland |

Source: REN21, 2017

## 2.2 African Energy Overview

Africa as a continent of 55 countries is considered the second largest continent after Asia. It is bounded in the North by the Mediterranean Sea, in the West by the Atlantic Ocean, and in the East by the Indian Ocean and Red Sea. It straddles the equator thereby lying on 2 Tropics i.e. Tropic of Cancer at the North and Tropic of Capricorn at the South. Below table shows the basic facts and figures of the blessed continent Africa.

***Table 7:*** *Basic Facts and Figures of the African Continent*

| Parameter | Specification |
|---|---|
| Population (Inhabitants) in 2016 | 1.2 Billion |
| Land Area (Million $km^2$) | 30.3 |
| Population Density (Inhabitants/$km^2$) in 2016 | 39.6 |
| GDP (Nominal) (Trillion USD) in 2016 | 2.18 |
| GNI per Capita (USD/Cap.) in 2015 | 15,415 |

Source(s): Sayre, 1999; IMF, 2017; Pop. Ref. Bureau, 2016

I must start by mentioning the fact that Africa is a continent of paradox. Paradox in the sense that it is endowed with huge energy resources ranging from conventional to renewables the level of access is chronically poor. This is obvious to the information reported by the International Energy Agency (2014) stating that around two-third (2/3) of the continent is lacking access to modern energy service. This is majorly associated with the Sub-Saharan Africa. Another point to note is that adaptive measures regarding disasters are quite below satisfactory level hence making the continents vulnerable to diseases, flood, draught, environmental degradation as well as other challenges existing like food insecurity and so on.

Moving on to the energy resources of the continent, the reserves statistics have been presented in the below table. It was successfully obtained by combining the United Nations Economic Commission for Africa (UNECA) (2011), the British Petroleum (BP) (2018), the World Energy Council (WEC) (2016) and FAO (2017) databases, and is being presented below:

***Table 8:*** *African Energy Resources Reserves and Regional Distribution*

| **Conventional Resources** | | | |
|---|---|---|---|
| Energy Type | Reserves Specification | Regional Distribution | Year |
| Oil | 126.5 Billion Barrels / 771.65 EJ<br>16.7 Billion Tonnes / 771.65 EJ | All regions | 2017 |
| Gas | 13.8 Trillion Cubic Meters / 519.7 EJ<br>487.8 Trillion Cubic Feet / 519.7 EJ | All regions | 2017 |
| Coal | 13,217 Million Tonnes / 343.64 EJ | All regions | 2017 |
| Nuclear | 756.7 Thousand Tonnes / 61005.15 EJ | Cumulative of Malawi (1.1%), Namibia (32.8%), Niger (42.9%), and South Africa (23.2%) | 2014 |
| **Renewable Resources** | | | |
| Energy Type | Reserves Specification | Regional Distribution | Year |
| Solar | GHI: (1600- >2700) kWh/$m^2$/Yr.<br>DNI: (900-3200) kWh/$m^2$/Yr. | Most of Africa | N/A |

| | | | |
|---|---|---|---|
| Biomass | Wood Prod.: $6.66 * 10^8 m^3$ / 8.65 EJ | All regions | 2016 |
| | Crop Residue: $2.49 * 10^9$ kg | | 2014 |
| | Oil Crops: 12.27 Million Tonnes | | 2014 |
| Wind | Southern Africa: 6-7 m/s<br>Northern Africa: 5-8.5 m/s | Most Attractive Sites in the Northern and Southern Coasts | N/A |
| Hydro | Gross Theoretical: 3,909 TWh/Yr.<br>Tech. Exploitable: 1,834 TWh/Yr. | Central Africa: 57%<br>Eastern Africa: 32%<br>Other Regions: 11% | 2008 |
| Geothermal | Huge Reserve (Un-quantified) | Mostly in Eastern Africa | N/A |

Source(s): UNECA, 2011; British Petroleum, 2018; WEC, 2016; FAO, 2017

On the basis of the primary energy demand, it is obvious that the population growth rate on average over some decades has been 2.6% compared to the global growth rate of 1.5% (United Nations, Economic Commission for Africa, 2016). This is with no doubt a direct consequence of increasing energy demand. It could also be as a result of change in life style and other factors. To mention also is the fact that Fossil fuels have always been the major energy the continent deals with in solving most of its energy needs at virtually all levels. On moving to the primary energy production, it must be stated that according to International Energy Agency (2020), the total primary energy production during 2017 was secured as $13.2 \times 10^3$ TWh. This was observed to be dominated by oil, although biomass and wastes has got a significant contribution in the total value. With regards to the primary energy consumption, it is of great interest to reveal that energy consumption is a strong indicator of development and living standard. Moreover, it is also strongly affiliated with the level of population and life style. In the African context, the story line has been that the consumption level is chronically low, which according to the British Petroleum (2018), the consumption in Africa was only about 3.3% of the global total despite the African population being roughly 16% of the global value. This is majorly the reason why the final modern energy access like electricity being very fundamental is chronically poor especially in the Sub-Saharan region.

Basing the next argument on the electricity aspect, according to the preceding information on primary energy, it is obvious that the electricity status quo of the African continent might be in deficit. This is quite unfortunate especially in view of the drastic rise in the population that translates to continuous energy demand at all levels. The power plants could basically be classified in to Thermal (where steam generation is incorporated), Hydro, and Other categories. In terms of sizes, there exist three categories also viz.: small, medium and large depending on capacities. Small power plants have capacity range of 50-99 MW, medium scale power plants have capacity range of 100-499 MW, and finally the large-scale power plants have capacity rang of 500 MW and beyond (Program for Infrastructural Development in Africa (PIDA), 2011). In line with the existing power plants, the total installed capacity of the continent as of 2016 was 168GW, of which a target of 330GW was specified by 2025 (African Development Bank, 2017). The renewable energy contribution to the installed capacity value was observed to be only 33GW (i.e. 0.1%) (African Development Bank, 2017).

This takes our discussion in to the overview of the electricity generation in the continent. It was reported according to the British Petroleum (2018) that the total electricity generation during 2017 was 830.7TWh. This was just around 3% of the world's total during the year, hence, chronically low. The fuel mix that contributed to the arrived generation value above were: oil (81.5 TWh), natural gas (325.1 TWh), coal (250.9 TWh), nuclear energy (15.8 TWh), hydro and other renewables (153 TWh), and others (4.5 TWh) (British Petroleum, 2018). It must also be mentioned that the North African region is really doing great inclusive of South Africa in the Sub-Saharan region. The region with under performance or poor record is the Sub-Saharan region (i.e. Eastern, Western, Central and Southern). Moving on to the projections on the electricity generation, information obtained could serve as a template on how the population growth and other factors affect the electricity supply both on installed capacities and Generations in the nearby future. This information was successfully obtained from the Energy Information Administration database of 2016 and is as shown from the below table:

***Table 9:*** *African Installed Capacity and Electricity Generation Projections (2011-2040)*

| Installed Capacity | 2011 | 2012 | 2020 | 2025 | 2030 | 2035 | 2040 | Av. % Δ (2012-2040) |
|---|---|---|---|---|---|---|---|---|
| | GW | GW | GW | GW | GW | GW | GW | |
| Africa | 135 | 141 | 191 | 202 | 232 | 266 | 306 | 2.8 |
| Generation Capacities | 2011 | 2012 | 2020 | 2025 | 2030 | 2035 | 2040 | Av. % Δ (2012-2040) |
| | TWh | TWh | TWh | TWh | TWh | TWh | TWh | |
| Africa | 659 | 682 | 827 | 970 | 1,129 | 1,328 | 1,550 | 3.0 |

Source: Energy Information Administration, 2016.

### 2.2.1 African Renewable Energy Market

I must begin by mentioning the fact that fossil fuels (i.e. Oil, Natural Gas and Coal) are the top sectors by capital investment in the African continent with a total investment valued at $15.7 million or 24% of total investments in 2015 (Geraldine et al., 2016). From the same source, the renewable energy investments for the same year which was 2015 has been obtained to be $12.2 billion as 18% of the total continent investments. The expansion of capacities in energy-based systems through investment is below standard in the continent.

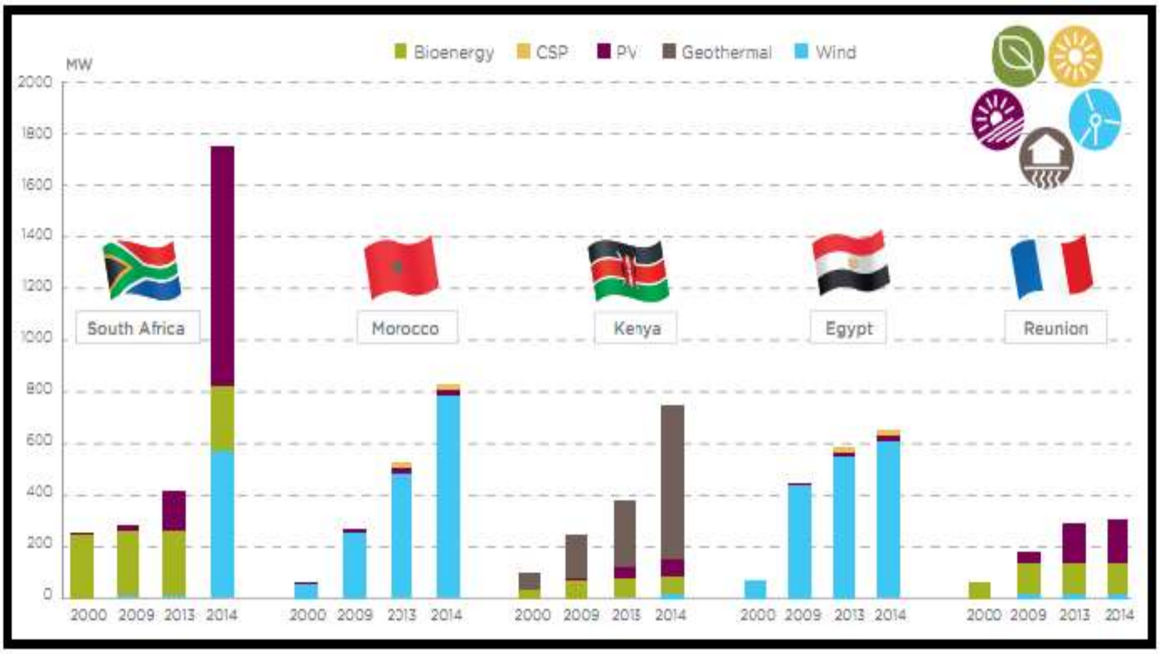
In line with the Nationally Determined Contributions (NDC) of the Paris Agreement at the COP 21 Summit, countries of the globe have come up with some measures or plans aimed at improving energy access and addressing the climate change mitigation and adaptation measures. Although, Africa has never been among the major greenhouse gas emitting continent as compared to the rest of the world. Report according to the United Nations Economic Commission for Africa (2011) states that Africa contributes only 4% in the global greenhouse gases emissions however, it is the most vulnerable to the impact of climate change, which pushes strong need for mitigation component of the joint action as well. In this joint intervention, renewable energy is at the fore front. The story for the African continent as a whole is superb. Considering the fact that the continent is endowed with huge solar potentials, the energy access improvement plans gives solar the highest priority specifically solar PV in capacities addition. This is followed by Hydro and Wind. The breakdown of the renewable energy planned capacities addition by the specified technologies for the NDCs of mostly up to 2030 is shown from the below figure.

***Table 10:*** *Renewable Energy Planned Capacity Additions in Africa by Technology*

| Technology | Planned Capacity Addition (MW) |
|---|---|
| Solar PV | 34,160 |
| Hydro | 26,443 |
| Wind | 25,739 |
| Geothermal | 7,427 |
| CSP | 3,310 |
| Biomass | 1,123 |
| Total | 98,202 |

Source: Global Economic Governance Initiative, 2016

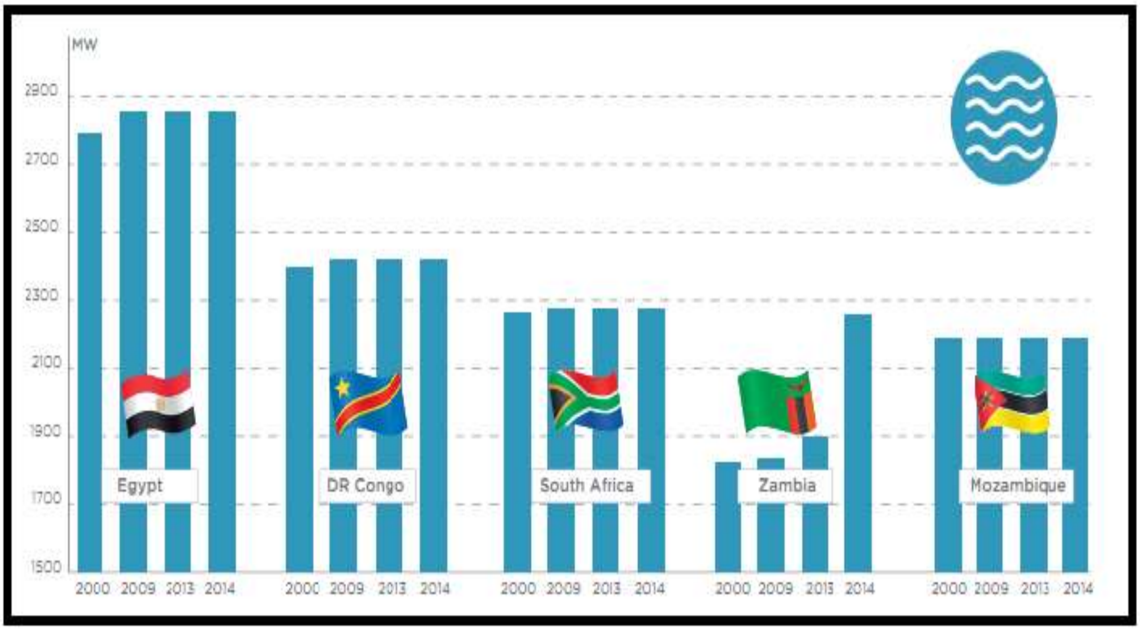
Having seen the planed capacity by technology in the whole continent, it is therefore crucial to look at the performance ranking by countries in the continent. This will be based on the historical values. The focus will be on the cumulative installed capacity performance. It became obvious that from the year 2000 to 2014, country with the highest renewable installed capacity record was none other than South Africa. South Africa has been found to be doing great especially on Solar PV, Hydro, and Bioenergy. This was followed by morocco and of course the third being Kenya. What made Kenya to stand out from the other Sub-Saharan countries was its ability to utilize its geothermal potential strongly hence boosting its renewable capacity. The figure below is a clear picture of what is being said above for more insight:




Source: Rainer et al., 2016

***Figure 1:*** *Renewable Capacity Performance (Excl. Hydro) for Top Countries in Africa*

Having the record above excluding Hydro, it could be relevant also to see the performance with regards to the Hydro alone. The Hydro capacity record also from the year 2000 to 2014 showed Egypt to be the leading, with a total capacity of nearly 2900 MW having maintained from 2009 up to 2014. The succeeding country on the ranking was the Democratic Republic of Congo (DRC), with a capacity of about 2400 MW maintained from 2009 to 2014. South Africa being a highly performing country was not left behind also in the Hydro uptake. It was following DRC with a steady capacity of almost 2300 MW from 2009 to 2014. This is as shown from the figure below:




Source: Rainer et al. (2016)

***Figure 2:*** *Hydro Capacity Performance for Top Countries in Africa*

On moving to the renewable investments by the available and implemented technologies in the continent, the ranges for the investment in terms of highest and lowest values coupled with their weighted averages has also been obtained from the same source i.e. REN21 (2017) for the range of 2010 to 2016. This is as described from the table below:

***Table 11:*** *Renewable Energy Investment Costs in Africa (2010-2016)*

| Investments (USD)<br>Technology | Minimum Value (USD) | Maximum Value (USD) | Weighted Average (USD) |
|---|---|---|---|
| Bio-power | 625 | 5,579 | 1,654 |
| Geothermal | 1719 | 7,689 | 3,814 |
| Hydro | 920 | 6,730 | 1,593 |
| Solar PV | 818 | 6,848 | 2,344 |
| CSP | 7164 | 11,300 | 8,392 |
| On-shore Wind | 1345 | 2,506 | 1,924 |
| Off-shore Wind | Nil | Nil | Nil |

Source: REN21, 2017

The investments in the renewable energy technologies on regional basis revealed clearly North Africa to be the leading with a total investment need valued at $220 Billion from 2015 to 2030 (International Renewable Energy Agency, 2015). This is 45% of the total for the whole continent. The region following is Southern Africa with a total value of $112 Billion as 23% of the continent's total. This is further described in the below table:

*Table 12: Cumulative Investment Needs for Renewable Energy between 2015 and 2030*

| **Region** | **Investment (Billion USD) (2015-2030)** | | | |
|---|---|---|---|---|
| | All Generations | Large Hydro | Other Renewables | Training and Dev. |
| North Africa | 342 | 2 | 218 | 186 |
| West Africa | 99 | 36 | 31 | 52 |
| Central Africa | 32 | 13 | 17 | 14 |
| East Africa | 72 | 36 | 21 | 49 |
| Southern Africa | 142 | 18 | 94 | 74 |
| Total / Africa | 681 | 106 | 381 | 375 |

Source: International Renewable Energy Agency, 2015

On a final note, the total already existing investments on a 2010 baseline with projections up to 2050 for the different renewable energy technologies has been secured from the International Renewable Energy Agency (2012a). The investment showed solar PV (i.e. cumulative of both utility scale supply and home based) to be the leading. Below table shows the breakdown for the interest of the readers:

*Table 13: Renewable Energy Investment Cost by Technology in Africa (2010-2050)*

| Technology | Investment Costs (USD/kWh) | | | |
|---|---|---|---|---|
| | 2010 | 2015 | 2030 | 2050 |
| Solar PV (Utility Scale) | 3,000-4,000 | 2,850-3,000 | 2,200-2,450 | 1,800-2,100 |
| Solar PV (Home System) | 5,000-6,000 | 4,500-5,700 | 3,600-4,100 | 2,200-3,500 |
| Solar CSP (with Storage) | 8,500 | 6,000-6,500 | 4,200-5,100 | 3,000-4,400 |
| Wind (2MW Turbine) | 1,750 | 1,700-1,800 | 1,400-1,700 | 1,100-1,300 |
| Biogas Engine (incl. Digestion) | 2,000 | 1,800 | 1,500-1,700 | 1,200-1,500 |
| Biomass Gasification | 2,000 | 1,800 | 1,500-1,700 | 1,200-1,500 |
| Biomass Combustion | 1,250 | 1,250 | 1,250 | 1,250 |
| Hydro | 3,000 | 2,700-2,900 | 2,300-2,800 | 2,000-2,700 |
| Geothermal | 4,000 | 3,600-3,900 | 3,000-3,250 | 2,400-3,000 |

Source: International Renewable Energy Agency (IRENA), 2012a

### 2.3 Nigerian Energy Overview

Nigeria being the case study country is blessed with huge potentials not only on energy affairs but also on other development sectors of the economy but has always not been able to realise its full potential or turn it into reality. The table below shows some basic facts ranging from geographic to demographic and to economic.

*Table 14: Nigerian Basic Facts (Socio-economic and geographic)*

| Parameter | Specification | Date |
|---|---|---|
| Nigeria | Federal Republic | N/A |
| Capital | Abuja | N/A |
| Largest City | Lagos (Also largest in Africa) | N/A |
| Geopolitical Zones | North-East, North-West, North-Central, South-South, South- East, and South-West | N/A |
| Climate | Temp.: Min.:20-25 ̊C; Max..: 25-37 ̊C Rainfall: 500-1800 mm | N/A |

| | | |
|---|---|---|
| Land Area | 924 * $10^3$ $km^2$ (Land: 86%, Water: 14%) | N/A |
| Population | 196 Million | 2018 |
| Population Projection | 356.5 Million | 2050 |
| Population Density | 212.12 Persons/$km^2$ | 2018 |
| Life Expectancy | 52.6 yrs./52.0yrs (i.e. Females/Males) | 2010-2015 |
| HDI | 0.534 | 2018 |
| GDP (Nominal) | 405.08 Billion USD | 2016 |
| GDP/Capital | 2,172.01 USD/Cap. | 2016 |

Source(s): Population Reference Bureau, 2016; Sambo, 2009; Ewesor, 2011; United Nations Development Programme (UNDP), 2016; World Bank, 2017; United Nations Statistics Division (UNSD), 2017; The World Bank Group, 2020; UNDP, 2019.

To proceed with the energy information, Nigeria is blessed with huge energy resources ranging from conventional (Oil, Natural Gas, and Coal) to renewables (Solar, Wind, Hydro, and Biomass). Some reports have shown the availability of mineral fuel i.e. Uranium / Nuclear however, has not been fully quantified nor fully exploited. Nigeria is not blessed with geothermal resource as having seen from the preceded African energy overview that the resource is majorly available in East Africa. From the regional survey, it was made clear that fossil fuels specifically oil and natural gas is only available in the extreme southern region of the country i.e. the South-South zone specifically the Niger-Delta region, and native to states such as Delta, Bayelsa, Rivers, Akwa-Ibom etc. Coal had been native to some parts of the North-Central and South-East zones with a major producing state being Enugu in the South-East. On moving to the renewables, solar energy is the most abundant as seen previously from both global and African energy review. However, in Nigeria, the resource is more concentrated in the North-Eastern zone, and in states like Adamawa, Borno, Yobe, Bauchi etc. Wind resource is mostly associated with high lands and specifically in the coasts. Hydro could be considered as resources available almost everywhere however, highest potential in some parts of North-Central and North-West in states like Niger, Kogi, Kwara, Kebbi etc. The last being Biomass is considered to have high potential in everywhere except the extreme Northern Parts that share boarder with Niger Republic. The table below gives the breakdown of the energy resource of the country.

***Table 15:*** *Nigerian Energy Resource Reserves*

| **Conventional Sources** | | |
|---|---|---|
| Resources | Reserve Specification | Date |
| Oil | 37.5 Billion Barrels / 228.75 EJ | 2017 |
| | 5.1 Billion Tonnes / 228.75 EJ | |
| | 2.2% share of Global Total | |
| | 51.6 Reserve to Production Ratio | |
| Gas | 5.2 Trillion Cubic Meters / 189.70 EJ | 2017 |
| | 183.7 Trillion Cubic Feet / 189.70 EJ | |
| | 2.7% share of Global Total | |
| | 110.2 Reserve to Production Ratio | |
| Coal | Hard Coal (Anthracite and Bituminous): 23.149 Million Tonnes / 601.87 PJ | 2011 |
| | Lignite: 186.291 Million Tonnes / 3725.82 PJ | |

| | | |
|---|---|---|
| | Total: 209.439 Million Tonnes / 4.33 EJ | |
| Nuclear / Uranium | Trace Amount (Not yet Quantified) | N/A |
| **Renewable Resources** | | |
| Resources | Reserve Specification | Date |
| Solar | Insolation: 3.5-7.0 kWh/day | N/A |
| | Sunshine Hours: 4-7.5 hrs./day | |
| Biomass | Wood Fuel Produced: 65287615 $m^3$ | 2016 |
| | Crop Residues Produced: 359085834.04 kg | 2014 |
| | Oil Crops: 2669235 Tonnes | 2014 |
| | Animal Waste: 245 Million Tonnes Assorted Animals | 2001 |
| Hydro | Huge Quantity (No specification Obtained) | N/A |
| Wind | 2-4 m/s @ 10 m Height (High lands) | N/A |

Source(s): British Petroleum (BP), 2018; Food and Agricultural Organization (FAO), 2017; National Bureau of Statistics (NBS), 2015; Afa & Anire, 2013; Sambo, 2010

In line with the continuous rising population and the need to satisfy the population with final energy service, the primary energy demand for the country has been on a drastic increase over year and with forecast of further increase in the future. The table below gives the general primary energy demand from historical up to projected values till year 2030 based on different scenarios and different sectors of the country's economy.

***Table 16:*** *Nigerian Primary Energy Demand by scenarios and by Sector in Mtoe*

| **Scenario Base** | **2000 (Mtoe)** | **2010 (Mtoe)** | **2015 (Mtoe)** | **2020 (Mtoe)** | **2025 (Mtoe)** | **2030 (Mtoe)** |
|---|---|---|---|---|---|---|
| Reference (7%) | 32.01 | 51.4 | 79.36 | 118.14 | 169.18 | 245.19 |
| High Growth (10%) | 32.01 | 56.18 | 94.18 | 190.73 | 259.18 | 414.52 |
| Optimistic (11.5%) | 32.01 | 56.18 | 108.57 | 245.97 | 331.32 | 553.26 |
| Optimistic (13%) | 32.01 | 72.81 | 148.97 | 312.61 | 429.11 | 715.7 |
| **Sector Base** | **2000 (Mtoe)** | **2010 (Mtoe)** | **2015 (Mtoe)** | **2020 (Mtoe)** | **2025 (Mtoe)** | **2030 (Mtoe)** |
| Industry (16%) | 8.02 | 12.59 | 26.03 | 39.43 | 92.34 | 45.21 |
| Transport (4.7%) | 11.7 | 13.48 | 16.59 | 19.70 | 26.53 | 33.36 |
| Household (2.6%) | 18.82 | 22.42 | 28.01 | 33.60 | 33.94 | 34.27 |
| Services (8.7%) | 6.43 | 8.38 | 12.14 | 15.89 | 26.95 | 38.00 |

Source: Emodi, 2016

*Note: The % values show the GDP Growth rates forecasting*

Further to the above information, primary energy production in the country has been over the years dominated by Oil, however, until recently from 2015 upward that the biomass and wastes takes the lead in the mix (International Energy Agency, 2020). The reason behind oil dominance was the fact the country so much depends on it for not only electricity generation but also in final refined fuels for use in transportation and other possible applications hence, the driver of the national economy. Gas being lower in production than oil was due to the fact that its major application was in power generation being the largest fuel in the electricity generation mix for over decades. The biomass and waste drastic rise of recent has been attributed to the drastic population rise, ultimately leading to increased wastes production, and also the strong adoption of agriculture and forestry practice. This leads to depiction of the energy production as well as the supply figures on energy balance basis in the below table obtained from the International Energy Agency database.

***Table 17:*** *Nigerian Energy Production and Supply Balance by Fuel during 2017 (Unit: ktoe)*

| Fuel | TPEP | Import | Export | IMB | IAB | Stock Exchange | TPES |
|---|---|---|---|---|---|---|---|
| Coal | 29 | 0 | 0 | 0 | 0 | 0 | 29 |
| Crude Oil | 95,040 | 0 | -90,912 | 0 | 0 | -732 | 3,396 |
| Oil Products | 0 | 23,645 | -858 | -310 | -437 | 105 | 22,144 |
| Natural Gas | 36,840 | 0 | -22,676 | 0 | 0 | 0 | 14,164 |
| Nuclear | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Hydro | 475 | 0 | 0 | 0 | 0 | 0 | 475 |
| Geothermal | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Biofuels and Wastes | 116,926 | 0 | 0 | 0 | 0 | 0 | 116,926 |
| Total | 249,312 | 23,645 | -114,446 | -310 | -437 | -627 | 157,137 |

Source: International Energy Agency (IEA), 2020

*Key Indication: TPES: Total Primary Energy Supply; TPEP: Total Primary Energy Production; IMB: International Marine Bunkers; IAB: International Aviation Bunkers*

Nigeria been the most populous country in Africa and a country with one of the highest population growths on yearly basis has a continuously high demand for electricity as a result of the continuous rise in population and economic growth as well as change in life style. However, the demand has always not been met with sufficient supply for over decades. The table below shows the historical electricity demand with projected results in terms of capacity installed up to 2030 based on different economic scenarios:

***Table 18:*** *Electricity Installed Capacity Demand in MW (2009-2030)*

| Scenarios | 2009 (MW) | 2010 (MW) | 2015 (MW) | 2020 (MW) | 2025 (MW) | 2030 (MW) |
|---|---|---|---|---|---|---|
| Reference (7%) | 4,952 | 7,440 | 14,000 | 40,000 | 79,798 | 115,674 |
| High Growth (10%) | 4,952 | 8,420 | 30,236 | 63,336 | 103,859 | 196,875 |
| Optimistic I (11.5%) | 4,952 | 9,400 | 36,124 | 76,124 | 145,113 | 251,224 |
| Optimistic II (13%) | 4,952 | 10,230 | 41,133 | 88,282 | 170,901 | 315,113 |

Source: Sambo, 2016

*Note: The % specification shows the GDP Growth Rate Forecasting*

Having seen the electric capacity demand data, the discussion now turns to the existed situation regarding what the country had as far as the electricity is concern. To begin with installed capacity, the country has been observed with a total installed power capacity of around 12,000 MW as of 2015, however, the actual generation reaching the final consumers was critically low near 4,000 MW as majorly from gas power plants with a small portion of hydropower plant (Energypedia, 2019). The table below gives the breakdown for such information by different fuels.

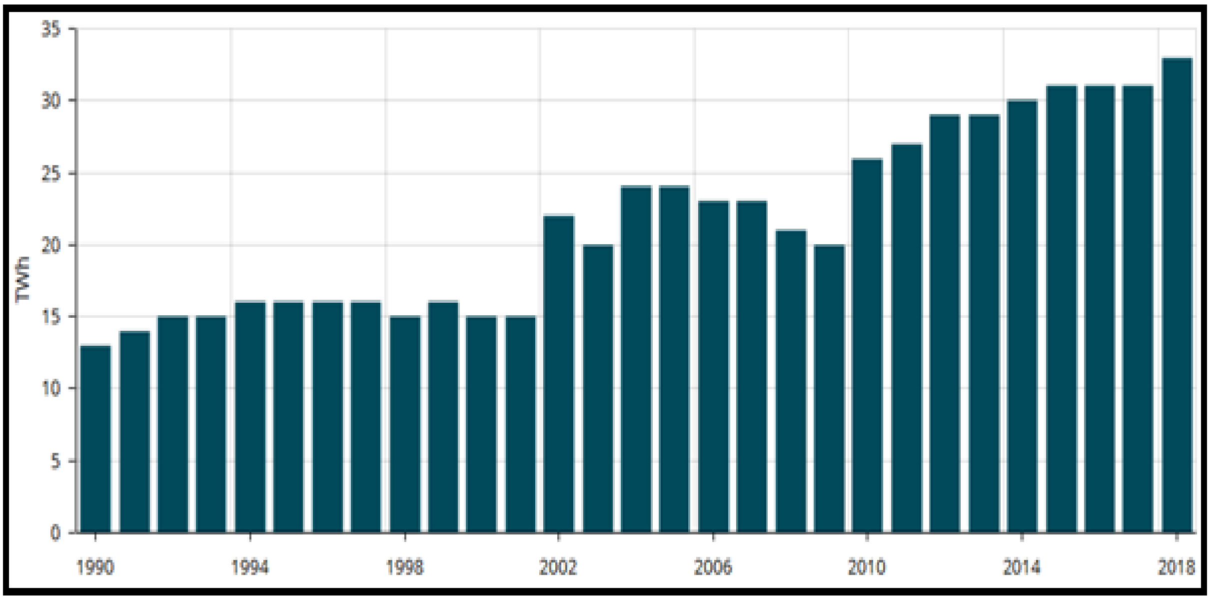
***Table 19:*** *Nigerian Electricity Installed Capacity Breakdown*

| **Power Plants** | **Fuel Type** | **Year Completed** | **Installed Capacity (MW)** | **Installed Available Capacity (MW)** | **Actual Generation Capacity as of 2015 (MW)** |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| AES | Gas | 2001 | 270 | 267 | 0 |
| Afam IV-V | Gas | 1982 | 580 | 98 | 0 |
| Afam vi | Gas | 2009 | 980 | 559 | 523 |
| Alaoji NIPP | Gas | 2015 | 335 | 127 | 110 |
| Delta | Gas | 1990 | 740 | 453 | 300 |
| Egbin | Gas | 1985 | 1320 | 931 | 502 |
| Geregu | Gas | 2007 | 414 | 282 | 138 |
| Geregu NIPP | Gas | 2012 | 434 | 424 | 90 |
| Ibom Power | Gas | 2009 | 142 | 115 | 92 |
| Ihovbor NIPP | Gas | 2012 | 450 | 327 | 225 |
| Jebba | Hydro | 1986 | 570 | 427 | 255 |
| Kainji | Hydro | 1968 | 760 | 180 | 181 |
| Okpai | Gas | 2005 | 480 | 424 | 391 |
| Olorunsogo | Gas | 2007 | 335 | 244 | 232 |
| Olorunsogo NIPP | Gas | 2012 | 675 | 356 | 87 |
| Omoku | Gas | 2005 | 150 | 0 | 0 |
| Omotosho | Gas | 2005 | 335 | 242 | 178 |
| Omotosho NIPP | Gas | 2012 | 450 | 318 | 90 |
| Rivers IPP | Gas | 2009 | 136 | 166 | 0 |
| Sapele | Gas | 1978 | 900 | 145 | 81 |
| Sapele NIPP | Gas | 2012 | 450 | 205 | 116 |
| Shiroro | Hydro | 1989 | 600 | 480 | 350 |
| Odukpani | Gas | 2013 | 561 | 70 | 0 |
| Total | | | 12,067 | 6,840 | 3,941 |

Source: Energypedia (2019).

On moving to the country's electricity generation, statistics of 2018 showed a total generation of around 33 TWh, and was found to be haphazard over the years (Global Energy Statistical Yearbook, 2019). The figure below shows the historical generation trend from 1990 to 2016 as procured from the Global Energy Statistical Yearbook of 2019.




Source: Global Energy Statistical Yearbook, 2019

***Figure 3:*** *Nigerian Electricity Generation Trend (1990-2018)*

Having seen the power generation trend, it is also of great interest to have a look in to the generation mix for some specific years. For that, 1995, 2014 and 2017 have been selected with the statistics of the generations observed. This generation was dominated by fossil fuels all through especially the Natural Gas being with the lion's share. Oil started performing in the 90s but its performance was later becoming insignificant. The table below shows clearly the generation mix.

***Table 20:*** *Nigerian Electricity Generation in 1995, 2014 and 2017*

| Fuel Type | 1995 Electricity Generation (TWh) | 2014 Electricity Generation (TWh) | 2017 Electricity Generation (TWh) |
|---|---|---|---|
| Oil | 3.02 (19.05%) | 6.01 (20.22%) | 0.026 (0.09%) |
| Gas | 7.33 (46.25%) | 17.64 (59.33%) | 26.67 (82.75%) |
| Hydro | 5.50 (34.70%) | 6.08 (20.45%) | 5.53 (17.16%) |
| Total | 15.85 (100%) | 29.73 (100%) | 32.23 (100%) |

Source: International Energy Agency, 2020; Shift project data Portal, n.d

With regards electricity consumption, and linkage to population growth, the following table shows a trend from 1990 to 2016 for both electricity consumption, population and the consumption per capita as obtained from the Global Energy Statistical Year Book (2017) and the worldometers population database.

***Table 21:*** *Electricity Consumption with Population Linkage (1990-2016)*

| Year | Electricity Consumption (TWh) | Population | Electricity Consumption (kWh/Cap/yr.) |
|---|---|---|---|
| 1990 | 7.87 | 95,269,988 | 82.61 |
| 1995 | 9.44 | 108,011,465 | 87.40 |
| 2000 | 8.69 | 122,352,009 | 71.02 |
| 2005 | 17 | 138,939,478 | 122.36 |
| 2010 | 21 | 158,578,261 | 132.43 |
| 2015 | 27 | 181,181,744 | 149.02 |
| 2016 | 24 | 185,989,640 | 129.04 |

Source(s): Worldometers Population, 2017; Global Energy Statistical Year Book, 2017

On concluding the electricity discussion come the electrification rate for the country. It was obtained according to the International Energy Agency (2017) that the population without access to electricity during 2016 was 74 Million hence, leading to national electrification rate of 61%. This was further analysed in to urban electrification rate of 86% and rural rate of 34% (International Energy Agency, 2017).

### 2.3.1 Nigerian Renewable Energy Market

To begin with the renewable energy main projects on ground, it is obvious from the preceded discussion that the only renewable energy performing on the grid and in high capacity is the hydropower. This is obvious from the historical renewable energy based major projects in the country from the existing ones right from inception to the latest ones both completed and on-going which were only on hydropower with the specifications in the table below:

***Table 22:*** *Hydropower Major Projects for Electricity Scale-up*

| Power Station | Location | Type | Installed Cap. (MW) | Year Completed |
|---|---|---|---|---|
| Kainji | Niger State | Hydro | 800 (provision for expansion to 1,156) | 1968 |
| Jebba | Niger State | Hydro | 540 | 1985 |
| Shiroro | Niger State | Hydro | 600 | 1990 |
| Zamfara | Zamfara State | Hydro | 100 | 2012 |
| Kano | Kano State | Hydro | 100 | 2015 |
| Kiri | Benue State | Hydro | 35 | 2016 |
| Mambilla (Planned) | Taraba State | Hydro | 3050 | 2018 (Ongoing) |
| Gurara I | Niger State | Hydro | 30 | N/A |
| Gurara II | Niger State | Hydro | 360 | N/A |
| Zungeru | Niger State | Hydro | 700 | N/A |
| Waya Dam | Bauchi State | Hydro | 2*75 kW | N/A |
| Ezioha Mboro Dam | Enugu State | Hydro | 1*30 kW | N/A |

Source(s): Emodi, 2016; Sambo, 2012

It must be stated further that there exist other copious renewable based projects both small and large scale apart from the hydro with the greatest performance. It is important to note also that Solar PV was considered the fast-growing renewable energy in the market for the country with about 15 MW of dispersed isolated standalone systems mainly on small scales (Sambo and Bala, n.d). However, the scale up and incorporation to the country's grid is what is yet to be achieved. In addition, there exists a 7.5 MW solar PV module manufacturing plant based in Abuja, which was developed by the National for Science and Engineering Infrastructure (NASENI) and the Federal Ministry of Science and Technology (FMST) (Sambo and Bala, n.d). This is a clear indication on the miles the country has gone so far on renewables uptake. However, there should be expected future expansion and also the need to meet country's targets. The table below gives insight on some of the pilot scale renewable based projects in the country.

***Table 23:*** *Some Renewable Energy Projects Outside Hydropower*

| R.E Type | Specification | Costs | Site | Sponsor | Year |
|---|---|---|---|---|---|
| Wind Power | 5 kW for Village Electrification | N/A | Sayya, Sokoto State | SERC | N/A |
| Solar PV | Water Pumping | N/A | Usman Danfodio University | N/A | N/A |
| Solar PV | 7.2 kWp for Village Electrification | N/A | Kwalkwalawa, Sokoto State | SERC | N/A |
| Solar PV | 500 kW | N/A | Katsina State | JIKA and FMP | N/A |
| Solar PV | 50 kW | N/A | Kaduna State | FMEnv. and Private Sector | N/A |
| Solar Thermal | Community based Water Heater.<br>Capacity: 1000 Liters | N420,000 | Usman Danfodio University Hospital | ECN | 1998 |
| Solar Thermal | Riser and Spiral Water Heater for R&D + Demonstration.<br>Capacity: 20Litres | | SERC Demonstration Area | SERC | 2003 |

| | | | | | |
|---|---|---|---|---|---|
| Solar Thermal | Solar Rice Dryer. Capacity: 2 tons | N/A | Adarice Co. Enugu State | NCERD | N/A |
| Solar Thermal | Solar Dryer. Capacity: 2 Tons | N/A | NAPRI, Zaria | SERC | |
| Bioenergy | Fixed Dome Biogas Digester | N/A | Ikenne, Ogun State | N/A | N/A |
| Bioenergy | Household Biogas Digesters | N/A | Nsukka, Enugu State | NCERD | N/A |
| Bioenergy | Single-hole Improved Wood Burning Stove for Cooking. Capacity: Average Family of 15-20 Persons Meals | N/A | Argungu, Kebbi State | SERC | 2006 |
| Bioenergy | Double-hole Improved Wood Stove for Cooking. Capacity: About 40 Persons Meals | N5000 | Argungu, Kebbi State | SERC | 2006 |
| Wind Power | 2*215 kW | N/A | Usman Danfodio University | SERC | N/A |
| Wind Power | 70*3 kW | N/A | Zamfara State | Zamfara State Gov't | N/A |

Source(s): Sambo, 2009; Sambo, 2012

*Key: SERC: Sokoto Energy Research Centre, NCERD: National Centre for Energy Research and Development, ECN: Energy Commission of Nigeria, FMP: Federal Ministry of Power, JICA: Japan International Corporation Agency, FMEnv.: Federal Ministry of Environment*

Based on this, it must be noted in line with the above efforts that the country had set some targets according to the Eleri et al. (2005). These targets were in three categories i.e. short term of year 2007 targets, medium term of year 2015 target, which is now considered historical, and lastly the long-term target of year 2025. This has gone in to extension to include other renewables apart from hydro with all the specifications from the below table:

***Table 24:*** *Renewable Energy Targets to Electricity Generation in Nigeria (MW)*

| R.E Type | Short Term (MW) / 2,007 | Medium Term (MW) / 2,015 | Long Term (MW) / 2,025 |
|---|---|---|---|
| Hydro (Small) | 50 | 600 | 2,000 |
| Solar PV | 5 | 120 | 500 |
| Solar Thermal | N/A | 1 | 5 |
| Biomass | N/A | 100 | 800 |
| Wind | 1 | 20 | 40 |
| Total | 56 | 841 | 3,345 |
| ECN High Growth Projection | 7,000 | 14,000 | 29,000 |
| % Share of Projected Energy | 0.8% | 6% | 11.53% |

Source: Eleri et al., 2005

The finance or investments breakdown for the different plans / targets are also presented here below:

***Table 25:*** *Estimated Costs for the Renewable Energy Investment in the Targets (Million Naira)*

| Activity | Short Term / 2007 | Medium Term / 2015 | Long Term / 2025 | Total |
|---|---|---|---|---|
| Programs | 170 | 430 | 322 | 922 |
| Biomass | 1,793 | 3,231 | 11,353 | 16,377 |
| Solar Energy | 1,240 | 2,525 | 3,210 | 6,975 |
| Hydro (Small) | 134 | 1,244 | 1,726 | 3,104 |
| Wind Energy | 920 | 170,200 | 410,640 | 581,760 |
| Total | 4,257 | 177,630 | 427,251 | 609,138 |

Source: Udochukwu and Ogbonnaya, 2014

*Note: Micro Hydro: 100 kW Electricity Capacity, Small Hydro: 100 kW – 30 MW Electricity Capacity, Large Hydro: More than 30 MW Electricity Capacity*

Regarding the Intended Nationally Determined Contributions (INDC) for the country that was based on the Paris Agreement of COP21, the country had also set some targets from 2015 to 2030. The aim of the targets was basically on improving energy access, lowering greenhouse gas emission from the Business as Usual (BAU) coupled with adaptation measures. For the emissions reduction aspect, 20% reduction from BAU would be on Unconditional basis whereas, 45% reduction from BAU would be on Conditional basis (USAID, 2016). In line with this, the renewable contributions for under the energy production specifically on the mitigation component were having more decentralised systems, Off-grid Solar PV of 13GW, and finally blending 10% by volume of bioethanol with gasoline and 20% by volume of biodiesel with gasoline (USAID, 2016).

# CHAPTER THREE

## 3. DECENTRALIZED HYBRID POWER SYSTEM DESIGN

### 3.1 Energy System Background

Having seen the energy land scape background in the preceding chapter, the power system design on grid-integration target is obviously the next concern. In line with that, numerous research works conducted have shown the depleting nature of conventional energy sources especially fossil fuels coupled with direct consequences of global warming, necessitating going for alternatives in energy solution. These alternative energy sources are in other words termed the renewable energy sources such as solar, wind, hydro, biomass, and geothermal. However, the combination of two or more of these sources is sometimes necessary giving rise to the hybrid energy system. Hence, by definition, hybrid energy system is the combination of two or more energy conversion devices aimed at overcoming limitations associated with any of them (US DoE, 2001). The major limitation to the renewable systems and their sources has been intermittency in executions as some resources are available in stock or fixed all the time while some are fluctuating. The hybrid system has some advantages with incorporation of renewable sources having obtained from literature. These are fuel flexibility due to different adjustment that could be made in the different combinations for ensuring optimum system, efficiency of systems, reliability, and viability in terms of economics, energy security, improved power quality, reduced carbon emission, fossil fuels saving and employment opportunity(U.S DOE, 2001; Negi & Mathew, 2014).

In addition, power generating system could be either decentralized (distributed) or centralized. The former involves having different sets of power generating systems for different load demands as the intended target for this research paper whereas, the latter involves securing a single power plant to one or many load centres without the need for distribution in the system execution (Rakesh et al., 2016). The centralized power generations could be relatively more challenging than the decentralized generations due to their high costs of execution and more losses on operations. This is because the power has to be transported either on a national/regional utility grid or mini/isolated grid depending on the network category.

Furthermore, still on the basis of network, the power system be it single component-based or in hybrid could be conventionally designed in two ways viz. grid-connected and off-grid or standalone. The grid-connected hybrid system works in such a way that the power generated gets integrated to grid network on either the transmission, sub-transmission or distribution site of network and then the load gets its power from the grid or from the system directly with excesses going to the grid and deficits requiring the grid sourcing. The major advantage of the grid-connected systems is the fact that flexibility exists in operation such that loss or shut down of the system could easily be compensated by other alternatives in the utility grid, keeping the system continuously empowered (Paradise Energy Solutions, 2019). Also, excess generation when compared to electricity consumed from the grid results in credits in line with the renewable power policy instruments proceedings based on countries' regulations. Off-grid based systems in contrast are usually deployed in remote areas i.e. areas that are far away from the existing grid where the grid extension to those locations is technically or economically impossible or challenging (Tiyou, 2020). It has less impact as compared with the grid connected systems due to the flexibility and credits securing not peculiar to it.

Energy storage is considered as equally important in execution of hybrid system especially on event of fluctuation of some resources or excess generation. This is particularly more necessary on off-grid systems operation as compared with the grid-connected system. This serves as a disadvantage to the off-grid system operation due to the costs impact of the storage system requirement (Paradise Energy Solution, 2019). Additional disadvantage might be bulk nature of the storage system and its possible environmental impact. Nonetheless, the storage system ensures efficiency in operation and energy wastage minimization. Many techniques are usually employed in the energy storage and were reported by Negi and Mathew (2014) as follows:

***Table 26:*** *Breakdown of the Features of Energy Storage techniques*

| Attributes | Efficiency | Maturity | Costs | Energy Density | Power Density |
|---|---|---|---|---|---|
| CAES | 70% | Matured | High | High | High |
| PHS | 75-85% | Matured | High | Depend on Reservoir Size | Depend on Height Distance between Reservoirs |
| Hydrogen | 50-60% | Early Stage | High | Depends on $H_2$ Reservoir | Depend on Speed on Reaction |
| Flywheel | 80-90% | Mature | Low | Low | High |
| Super Capacitor | 80-95% | Immature | High | Low | High |
| SMES | 90-95% | Immature | High | Low | High |
| Battery | 75-85% | Matured | Low | High | High |

Source: Negi and Mathew (2014)

*Key: CAE: Compressed Air Energy Storage, PHS: Pumped Hydro Storage, SMES: Superconducting Magnetic Energy Storage*

Based on the above information, the design approaches generally performed on any hybrid power system are in stages, of which usually begins with energy demand assessment, the resource assessment, barriers / constraints in terms of costs, environmental influences etc., and finally fulfilling the demand with an energy system coupled with optimization and so on. Hybrid energy system design can be addressed using different software packages such as Hybrid Optimization of Multiple Energy Resources (HOMER), Matrix Laboratory MatLab/Simulink, System Advisor Model (SAM), Transient System (TRNSYS), Ganzleitlichen Bilanz (GaBi) etc., enabling accurate simulations, optimization, economics, control, life cycle assessments and so on. Adopting two or more of this software packages becomes necessary depending on research questions to be tacked in a power system design, as limitations may arise in handling or dealing with only one.

Within the context of Africa and beyond, so many studies where done with regards to hybrid energy systems both grids connected based and off-grid based. For simplicity, summarizing the studies was done in 2 categories i.e. the grid connected studies and off-grid studies. This enables seeing the gap in the research networks and areas addressed so far in ascertaining the need and outstanding contributions or novelty of the hybrid system design in this research work.

***Table 27:*** *Summary of the Grid-connected Renewable Energy System Studies Reviewed*

| **Author(s)** | **Study location** | **Load info / Peak demand** | **Appropriate Configuration** | **Findings / Observations for the studies** | **Life / yr.** | **Tool(s) / Approach** |
|---|---|---|---|---|---|---|
| **Christoper & Frank** | South Africa | 100 MW Base load Capacity | CSP/PV with battery storage | C.F: 90%, LCOE: $0.133-0.157/kWh | 25 | System Advisor Model (SAM) |
| **Ileberi et al.** | Abuja, Nigeria | 305 kW peak load | PV/wind without battery storage | RF: 70%, and Could sell 115605 kWh/yr. to the grid. | 20 / 1yr. sim | HOMER |
| **Numbi & Malinga** | EThek., South Africa | 3 kW residential single phase grid relations | PV System / FiT interactions / irrelevance of storage | The Higher the FiT, the higher the energy costs savings and PBP | 30 | optimal control model |
| **Nadjema et al.** | Ghard., Algeria | 2 Loads distribution | PV/wind with battery storage | High cost requiring subsidy and more attractive FiT | 25 | cuckoo search algorithm |
| **Mohammed et al.** | Morocco | 2 Loads (379 kWh/day, 113 kWh/day av. energy consumptions) | PV/wind with battery storage | RF is 81%, remaining 19% from grid, 323815 kWh/yr. production | 25 / 1yr. sim | HOMER |
| **Amos et al.** | Stelenb., South Africa | Plant designed for 100,000 MWh/yr. energy to grid | PV/wind with water interaction | PV requires more water. Optimized system LCOE is €0.17/kWh with water demand of 60,000m$^3$. i.e. Water demand reduced by 24% in the scenario | 20 | water constrain model / MATLAB developed Program |
| **Silinga et al.** | South Africa | Plant Cap.: 3.3 MW beyond base load for the grid | CSP peaking system with battery storage | 20% CSP part load operation with 7 hrs. storage: the 2-tier Tariff structure generates 2% more profit than the Fixed Tariff | 30 | spatial temporal analysis |
| **Kazein and Khatib** | Sohar, Oman | 3.08 kWp capacity installed for grid integration solely | Photovoltaic system | PV technology investment is very promising in the site. Annual yield factor of the system was 1696.6 kWh/kWp, capacity factor was 19.46%, and CoE was 0.158 USD/kWh | 20 | Use of MATLAB based on hourly meteorological data and a model for PV system |
| **Gonzalez et al.** | Central Catalonia, Spain | Vector of 8760 points (365 days × 24 h) | PV/Wind/Biomass system | The optimized configuration has been concluded to be of tremendous benefits regarding economic and environmental concerns. | 25 | Life Cycle Costing Optimization using MATLAB |
| **Salahi et al.** | Bishesh Village, Iran | 146kW peak load | PV/Wind/Battery and a Diesel/Battery System | The benefits of the transition have been clearly observed from the off-grid configurations of the systems | 25 | HOMER |
| **Dali et al.** | N/A | Variable local load utilization | PV/Wind/Battery system | Operational capability and effectiveness have been confirmed for both the grid-connected mode and the standalone mode. | N/A | Experimental study with emulators, 2-operation mode inverter etc. |
| **Nurunnabi and Roy** | Bangladesh | 101kW peak | PV/Wind/Battery | The overall benefits have been observed in terms of economics and so on for the transition from its off-grid configuration | 20 | HOMER |

NB: sim – simulation; FiT – Feed-in tariff; RF – Renewable Fraction; C.F – Capacity Factor; PBP – Payback Period

*Table 28: Summary of the Off-grid Renewable Energy System Studies Reviewed*

| Author(s) | Study location | Load info / Peak demand | Appropriate Configuration | Findings / Observations for the studies | Life / yr. | Tool(s) / Approach |
|---|---|---|---|---|---|---|
| **Puglia et al.** | Isolated Village, Uganda | Peak load: 140 kW, base Load: 20 kW | PV/diesel generator with battery storage | TLCC: $1,228,800, annual fuel consumption: 41026 Liters i.e. 77% reduction from Conv. diesel only system | 25 | In-house developed MATLAB programming code |
| **Muyiwa et al.** | South of Ghana | Peak load: 83 kW | PV/wind/ diesel generator with battery storage | NPV: $3905600, LCOE: $0.281/kWh with stressing the need for storage system | 25 / 1yr. sim | HOMER |
| **Muyiwa et al.** | Jos, Nigeria | Peak load: 236 kW | PV/diesel generator with battery storage | LCOE Range: $0.348-$0.390/kWh based on sensitivity for a range of interest Rates | 25 / 1yr. sim | HOMER |
| **Taher et al.** | Bizerte, Tunisia | 2 primary loads 3 kW peak each | Wind/diesel generator with battery storage | NPC: $57320 and LCOE: $0.26/kWh. Also, storage reduces the fraction of excess energy, NPC, and emission by 81%, 85%, and 29% respectively | 25 / 1yr. sim | HOMER |
| **Souheil et al.** | Monast., Tunisia | 3 loads: 3.25 kW, 3.25 kW, and 4.25 kW | PV/wind with battery storage | LCOE: €0.3082/kWh, annual total cost: €2481.1 | 20 | Generic technique based on principle of det. Approach |
| **Kusakana & Vermaak** | South Africa | 2 loads: 5.6 kW peak, 3.8 kW peak | hydro turbine / diesel generator | Load A:<br>NPC: $43599, LCOE: $0.265/kWh.<br>Load B:<br>NPC: $51887, LCOE: $0.189/kWh | 25 / 1yr. sim | HOMER |
| **Bekele and Boneya** | Ethiopia | Peak load: 11 kw | PV/wind/ generator with battery storage | NPC: $103914, LCOE: $0.302/kWh, and RF: 84%. | N/S / 1yr. sim | HOMER |
| **Douglas** | Port H., Nigeria | Peak load: 2.46 kW | PV with battery and hydrogen storage | PV module conv. efficiency: 34%.<br>Battery: lower power load with high operating hours.<br>Fuel cell: higher power load with low operating hours | N/S | MATLAB / Simulink |
| **Dekker et al.** | South Africa | 5.6 kW peak load | PV/diesel generator with battery storage | Sensitivity analysis done on diesel price with observed Upington zone being the best in terms of Economic viability | 25 / 1yr. sim | HOMER |
| **Yamegueu et al.** | Kamb., Burkina Faso | not specified | PV/diesel without battery storage | Operations with peak load equals rated capacity of the generator coupled with high solar irradiation is the optimum | N/A | Experimental studies |
| **Fazia et al.** | Adrar, Algeria | 13 kW peak load | PV/wind/ diesel generator with battery storage | The configuration can reduce diesel consumption by 70% compared to the conv. diesel only systems | 25 / 1yr. Sim | HOMER and MATLAB / Simulink |
| **Rezzouk & Mellit** | North of Algeria | 60 kW peak load | PV/diesel with battery storage | Best configuration had 25% PV share with NPC and LCOE of $617489 and $0.26/kWh respectively | 25 / 1yr. sim | HOMER |
| **Bekele & Palm** | Ethiopia | 2 loads (42 kW peak and 1.05 kW peak) | PV/wind/ diesel with battery storage | Zero renewables configuration was the most economical however the authors considered configurations with 51% and 81% RF due to realization in minor difference in costs but high emissions reduction | 25 / 1yr. sim | HOMER |
| **Khelif et al.** | South of Algeria | 12 kW peak load | PV/diesel with battery storage | Results revealed hybrid system as feasible but very sensitive to diesel fuel costs | 25 | Developed mathematical program based on electrical and economic models |
| **Muyiwa et al.** | Northern Ghana | 2 loads (34 kW and 1.3 kW peaks) | PV/biodiesel with battery storage | Results revealed high LCOE compared to average user tariff but capital incentives reduction sensitivity gave a more reliable costs values for the system | 25 / 1yr. sim | HOMER |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Bentouba et al.** | Southern Algeria | 1.6 kW Peak Load | PV/Wind with Battery Storage | NPC and LCOE for the best configuration were $74572 and $1.07/kWh with about 5.2tons/yr. of avoided emission from the conventional use of gasoline generator. | 25 / 1yr. sim | HOMER |
| **Joseph et al.** | Cameron | 7.5 kW peak load | PV/hydro with battery storage | NPC and LCOE for the best configuration were $54633 and $0.234/kWh respectively. | 25 / 1yr. sim | HOMER |
| **Gerro et al.** | Giyani, South Africa | N/A | Stirling solar micro cogeneration | System could generate 1500$kW_e$ per annum, and recovered heat usage could reduce fuel wood usage by 78kg per day | N/S/ 1yr. sim | TRNSYS |
| **Bing et al.** | South Africa | 3.25 kW Peak load | PV/diesel with battery storage | PV only with battery sufficient for summer but with need for diesel incorporation in winter | N/S / 4d sim | Mathematical modelling & transform to MIMO linear state-space form |
| **David et al.** | Ougad., Burkina Faso | 160 kW peak load | PV/diesel without storage | PV/diesel identical & PV/diesel un-identical were the best with LCOEs of $0.289/kWh and $0.284/kWh respectively lower than that for standalone diesel only | 25 / 1yr. sim | Techno-economic model and HOMER |
| **Nwosu et al.** | Nsukka, Nigeria | 1.5 kW peak in hot season and below 1 kW peak in rainy season | PV/wind with battery storage | System is feasible for the load demand satisfaction | N/S | Model power plant |
| **Ogunjuyib et al.** | Ibadan, Nigeria | 5.6 kW peak load | PV/wind/split diesel generators with battery storage | LCC: $11,273, LCOE: $0.13/kWh, energy dump: 3MWh and $CO_2$ emission: 13,273kg/yr., equivalent to 46%, 28%, 82%, and 94% reduction from the big sized single diesel generator respectively. | 25 | Genetic algorithm |
| **Elias et al.** | DRC | 6.5 kW peak load | PV/biomass gasifier plant | The best configuration had total energy generation of 24939kWh/yr. with PV covering 76% of the mix, leaving the gasifier plant with 24%. | 30 / 1yr. sim | HOMER |
| **Khalil et al.** | Misurat., Libya | 21 kW peak load | PV/wind/DG with battery storage | The best configuration had NPC of $293961, LCOE of $0.191/kWh, and a renewable fraction of 53% | 25 / 1yr. sim | HOMER |
| **Alan & David** | Eastern C.P, South Africa | 97 kW peak for the system | PV/wind | 97 kW peak from the system results in power availability of only 0.125 kW per household per day which is a deficit | N/S | Introduced Learning Model |
| **Eziyi & Krothapali** | Umudike Comnty., Nigeria | 32.5 kW peak load | PV/biomass gasified generator with battery storage | The LCOE is $0.113/kWh that is 30% cheaper than that for conventional petrol and diesel system, and incorporating desalination system results in overall costs of $0.11/kWh | 25 / 1yr. sim | HOMER |
| **Rezk & Gamal** | Minya, Egypt | Peak energy demand of 155 kWh/day for monthly evaluations | PV/fuel cell | The best configuration had NPC of $48,070 and LCOE of $0.058/kWh. | N/S / 1yr. sim | HOMER |
| **Bogno et al.** | Maroua, Cameron | daily energy demand is 37.4 kWh | PV/wind with battery storage | Battery sizing should be equal to the basic requirement capacity for daily requirement. The combined system reduces the overall cost of installation to more than 43%. | 10 yr. bat. Life | Top-down dimension approach |
| **Ajao et al.** | Nigeria | 0.143 kW peak load | PV/wind with Battery Storage | The NPC is $4251 and LCOE is $1.74/kWh for the best configuration | 20 / 1yr. sim | HOMER |
| **Sara et al.** | Kenya | 16.5 kW peak load | PV/wind/ biogas generator with battery storage | The NPC and LCOE were $196700 and $0.25/kWh i.e. 18% and 24% lower than that with diesel substitute for the biogas | 25 / 1yr. sim | HOMER |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Sara et al.** | Nairobi, Kenya & Nyala, Sudan | 2 kW peak load | PV/Wind with Battery Storage | The share of power generation for Kenya is 63% solar and 27% wind; for Sudan is 80% solar and 12% wind | N/S / 1yr. sim | TRNSYS |
| **Cherif & Belhadj** | Southern Tunisia | N/A | PV/wind without Storage | The system for the RO desalination could supply potable water with salinity of 6g/l. | N/S | BG envir. Of 20-sim software |
| **Henry** | Mahuru, Kenya | 5 kW system Size | PV/wind with battery storage | Average efficiency of the system was 67% | N/S /14 Mo. test | Stat. and time series analysis and diagnosis |

*NB: sim - simulation; N/S - Not Specified; Yr. - Year; d - Day(s); TLCC – Total Life Cycle Cost; LCOE – Levelized Cost of Electricity; NPC – Net Present Cost; NPV – Net Present Value; DG – Diesel Genset; RF – Renewable Fraction*

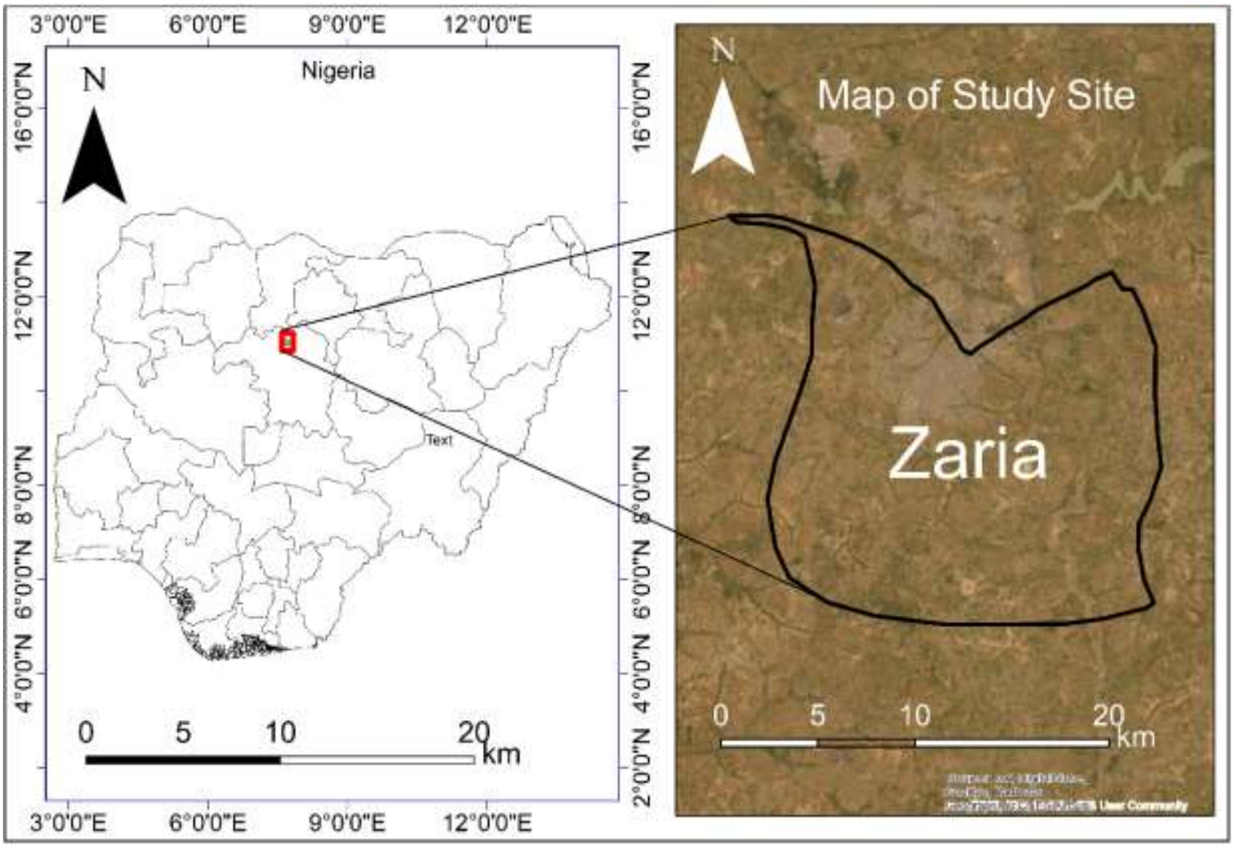
This design aspect will therefore be focussing on grid connected hybrid system, utilizing 100% renewable sources for a specific site with comparison to off-grid based systems for better decision.

## 3.2 Site Selection and Detailed Energy Assessment

### 3.2.1 The Site Description

Firstly, Nigerian electricity situation is really critical based on the electricity consumption analysed as 129.04 kWh/Cap./yr. during 2016 (Global Statistical Year Book, 2017; Worldometers Population, 2017). This is equivalent to a consumption of 0.35 kWh/Cap./day. For this study, the selected region or site is Zaria (Coordinates: 11.085˚N, 7.72˚E), which is a local government and a major city in Kaduna State of Northern Nigeria. On the baseline for the selected site, having seen initially, the whole country has a high deficit of power based on the consumption per capital data and the electrification rates. However, some regions tend to be on a more critical situation than others. From experience, this selected region is faced with frequent power cut and most households rely on gasoline or diesel generator sets to address their power shortages. The negative impacts of the generator sets are numerous viz. air and noise pollution resulting in health hazards, environmental degradation resulting from oil spillage on lands and water, excessive greenhouse gas emissions etc.

The site on a further description is situated on a plateau at an elevation of 670 m above Sea level (Stephen et al., 2012); and has a total area of 563 $km^2$ and a population of about 975,200 during 2015 (Population.city, 2015). Furthermore, Zaria’s climate is tropical wet and dry caused by movement of the inter-tropical discontinuity under two air mass influences viz. tropical continental and tropical maritime (Samuel, 2013). The wet season (summer) lasts from April to October whereas, the dry season (winter) lasts from November to March.

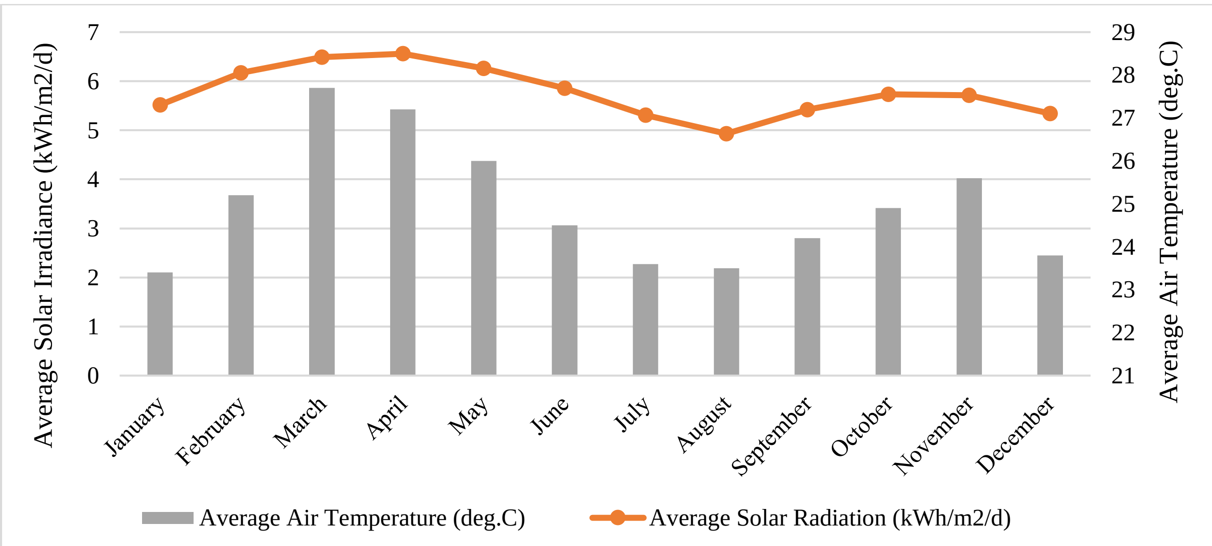



Source: with data from Global Biodiversity Information Facility (GBIF) (2015)

***Figure 4:** Map of Nigeria Showing the Study Site*

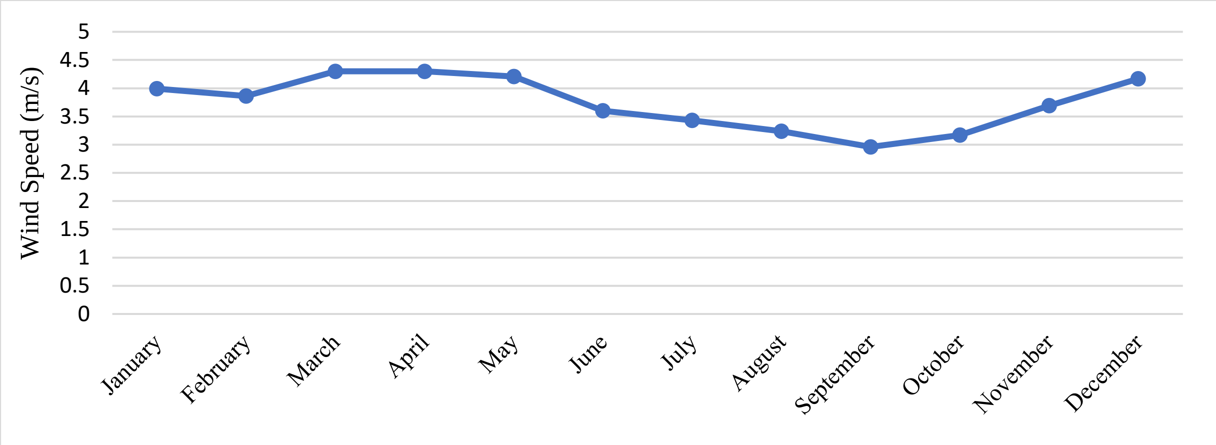
### 3.2.2 Site Resource Information

The renewable resource information for the site is crucial for the system analyses. The solar irradiance with the accompanied temperature and wind speed are the fundamental climate data of consideration. These have been presented in figures below:



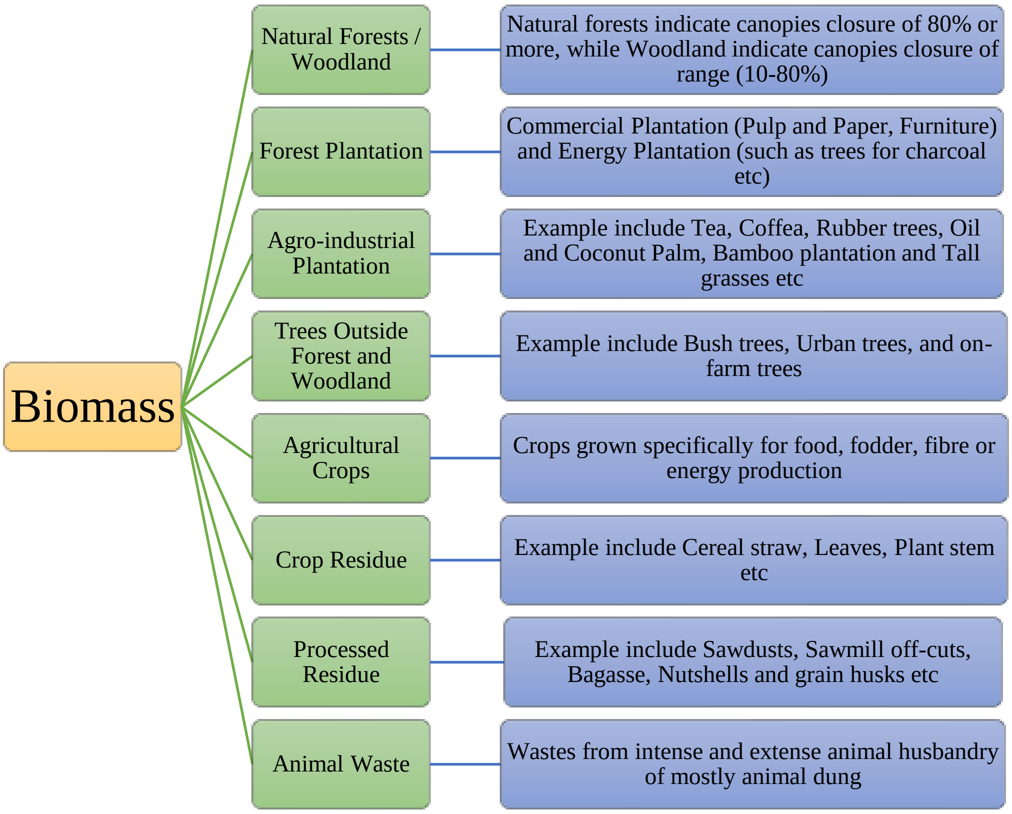

Source: with data from National Aeronautics Space Administration (NASA) (2017)

***Figure 5:** Average Monthly Solar Irradiation and Air Temperature for the Site*




Source: with data from National Aeronautics Space Administration (NASA) (2017)
***Figure 6:*** *Average Monthly Wind Speed for the Site at 50m*

Furthermore, on switching to biomass resource as very substantial to the power system, it is a stock resource and really a complex field of endeavour compared to the other renewables (Global Tracking Framework, 2017). It covers a wide range of resources including forestry and agricultural products, with their associated residues, and animal wastes (David, 2014). A broad classification of the biomass is provided below Appropriate measures need to be taken in its energy extraction in order to make it sustainable.:




Source: with data from Biomass Users' Network, et al., 2007
***Figure 7:*** *Biomass Resource Broad Classification with Specifications*

The breakdown of the different feedstock production for the country as well as for the analysed average production for the site based on the national total production values are presented.

***Table 29:*** *National Biomass Production and the Analysed Values on Average for the Site (Agro- production and Forestry)*

| **Crops Production Data** | | | |
|---|---|---|---|
| **Item** | **National Production (Tonnes)** | **Site's Production on Average (Tonnes)** | **Year** |
| Cereals | 25802662 | 30320.4019 | 2014 |
| Coarse Grains | 18998662 | 22325.1022 | 2014 |
| Oil Crops | 2669235 | 3136.5864 | 2014 |
| Tubers | 108069230 | 126990.8696 | 2014 |
| **Crop Residues** | | | |
| **Item** | **National Prod. (N.C in kg)** | **Site's Prod. on Av. (N.C in kg)** | **Year** |
| Crop Residues | 359085834.04 | 421957.5018 | 2014 |
| **Forestry Production** | | | |
| **Item** | **National Production ($m^3$)** | **Site's Production on Average ($m^3$)** | **Year** |
| Wood Fuel | 65287615 | 76718.7015 | 2016 |
| **Forest Residues** | | | |
| **Item** | **National Production ($m^3$)** | **Site's Production on Average ($m^3$)** | **Year** |
| Wood Residues | 65753628 | 77266.3079 | 2010 |
| Wood Charcoal | 4371175 | 5136.5159 | 2016 |

Source(s): FAOSTAT, 2017; Simonya & Fassina, 2013

***Table 30:*** *National Biomass Production and the Analysed Values on Average for the Site in 2014 (Animal Wastes)*

| **Item** | **National Production / Heads** | **National Dry Matter Production (kg/yr.)** | **Site Prod. on Average / Heads** | **Site's Dry Matter Prod. on Average (kg/yr.)** | **Dry Matter Production (kg/head/day)** | **C. Content on Average (Ultimate Analysis)** | **Biogas Potential ($m^3$/kg / kg/kg of Dry Matter)** |
|---|---|---|---|---|---|---|---|
| Cattle | 19,542,583 | $2.04 \times 10^{10}$ | 22,965 | $2.40 \times 10^{7}$ | 2.860 | 22.5% | 0.20 / 0.24 |
| Goat | 72,466,698 | $1.46 \times 10^{10}$ | 85,155 | $1.72 \times 10^{7}$ | 0.552 | 29.5% | 0.25 / 0.30 |
| Pig | 7,066,905 | $1.71 \times 10^{9}$ | 8,304 | $2.00 \times 10^{6}$ | 0.661 | 40.7% | 0.56 / 0.67 |
| Sheep | 41,326,780 | $4.96 \times 10^{9}$ | 48,563 | $5.83 \times 10^{6}$ | 0.329 | 31.4% | 0.25 / 0.30 |
| Chicken | 144,952,000 | $2.28 \times 10^{9}$ | 170,332 | $2.67 \times 10^{6}$ | 0.043 | 32.6% | 0.28 / 0.34 |
| Horse | 108,170 | $1.30 \times 10^{8}$ | 128 | $1.54 \times 10^{5}$ | 3.3 | 41.5% | 0.30 / 0.36 |
| Total | 285,463,136 | $2.04 \times 10^{10}$ | 335,447 | $5.22 \times 10^{7}$ | N/A | N/A | N/A |

- Note: Density of Biogas: 1.2 kg/$m^3$ (Dieter & Angelica, 2008)
- Biogas' Low Calorific Value / Low Heating Value: 20 MJ/kg (Swedish Gas Tech Centre Ltd, 2012)
- Biogas' Energy Density: 6.0-6.5 kWh/$m^3$ (Dieter & Angelica, 2008)
- Biogas' Methane Range (60-70%), Carbon Dioxide Range (30-40%) (Swedish Gas Tech Centre Ltd, 2012)

Source(s): FAOSTAT, 2017; United Nations Environmental Program (UNEP), 2013; Paul et al. (2014); Simonyan & Fasina (2013); Moral et al. (2004)

Regarding the hydro resource, which has been performing significantly in the electricity mix of the country, Kaduna state where the site is based, has been reported with the existence of fifteen (15) potential sites having a cumulative power estimate of 25 MW Roseline et al. (2015).

Focussing on the site, a lot of hydropower potentials exist due to existence of many water bodies viz. rivers, lakes, ponds, and Dams however, most of the water bodies are drained majorly by a river called Galma with three other rivers as its tributaries which are Kubanni, Shika, and Saye (Samuel, 2013).

Based on the site's renewable energy resource assessments, it's obvious that a lot of potentials exist which could be turned to reality in addressing our energy concerns and at the same time ensuring a sustainable development balancing the economic, social and environmental pillars. From the solar resource assessment, it's obvious that the monthly average solar irradiation on a horizontal surface has its maximum value as 6.56 kWh/m$^2$/day with an annual average of 5.77 kWh/m$^2$/day. It is however noted that the irradiation annual average values increase with panels tilting to some certain angles below 90 degrees. For the wind strength / speed, a maximum monthly average value of 4.3m/s has been obtained with the corresponding annual average value of 3.74 m/s all at 50 m altitude. It was noted that the speed / resource availability increases with increase in altitude. Regarding the biomass potential, there was recognition of the existence of abundant and quantified biomass resources in the country at large with allocated site's values on average. The ranges were from agro-production to forestry with the associated residues as well as animal wastes. It must be emphasized that the adoption of bio-power system is really recommended especially focussing on residues and wastes due to ensuring continuous environmental savings while at the same time scaling up energy / electricity supply all at low costs. Also became obvious the existence of numerous water bodies as shown, being obviously the potential also for setting up hydropower system to complement to the already existing ones in the country.

Within the context of this energy system design, solar, wind, and biomass wastes to biogas were the selected resources for the proposed Solar PV, Wind Power and Biomass Power hybrid system in the site. Hydro is deliberately neglected due to the high performance it's having in the country's electricity mix with future plans of expansion.

### 3.2.3 Load Demand Specification for the Site

The aim of the hybrid power design was to address the energy situation of the specified site i.e. Zaria by supplying a grid-connected decentralised power to the population based on a given number of households with the demand / load specification. Within the limit this design, about 200 households would be considered in the site with an average of 6 persons per household for the power system sizing. This would be equivalent to supplying energy to 1200 persons in the site. The breakdown of the load demand based on a list of appliances per household on daily basis is hereby presented in the below table: It must however be noted that the households' energy consumption is seasonal dependent as consumption in summer / wet season differs from that of winter / dry season for the site. Hence, a more realistic design approach needs to take that in to account. Therefore, the load demand would be specified for both the summer and the winter for there to be accurate sizing of the energy system components.

***Table 31:*** *Daily Load Demand for the Site: Summer (April to Oct.) and Winter (Nov. to March)*

| **Appliances** | **Power Rating (W)** | **Quantity / Household** | **Power Req. / Household (W)** | **Time of Use (hrs) / out of 24 hrs** | **Energy Use / Household (kWh)** | **Power Req. for 200 Households (kW)** | **Energy Use for 200 Households (kWh)** |
|---|---|---|---|---|---|---|---|
| Light Bulb (Incandescent) | 100 | 10 | 1000 | 19:00-7:00 (12hrs) | 12.00 | 200.00 | 2,400.00 |
| Radio | 12 | 2 | 24 | 6:00-19:00 (13hrs) | 0.31 | 4.80 | 62.00 |
| Television | 100 | 1 | 100 | 18:00-0:00 (06hrs) | 0.60 | 20.00 | 120.00 |
| Refrigerator | 160 | 1 | 160 | 0:00-23:00 (24hrs) | 3.80 | 32.00 | 760.00 |
| Water Dispenser | 600 | 1 | 600 | 0:00-23:00 (24hrs) | 14.40 | 120.00 | 2,880.00 |
| Computer / Charging | 150 | 3 | 450 | 7:00-10:00 / 18:00-21:00 (06hrs) | 2.70 | 90.00 | 540.00 |
| Mobile Phone / Charging | 5 | 6 | 30 | 7:00-9:00 / 18:00-20:00 (04hrs) | 0.12 | 6.00 | 24.00 |
| Electric Kettle | 1200 | 2 | 2,400 | 6:00-7:00 / 19:00-20:00 (02hrs) | 4.80 | 480.00 | 960.00 |
| Washing Machine | 500 | 1 | 500 | 6:00-8:00 (02hrs) | 1.00 | 100.00 | 200.00 |
| Electric Cooker | 1200 | 2 | 2,400 | 6:00-8:00 / 11:00-13:00 / 18:00-20:00 (06hrs) | 14.40 | 480.00 | 2,880.00 |
| Pressing Iron | 1000 | 2 | 2,000 | 7:00-8:00 (01hr) | 2.00 | 400.00 | 400.00 |
| Internet Router | 5 | 1 | 5 | 0:00-23:00 (24hrs) | 0.12 | 1.00 | 24.00 |
| Space Heater (Incorporated in Winter) | 1500 | 3 | 4,500 | 19:00-10:00 (15hrs) | 67.5 | 900.00 | 13,500.00 |
| Fan (Incorporated in Summer) | 75 | 3 | 225 | 22:00-7:00 (09hrs) | 2.03 | 45.00 | 406.00 |
| Air Conditioner (Incorporated in Summer) | 1200 | 1 | 1,200 | 8:00-21:00 (13hrs) | 15.60 | 240.00 | 3,120.00 |
| Total for Summer Case | N/A | N/A | 11,094 | N/A | 73.88 | 2218.80 | 14,776.00 |
| Total for Winter Case | N/A | N/A | 14,169 | N/A | 123.75 | 2,833.80 | 24,750.00 |

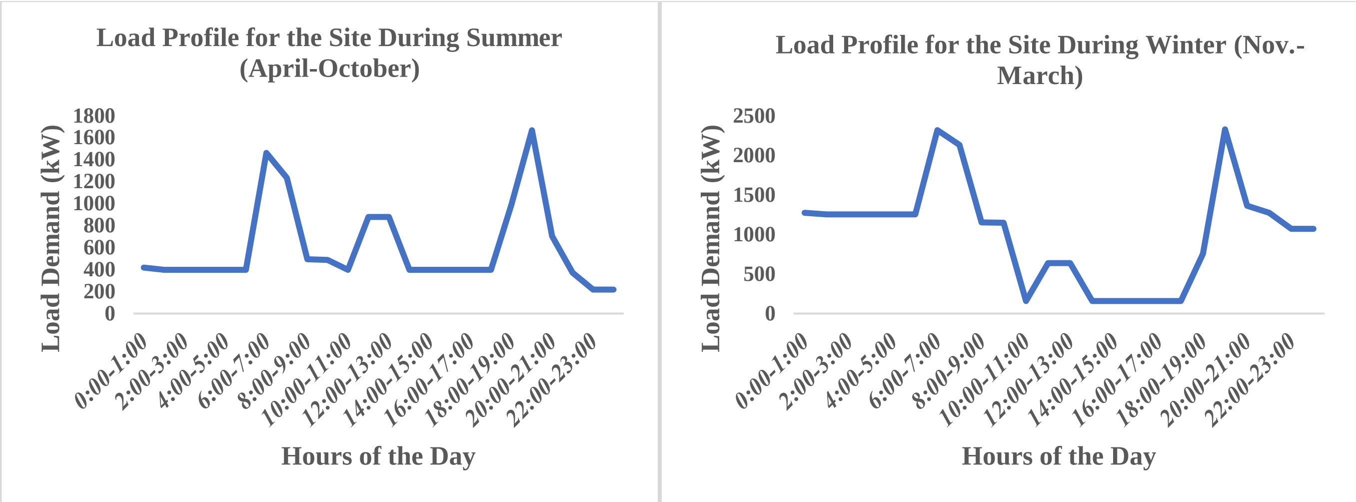


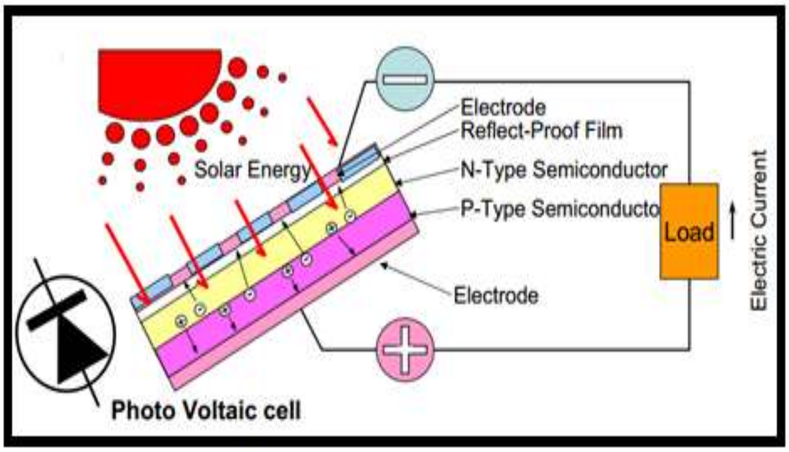

***Figure 8:*** *Baseline Load Demand Specification for the Site in Summer and Winter*

***Table 32:*** *Additional Load Demand Specifications for Scaling in HOMER Software*

| Random Variability Assumption for the Scaling: Day to Day = 15%, Time Step to Time Step = 20% | | |
|---|---|---|
| Parameter | Baseline Data (No Random Variability) | Scaled Data |
| Average Energy Demand (kWh/day) | 18,529 | 18,529 |
| Average Power Demand (kW) | 772 | 772 |
| Peak Power Demand (kW) | 2,329 | 4,059 |
| Load Factor | 0.33 | 0.19 |

### 3.2.4 System Components Descriptions with their Models and Economic Aspect

1) Solar PV System: The Solar PV System converts solar irradiation directly in to electricity based on Photovoltaic effect. The photovoltaic effect defines how the electrons move from the valence band to conduction band in powering an electric load. The figure below shows the working principle:




Source: Osamu, 2005

***Figure 9:*** *Photovoltaic System Operational Principle*

The models for PV system are quite numerous. Muyisawa et al. (2017) and Muyisawa et al. (2014) reported the solar PV power output models based on different input parameters as follows:

$$P_{pv} = Y_{pv} f_{pv} \left( \frac{G_T}{G_{T,STC}} \right) \left[ 1 + \alpha_p \left( T_C - T_{C,STC} \right) \right] --------(1)$$

where: $P_{pv}$ = Solar PV output power (kW), $Y_{pv}$ = Rated capacity of the PV array i.e. its power output under STC (kW), $f_{pv}$ = PV derating factor (%), $G_T$ = Solar radiation incident on PV array (kW/m$^2$), $G_{T,STC}$ = Incident solar radiation at standard test condition (1kW/m$^2$), $\alpha_p$ = Temperature coefficient of power (%/°C), $T_C$ = PV cell temperature (°C), $T_{C,STC}$ = PV cell temperature @ standard test condition (25°C).

Where the PV Cell Temperature ( $T_C$ ) could be calculated based on the below model:

$$T_C = \frac{T_a + (T_{C,NOCT} - T_{a,NOCT}) \left( \frac{G_T}{G_{T,NOCT}} \right) \left[ 1 - \frac{\eta_{mp,STC} \left( 1 - \alpha_p . T_{C,STC} \right)}{\tau\alpha} \right]}{1 + (T_{C,NOCT} - T_{a,NOCT}) \left( \frac{G_T}{G_{T,NOCT}} \right) \left( \frac{\alpha_p . \eta_{mp,STC}}{\tau\alpha} \right)} ----(2)$$

Where: $T_a$ = Ambient Temperature, $G_{T,NOCT}$ = Solar Radiation at Nominal Operating Cell Temperature (0.8kW/m$^2$), $T_{C,NOCT}$ = Nominal Operating Cell Temperature, $T_{a,NOCT}$ = Ambient Temperature at which the NOCT is defined (20°C), $\eta_{mp,STC}$ = Efficiency at Standard Test Condition, $\tau\alpha$ = Product of Solar Transmittance and Solar Absorbance = 0.9

Neglected the effect of temperature, the power model becomes less complicated as follows:

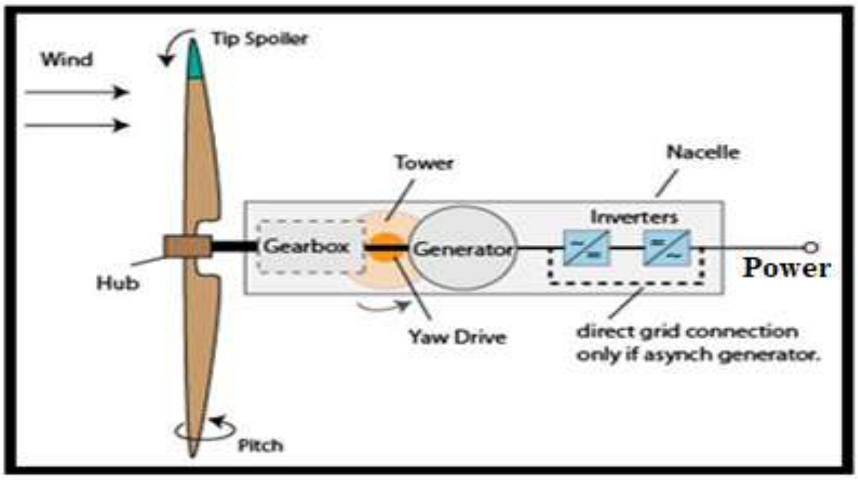
$$P_{pv} = Y_{pv} f_{pv} \left( \frac{G_T}{G_{T,STC}} \right) ------- (3)$$

On the energy generation bit of it, Kusakana and Vermark (2014) reported a model for predicting the electrical energy output of a PV system as follows:

$$E_{PV} = A \times \eta_m \times P_f \times \eta_{PC} \times I -----------(4)$$

where: $E_{PV}$ = The Total electrical energy output, A = Total area of the photovoltaic generator (m$^2$), $\eta_m$ = Module efficiency (%), $\eta_{PC}$ = Power conditioning efficiency (%), I = Hourly irradiance (kWh/m$^2$), $P_f$ = Parking factor

2) Wind Turbine System: The Wind turbine generator system generates power based on the kinetic energy of wind. The figure below shows the operational principle:




Source: Green Rhino Energy Limited, 2013

***Figure 10:*** *Wind Turbine Operational Principle*

Many mathematical models also exist in predicting the behaviour of a wind turbine system. Amos et al. (2015) and Taher et al. (2016) put forward the models for estimating the power output of a wind turbine as follows:

$$P_{WT} = \begin{cases} aV^3 - bP_{rt} & V_{ci} < V \le V_{rt} \\ P_{rt} & V_{rt} < V < V_{co} \\ 0 & V > V_{co} \end{cases} \quad ----(5)$$

$$\text{Such that: } a = \frac{P_{rt}}{V_{rt}^3 - V_{ci}^3} \text{ and } b = \frac{V_{ci}^3}{V_{rt}^3 - V_{ci}^3}$$

where: $P_{WT}$ = The wind turbine output power, $P_{rt}$= Rated power of the wind turbine, $V_{rt}$ = Rated wind speed, $V_{ci}$ = Cut-in wind speed, $V_{co}$ = Cut-out wind speed

$$\text{Also, } P_{WT} = {}^1/_2\, \rho A V^3 C_p ----------------- (6)$$

where: $\rho$ = Density of air = 1.225kg/m$^3$, A = Wind turbine area = $\pi\frac{d^2}{4}$ where d = rotor diameter (m$^2$), V = Wind velocity (m/s), $C_p$ = Coefficient of power = Max. value is 0.59.

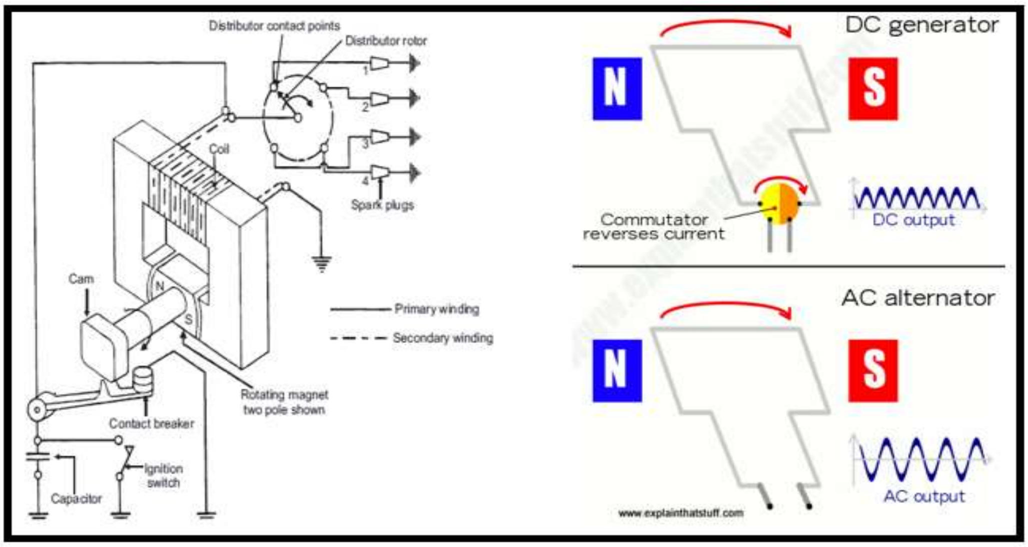
$$\text{Similarly, } P_d = {}^1/_2\, \rho V^3 C_p = \text{Power Density} -----------(7)$$

Finally, A model for predicting the Energy Output of a wind turbine has been reported by Kusakana and Vermark (2014), in terms of almost similar parameters to that of the power output. It is therefore, presented below:

$$E_{WT} = {}^1/_2 \times \rho \times V^3 \times C_{pw} \times \eta_{WT} \times t ---------- (8)$$

where: $E_{WT}$ = Energy output of the wind turbine, $C_{pw}$ = Wind turbine performance coefficient, $\eta_{WT}$ = Combined efficiency of wind turbine (%), t = Time

3) Generator Set (Biomass): The chemical energy fuel-based generator in this regard refers to the combination of a fuel ignition engine with an electric generator for electricity generation. The electric generator could be a Dynamo which generates Direct Current (D.C) or an Alternator which generates an Alternating Current (A.C), but quite often an Alternator is used. The figure below shows the operational principle of the generator sets.




Source: Woodford, 2009/2012

***Figure 11:*** *Fuel Ignition Genset Working Principle*

Based on the short description, the mathematical models in predicting the performance of the fuel ignition genset are also numerous. Muyiwa et al. (2017) and Muyiwa et al. (2014) reported some models to predict the fuel consumption as well as the total life and efficiency of the genset system as presented below:

$$F_c = aP_{rated} + bP_{gen} \text{ ---------------- } (9)$$

where: $F_c$ = Fuel consumption (L/hr), $P_{rated}$ = Rated power capacity of the generator (kW), $P_{gen}$ = Generator power output (kW), a = Generator's fuel curve intercept coefficient (L/hr/$kW_{rated}$), b = Generator's fuel curve slope (L/hr/$kW_{output}$)

$$\text{Also, } R_{gen} = \frac{Q_{running-time}}{Q_{year}} \text{ ---------------- } (10)$$

where: $R_{gen}$ = Generators operational life (yr.), $Q_{running-time}$ = Total running hours for the generator (hr), $Q_{year}$ = Actual annual operating hours (hr/yr.)

$$\eta_{gen} = \frac{3.6P_{gen}}{\dot{m}_{fuel}LHV_{fuel}} \text{ ---------------- } (11)$$

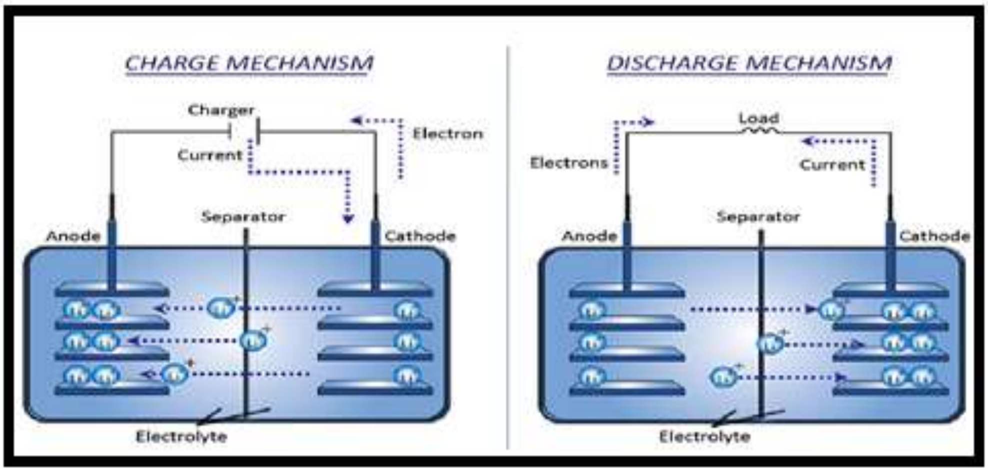
Such that: $\dot{m}_{fuel} = \rho_{fuel}(\frac{F_c}{1000})$

where: $\eta_{gen}$ = Generator's efficiency, $\dot{m}_{fuel}$ = Mass flowrate of the fuel (kg/hr), $\rho_{fuel}$ = Density of the fuel (kg/m$^3$), $LHV_{fuel}$ = Latent heat of vaporization of the fuel.

Lastly, Kusakana and Vermark (2014) puts forward a model suitable for predicting the total electrical energy generation from a fuel ignition generator as follows:

$$\text{Electrical Energy Output } (E_G) = P_{rated} \times \eta_{gen} \times t - - - - - - - - - - (12)$$

4) Battery Bank / Storage System: The battery is an energy storage system which takes electrical energy and stores it in form of chemical energy and then converts it back to electrical energy on discharge. The battery consists of multiple cells of which each cell consists of 2 electrodes i.e. cathode and anode with an electrolyte. Below figure shows the charging and discharging operation of the battery system:




Source: Noshin et al. (2012)

***Figure 12:*** *Charging and Discharging Principles of a Particular Battery System*

The mathematical models in terms of different parameters for characterizing battery are also numerous. Fazia et al. (2015) suggested some models for determining a battery state of charge (SOC), depth of discharge (DOD), as well as the battery capacity during charging and discharging as follows:

$$SOC(t) = \frac{C_{bat}(t)}{C_{bat\ max}} - - - - - - - - - - - - - - - (13)$$

Such that: $0 \leq SOC(t) \leq 1$

$$DOD(t) = 1 - SOC(t) - - - - - - - - - - - - - - - (14)$$

Note that when SOC(t) = 0, and DOD(t) =1 the battery is empty but when SOC(t) = 1, and DOD(t) = 0, the battery is full.

Where: $SOC(t)$ = State of Charge of the Battery at time (t), $DOD(t)$ = Depth of Discharge of the Battery at time (t), $C_{bat}(t)$ = Energy Capacity of the Battery at time (t), $C_{bat\,max}$ = Maximum Energy Capacity of the Battery

$$\text{Charging: } C_{bat}(t) = C_{bat}(t-1) + ((P_{tot}(t) - P_{cha}(t)) + P_{g.ac}(t))\eta_{ac/dc}\eta_{cha}\Delta t - -(15)$$

$$\text{Discharging: } C_{bat}(t) = C_{bat}(t-1) + (P_{tot}(t) - P_{cha}(t))\Delta t/\eta_{dc/ac}\eta_{decha} - - - -(16)$$

Where: $P_{cha}(t)$ = Power Demand, $P_{g.ac}(t)$ = Power generated by an A.C component for battery charging, $\eta_{ac/dc}$ = Conversion Efficiency from ac to dc; $\eta_{dc/ac}$ = Con. Efficiency from dc to ac, $\eta_{cha}$ = Charging Efficiency; $\eta_{decha}$ = Discharging Efficiency, $\Delta t$ = time interval

Moreover, Muyiwa et al. (2017) put forward a model for predicting the total life of a battery bank as follows:

$$R_{bat} = \begin{cases} \frac{N_{bat}.Q_{lifetime}}{Q_{throughput}} & \text{if Limited by throughput} \\ R_{bat,f} & \text{if Limited by Time} - -(17) \\ MIN(\frac{N_{bat}.\,Q_{lifetime}}{Q_{throughput}}, R_{bat,f}) & \text{if Limited by throughput and time} \end{cases}$$

Where: $R_{bat}$ = Battery Storage Bank Life (yr.), $R_{bat,f}$ = Storage Float Time (yr.), $N_{bat}$ = Number of Batteries for the Storage, $Q_{lifetime}$ = Life time Throughput of a Single Storage (kWh), $Q_{throughput}$ = Annual Storage Throughput (kWh/yr.)

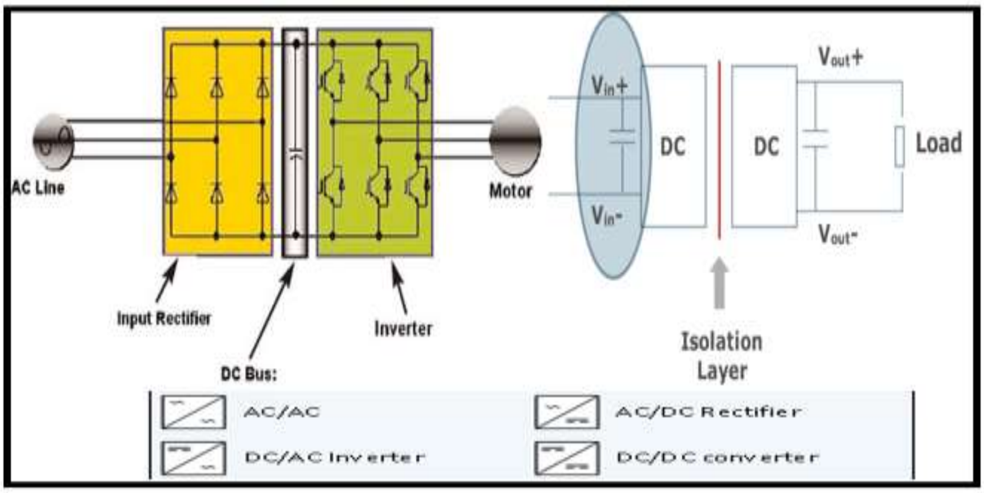
Lastly, the maximum power capacity of a battery bank is given by the below model in terms of other performance parameters:

$$P_{bat\,max} = \frac{N_{bat}.\,I_{max}.\,V_{nom}}{1000} - - - - - - - - - - - -(18)$$

Where: $P_{bat\,max}$ = Maximum Battery Charge Power (kW), $N_{bat}$ = Number of Battery Banks, $I_{max}$ = Maximum Charge Current (A), $V_{nom}$ = Nominal Voltage of the Battery (V)

5) Converter System: A converter is always necessary in a system with discrepancy in the nature of components power generation to the load requirement. Basically, the converter could be in the form of inverter for DC to AC power conversion, a rectifier for AC to DC power conversion, an AC to AC power conversion for changing the wave signal (frequency and voltage) to meet up with a requirement, or in the form of a DC to DC power converter for voltage adjustment to a certain requirement. Moreover, some converters perform both AC to DC and DC to AC conversions and hence, they are called bi-directional inverters.

The conversion is strongly based on the efficiency of the specified converter system such that the required power output is obtained by multiplying the power input to the devise by the device conversion efficiency. The figure below shows exactly the operational principle of the converter system.




Source: CUI Inc. (2017); http://www.acdrive.org/wiki.html (2017)

***Figure 13:*** *Power Converter Operational Principles*

Regarding the economic aspects, many analytical parameters exist with their models as applicable in the design aspects. These have been briefly discussed below:

**1)** Net Present Costs (NPC): This is defined as the aggregate of the capital costs and the discounted future costs incurred by the system over the entire life of the project. The model for evaluating such economic parameter has been provided in equation 19. In line with the NPC is the operating cost, where its formula is given in equation 20.

$$NPC = C + \sum_{n=1}^{N} \frac{O\&M}{(1+i)^n} ------------ (19)$$

where: C = Capital/Investment Costs ($), O&M = Operation and Maintenance Costs, i = discount rate / real discount rate, N = project life time

$$Operating\ Cost = \mathrm{CRF}(i, N_{Project}).\mathrm{NPC} - \mathrm{CRF}(\mathrm{i}, N_{\mathrm{Project}}).\mathrm{C} ------(20)$$

Where: $\mathrm{CRF}(i, N_{Project}).\mathrm{NPC}$ = Total Annualised Cost, and CRF = Capital Recovery Factor

**2)** Capital Recovery Factor (CRF): This is defined as the ratio used to calculate the present value of an annuity. It is represented by the below formula that was reported by Muyiwa et al (2017).

$$\mathrm{CRF} = \frac{\mathrm{i} \times (1+\mathrm{i})^{\mathrm{n}}}{(1+\mathrm{i})^{\mathrm{n}} - 1} ------------ (21)$$

**3)** Discount Rates (Real and Nominal): These are interest rates that are considered in a cash flow analysis, of which the real one takes inflation rate in to account whereas, the nominal one neglect the effect of inflation. The following formula relates the 2 discount rates as put forward by Nurunnabi and Koy, 2015:

$$i = \frac{i' - F}{1 + F} ----------------- (22)$$

Where: i = Real Discount Rate, i' = Nominal Discount Rate, F = Annual Inflation Rate

**4)** Levelized Cost of Energy (LCOE): This could be defined as the total costs to generate a unit of energy for a system over its entire life. It could also be seen as the amount to which the energy must be sold to have a break-even. It is given by the below formula as suggested by the Fraunhofer Institute for Solar Energy System, 2012:

$$LCOE = \frac{I + \sum_{n=1}^{n=N} \frac{O\&M}{(1+i)^n}}{\sum_{n=1}^{n=N} \frac{Mel}{(1+i)^n}} ----------- (23)$$

Where: I = Capital Costs / Investment Costs ($), O&M = Operation and Maintenance Costs ($), Mel = Quantity of Energy / Electricity Generated (kWh)

## 3.3 Design Approach and Input Specifications

### 3.3.1 Design Approach

Based on reviewed literature regarding the studies conducted, the design approach adopted here was the grid-connected Solar PV/Wind-turbine/Biomass gasified power system without storage. The reason behind neglecting storage system was due to the incorporation of utility grid as a back-up system. Hence, generations in excess of demand necessitates sending the excess energy to the grid, whereas, generation in short of the demand results in the compensation of grid power to meet up with the demand. This configuration was then compared to its off-grid based configuration where battery storage is incorporated as the back-up system in order to see clearly the gap between the two scenarios for a better decision making. The overall system architecture has been described in the below figure.

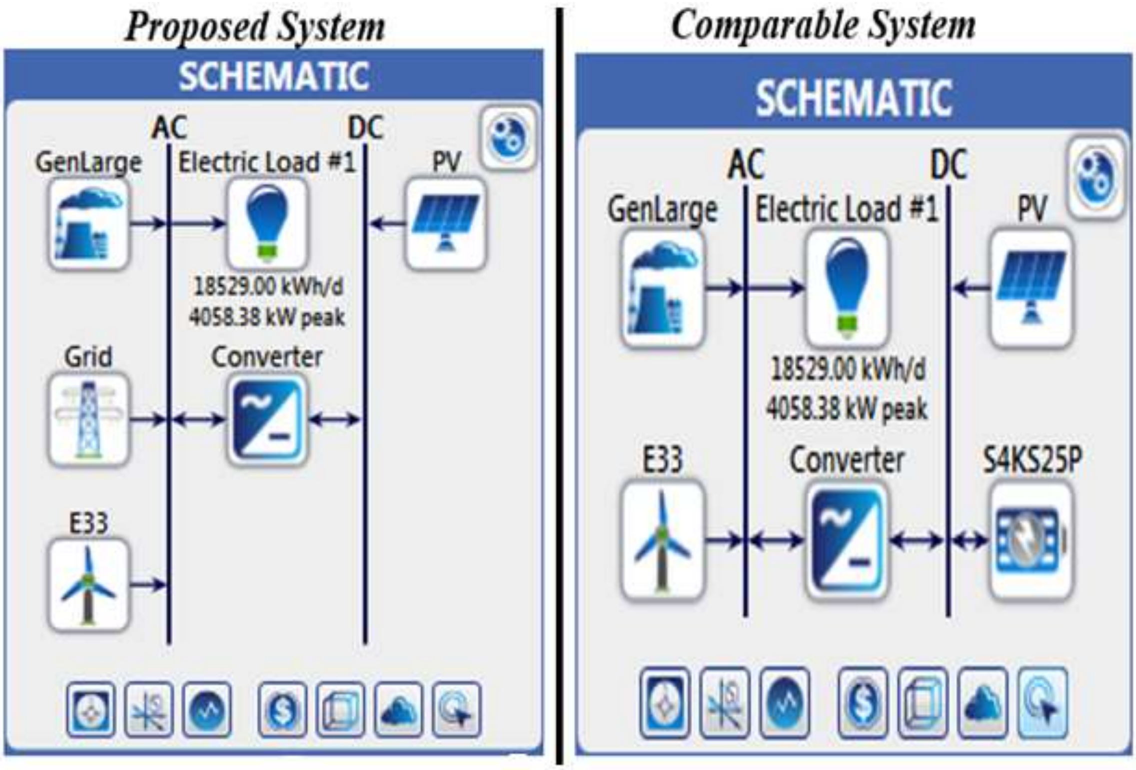



***Figure 14:*** *Screenshot HOMER Block Diagram for the Systems Architecture*

In each case, ‘’HOMER software’’ was used for sizing, simulation and optimization in obtaining the technically optimum parameters with the corresponding optimum configuration based on least net present cost (NPC), and in line with the analysed design input parameters presented in the appendices section i.e.  Tables A1, A2 and A3. Further economic analysis for operating costs and levelized Cost of Energy (LCOE) determination for each system case was conducted using Microsoft Excel.

The general description of how the HOMER software works in the system design based on the load specification to the components modelling and optimization and so on has been clearly given in the model figure below.

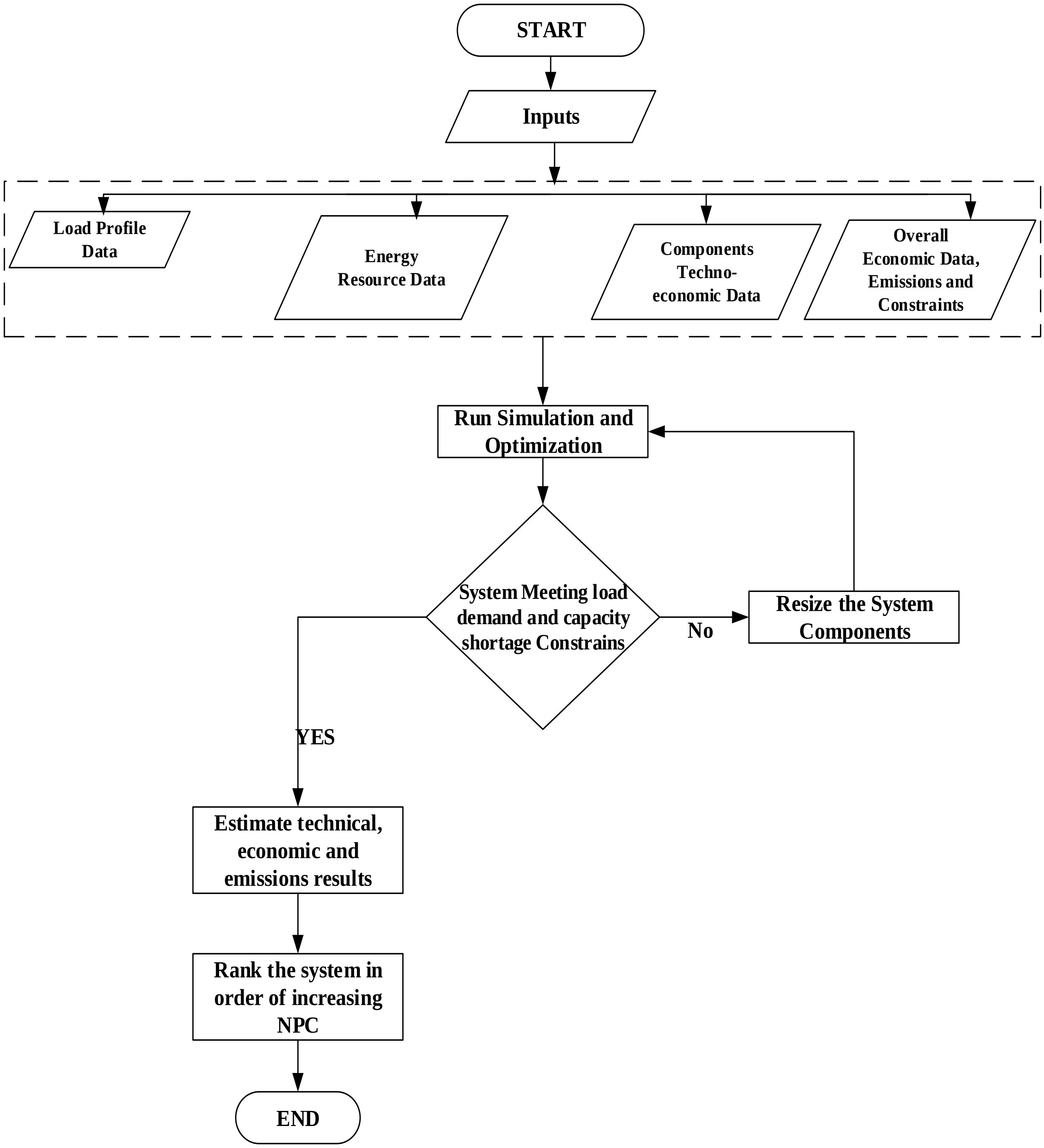



***Figure 15:*** *HOMER Model Description in the Design*

Regarding the operational principle in energy management for the proposed grid-connected system, it goes in three stages. The first stage has been on the solar PV and wind turbine components focus in fulfilling the demand, of which the thirst component being the biogas genset is optimized to automatically activate based on its minimum load ratio on occasions of insufficiency of the solar PV and wind turbine components. The second stage relates to the grid-intervention on occasions of total power deficit of the whole system in comparison to the load demand, where the utility gird power is being sourced / purchased in meeting up with the demand based on the defined limit. The third stage also relates to the grid-intervention on occasions of total power of system in excess of the load demand, where the surplus is sent /

sold to the utility grid based on the defined limit. The management strategy has been described clearly in the model figure. The excel program adopted as an extra work for the energy management has been provided in the table below

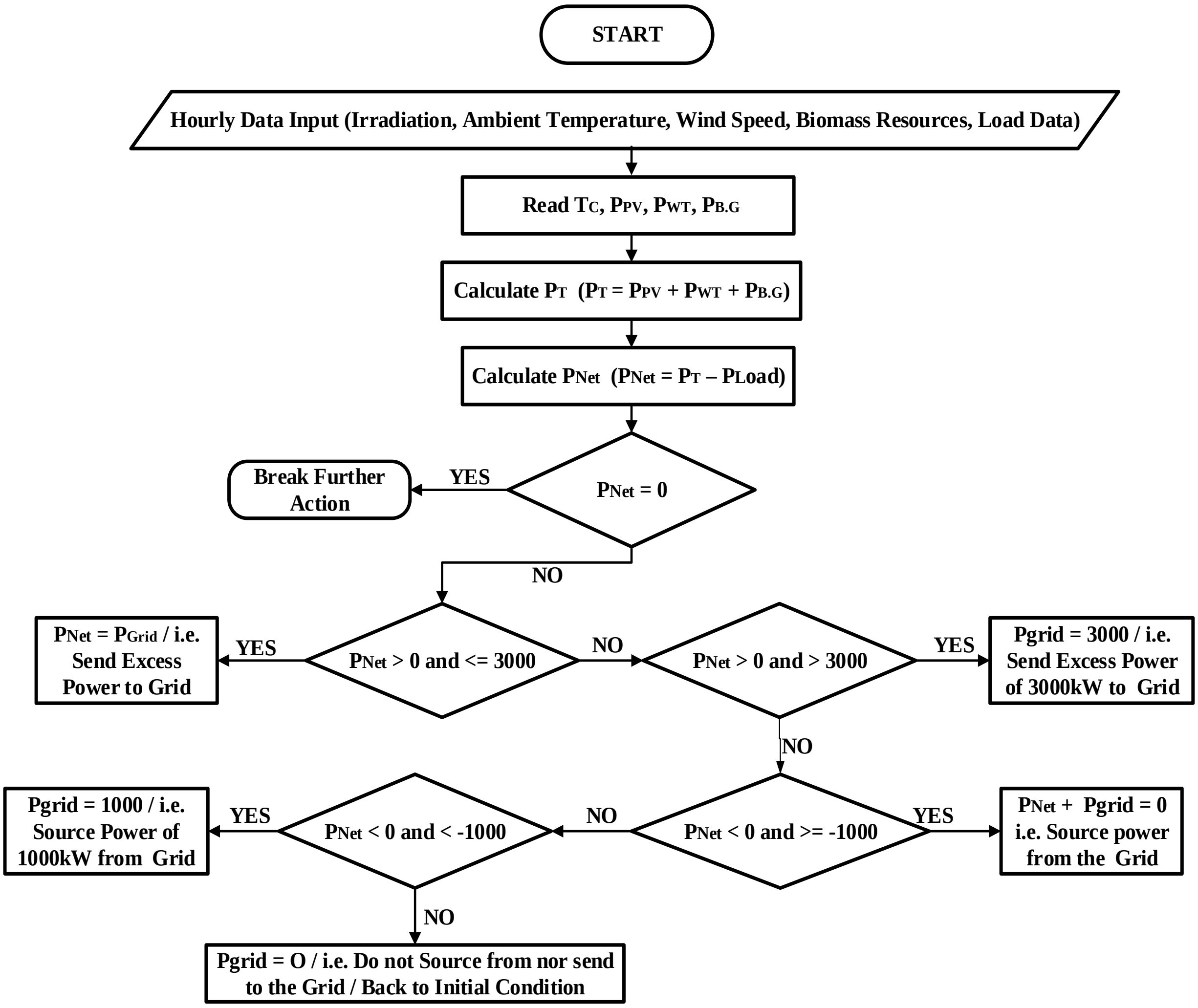



***Figure 16:*** *Energy Management Principle for the Proposed Grid-connected System*

***Table 33:*** *The Advanced Excel Control Instructions Incorporated*

| **Visual Basic App. Programming Instruction (Power to Grid)** | **Visual Basic App. Programming Instruction (Power from Grid)** |
|---|---|
| Sub Conditional _ Program1 ( )<br>For X = $x_1$ to $x_n$<br>If cells (X, $Y_n$) > 0 and cells (X, $Y_n$) < = 3000, Then<br>cells (X, $Y_m$) = cells (X, $Y_n$)<br>Else if cells (X, $Y_n$) > 3000 Then<br>cells (X, $Y_m$) = 3000<br>Else cells (X, $Y_m$) = 0<br>End if<br>Next X<br>End Sub | Sub Conditional _ Program2 ( )<br>For X = $x_1$ to $x_n$<br>If cells (X, $Y_n$) < 0 and cells (X, $Y_n$) > = -1000, Then<br>cells (X, $Y_p$) = -cells (X, $Y_n$)<br>Else if cells (X, $Y_n$) < -1000 Then<br>cells (X, $Y_p$) = 1000<br>Else cells (X, $Y_p$) = 0<br>End if<br>Next X<br>End Sub |
| **Visual Basic App. Programming Instruction (Excess/Unmet Power after Grid Intervention)** | Key Indications: |

| | |
|---|---|
| Sub Conditional _ Program3 ( )<br>For X = $x_1$ to $x_n$<br>If cells (X, $Y_m$) = 0, Then<br>cells (X, $Y_s$) = cells (X, $Y_n$) + cells (X, $Y_p$)<br>Else if cells (X, $Y_p$) = 0 Then<br>cells (X, $Y_s$) = cells (X, $Y_n$) - cells (X, $Y_m$)<br>Else cells (X, $Y_s$) = 0<br>End if<br>Next X<br>End Sub | 1) X = rows considered<br>2) cells (X, $Y_n$) = $P_{Net}$<br>3) cells (X, $Y_m$) = Power to Grid<br>4) cells (X, $Y_p$) = Power from Grid<br>5) cells (X, $Y_s$) = Excess / Unmet Power after the Grid Intervention |

Sensitivity analysis was addressed for the proposed grid-connected system based on some technical and economic parameters. The technical parameters where solely the climate-based resource data viz. scaled annual average wind resource, scaled annual average solar resource, with the accompanied scaled annual average ambient temperature, where an assumption of 5% decrement and 5% increment was made to the original data. This is in view of possible fluctuations due to high uncertainty in the climate data. The economic parameter considered was the discount rate being a strong determinant for time value of money in the cash flow evaluations. The assumption to the baseline discount rate considered was decrement and increment of 1% and 2% respectively in the sensitivity.

Additionally, Energy Efficiency (EE) assessment was offered to the optimized proposed grid-connected configuration with further simulations and re-optimization using ‘’HOMER tool’, in seeing its impact. The focus was on the adjustment of load demand by switching of appliances specifically for lighting and heating requirements. For the lighting aspect, switching was done from the already specified use of incandescent bulbs in the load calculations to the use of ‘’Light Emitting Diode (LED)’’. Whereas, for the heating aspect, the switching was from the electric cooking and electric water heating specified to the use of ‘’Improved Biomass Cook Stove (IBCS)’’ for both cooking and water heating. In all the cases, the power demand and cost implications were analysed and summarized in Appendices section in Table A4.

Furthermore, supplementary economic assessments have been successfully done using Microsoft EXCEL, in analysing the economic benefits associated with the switch from the comparable standalone system to the proposed grid-connected system, and also from the proposed grid-connected system to its energy efficiency measures.

Finally, extrapolation for the optimized system configurations was done for both the proposed grid-connected system and its energy efficiency measure. This was basically to see clearly the additional savings in terms of optimized configurations and well as the cost implications. The Extrapolations was achieved by applying the load multiplier approach for the decentralized or distributed systems extension as well as incorporating the resource variability parameters namely the Solar resource variability, Wind resource variability and the extension of biomass resource. 50 Decentralized systems were assumed for the extrapolations from different locations in the case-study country i.e. Nigeria such that the solar and wind resource variability parameters were taken on average of all the considered sites inclusive of the site studies above, prior to these extrapolations. The table below gives clearly the extrapolation parameters.

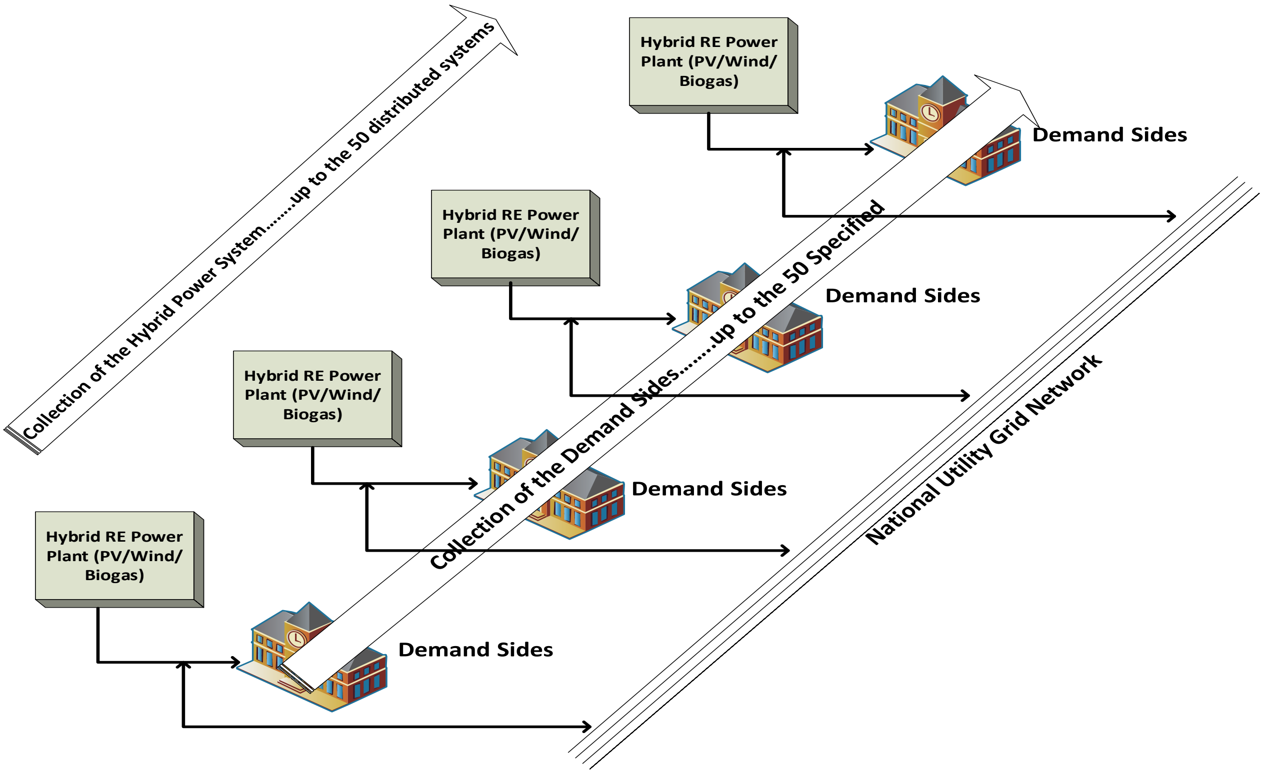



***Figure 17:*** *Distributed Generations Description on Extrapolations*

The project life has been taken as 25 years, and the interest rate for the overall economic assessment in the study has been assumed to be 6% as a conventional setting. The additional input data having referenced in the methodology can be accessed in the Appendices section with citations where necessary.

### 3.3.2 The Components Modelling Input Data

The input data for the physical component modelling have been provided in the below tables in much detail.

***Table 34:*** *Utility Grid Input Specifications*

| Parameter | Specification | Remark / Reference |
|---|---|---|
| Purchase price ($/kWh) | 0.06 | R2 Specification i.e. for single and three phase Residential power / Nigerian Electricity Regulatory Commission (NERC), 2015 |
| Sellback price ($/kWh) | 150% of 0.06 | For better motivation to R.E Projects |
| Net Metering | Net Purchase | On monthly Basis as a Choice |
| Emissions (g/kWh$_e$) | $CO_2$: 378; CO: 0.03; $SO_2$: 1.9; $NO_x$: 0.41; PM: 0.14 | Calculated based on the country's electricity mix ratio / Green Stat Network, 2017; https://engineering.dartmouth.edu |
| Sales capacity (kW) | 3000 | Assumed max. power to be sold to grid on an event of excess generation |
| Purchase capacity (kW) | 1000 | Assumed max. power to be purchased from grid on an event of shortage |

***Table 35:*** *Input Specifications for the Power System Components*

| Components | Costs | Life span | Sizes used | Others |
|---|---|---|---|---|
| PV panel (Q-Cell 225 / Polycrystalline) | C.C: \$3,000/kW; R.C: \$3,000/kW; O&M: \$10/kW / Muyiwa et al., 2017 | 25 years | Range of (400 kW – 3,500 kW) | Efficiency @ STC: 15.3%; Nom. op. cell temp.: 45˚C; Temp. Coefficient of power: -0.42%/˚C; Derating F.: 80%; Ground Ref.: 20%. / Muyiwa et al., 2017. |
| Wind turbine (Enercon E33) | C.C: \$131,146.11/unit; R.C: \$128,469.66/unit; O&M: \$1,338.23/unit (Updated cost of 2012 @ 6% I.R) / Sadeghi et al., 2012. | 25 years | Range of (1 – 30 units) | Rated power: 330 kW AC; Tower height: 50 m; Cut-in speed: 3 m/s; Rated speed: 13 m/s. / [HOMER Specification]. |
| Biogas power genset | C.C: \$1685.4/unit; R.C: \$1348.32/unit; O&M: \$0.11/unit (Composite of the biodigester and the biogas genset: (Updated cost of 2015 @ 6% I.R) / Sara et al., 2015. | 15,000 Hrs | Range of (400 – 3500 kW) | Min. Load Ratio: 30; Calculated Biogas Intercept Coefficient:0.1083 $kg/hr/kW_p$ (Cat-Electric Power, 2011); Calculated Biogas Slope: 0.5685 $kg/hr/kW_{out}$ (Cat-Electric Power, 2011); Emissions (kg/kg fuel): CO – 33, $NO_x$ – 6.17, PM – 0.00068 (Common Wealth of Australia, 2008; Davis, 2012). |
| Battery (Surette 6CS25P) / For the off-grid case only. | C.C: \$1,348/unit; R.C: \$1,123.6/unit; O&M: \$16.85/unit (Updated costs of 2015 @ 6% I.R) / Sara et al., 2015. | 12 years | Range of (10 – 150 Units) | Voltage: 6V; Nominal capacity: 1156 Ah; Round trip efficiency: 80%; Life throughput: 9645 kWh; Min SOC: 40%; Max power: 0.25 kW / [HOMER Spec.]. |
| Inverter (Generic C) | C.C: \$700/unit; R.C: \$700/unit; O&M: \$10/unit / Muyiwa et al., 2017. | 15 years | Range of (200 – 1,200 kW) | DC-AC efficiency: 90%; AC-DC efficiency: 85%; Capacity (Rectifier/inverter): 100%. |

NB: C.C: Capital Cost; R.C: Replacement Cost; O&M: Operation & Maintenance Cost; I.R: Interest Rate

***Table 36:*** *Additional Input Specification for Biogas Generator Fuel*

| Parameter | Specification | Remarks / Reference |
|---|---|---|
| Biomass quantity (tons/day) | 136.58 | Summation of all the considered dry matters below |
| Biomass cost (\$/tons) | 0 | Wastes minimization for environmental benefits |
| Biomass aggregate carbon C (%) | 26.34 | Calculated based on the share of each Waste in total |
| Biogas to biomass Ratio on aggregate (kg/kg) | 0.27 | Calculated based on the share of Biogas Potential of each Waste in the total |
| LHV of biogas (MJ/kg) | 20 | Selected from a range / Ludington, n.d |
| Biogas' density ($kg/m^3$) | 1.2 | Selected from a range / Ludington, n.d |
| Biogas' $CO_2$ emission factor ($g/kWh_{elec.}$) | 3.12 | Homer Pro Conventional Setting |

**Note:** Biomass considered: Cow-dung: (65.75 tonnes/day, C:22.5%, 0.24 kg-biogas/kg-DM), Goat-dung: (47.12 tonnes/day, C:29.5%, 0.2 kg-biogas/kg-DM), Sheep-dung: (15.97 tonnes/day, C:31.4%, 0.3 kg-biogas/kg-DM), Chicken-dung: (7.32 tons/day, C:32.4%, 0.34 kg-biogas/kg -M), Horse-dung: (0.42 tons/day, C:41.5%, 0.36 kg-biogas/kg-DM). [Reference to Table 1]

***Table 37:*** *Power and Costs for the Energy Efficiency Measure and the Baseline Case*

| Baseline Specifications with No Efficiency Measure | | | | Energy Efficiency Measure Specifications | | | |
|---|---|---|---|---|---|---|---|
| Appliances | Power Req. (kW) | Total E˚ (kWh/day) | Costs (USD) | Appliances | Power Req. (kW) | Total E˚ (kWh/day) | Costs (USD) |
| Incandescent Bulb | 200 | 2,400 | 340 | LED | 28 | 336 | 7,420 |
| Electric Cooker | 480 | 2,880 | 1,240 | IBCS + Wood Pellets Fuel | 0 | 0 | 8,000 |
| Electric Kettle | 480 | 960 | 1,600 | | | | |
| Others (Summer / Winter) | 1,058.8 / 1,673.8 | 8,536 / 18,510 | N/A | Others (Summer / Winter) | 1,058.8 / 1,673.8 | 8,536 / 18,510 | N/A |
| Total for Summer | 2,218.8 | 14,776 | N/A | Total for Summer | 1,086.8 | 8,872 | N/A |
| Total for Winter | 2,833.8 | 24,750 | N/A | Total for Winter | 1,701.8 | 18,846 | N/A |

Overall Assessment for the Energy Efficiency:
Total Costs of Considered Appliances in Baseline Case = $3,180
Total Costs of Appliances as Substitute for the Energy Efficiency Measure = $15,420
Capital Cost Increment on implementing the Energy Efficiency Measure = $12,240
Load Power Requirement Reduction on Implementing the Energy Efficiency Measure in Summer = 51%
Load Power Requirement Reduction on Implementing the Energy Efficiency Measure in Winter = 40%
Overall Power Requirement Reduction Based on the seasons' energy weights = 44%
Efficiency Multiplier = 100 - 44% = 56% = 0.56
Energy Efficiency Lifetime = 25 years (i.e. for the whole project lifespan)

Note: Costs Per Unit information are obtained from Alibaba Group (2017) and then scaled up.

***Table 38:*** *Extrapolation Parameters for the Proposed Grid-connected System*

| **Parameters of Extrapolation** | **Specifications** | **Remarks** |
|---|---|---|
| Number of Decentralized Systems (of Equal Load Demand Ratings and 5 per Region for a Total of 10 Regions) | 50 | For 50 different sites in the case-study country (inclusive of the Zaria site considered previously and addressed) |
| Number of Households for the Initial Site Case | 200 | Zaria municipal case addressed |
| New Number of Households for the Extrapolated Capacity | 10,000 | Cumulative of the 50 different sites (inclusive of the Zaria site considered and addressed) |
| Load Annual Average for the Site | 18,367 kWh/day | Zaria municipal case addressed |
| Scaled Value of Load Annual Average | 918,350 kWh/day | Cumulative of the 50 different sites (inclusive of the Zaria site considered and addressed) |
| Annual Average Solar Resource for the Site | 5.78 $kWh/m^2/day$ | Zaria municipal case addressed |
| Scaled Annual Average Solar Resource | 5.73 $kWh/m^2/day$ | Cumulative average, taking care of all the 50 different sites considered for the extrapolations |
| Annual Average Wind Resource for the Site | 3.74 m/s | Zaria municipal case addressed |
| Scaled Annual Average Wind Resource | 3.65 m/s | Cumulative average, taking care of all the 50 different sites considered for the extrapolations |
| Annual Average Biomass Resource for the Site | 137 tons/day | Zaria municipal case addressed |
| Scaled Annual Average Biomass Resource | 6,850 tons/day | Cumulative aggregate, taking care of all the 50 different sites considered for the extrapolations |

### 3.4 Results and Discussion of the Hybrid System

The results of the overall analyses for the hybrid energy system in the considered site in Nigeria have been successfully obtained. These include the results for the proposed grid-connected system and its comparable off-grid system, hourly energy management results for some typical days in summer and winter, sensitivity analysis results, and energy efficiency results as follows:

#### 3.4.1 Optimization Results of the Proposed System and the Comparable System

The categorized optimization results for the proposed grid connected system and the comparable off-grid system have been presented in the below tables.

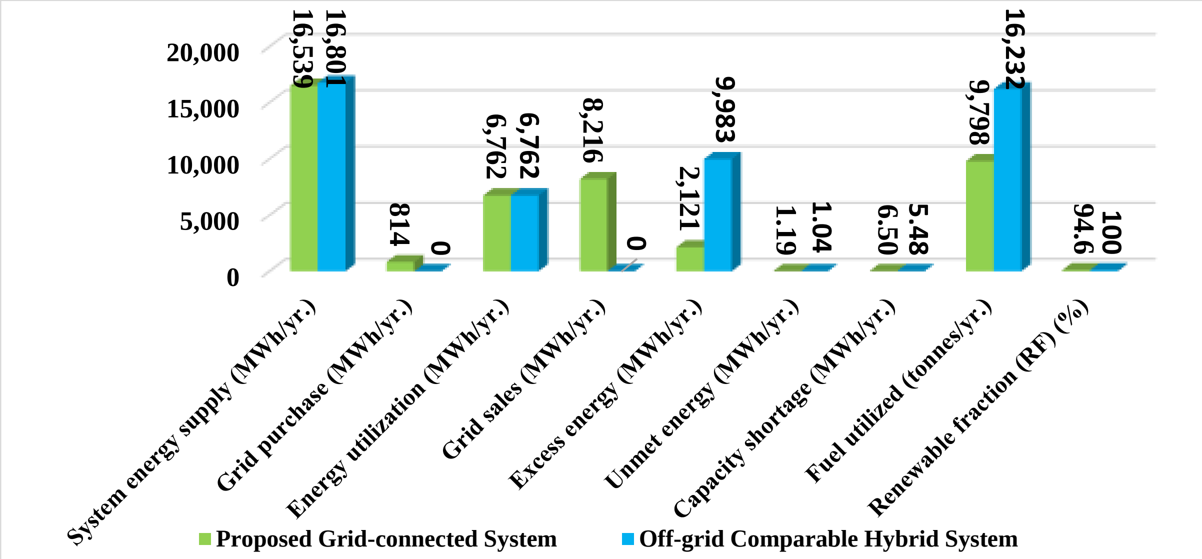
***Table 39:*** *Categorized Optimized Configurations for the Comparable Off-grid System*

| PV (kW) | Wind T. | B. Gen (kW) | Bat. | Conv. (kW) | I. Cap ($) | NPC ($) | RF | Biomass Used (t) | B. Gen / hrs. |
|---|---|---|---|---|---|---|---|---|---|
| **1,500** | **30** | **3,500** | **150** | **1000** | **15.2M** | **51.6M** | **1.00** | **16,232** | **4,194** |
| N/A | 30 | 3,500 | 150 | 400 | 10.3M | 54.3M | 1.00 | 19,585 | 5,074 |
| 200 | | 3,500 | 150 | 1,200 | 12.9M | 62.4M | 1.00 | 22,740 | 5,672 |
| 600 | 20 | 3,500 | | 400 | 11.9M | 63.7M | 1.00 | 22,672 | 5,951 |
| | 30 | 3,500 | | | 9.83M | 65.3M | 1.00 | 24,302 | 6,379 |

***Table 40:*** *Categorized Optimized Configurations for the Proposed Grid-connected System*

| PV (kW) | Wind T. | B. Gen (kW) | Conv (kW) | Grid (kW) | I. Cap ($) | NPC ($) | RF | Biomass Used (t) | B. Gen / hrs. |
|---|---|---|---|---|---|---|---|---|---|
| **2,000** | **30** | **2,500** | **1000** | **1000** | **14.8M** | **16.7M** | **0.95** | **9,798** | **1,722** |
| **-** | - | - | - | - | - | - | - | - | - |

The simulation and optimization results revealed clearly the most feasible optimized configuration with PV of 1,500 kW capacity, converter of 1000 kW, 150 batteries, 30 wind turbines of the specified rating, and the biogas genset of 3,500 kW capacity for the comparable off-grid scenario. This was in contrast to the proposed grid-connected system where its most feasible optimized configuration gave 2,000 kW capacity for the PV component with its accompanied converter having a size of 100 kW, 30 wind turbines with similar specified ratings, and 2,500 kW capacity for the biogas genset component. The in-depth results for the further technical, economic and emissions parameters have been presented in below Figures:




NB: Energy Supply Components Ratio (Off-grid system: PV: 14.60%, Wind T: 56.15%, Biogenset:29.25% / Proposed Grid-connected System: PV: 19.78%, Wind T: 57.04%, Biogenset:23.18%)

***Figure 18:*** *Technical Parameters Results for the Proposed System and Comparable System*

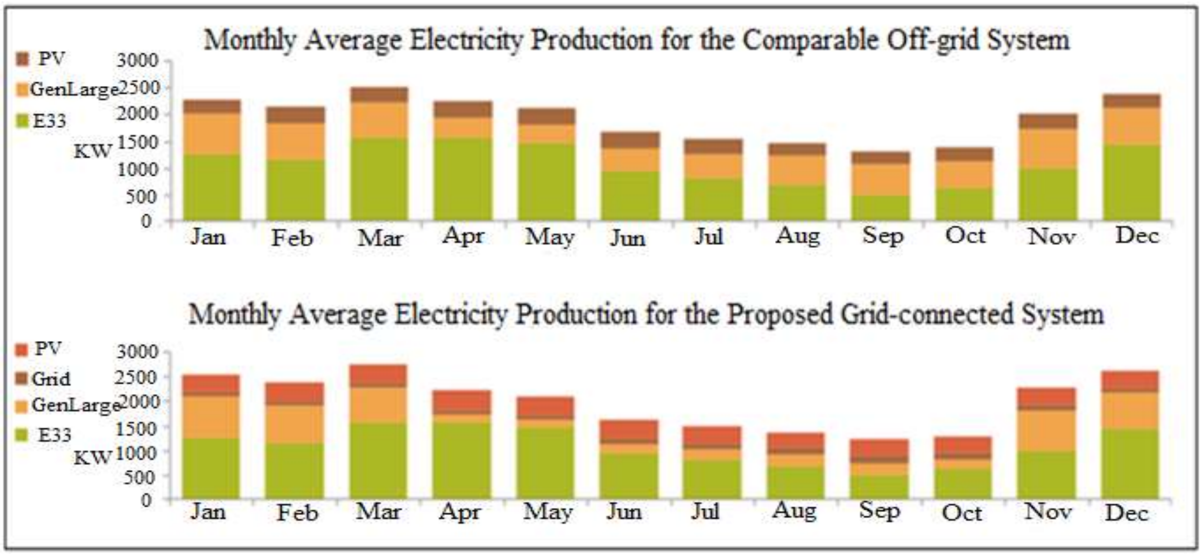



***Figure 19:*** *HOMER Screenshots Monthly Average Energy Production for the Comparable Off-grid System and the Proposed Grid-connected System*

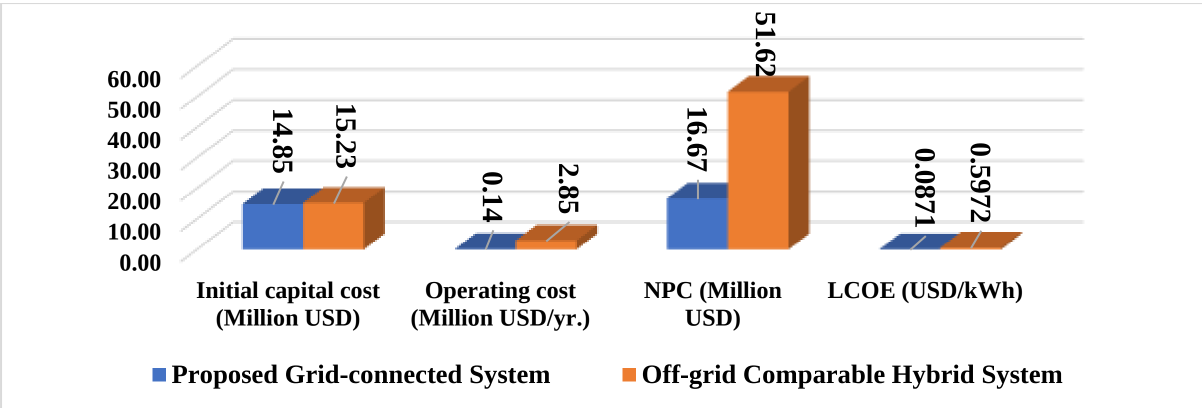
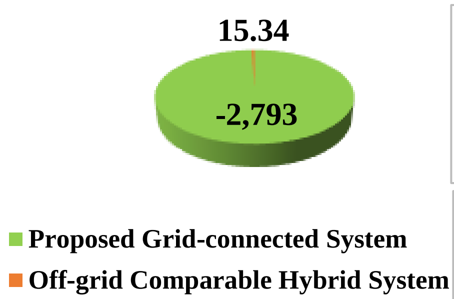



***Figure 20:*** *Economic Parameters Results for the Proposed System and Comparable System (Excel-based)*

**Calculated Net GHG emission / CO2 (tonnes/yr.)**




**Net Emissions / Avoided Emissions for the Utility Grid Case = $(P - S)(X_{G.C.E} - Y^*X_{G.I.R.E})$**
**Where: P = Purchased Energy from the Grid (kWh/yr.), S = Sold Energy to the Grid (kWh/yr.), $X_{G.C.E}$ = Emission factor for Grid Conventional Energy ($kg/kWh_{elec.}$), $X_{G.I.R.E}$ = Emission factor for the Grid-in Renewable Energy ($kg/kWh_{elec.}$), Y = % share of biogenset in the Energy Supply.**

**Net Emissions / Direct Emissions for the Off-grid System Operation = $T^*Y^*X_{R.E}$**
**Where: T = Total Electricity Generated by the System (kWh/yr.) $X_{R.E}$ = Emission factor for the Renewable Energy ($kg/kWh_{elec.}$), Y = % share of biogenset in the Electricity Supply**

***Figure 21:*** *Evaluated Emissions for the Proposed and Comparable System*

The results have clearly shown the other technical and economic parameters determined. Looking at the proposed grid-connected system, it is obvious that the total yearly energy supply was 17,353 MWh, which incorporated both utility-grid sourced or purchased energy as well as the energy produced by the system components. The yearly energy consumption is observed to be 14,978 MWh as divided in to load utilization and grid utilization on excess generations. This is relatively comparable to the off-grid scenario, where the supplied energy from its system component is found to be slightly more and with more excess generations than that of the proposed grid-connected system. Moreover, the fuel consumption in favour of the proposed grid-connected system has obviously reduced by around 40% due to obvious reduction in the optimized capacity rating for the biogas genset from 3,500 kW to 2,500 kW. These technical performance parameters observed have to definitely affect the economics of the system resulting in the huge reduction in NPC as well as the LCOE values by roughly 68% and 67% respectively. The environmental or emission parameter has further shown more benefit of the grid-connected system, in which the greenhouse gas emission value turned to negative as compared to the off-grid slightly positive value. The implication of the negative greenhouse gas emission of the system is the avoided emission as a result of the grid interaction, based on the substituted fossil power from the grid that is a high contributor to greenhouse gas emission. The specified positive emission value for the comparable off-grid case was due to the presence of the biogas genset with its associated direct emission at the operational level as compared to the life cycle basis where the direct emissions turned to neutral. The emissions evaluation formulas for the 2 systems have been displayed in the figure of emissions.

### 3.4.2 Results of the Energy Management Strategies and Evaluations

In line with the energy management or control strategies for the proposed system that was addressed in MS Excel environment based on the Visual BASIC conditional program, the below Figures showed the results for the power generation with load and grid interactions for a typical day in summer and winter. This was broken in to instant energy purchase to the grid, instant energy sold to the grid, and the instant excess/unmet energy after the grid intervention as analysed. These have been based on the defined energy management model of the software. For the typical days considered, the excess/unmet energy after the grid intervention was obviously insignificant. However, the summation of all possible excesses and unmet energy after the grid intervention arising at some hours in the whole year simulation (i.e. 8760 hours) and based on the set limit for grid purchase and sales were quantified as the excess and unmet energy of the system per annum.

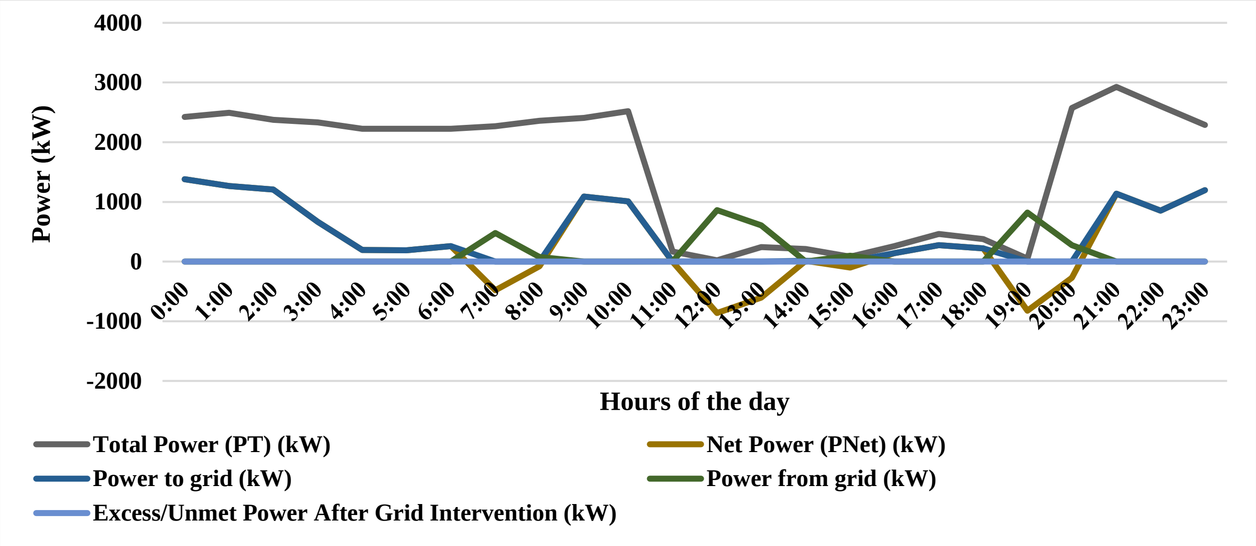



***Figure 22:*** *Power Generation with Load and Grid-interaction for a Typical Day in Summer*

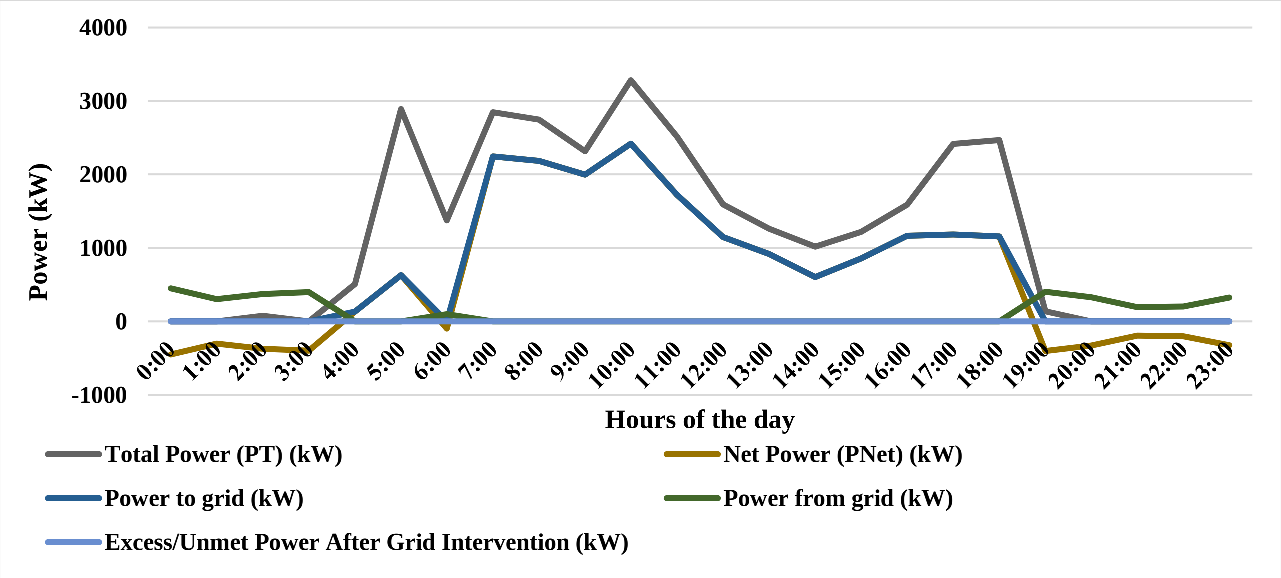



***Figure 23:*** *Power Generation with Load and Grid-interaction for a Typical Day in Winter*

### 3.4.3 Sensitivity Analysis Results for the Proposed Grid-connected System

The sensitivity analysis results have been successfully procured of the different parameters considered. Beginning with the economic-based sensitivity, varying the discount rates obviously affected the operating costs, and ultimately the NPC that is also linked to the operating costs, and the LCOE as shown in its Table below. It is obvious that the increment in the discount rate decreases the NPC, ultimately decreasing the LCOE and operating costs.

On moving to the technical and climate-based parameters, beginning with the scaled annual average solar irradiation sensitivity result as presented in its Table below, it is obvious that the changes affected many other parameters of the system performance. The scaled annual average irradiance increase only affects the optimized sizing for the system component at the 6.06 kWh/m$^2$/d, where the sizing for solar PV and bio-genset changed. Also, the solar PV energy production increases with the increase in the irradiance value all through, which triggers decrement in the bio-genset production due to the flexible nature of the operating hours for the genset as being optimized to depend on the energy supply of other components. The irradiance changes also affected the economic parameters as well as the grid energy purchase and sales with decrease for every increase in the irradiance value. Regarding the scaled annual wind speed variations as presented in its Table below, the optimized sizing for solar PV is affected. This is in view of readjustments of other components in meeting up with the demand in a most economic manner. The energy production values for the different components all vary. These affected the economic parameters as well as the grid energy purchase and sales. The last parameter considered in the sensitivity was the ambient temperature that is linked to the irradiation data in the modelling, with its results in Table 8. In the case of these parameter, the solar PV energy supply was affected in an inverse proportion manner. This is due to the temperature impact on the performance of solar PV modules by lowering their efficiencies. The bio-genset energy supply was seen to increase based on hours of operation altering in ensuring the most economically optimum generations. Ultimately, the grid energy purchase and sales were also altered but mostly in a decreasing manner.

***Table 41:*** *Discount Rate Sensitivity Analysis Results*

| **Discount rate** | **NPC ($)** | **LCOE ($/kWh) / Excel-based** | **Operating cost ($/yr.) / Excel-based** |
|---|---|---|---|
| 4% | 17.2 M | 0.0814 | 0.153 M |
| 5% | 16.9 M | 0.0799 | 0.149 M |
| 6% | 16.7 M | 0.0790 | 0.149 M |
| 7% | 16.5 M | 0.0780 | 0.146 M |
| 8% | 16.3 M | 0.0771 | 0.141 M |

***Table 42:*** *Scaled Annual Average Solar Resources Sensitivity Analysis Results*

| Solar resources (kWh/m$^2$/d) | PV cap. (kW) | B. genset cap. (kW) | PV supply (MWh/yr.) | B. genset supply (MWh/yr.) | Grid energy (MWh) (Purchase / Sales) | Initial costs ($) | NPC ($) | LCOE ($/ kWh) / Excel-based | Operating Cost ($/yr.) / Excel-based |
|---|---|---|---|---|---|---|---|---|---|
| 5.49 | 2,000 | 2,500 | 3,110 | 3,861 | 815 / 8,173 | 14.8M | 16.8M | 0.0801 | 0.156 M |
| 5.78 | 2,000 | 2,500 | 3,272 | 3,833 | 814 / 8,216 | 14.8M | 16.7M | 0.0790 | 0.149 M |
| 6.06 | 2,500 | 2,200 | 3,934 | 3,709 | 789 / 8,139 | 16.0M | 16.1M | 0.0723 | 0.008 M |

***Table 43:*** *Scaled Annual Average Wind Resources Sensitivity Analysis Results*

| Wind resources (m/s) | PV cap. (kW) | Wind T. supply (MWh/yr.) | PV Supply (MWh/yr.) | B. genset supply (MWh/yr.) | Grid energy (MWh) (Purchase / Sold) | Initial costs ($) | NPC ($) | LCOE ($/ kWh) / Excel-based | Operating Cost ($/yr.) / Excel-based |
|---|---|---|---|---|---|---|---|---|---|
| 3.55 | 3,000 | 8,080 | 4,907 | 3,900 | 825 / 8,554 | 18.2M | 20.1M | 0.0931 | 0.149 M |
| 3.74 | 2,000 | 9,434 | 3,272 | 3,833 | 814 / 8,216 | 14.8M | 16.7M | 0.0790 | 0.149 M |
| 3.93 | 1,200 | 10,827 | 1,963 | 3,826 | 809 / 8,186 | 12.2M | 13.7M | 0.0645 | 0.117 M |

*Table 44: Scale Annual Average Ambient Temperature Sensitivity Analysis Results*

| Ambient temperature (˚C) | PV supply (MWh/yr.) | Bio-genset supply (MWh/yr.) | Grid energy (MWh) (Purchase / Sold) |
|---|---|---|---|
| 23.7 | 3,291 | 3,831 | 813 / 8,220 |
| 25.0 | 3,272 | 3,833 | 814 / 8,216 |
| 26.2 | 3,253 | 3,838 | 813 / 8,212 |

### 3.4.4 Results of the Energy Efficiency (EE) Assessment

Concerning the Energy Efficiency (EE) assessment analysed input specifications, the detailed breakdown of the results has been presented in the below Figures for the in-depth technical, economic and emissions aspects respectively. The baseline optimized configurations for the proposed grid-connected system having put forward previously was PV (2000 kW), converter (1000 kW), wind turbine (30 pieces of similar specified capacity rating), and biogas genset (2,500 kW). The energy efficiency analysis optimized configurations showed a reduction on the genset component to a capacity of 800 kW, and a reduced solar PV component size to 400kW with its accompanied converter of 200 kW, leaving the sizing for the wind turbine unchanged.

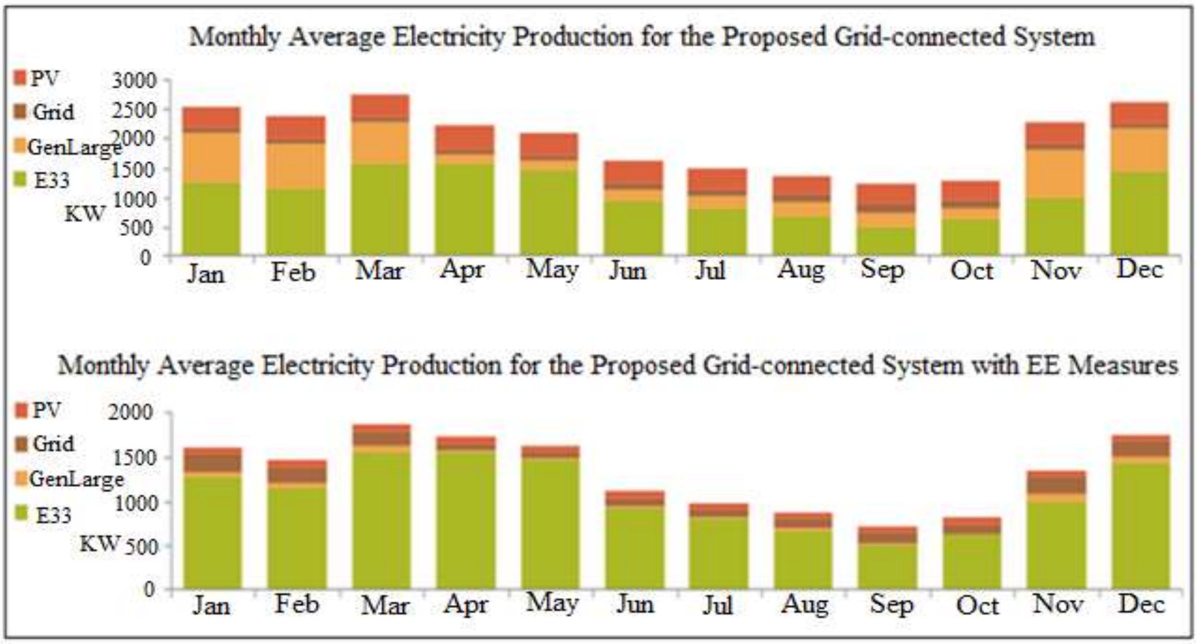
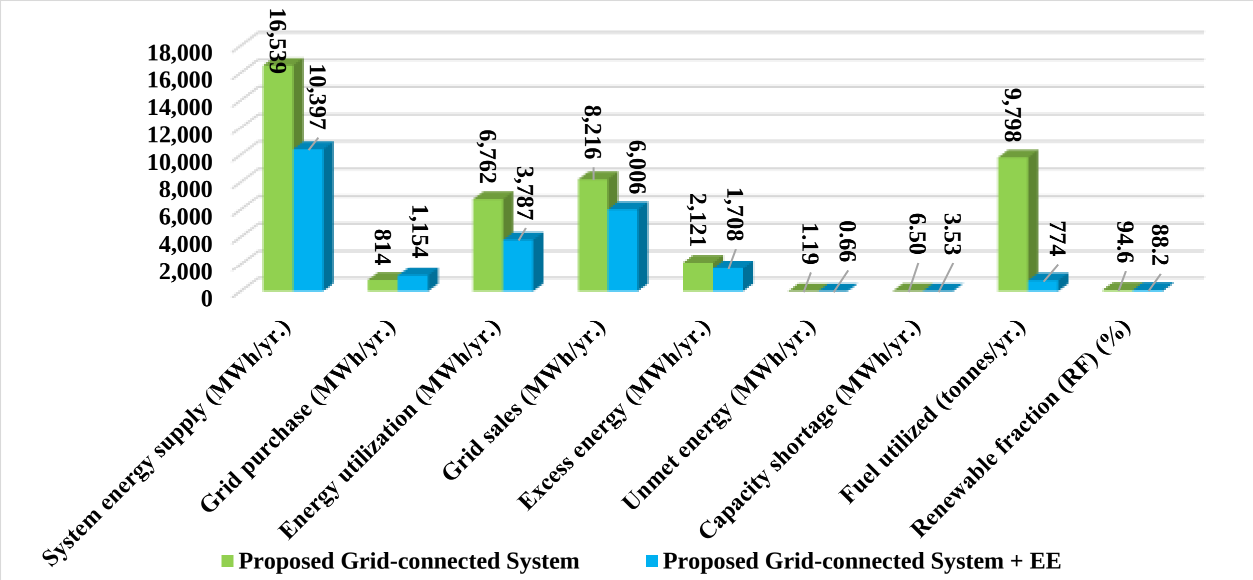



***Figure 24:*** *HOMER Screenshots Monthly Average Energy Production for the Proposed System and its Energy Efficiency Adoption Case*




NB: Energy Supply Components Ratio (Proposed Grid-connected System: PV: 19.78%, Wind T: 57.04%, Biogenset:23.18% / Proposed Grid-connected System + EE: PV: 6.29%, WT: 90.74%, Biogenset:2.97%)

***Figure 25:*** *Technical Parameters Results for the Proposed System and its EE Measures*

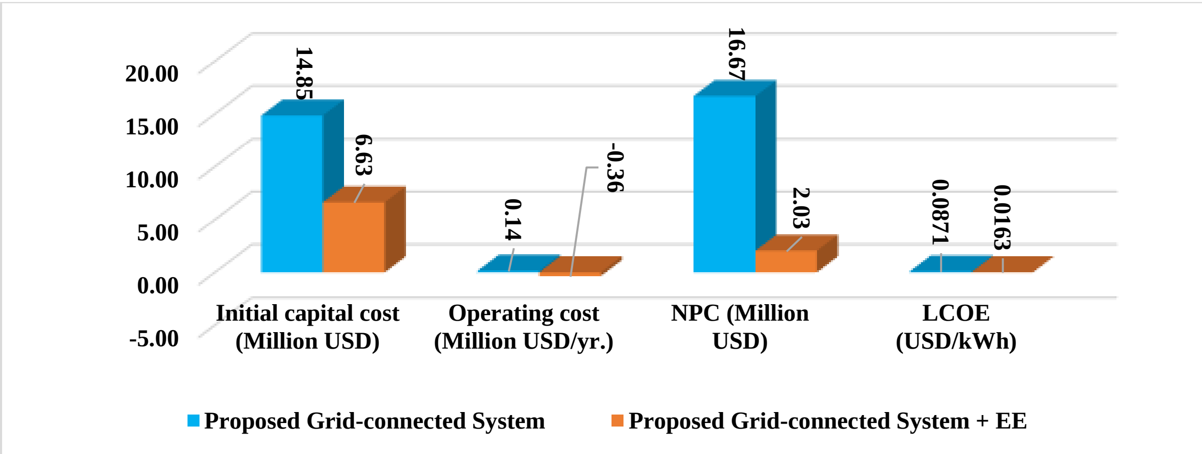



***Figure 26:*** *Economic Parameters Results for the Proposed System and its EE Measures (Excel-based)*

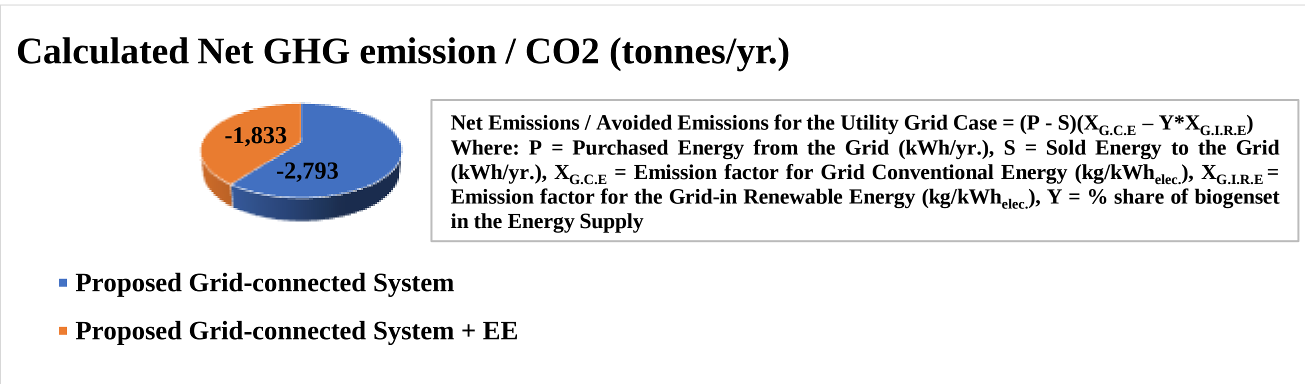



***Figure 27:*** *Evaluated Avoided Emissions for the Proposed System and its EE Measures*

The reduction in the optimized component sizing for the new load demand arising from the efficient appliances switching resulted in energy supply reduction by 37% (i.e. from 16,539 MWh/yr. to 10,397 MWh/yr.). This has also affected the consumption ultimately as clearly seen. Regarding the fuel consumption, reduction is noticed by around 44% in favor of the energy efficiency case. The economic parameters, specifically the NPC has been drastically reduced by 88%, while the LCOE by 81% despite the cost implications of the energy efficiency measures put forward. However, avoided greenhouse gas emission is seen to reduce by around 34% based on the displayed emission formula in the Figure 15, and it's as a result of the reduced net energy of the system available in the grid.

### 3.4.5 Supplementary Economic Benefits Analysis Result

In ascertaining further, the supplementary economic benefits of the proposed grid-connected system from the comparable base case standalone system having analysed in Microsoft Excel showed amazing outcomes in the below table. It is obvious that the net of the NPC values indicating the saved amount of money in the transitioning to the proposed grid-connected system has been closed to $35 Million. This amount on the annuity analysis that incorporate the discount factors, capital recovery factor, and the project life span led to a simple payback period of about six years, as well as a discounted payback period of about seven years. This payback periods could be interpreted as the years required in realizing the total costs needed in the implementation of the proposed grid connected system from the saved amount of money in the system switch over both with and without the benefits discounting. Ultimately, a return on investment in the switch over has been estimated to be around 16%, which is nearly similar to the internal rate of return.

***Table 45:*** *Economic Benefits Analysis of the Proposed Grid-connected System from the Base Case Off-grid System (Excel Results)*

| Analysed parameters | Specification |
|---|---|
| Calculated Capital Recovery Factor (CRF) | 0.0782 |
| Net of NPC as benefit of the switch to the proposed grid-based system | $34.96 M |
| Calculated annualized value of the benefit | $2.73 M |
| Calculated Payback Period (PBP) | 6.09 years |
| Discounted Payback Period (DPBP) | 7.18 years |
| Calculated Rate of Return (ROI) | 16.41% |
| Calculated Internal Rate of Return (IRR) | 16% |

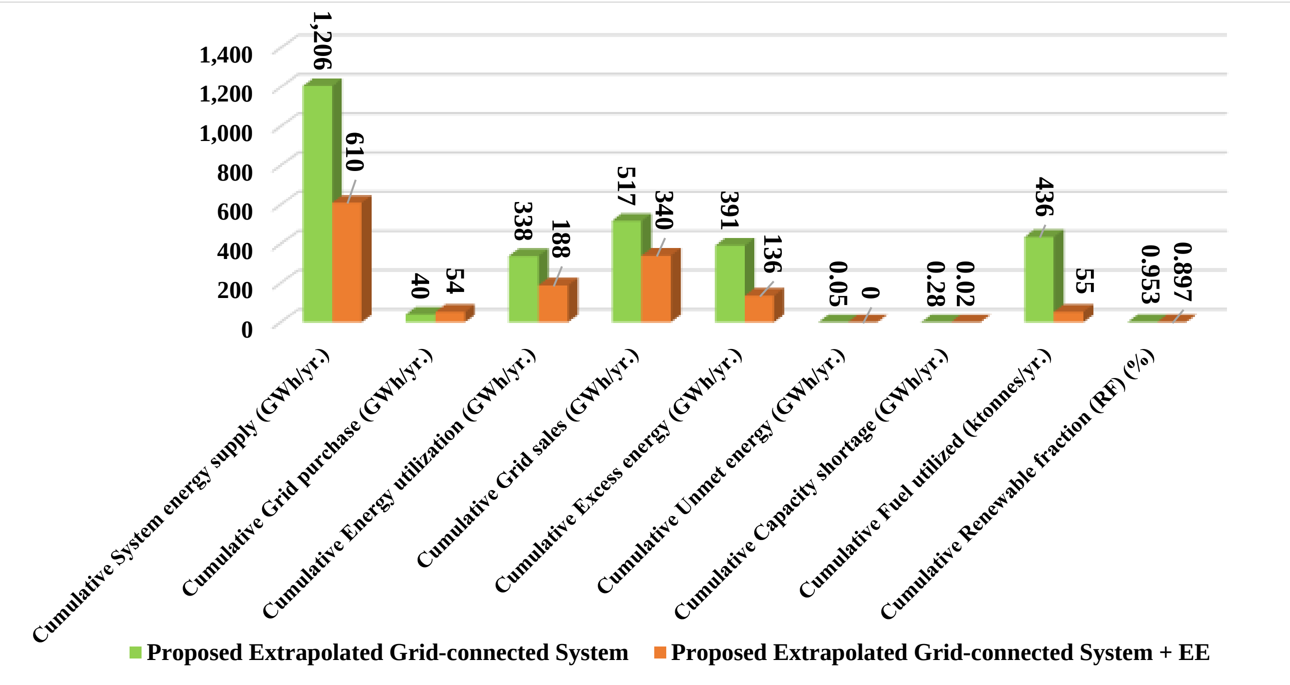
Similarly, in ascertaining the benefits of adopting the energy efficiency to the proposed grid-connected system basing on the save amount of money in such switchover from the grid-connected system being the base case in this regard, similar analysed parameters have been achieved. The saved amount being closed to $15 Million in the switch over led to a payback period of 1.78 years, a discounted payback period of 1.99 years, and ultimately a return on investment as well as an internal rate of return of all approximately 56%. The impact in this scenario is even more rewarding as compared to the impact in the preceded analysis of the grid-connected system to the base case standalone system. This is due to lesser number of years in the recovery of the total investments and a more return. Table below summarized the whole results of the excel analysis in the comparison.

***Table 46:*** *Economic Benefits Analysis of the Switch to the EE-based System from the Grid-connected System (Excel Results)*

| **Analysed parameters** | **Specification** |
|---|---|
| Calculated Capital Recovery Factor (CRF) | 0.0782 |
| Net of NPC as benefit of the system switch to EE-based system | $14.63 M |
| Calculated annualized value of the benefit | $1.14 M |
| Calculated Payback Period (PBP) | 1.78 years |
| Discounted Payback Period (DPBP) | 1.99 years |
| Calculated Rate of Return (ROI) | 56.25% |
| Calculated Internal Rate of Return (IRR) | 56% |

### 3.4.6 Results of the Extrapolation at bigger capacity

On the last bit of the assessment, i.e. the overall extrapolations at bigger capacities based on its analysed input specifications already presented, the optimization results were solar PV and converter (5 MW & 1.2 MW), genset (120 MW), wind turbines (3,500 pieces of similar specified rating). The energy efficiency-based optimization results led to solar PV and converter (1.2 MW & 800 kW), genset (60 MW), and wind turbine (2,000 pieces of similar specified rating). Further results have been presented in the below figures regarding the technical, economic and the emissions aspects.




NB: Energy Supply Components Ratio (Proposed Extrapolated Grid-connected System: PV: 0.7%, Wind T: 85.0%, Biogenset:14.3% / Proposed Extrapolated Grid-connected System + EE: PV: 0.3%, WT: 96.1%, Biogenset:3.6%)

***Figure 28:*** *Technical Parameters Results for the Proposed Extrapolated System and its EE Measures*

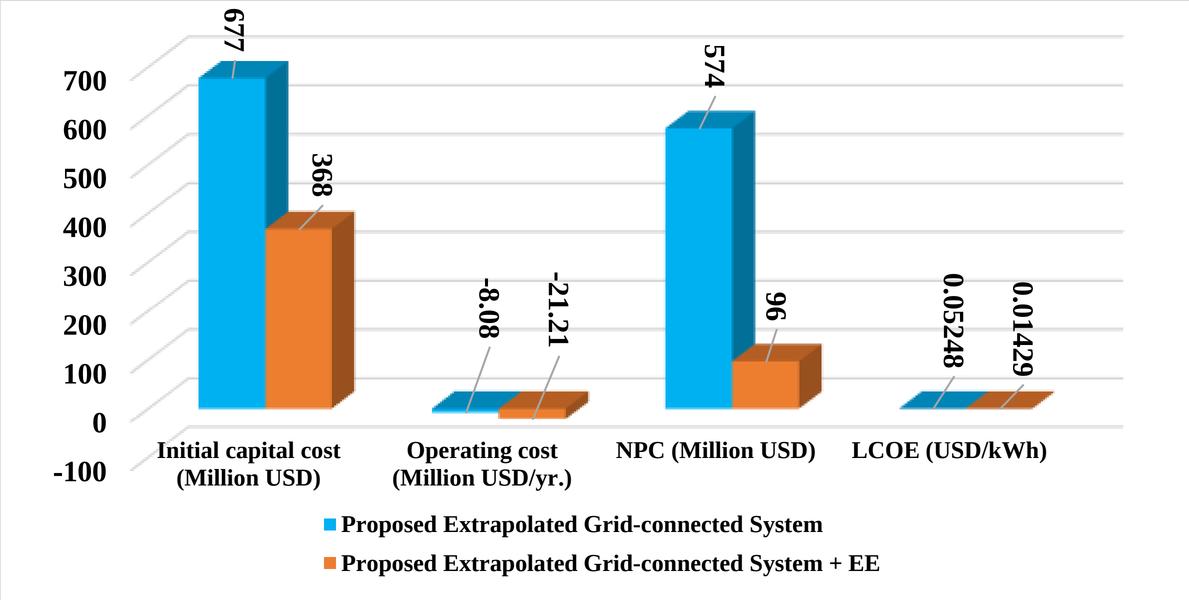



***Figure 29:*** *Economic Parameters Results for the Proposed Extrapolated System and its EE Measures*

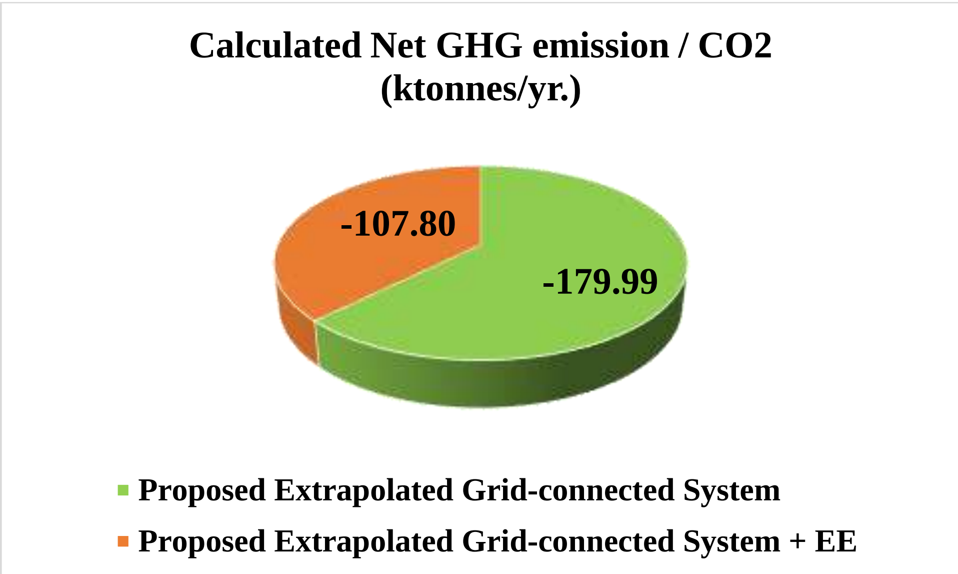



***Figure 30:*** *Evaluated Emissions for the Proposed Extrapolated System and its EE Measures*

The results of the system extrapolation at bigger capacity has been monitored in the above figures based on all the parameters, as a clear reflection of the previous results in close percentages margin. The close margins where specifically regarding the distinctive measure in the proposed system with and without the efficiency measures extrapolated. For example, the cumulative energy production has been observed to decrease by 29%, whereas the economic parameters, i.e. the cumulative NPC and cumulative LCOE on average have been on 40% reduction and 6% increment respectively. In overall, the economic performance parameters could be compared with the results prior to the extrapolations and could be deduced that economy of scale had played an important role on the extrapolation process.

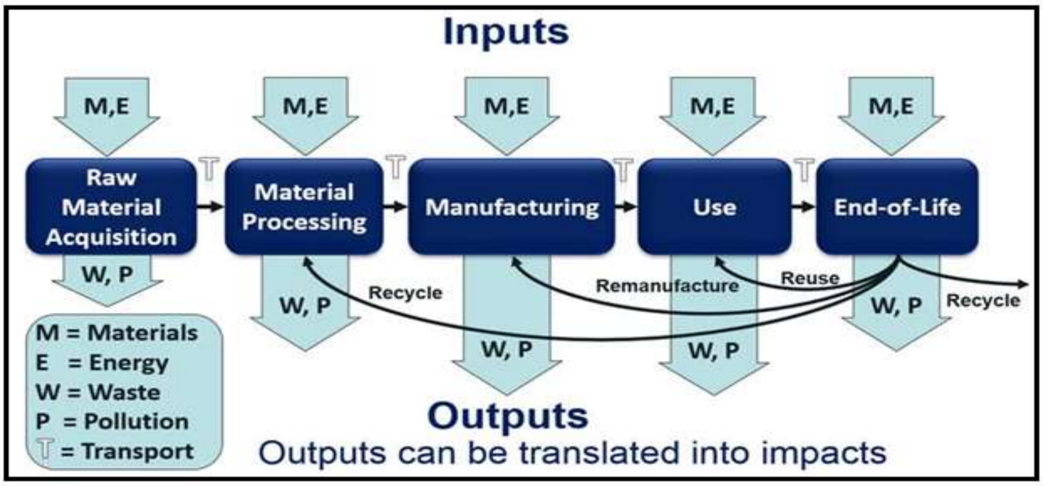
## 3.5 Environmental Life Cycle Assessment of the Proposed Grid-connected System

### 3.5.1 Environmental Life Cycle Assessment General background

To proceed with the overall environmental assessment of the proposed power system, life cycle assessment (LCA) is a key, and basically entails holistic assessment of a material, product, process, or service on its environmental impacts over its entire life cycle (i.e. from cradle to grave) (Kelly, 2016). In this regard, many software packages with extensive databases comprising of inventory data sets in a wide a range of areas necessary and sufficient for conducting any LCA have been developed. The Environmental Protection Agency (EPA) has identified and vividly described around 25 software packages each having different features but similar concepts however, the commonest used ones are the Ganzheitliche Bilanz (GaBi) and System for Integrated Environmental Assessment of Products (SIMAPRO) (Kelly, 2016).

LCA gives enlightenment strongly on production and consumption chain for prompt and proper decision making. Therefore, the motivation behind the study is to address natural resources depletion as well as environmental degradation in making a proper decision as to what is appropriate and sustainable for the environment. This is because human survival and their living standard level strongly depend on their environment either directly or indirectly.

The general principle for life cycle assessment from raw material extraction to the end of life showing the various inputs and outputs could be depicted in the below figure proposed by the US Department of Transportation Federal Highway Administration (2017).




Source: US Department of Transportation (2017)

***Figure 31:*** *Generic Life Cycle Assessment of a Production System*

Regarding the Impact assessment, further details could be necessary on the impact category in displaying its possible subdivisions. These subdivisions could be based on the fundamental methods applied namely ReCiPe developed by the Radboud Universiteit Nijmegan and CE Deff, the Centre for Environmental Studies methodology (CML) of the University of Leiden, the Tool for Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) developed by the Environmental Protection Agency (EPA) etc. These further subdivisions of the Impact Category are highlighted in the below table as proposed by the PE International Sustainability Performance (n.d).

***Table 47:*** *Some of the Methodologies for Impact Assessment (Impact Category Subdivisions)*

| Impact Category (CML Method) | Unit | Impact Category (TRACI Method) | Unit | Impact Category (ReCiPe Method) | Unit |
|---|---|---|---|---|---|
| Global Warming Potential (GWP 100 Years) | Kg $CO_2$ eq. | Global Warming Air | kg $CO_{2\,e}$q. | Climate Change | kg $CO_{2\,e}$q. |
| Ozone Layer Depletion Potential (ODP, Steady State) | kg R-11 eq. | Ozone Depletion Air | kg CFC-11 Eq. | Ozone Depletion | kg CFC-11 eq. |
| Acidification Potential (AP) | kg $SO_2$ eq. | Acidification Air | Mol $H^+$ eq. | Terrestrial Acidification | kg $SO_2$ eq. |
| Eutrophication Potential (EP) | kg Phosphate eq. | Eutrophication Air / Eutrophication Water | kg N eq. | Fresh Water Eutrophication | kg Phosphate eq. |
| Photochemical Ozone Creation Potential (POCP) | kg Ethene eq. | Smog Air | kg $NO_x$ eq. | Fossil Depletion | kg Oil eq. |
| | | | | Fresh Water Ecotoxicity | kg DCB eq. |
| Human Toxicity Potential (HTP) / Terrestrial Ecotoxicity Potential (TETP) | kg DCB eq. | Human Health Cancer Air / Human Health Cancer Water | kg Benzene eq. | Terrestrial Ecotoxicity | kg DCB eq. |
| | | | | Human Toxicity | kg DCB eq. |
| Fresh Water Aquatic Ecotoxicity Potential (FAETP) / Marine Aquatic Ecotoxicity Potential (MAETP) | kg DCB eq. | Ecotoxicity Air / Ecotoxicity Water / Ecotoxicity Soil | PAF $m^3$ day/kg | Ionizing Radiation | kg U235 eq. |
| | | | | Particulate Matter Formation | kg PM10 eq. |
| | | Human Health Non-Cancer Air / Human Health Non-Cancer Water | kg Toluene eq. | Photo-chemical oxidant formation | kg NMVC |
| | | | | Water Depletion | $m^3$ |
| Abiotic Depletion Potential (ADP) | kg Sb eq. | Human Health Criteria Air Point Source | kg PM10 eq. | Metal Depletion | kg Fe eq. |
| | | | | Natural Land Transformation | $m^2$ |

*Key: R-11 / CFC-11 – Trichloro Fluoro Methane, DCB – 1,4 Dichloro Bemzene, Sb – Antimony, PM – Particulate Matter, DCP – Dichlorophenoxyace, U235 – Uranium, Fe – Iron, PAF – Potentially Affected Fraction etc.*

Source: PE International Sustainability Performance (n.d)

Moreover, different varieties of data sources or databases applicable to LCA exist, which are integrated to the LCA analytical software packages. One of the commonest databases is the Eco-invent, which contains international industrial life cycle inventory data on many aspects viz. energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transportation services (Thinkstep GmbH, n.d). Another database used is the U.S Life Cycle Inventory (LCI) Database. This database offers a cradle to grave accounting of the energy and material balances with reference to the environment that are associated with producing a material, component or assembly (Thinkstep GmbH, n.d). Another available database for LCA is the Inventory of Carbon and Energy (ICE) database providing carbon and energy data for copious materials associated with construction industry (Kelly, 2016) and lots more. Based on the above information, Anoop et al (2013) proposed 2 basic approaches to LCA viz. Attributional and the Consequential approach. The Attributional LCA approach describes the physical flows to and from the LCA system as well as the potential environment impacts associated while the Sequential LCA approach describes the environmental consequences of possible future altering of physical flows from and to LCA system environment change in response to decisions. The following table gives clearly the distinction between the 2 approaches as suggested by Roland (2014).

***Table 48:*** *Distinctions in the Two Basic LCA Approaches*

| **Attributional Approach** | **Sequential Approach** |
|---|---|
| Defines functional units / static situation | Define changes in product system |
| Identify and describes states of all unit processes | Identify and describes initial states of all unit processes |
| Scale unit processes to the required input or output | Model relevant physical and social processes |
| Solve all allocation issues | Describe new states of all affected unit processes |
| Utilizes average and historical inventory data | Utilizes marginal and future inventory data |
| Sensitive to uncertainty | Higher sensitivity to uncertainty |
| Physical mechanisms on cause-effect chains | Physical and market mechanisms on cause-effect chain |

Source(s): Roland, 2014; Anoop et al, 2013

The LCA of renewable energy production systems is somewhat complicated due to the challenging task of data collection. Careful design on the goal and scope definition, choice of functional units, reference systems, system boundaries, as well as appropriate inventory establishment with allocations to emissions (greenhouse gases and pollutants) in products and by-product is needed (Anoop et al., 2013). The sustainability of renewable energy solutions on balancing the socio-economic and the environmental pillars is very necessary to be ascertained and has to follow a holistic approach using LCA tool.

Based on the above information, it is noted that many studies were conducted of power systems in ascertaining their life cycle assessment impacts for decision making. A lot have been reviewed and analysed in ascertaining the uniqueness and novelty of the environmental LCA offered in this research as a linkage to the already conducted modelling and optimization task of the power system. The summary of the reviewed studies was given in the table below:

***Table 49:*** *Summary of the Power System LCA Studies Consulted*

| **Reference** | **Location / year** | **Main content (Research approach and observation)** |
|---|---|---|
| Luo et al. | Singapore / 2018 | Life cycle energy performance and greenhouse gas emission analysis approach for PV generations (Multi-crystalline technologies). PERC solar cells with frameless double glass-module was observed with lowest energy payback and greenhouse gas emission in the scope of materials considered. |
| Li et al. | North East of England / 2017 | Full sustainability impacts assessment on LCA ground for solar PV. Solar availability was proved to have direct impact on the sustainability pillars however, the costs implications required proper policy shaping in its favor. |

| | | |
|---|---|---|
| Liptow et al. | Sweden & Brazil / 2018 | Global warming potential and land use impact evaluations for biomass-based products. Land use impacts was observed to have a profound effect on the GWP. |
| Jones et al. | 2017 | Benefits and limitations qualitative approach for consequential LCA and NEA of decentralized power. It was ascertained that the combined LCA and NEA approach are appropriate, provided a number of policy related issues are addressed |
| Siddiqui & Dincer | Ontario, Canada / 2017 | CML 2015 LCA based approach with GaBi employed for nuclear, wind & hydro, with different environmental impact indicators analysed. Sensitivity analysis covered on recycle rates. Hydro had the least GWP. Increased recycling rate lowered the env. Impacts |
| Uddin & Kumar | Thailand / 2014 | Energy and environmental impact performance based LCA approach for wind technologies using SimaPro. The vertical axis turbine was found to be energy and emission intensive. |
| Atilgan & Azapagic | Turkey / 2016 | GaBi too based analysis based on CML 2001 approach for different renewable power plants. Many env. impact categories analysed. Impacts from large hydropower was observed to be lower than for small hydropower. Other observations were provided in the study. |
| Rajput et al. | India / 2018 | Energy performance and costs-based LCA approach for a PV CdTe PV technology. The embodied energy and the energy payback were observed to be low as compared to c-Si PV technology. |
| Santoyo-Castelazo and Azapagic | Mexico / 2014 | Environmental LCA and LCC, social sustainability and multi-criteria decision analyses were the approaches for the sustainability of different future energy supply. It was observed that BAU fossils are not sustainable regardless of the criteria preference. Higher renewable and nuclear penetration are the most suitable in meeting the low carbon future target. |
| Repele and Bazbauers | Latvia / 2015 | Recipe and EcoIndicator ''99'' environmental based LCA approaches were employed for biofuels to heat system. High impact reduction was observed especially for biogas and 2nd generation biofuels from natural gas utilization. |
| Menoufi et al. | Spain / 2017 | Energy performance measures and environmental indicators were applied for LCA of BIPV and BACPV technologies. It was observed that the BACPV has lower env. Impact than the BIPV. BACPV has lower energy payback and higher energy return factor than BIPV. |
| Ristimari et al. | Finland / 2013 | Different energy systems i.e. heat and power with hybrid-based LCA was done by life cycle carbon emission and LCC approach. It was observed that the system with the highest initial cost is the most viable on life cycle ground. |
| Ayodele et al. | Nigeria / 2017 | Electricity generation potential and environmental impact based LCA approach for waste to energy technologies including hybrids (power) addressed. Some of the observations is the Incineration/Anaerobic Digestion is more viable in terms of GWP and AP. |
| Petrillo et al. | Egypt / 2016 | Env. LCA and LCC based on EcoIndicator ''99'' was addressed for off-grid renewable power systems both singly and in hybrids. |
| Wang et al. | Beijing, China / 2015 | LCA optimization was conducted of solar-aided trigeneration system. The optimization approach was based on configuration and load operational variability for env. Impact minimization. It was observed that minimizing the total env. impact potential for non-benefit case i.e. benefit surplus products excluded from CCHP, following an electric load is the objective with the lowest env. Impacts |

### 3.5.2 The LCA Approach Conducted

The approach followed an exemplary life cycle stages based on the "ISO 14044". This standard defined in much details, the goal and scope, the inventory analysis with its broad discussions, leading to the different LCA impact parameters evaluations.

#### 3.5.2.1 Goal and Scope Definition

The ultimate goal of the LCA work has been to investigate in details, the environmental impact on life cycle ground as well as the best hybrid option(s) in the proposed power system for the grid integration. This is in favor of improved decision making in the energy operations. The Functional Unit (FU) that defines the reference flow for the systems and models' comparison has been scaled down to "unit kWh of electricity generation'', with all the arguments in the analyses basing on it.

Regarding the scope, of all the different scenarios analysed in the inventory part, the overall mass balance analysis for different elementary flows was looked in to, coupled with in-depth environmental impact categories evaluations based on the selected "LCIA-CML 2015 attributional-based approach". The selected impact categories within the limit of this research were the Global Warming Potential (GWP), Acidification Potential (AP), Ozone layer Depletion Potential (ODP), Eutrophication Potentials (EP), Human Toxicity Potential (HTP), and Abiotic Depletion Potential ($ADP_{fossils}$). Accompanied impact categories evaluations was then the impact data uncertainty analysis. In all cases, the analyses have been on a cradle to grave basis. The different components or technologies in the scenarios were based on medium operational conditions for production in the mix, having being predicted by researchers to be the main world market. Regarding the system boundary, different materials and energy inputs and outputs were incorporated as the life cycle flows. These include agricultural related materials, radioactive-based materials, water, organic-based materials, volatile organic compounds, halogenated materials, heavy metals, as well as all the necessary energy inputs and the electricity outputs of the different processes involved in the different models and so on.

#### 3.5.2.2 Inventory Analysis

The inventory analysis for the research begins with the collection and analysis of the Nigerian electricity generation data of a given 2014 baseline year, which is 29,729 GWh, having a mix of ~60% natural gas, ~20% oil, and ~20% hydropower as obtained from shift project data portal (n.d). However, the overall task was based on the optimization results of HOMER software for grid-connected solar PV, wind turbine, and biomass-gasified power components of the power system exercise done prior to its energy efficiency and extrapolation assessments. This was based on the resource data obtained and other various input specifications and evaluations. Only the optimization results have been brought forth for the LCA. The optimized results were on an attempt to supply energy to 200 households (1,200 persons in total) in the considered site, with a peak load of 4 MW. The annual analysed load profile for the site has been brought here in the below Figure, and the optimization results summary in addressing the load demand as applicable to the environmental life cycle analyses was shown in the below Table.

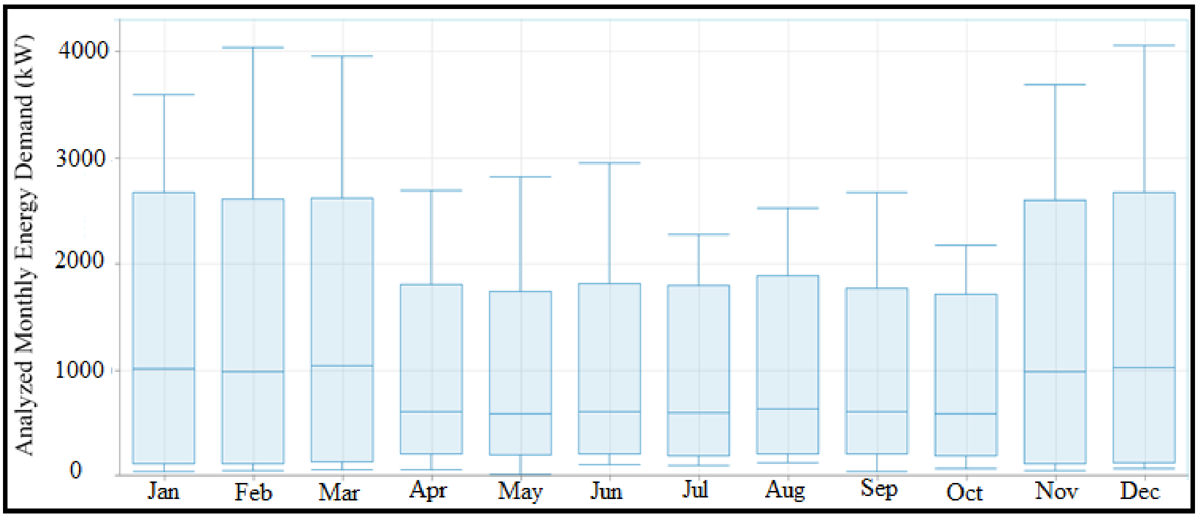



***Figure 32:*** *The Site's Analysed Monthly Energy Demand Data for the HOMER Optimization*

***Table 50:*** *HOMER Optimization Results for the Site as Input to the LCA Assessment.*

| **Optimum parameters** | **Specification** |
|---|---|
| Optimized configuration | PV System: 2,000 kW; Wind Turbine: 30 Pieces (330 $kW_{rated}$ each); Biogas System: 2,500 kW |
| Energy production from solar PV subsystem | 3.27 GWh/yr. |
| Energy production from wind turbine subsystem | 9.43 GWh/yr. |
| Energy production from biomass-gasified subsystem | 3.83 GWh/yr. |
| Total energy production | 16.53 GWh/yr. |

From the optimization results presented, with the cumulative energy production of about 16.53GWh/yr., and the shares of the subsystem components, different scenarios were formulated. The first being the conventional system scenario based on the country's baseline generation data of 2014, and considered as the grid-only power case. The other scenarios were the hybrid renewable grid-integration, based on the shares of contributing subsystems in the total for each case in the optimization results of the table 3. The analysis of the different scenarios with the assumptions made were presented in the below Table.

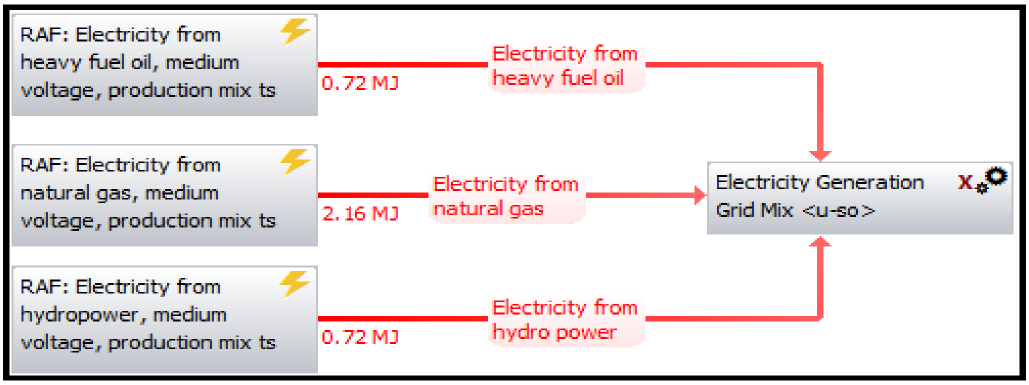
***Table 51:*** *The Different Scenarios with their Analysed Mix Ratios.*

| **Scenarios with description and assumptions** | **Mix specification** |
|---|---|
| 1st Scenario: Assuming the 16.53 GWh is being sourced from the grid. i.e. grid-only power for the demand side, taking the baseline 2014 generation mix path of the country. | Total - 16.53 GWh<br>(Generation mix below)<br>N.G - ~60%<br>HFO - ~20<br>Hydro - ~20% |
| 2nd Scenario: Assuming the 16.53 GWh goes to scaled hybrid PV/wind power solely, by neglecting the bio-genset component of the HOMER results in the study location. | Total - 16.53 GWh<br>(Generation mix below)<br>Solar PV - ~25.75%<br>Wind power - ~74.25% |

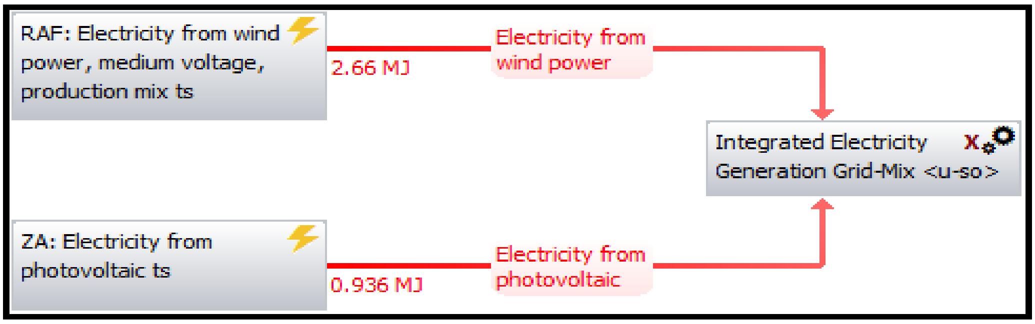
| | |
|---|---|
| 3rd Scenario: Assuming the 16.53 GWh goes to scaled hybrid PV/biomass-biogas power solely, by neglecting the wind power component of the HOMER results in the study location. | Total - 16.53 GWh (Generation mix below) Solar PV - ~46.05% Biomass-biogas Power - ~53.95% |
| 4th Scenario: Assuming the 16.53 GWh goes to scaled hybrid wind/biomass-biogas power solely, by neglecting the solar PV component of the HOMER results in the study location. | Total - 16.53 GWh (Generation mix below) Wind power - ~71.11% Biomass-biogas power - ~28.89% |
| 5th Scenario: Maintaining the 16.53 GWh for each share in the hybrid PV/Wind/Biomass power integration of the HOMER results in the study location. | Total - 16.53 GWh (Generation mix below) Solar PV - ~19.78% Wind power - ~57.04% Biomass-biogas power - ~23.18% |

Note: The whole scenarios were scaled down to 1kWh FU each as reference flow for the comparative analyses.

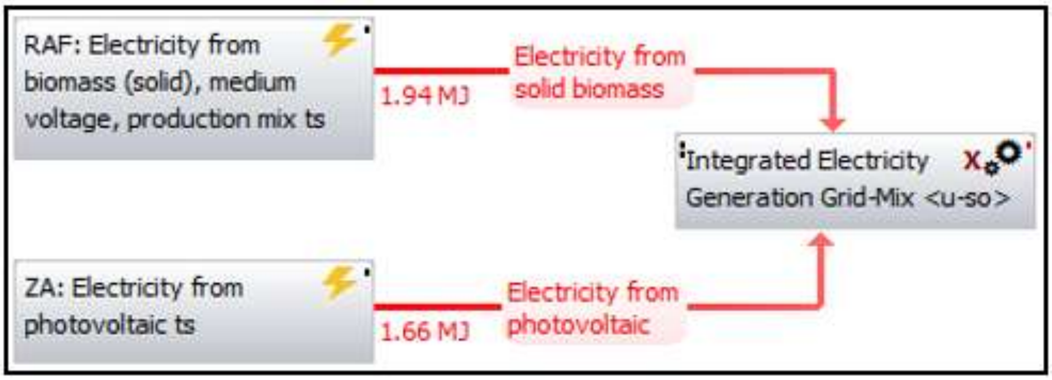
The block diagrams of all the concerned scenarios analysed in above Table of the environmental life cycle assessment have been provided in the below Figure as the analysed GaBi models.



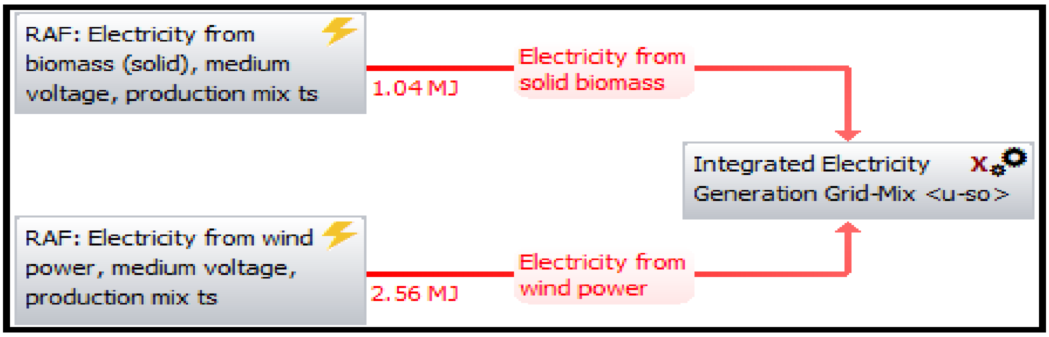

a) 1st Scenario (The grid-only Power / HFO/Gas/ Hydro Conventional Power System)



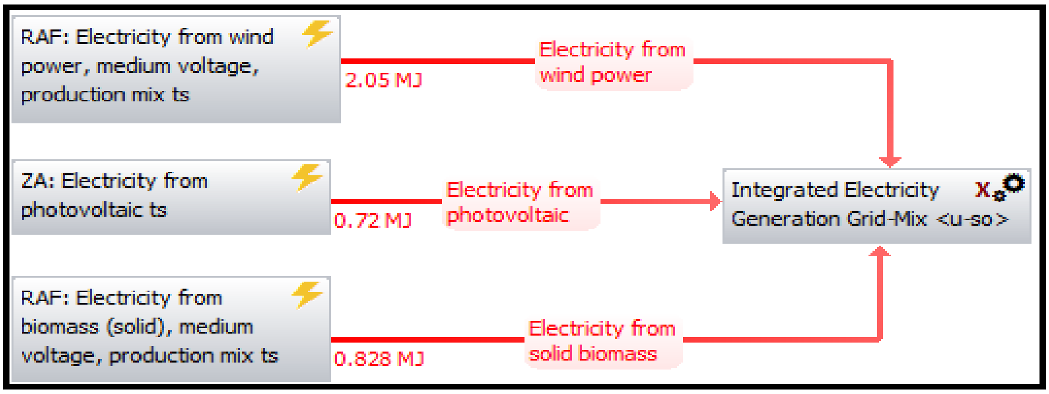

b) 2nd Scenario (PV/Wind Integrated Power System)




c) 3rd Scenario (PV/Biomass-biogas Integrated Power System)




d) 4th Scenario (Wind/Biomass-biogas Integrated Power System)




e) 5th Scenario (PV/Wind/Biomass-biogas Integrated Power System)

***Figure 33:*** *Models for the Different Scenarios Developed in GaBi. [Note: The 1 kWh FU is equivalent to the 3.6MJ total reference flow in each of the scenarios shown]*

In line with the different analysed mix data having shown in figure 4, the GaBi software electricity processes data used for the different technologies involved were electricity generation from natural gas, electricity generation from hydropower, electricity generation from solar PV, electricity generation from wind power, and electricity generation from biomass-biogas power. These were mostly ''RAF'' data, i.e. data for the African continent on average, however, for the photovoltaic process, the South African data was incorporated being also an African based data due to the absence of RAF data in that regard. The specified year interval from the database was from 2014 to 2020, hence a 6-year validity. The application of the RAF data all through, coupled with the application of South Africa (ZA) data for the photovoltaic process becomes necessary and worth doing. This is because they are African continent analysed data, and based on African regulations, efficiency of operations and equipment. This in overall were due to the absence of data specifically for the case study country point of view.

Lastly, in view of the nature of the data collected for the concerned processes having highlighted in the preceded paragraph, uncertainty analysis has been ensured based on the pedigree matrix data, coupled with excel program in accounting for the different variations in the impact data as a quality measure. This incorporates basic uncertainties, as well as the different default uncertainty factors with their level assignments for the different processes in getting the overall uncertainties and standard deviations which are applicable for the band estimations of the impacts data. The data distributions considered were lognormal and normal, based on a confidence interval of 68%.

The overall and summarized approach for the environmental life cycle assessment task to the hybrid power system has been presented in the below Figure, in a block flow for more clarity to the readers.

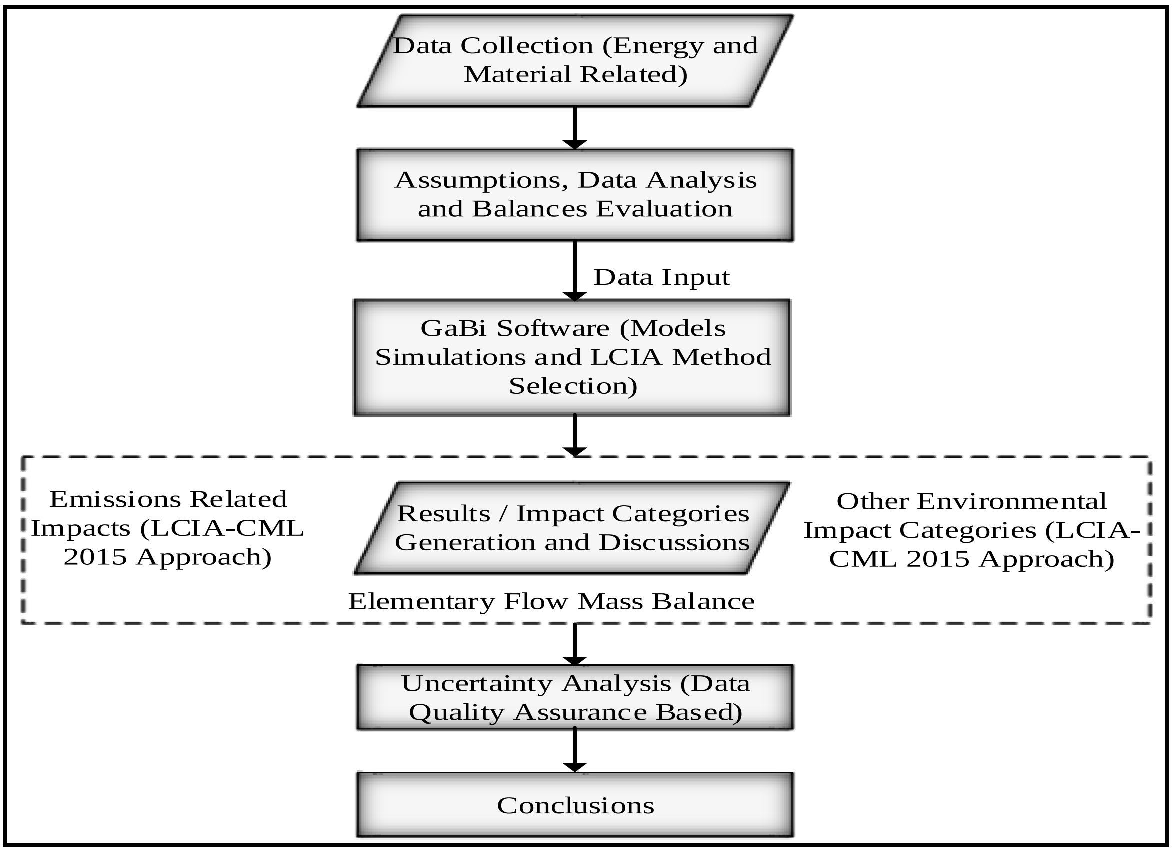



***Figure 34:*** *The LCA Summarized Flow Steps Adopted in the Analysis*

### 3.5.3 The Results of the Environmental Impact Analysis

The results of the defined LCA scope, namely the elementary mass balance results, as well as the results of the considered impact categories for the different hybrid scenarios have been successful as displayed and discussed next.

#### 3.5.3.1 Elementary Mass Flow Balance and Interpretations

The elementary flow balance based on the already explained participating parameters and indicators for all the considered scenarios of the LCA system has been successfully procured, as presented in the below Table. It became obvious from the estimated total resource values for the different scenarios that 1st scenario (i.e. the conventional system path) has got the largest value, which is 1.84E3 kg/kWh$_{elec.}$, and mostly due to the hydro portion of it, showing its high materials and specific energy requirement. The scenario with the lowest resource input has been the 4th one, specifically the hybrid wind/biomass-biogas power considerations in the study location, with its value being 32 kg/kWh$_{elec}$. On moving to the output parameters of the balance, beginning with the aggregate deposited goods, 3rd scenario (i.e. hybrid PV/biomass-biogas power) is considered with the highest value, while the 1st scenario the lowest. On the aggregate emissions to air, same 3rd scenario was considered with the highest value from the others, which is in contrast to the aggregate emissions to freshwater where the 1st scenario contributes the most, leaving the 3rd scenario with the lowest contribution. 3rd scenario is seen with the largest contribution on the other output indicators namely the Aggregate emissions to seawater, aggregate emissions to agricultural soils, and aggregate emissions to industrial soil. These remaining indicators leave the 1st scenario with the least share but with the exception of the aggregate emissions to agricultural soil where the 2nd scenario was seen with the least contribution. Therefore, it can finally be deduced as reflected in the hybrid system that based on specific technologies, solar PV contributes the most on the aggregate deposited goods, emissions to industrial soil, and emissions to seawater, whereas; the biomass-biogas power system is seen with major contributions to the aggregate emissions to air and agricultural soil. Emissions to fresh water major impact linked to the conventional system could be attributed to hydropower participation. Wind power system is seen with low and moderate impacts of all the indicators.

***Table 52:*** *The Grid Power Mix Mass Balance for all the Consecutive Scenarios.*

| **Resource Input** | | **Tracked Output** | |
|---|---|---|---|
| **Mass by Scenario** | **Value by power system** | **Impact Indicator** | **Value by Scenario** |
| 1st Scenario:<br>$1.84*10^3$ kg | HFO power: 26.3 kg Hydropower: $1.78*10^3$ kg<br>NG power: 42.2 kg | Aggregate deposited goods | 1st: 0.0130 kg<br>2nd: 0.0903 kg<br>3rd: 0.1130 kg<br>4th: 0.0492 kg<br>5th: 0.0788 kg |
| 2nd Scenario:<br>46.1 kg | PV power: 37.4 kg<br>Wind power: 8.71 kg | Aggregate emissions to air | 1st: 10.60 kg<br>2nd: 5.93 kg<br>3rd: 44.70 kg<br>4th: 18.50 kg<br>5th: 19.20 kg |
| 3rd Scenario:<br>110 kg | PV power: 66.2 kg<br>Bio-power: 44.1 kg | Aggregate emissions to freshwater | 1st: $1.83*10^3$ kg<br>2nd: 46.50 kg<br>3rd: 7.70 kg<br>4th: 14.10 kg |

| | | | |
|---|---|---|---|
| | | | 5th: 40.40 kg |
| 4th Scenario: 32 kg | Wind power: 8.36 kg<br>Bio-power: 23.7 kg | Aggregate emissions to seawater | 1st: 0.009 kg<br>2nd: 0.094 kg<br>3rd: 0.200 kg<br>4th: 0.023 kg<br>5th: 0.090 kg |
| 5th Scenario: 54.3 kg | PV power: 28.80 kg<br>Wind power: 6.71 kg<br>Bio-power: 18.80 kg | Aggregate emissions to agricultural soil | 1st: $1.09*10^{-9}$ kg<br>2nd: $-1.48*10^{-9}$ kg<br>3rd: $4.55*10^{-7}$ kg<br>4th: $2.44*10^{-7}$ kg<br>5th: $1.93*10^{-7}$ kg |
| | | Aggregate emissions to industrial soil | 1st: $4.31*10^{-9}$ kg<br>2nd: $5.29*10^{-7}$ kg<br>3rd: $7.94*10^{-7}$ kg<br>4th: $1.55*10^{-8}$ kg<br>5th: $4.19*10^{-7}$ kg |

*[Note: Heavy metals are associated with the emissions to air, emissions to freshwater, emissions to seawater, emissions to agricultural soil, and emissions to industrial soil, and could include Cadmium (Cd), Lead (Pb), Arsenic (As), Mercury (Hg), Chromium (Cr), Thallium (Tl), etc. Radioactive emissions are associated with deposited goods, emissions to freshwater and seawater, and could include Carbon (C), Cesium (Ce), Uranium ($U_{235}$), Hydrogen (H) etc. Stockpile Goods are associated with deposited goods, and could include hazardous wastes (deposited), overburden (deposited), slag (deposited), spoil (deposited), tailings (deposited), and waste (deposited). VOC are associated with emissions to air with examples viz. formaldehyde, acetone, acetic acid, some alkanols and alkanals etc. Finally, Organic/halogenated organic and in-organic emissions are associated with emissions to air, emissions to freshwater and seawater, emissions to agricultural and industrial soils].*

### 3.5.3.2 Impact Categories Results and Interpretations

The results in specifics for the various environmental impact categories selected viz. GWP, AP, EP, ODP, HTP, and $ADP_{fossils}$, for the comparative assessment of the different scenarios considered have been successfully procured as depicted and analysed next.

1. Global Warming Potential (GWP) Results

The global warming potential arising from the release of greenhouse gases (i.e. $CO_2$, $CH_4$, $N_2O$, VOC etc. but majorly $CO_2$) is a critical criterion in power systems decision. This is owing to climate variability and climate change and their strong negative consequences to the environment. The results of this analysis have been presented in below Figure. It is obvious that 1st scenario where the conventional systems pattern was taken in maintaining the BAU trajectory has got the highest GWP, valued at 507 g $CO_2$-eq./$kWh_{elec.}$ This has been contributed majorly by the natural gas and oil power plants being fossil based, with high direct emissions during the operational stage in the life cycle. However, on the renewables-integration scenarios, the value has decreased significantly to some extent all through. The 4th scenario, i.e. the scenario with the hybrid wind/biomass-biogas power system consideration was found with the lowest GWP value, which is 17.8 g $CO_2$-eq./kWh$_{elec.}$ The renewable-based scenario with relatively the highest GWP value was found as 52.9 g $CO_2$-eq./kWh$_{elec.}$ for the hybrid PV/biomass-biogas power system in the 3rd scenario. This is a clear indication that the indirect greenhouse gas emissions associated with all the processes involved in the entire life cycle assessment of the renewable-based scenarios favor wind power generations in the systems architecture as compared to the solar PV being the most contributor to the GWP in the renewable scenarios, and biomass-biogas power system being with intermediate greenhouse gas emissions impact. On a final note, the GWP of the renewable integration in the 5th scenario, where the complete hybrid system exists based on the full share of each in the HOMER optimization results was noted as 27.4 g $CO_2$-eq./kWh$_{elec.}$

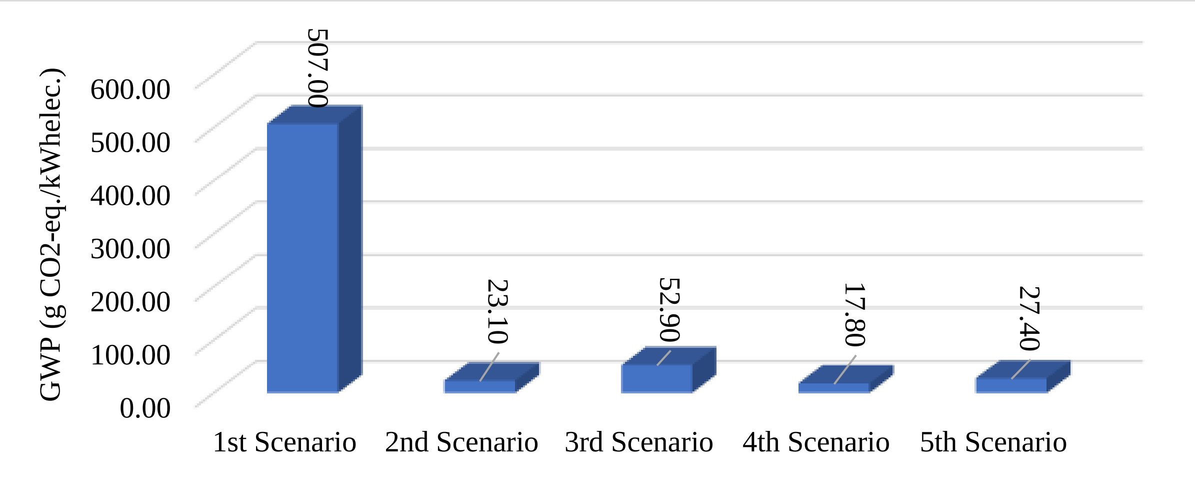



***Figure 35:*** *Global Warming Potential Results for all the Scenarios.*

2. Acidification Potential (AP) Results

Regarding the Acidification Potential (AP), which has been based on the air pollutants viz. $NO_x$, $SO_2$, HCl, $NH_3$, and HF gases, the result is obvious with obtained values for all the scenarios in below Figure. It is evident that 1st scenario which has the hybrid conventional sources incorporation in its system architecture contributes the most in the AP indicator valued at 5.32 g $SO_2$-eq./kWh$_{elec.}$ This has been due to the complexity in the system where the fossil-based subcomponents are associated with acidification impact air pollutants apart from the greenhouse gas emissions majorly in the operational level of the life cycle. The 3rd scenario (hybrid PV/biomass-biogas) has got the second largest contribution to this impact category due to the presence of the biomass-biogas complex system that has got also direct acidification impact air pollutants release apart from the direct greenhouse gas emissions at the operational level for power generation. However, the share of the biomass-biogas in the hybrid renewable system scenarios with such is not strong enough to compete with the share and complexity of the conventional system scenario which had the oil and the large natural gas-based subsystems incorporation. The existence of the biomass-biogas system impact also reflected in the 4th and 5th scenarios making them the 3rd and 4th highest contributors in the category respectively. The

2nd scenario being the hybrid PV/wind power system is considered with the lowest contribution in the impact.

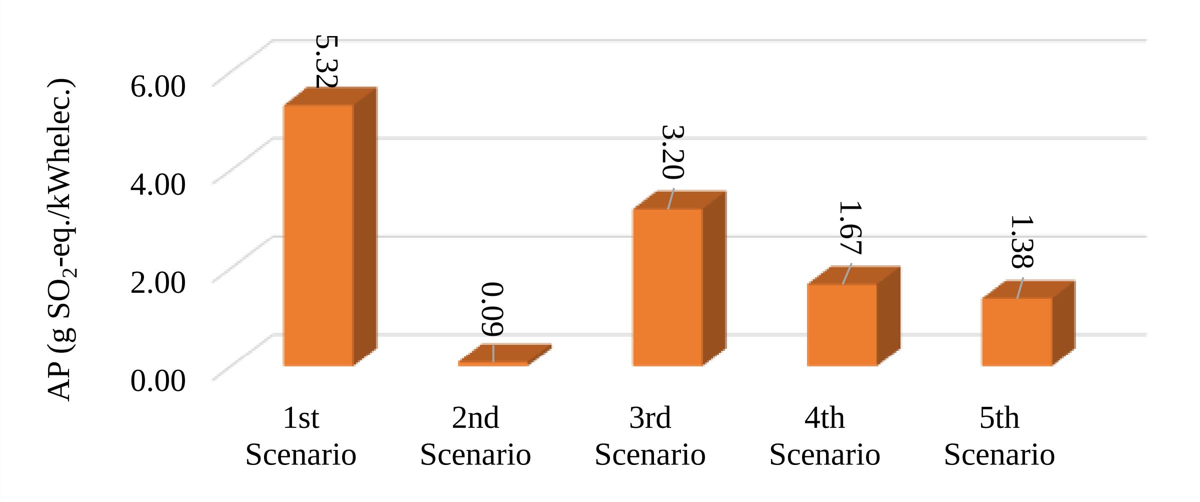



***Figure 36:*** *Acidification Potential (AP) Results for all the Consecutive Scenarios.*

3. Eutrophication Potentials (EP) Results

The Figure below depicts the Eutrophication Potential (EP) of the different scenarios. This impact is to water bodies for oxygen depletion due to excessive minerals and nutrients viz. $N_2$, $NO_x$, $NH_4^+$, $PO_4^{3-}$, and P. The major contributor to the EP impact has been found to be the 3rd Scenario having the hybrid PV/biomass power system. The value was 0.38 g Phosphate-eq./$kWh_{elec.}$ 2nd scenario with hybrid PV/wind power system incorporation is seen with the lowest impact where its EP value was around 0.01 g Phosphate-eq./$kWh_{elec.}$ It can be implied that the biomass-biogas power system has more negative impact to the EU category as the 3rd scenario reflected in 4th and 5th scenarios due to its existence, making them also high. Although the 1st scenario also has got a relatively high contribution and specifically the third-most contributing to the impact category. Therefore, it can be deduced that the more the biomass-biogas power in a hybrid system, the more the potential release of the minerals and nutrients inducing the excessive growth of aquatic plants, especially Algae, as the nutrients and minerals have got high tendency of contacting water bodies, ultimately more tendency for oxygen depletion in the water bodies.

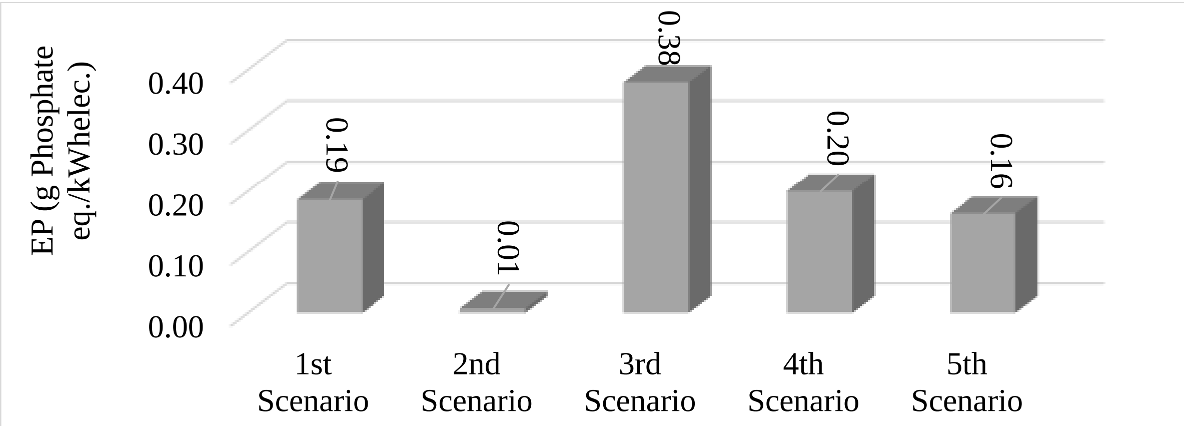



***Figure 37:*** *Eutrophication Potential (EP) Results for all the Consecutive Scenarios.*

4. Ozone-layer Depletion Potentials (ODP) Results

Moving to the Ozone layer Depletion Potential (ODP) impact category as a crucial concern, the results have been presented in the below Figure of the different scenarios and basically associated with CFC and other halogenated compounds release. It must first be stated that anthropogenic activities where in this case being energy related could have a strong impact on the stratospheric component of the ecosystem depending on the emitting gases on overall processes in systems life cycle. The results have clearly shown values ranging from 2.74E-13 g $R_{11}$-eq./kWh$_{elec.}$ for the 1$^{st}$ scenario to the 1.73E-10 g $R_{11}$-eq./kWh$_{elec.}$ for the 3$^{rd}$ scenario. Although it could be said that all the values were negligible and in extremely smaller fractions, hence, impact to the ozone layer might be infinitesimal. In a nutshell, it can be said that technologically speaking as a reflection to what is seen in the hybrids, the solar PV components is the worst of all in the impact category due to its high potential release of the ozone depleting gases. This could be attributed to the measures put in place mainly during the fabrication stage of the materials of the component. Hence the more the share of the PV component to the system, the more the tendency for the ozone depleting gases release in the entire life cycle basing on negligible fractions.

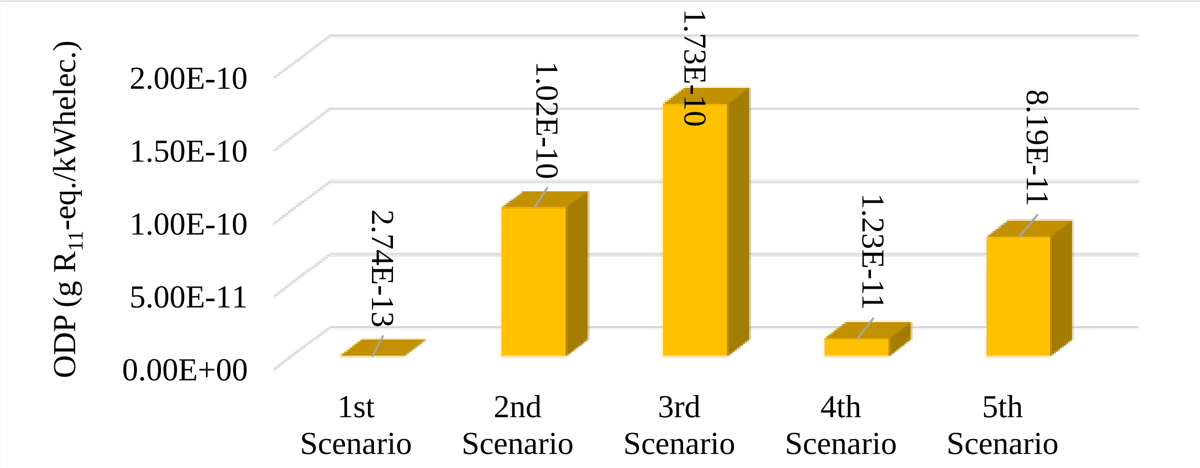



***Figure 38:*** *Ozone-layer Depletion Potential (ODP) Results for all the Consecutive Scenarios.*

5. Human Toxicity Potential (HTP) Results

Human impact from anthropogenic activities for energy generation is worthy of consideration as well. The potential release of harmful substances to the components of the ecosystem viz.: soil, water, and air that ultimately affects the quality of human health has been analysed with the results presented in the below Figure. It is obvious from the results that the 1$^{st}$ scenario has got a value of around 177 g DCB-eq./kWh$_{elec.}$, which exceeded all the values for the renewable integration scenarios, hence the major contributor to this impact category. On the renewable integration scenarios i.e. from 2$^{nd}$ to 5$^{th}$ scenarios, 3$^{rd}$ scenario (hybrid PV/biomass-biogas power system) followed the 1$^{st}$ scenario, with an evaluated value of 83.9 g DCB-eq./kWh$_{elec.}$ This makes the 5$^{th}$ and 4$^{th}$ scenarios consisting of the biomass-biogas component to respectively follow the 3$^{rd}$ scenario with values 37.9 g DCB-eq./kWh$_{elec.}$ and 35.6 g DCB-eq./kWh$_{elec.}$ respectively. Hence the biomass system could be seen with high impact on the renewable integration scenarios, and could be attributed to more release of toxic substances majorly the heavy metals to air, water, or soil during its fabrication stages. Also, due to the tendency of release of harmful gases in operation stage to the humans, which is similar to the conventional case participating fossils as compared to the solar PV and wind power components in the study location.

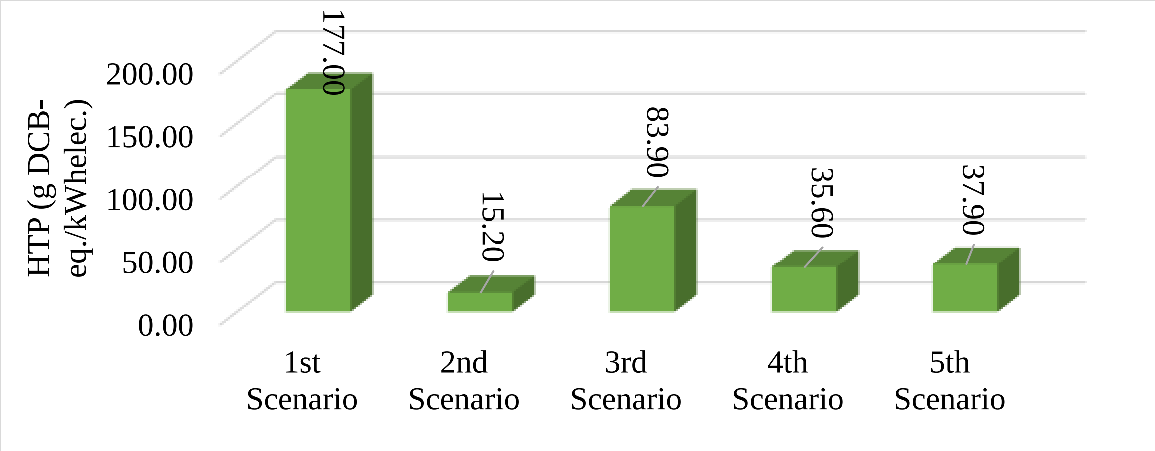



***Figure 39:*** *Human Toxicity Potential (HTP) Results for all the Consecutive Scenarios.*

6. Abiotic Depletion Potentials ($ADP_{fossils}$) Results

These evaluations differ from the preceded impacts evaluations, as it carried the unit of energy with the software default setting of Mega Joule (MJ). Based on the already known definition of this impact category however, in this regard, relating to fossil fuels, which is the fossil energy utilized all through the entire life cycle of each of the sub-components in the overall systems, the results obtained of all the scenarios have been presented in the below Figure. It is evident that the 1$^{st}$ scenario has got the largest value, which is 7.46 $MJ/kWh_{elec.}$, obviously due to more consumption or use-up of fossil energy in the life cycle of the considered sub-components of the system, most especially the oil and natural gas-based system subcomponents, that needed fossil fuels specifically oil and natural gas majorly in operational stage to generate electricity on a Rankine cycle basis. Moving to the scenarios for renewable integration, it is noted that 3$^{rd}$ scenario (hybrid PV/biomass-biogas power) followed the 1$^{st}$ scenario with a value of around 0.6 $MJ/kWh_{elec}$. The 4$^{th}$ scenario (hybrid wind/biomass-biogas) has the lowest of all, where its value was 0.2 $MJ/kWh_{elec.}$ This could be deduced technologically speaking as reflected in the hybrids that solar PV consumes more fossil energy, while wind power consumes the lowest, and the biomass-biogas power system being at intermediate. These fossil energies consumptions assigned to the hybrid renewable systems majorly arise during fabrications of components of the systems as machines powered by fossil fuels are needed, hence considered indirect fossil energy consumptions in the life cycle analysis.

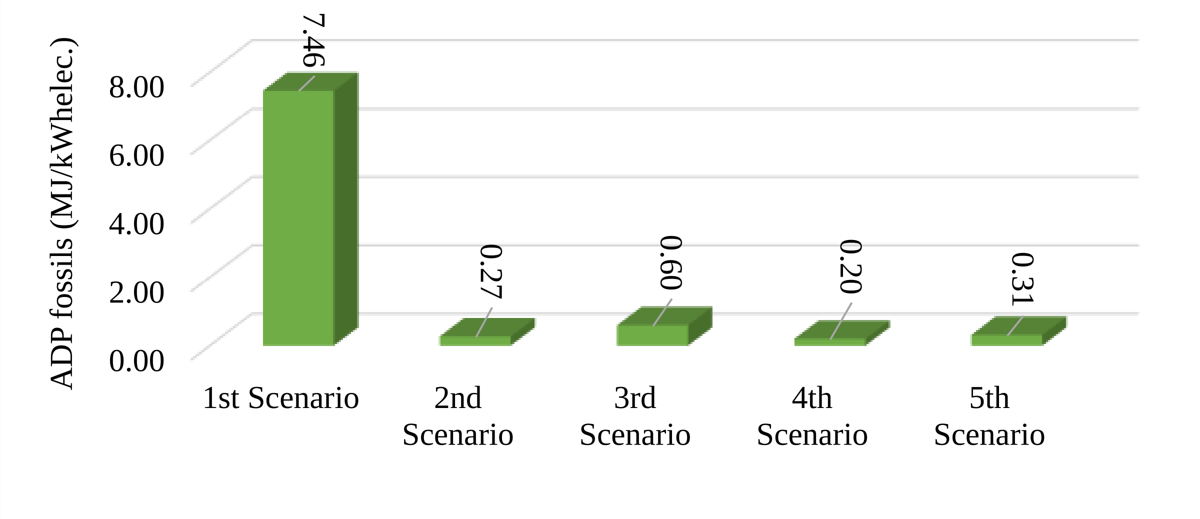



***Figure 40:*** *Abiotic Depletion Potential (ADPfossils) Results for all the Consecutive Scenarios.*

7. Uncertainty Analysis Results

The baseline pedigree matrix having employed to the uncertainty analysis was developed by Funtowiez and Ravetz in 1990 as a tool for coding qualitative assessment of data due to uncertainty challenges (Ciroth et al., 2016). The Table below provided the default uncertainty factors applicable. Another accompanied Table described in much detail, the pedigree matrix and the evaluation approach in the excel program for the uncertainties linked to the environmental impact data.

***Table 53:*** *Default Uncertainty Factors Incorporated in the Uncertainty Evaluations.*

| Indicators / Levels | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Reliability | 0.000 | 0.0006 | 0.002 | 0.008 | 0.04 |
| Completeness | 0.000 | 0.0001 | 0.0006 | 0.002 | 0.008 |
| Temporal Correlation | 0.000 | 0.0002 | 0.002 | 0.008 | 0.04 |
| Geographical Correlation | 0.000 | 2.5E-5 | 0.0001 | 0.0006 | 0.002 |
| Further Technological Correlation | 0.000 | 0.0006 | 0.008 | 0.04 | 0.12 |

Source: Ecoinvent, n.d.

***Table 54:*** *Overall Pedigree Matrix for the Uncertainty Evaluations Program.*

| Levels/Indicators | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Reliability | Verified data based on measurement | Verified data partly based on assumptions or non-verified data based on measurements | Non-verified data partly based on qualified estimates | Qualified estimate (e.g. by industrial expert) | Non-qualified estimate |
| Level choice | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Completeness | Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations | Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuation | Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods | Representative data from only one site relevant for the market considered or some sites but from shorter periods | Representativeness unknown or data from a small number of sites and from shorter periods |
| Level choice | | | | | |
| Temporal correlation | Less than 3 years of difference to the time period of the dataset | Less than 6 years of difference to the time period of the dataset | Less than 10 years of difference to the time period of the dataset | Less than 15 years of difference to the time period of the dataset | Age of data unknown or more than 15 years of difference to the time period of the dataset |
| Level choice | | | | | |
| Geographical correlation | Data from area under study | Averaged data from larger area in which the area under study is included | Data from area with similar production conditions | Data from area with slightly similar production conditions | Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia) |
| Level choice | | | | | |
| Further technological correlation | Data from enterprises, processes and materials under study | Data from processes and materials under study (i.e. identical technology) but from different enterprises) | Data from processes and materials under study but from different technology | Data on related processes or materials | Data on related processes on laboratory scale or from different technology |
| Level choice | | | | | |

<u>Level Choices applied for the different processes:</u>
Hydropower Process [1,3,3,2,3], Natural gas power process [1,3,3,2,3], Heavy fuel oil power process [1,3,3,2,3], Wind power process [1,3,3,2,3], Biopower process [1,3,3,2,3]; Solar PV process [1,4,3,3,3].
<u>Extra Indicators:</u>
Confidence Interval used: 68%; Basic uncertainty applied for lognormal distribution: 1.00; Basic uncertainty applied for the normal distribution: 0%.
Analysed parameters linked to the estimated impacts band:

- Overall uncertainties for lognormal and normal distribution
- Standard deviations for the lognormal and normal distribution
- Upper and lower limit values based on the impact data specification

*Note: data obtained from Ciroth et al. (2016) as applied in the excel program for the different evaluations*

The results of the different impact categories based on the upper and lower limits and in view of having the data as normally distributed and lognormally distributed have been given in tables below. The ranges specified include the actual or true value of the impact categories for the specified case study examined. It is evident from the bands that the normal distribution in virtually all the analysed data have got larger band gap from the top cap to the mid values than the lognormal distribution. While on the other hand, the lognormal distribution case has larger gap from the mid values to the bottom cap. This has been due to the orientations of the distributions as the normal is symmetrical whereas the lognormal is right-skewed. This shows the advantage and disadvantage of the 2 data distribution cases depending on different circumstance, as the normal distribution tends to give ranges with proximity and ease to the exact values when falling on the lower cap than the lognormal distribution and vice versa.

***Table 55:*** *The Analysed Impact Categories Band (Normal Distribution Case).*

| Scenarios | 1st Scenario | 2nd Scenario | 3rd Scenario | 4th Scenario | 5th Scenario |
|---|---|---|---|---|---|
| GWP (g CO2 eq./kWh$_{elec.}$) / Lower limit | 398.494 | 17.9 | 41.15 | 13.97 | 21.3 |
| GWP (g CO2 eq./ kWh$_{elec.}$) | 507.00 | 23.1 | 52.9 | 17.80 | 27.4 |
| GWP (g CO2 eq./ kWh$_{elec.}$) / Upper limit | 614.306 | 28.3 | 64.65 | 21.55 | 33.38 |
| AP (g SO2 eq./ kWh$_{elec.}$) / Lower limit | 4.18 | 0.0697 | 2.514 | 1.32 | 1.077 |
| AP (g SO2 eq./ kWh$_{elec.}$) | 5.32 | 0.09 | 3.2 | 1.67 | 1.38 |
| AP (g SO2 eq./ kWh$_{elec.}$) / Upper limit | 6.44 | 0.1103 | 3.89 | 2.02 | 1.663 |
| EP (g Phosphate eq./ kWh$_{elec.}$) / Lower limit | 0.15 | 5.76E-03 | 0.298 | 0.161 | 0.134 |
| EP (g Phosphate eq./ kWh$_{elec.}$) | 0.19 | 0.01 | 0.38 | 0.2 | 0.16 |
| EP (g Phosphate eq./ kWh$_{elec.}$) / Upper limit | 0.22 | 9.08E-03 | 0.462 | 0.242 | 0.197 |
| ODP (g R11 eq./ kWh$_{elec.}$) / Lower limit | 2.16E-13 | 7.60E-11 | 1.34E-10 | 9.67E-12 | 6.33E-11 |
| ODP (g R11 eq./ kWh$_{elec.}$) | 2.74E-13 | 1.02E-10 | 1.73E-10 | 1.23E-11 | 8.19E-11 |
| ODP (g R11 eq./ kWh$_{elec.}$) / Upper limit | 3.32E-13 | 1.18E-10 | 2.13E-10 | 1.49E-11 | 1.01E-10 |
| HTP (g DCB eq./ kWh$_{elec.}$) / Lower limit | 138.76 | 11.73 | 65.66 | 27.99 | 29.65 |
| HTP (g DCB eq./ kWh$_{elec.}$) | 177.00 | 15.2 | 83.9 | 35.60 | 37.90 |
| HTP (g DCB eq./ kWh$_{elec.}$) / Upper limit | 213.9 | 18.61 | 102.14 | 43.15 | 46.09 |
| ADP$_{fossils}$ (MJ/ kWh$_{elec.}$) / Lower limit | 5.87 | 0.211 | 0.463 | 0.158 | 0.246 |
| ADP$_{fossils}$ (MJ/ kWh$_{elec.}$) | 7.46 | 0.27 | 0.60 | 0.2 | 0.31 |
| ADP$_{fossils}$ (MJ/ kWh$_{elec.}$) / Upper limit | 9.05 | 0.333 | 0.727 | 0.244 | 0.383 |

***Table 56:*** *The Analysed Impact Categories Band (Lognormal Distribution Case)*

| Scenarios | 1st Scenario | 2nd Scenario | 3rd Scenario | 4th Scenario | 5th Scenario |
|---|---|---|---|---|---|
| GWP (g CO2 eq./kWh$_{elec.}$) / Lower limit | 409.796 | 18.47 | 42.42 | 14.37 | 21.95 |
| GWP (g CO2 eq./ kWh$_{elec.}$) | 507.00 | 23.1 | 52.9 | 17.80 | 27.4 |
| GWP (g CO2 eq./ kWh$_{elec.}$) / Upper limit | 625.772 | 28.89 | 65.97 | 21.94 | 34.04 |
| AP (g SO2 eq./ kWh$_{elec.}$) / Lower limit | 4.30 | 0.072 | 2.587 | 1.36 | 1.108 |
| AP (g SO2 eq./ kWh$_{elec.}$) | 5.32 | 0.09 | 3.2 | 1.67 | 1.38 |
| AP (g SO2 eq./ kWh$_{elec.}$) / Upper limit | 6.56 | 0.113 | 3.963 | 2.06 | 1.695 |
| EP (g Phosphate eq./ kWh$_{elec.}$) / Lower limit | 0.15 | 5.94E-03 | 0.308 | 0.161 | 0.135 |

| | | | | | |
|---|---|---|---|---|---|
| EP (g Phosphate eq./ $kWh_{elec.}$) | 0.19 | 0.01 | 0.38 | 0.2 | 0.16 |
| EP (g Phosphate eq./ $kWh_{elec.}$) / Upper limit | 0.23 | 9.28E-03 | 0.472 | 0.252 | 0.207 |
| ODP (g R11 eq./ $kWh_{elec.}$) / Lower limit | 2.21E-13 | 7.82E-11 | 1.38E-10 | 9.94E-12 | 6.54E-11 |
| ODP (g R11 eq./ $kWh_{elec.}$) | 2.74E-13 | 1.02E-10 | 1.73E-10 | 1.23E-11 | 8.19E-11 |
| ODP (g R11 eq./ $kWh_{elec.}$) / Upper limit | 3.38E-13 | 1.20E-10 | 2.17E-10 | 1.50E-11 | 1.03E-10 |
| HTP (g DCB eq./ $kWh_{elec.}$) / Lower limit | 142.69 | 12.12 | 67.61 | 28.79 | 30.52 |
| HTP (g DCB eq./ $kWh_{elec.}$) | 177.00 | 15.2 | 83.9 | 35.60 | 37.90 |
| HTP (g DCB eq./ $kWh_{elec.}$) / Upper limit | 217.89 | 19.00 | 104.12 | 43.95 | 47 |
| $ADP_{fossils}$ (MJ/ $kWh_{elec.}$) / Lower limit | 6.04 | 0.217 | 0.477 | 0.163 | 0.252 |
| $ADP_{fossils}$ (MJ/ $kWh_{elec.}$) | 7.46 | 0.27 | 0.60 | 0.2 | 0.31 |
| $ADP_{fossils}$ (MJ/ $kWh_{elec.}$) / Upper limit | 9.22 | 0.34 | 0.743 | 0.249 | 0.391 |

On rounding the power system design part, it is obvious the distinctions regarding the different aspects addressed on the hybrid system. This has been from the techno-economic modelling and optimization, the energy efficiency aspect as a commendable opportunity area, the in-depth economic evaluations, sensitivity analysis, system extrapolation at bigger capacity, and the in-depth environmental life cycle assessment. It must be noted however that the hybrid system components selected have been limited to a specific site based on that site's assessment as an exemplary case. And the extrapolation done beyond the study site has been driven from the virtually similar resources potentials in line with the selected technologies for the hybrid system as well as the decentralization and cumulativeness of the energy systems need. More so, the environmental life cycle assessment that enabled different scenarios build-up and evaluations in line with the proposed optimized hybrid system gave further insight regarding the different environmental indicators for any decisions to be made by the policy makers regarding a particular environmental impact prioritizing. Therefore, the decisions to be made on the renewable system selection and the hybrid system building is highly regional dependent and indicators based, and has been made open for the decision makers. In general, the policy analysis tasks to be followed, that incorporated the in-depth analysis of existing global successful policy instruments as well the policy recommendations or reformulations bit can be viewed as central to the entire country in view of the renewable energy integration favouring, especially with preference to hybrid systems being more appropriate. This shall be in support of the viability of the renewable systems and making them sustainable.

## CHAPTER FOUR

# 4. RENEWABLE POWER POLICY ANALYSIS

## 4.1 Renewable Energy Policy Instruments Fundamentals

As a complementary aspect, the policy instruments are considered key or the drivers to implementation of any kind of project be it energy based or otherwise. Hence, it's an aspect of most consideration when it comes to offering a lasting solution. This is particularly fundamental when it comes to the power systems adoption as a central focus. Policy instruments are basically the means to which a policy objectives or specific targets could be met coupled with success moderation (World Bank Institute and ESMAP/IFC, 2012). Generally, there are five major categories with regards to relevant policy mechanisms in the energy sector as reported by Sawin and Flavin (2004), viz.:

- ''Regulations that governs capacity access to the market / electric grid and production or purchase obligations
- Financial Incentives (Grants, Loans, Subsidies, and Fiscal-Related Incentives)
- Industry Standards, Permitting and building codes
- Education and Information Dissemination
- Stakeholders Involvement''

In support of renewable energy, there are 2 broad policy instruments, namely the Regulatory Policies and the Fiscal Incentives and Public Financing (REN21, 2017). The Regulatory Policies could be in form of Feed-in Tariff / Premium Payment, Electric Utility Quota Obligations / Renewable Portfolio Standards, Net Metering, Transport Obligations / Mandates, Heat Obligations / Mandates, Tradable Renewable Energy Certificates, and Tendering. The Fiscal Incentives and Public Financing could be in form of Investment or Production Tax Credit, Reduction in Sales, Energy, VAT or other Taxes, Energy Production Payment, Public Investment, Loans, Grants, Capital Subsidies or Rebates. All these instruments are targeted towards driving final energy generation in the form of Heat, Power and Transport fuel from renewables. However, electricity is considered with the highest attention due to its multiplying effect on the other sectors of the economy.

Moreover, of all the policies highlighted, the most commonly applied as support mechanisms in renewable electricity deployment and promotion on a larger scale are feed-in tariff, tradable renewable energy credits / tradable green certificates in conjunction with quota obligations, and tenders (International Energy Agency, 2011). Others are less implemented and it is important that the renewable electricity generation has guaranteed integration to the grid for all the policy mechanisms related to electricity to be effective.

It'll be of great interest to briefly discuss each of the policy instruments before dwelling fully in to the status quo with regards to each in the global context / countries of the globe.

- **Feed-in Tariff (FiT):** The FiT or **gross FiT** is a form of support offered by the government through a minimum guaranteed payment per unit kWh to power producers (Dijk et al., 2003). As a follow up to the above, it must be noted also that there are fundamentally three distinct and awesome features of a feed-in tariff according to Gabriela and Luiz (2011), and they are namely: "a) guaranteed access to the grid, b) Stable long-term purchase agreement or an arrangement that ensures a stable revenue stream for a pre-specified period, and lastly c) payment level usually above market price, based on the cost of renewable energy generation". These same features were also mentioned in other terms according to the Federal Ministry of Economic Cooperation and Development (BMZ) (2012).

The **Feed-in Tariff (FiT)** can be classified in to either **Fixed Feed-in Tariff (FFiT)**, which is sometimes referred to as just **Feed-in Tariff (FiT)**, and **Feed-in Premium (FiP)** that is sometimes referred to as **Premium Payment (PP)**. The **Fixed FiT** or FiT in most literatures is the most widely used FiT-design although the **Feed-in Premium (FiP)** has been increasingly considered in some few global countries especially in Europe as we get to see later on in the global review process. The major difference between the 2 FiT structures is the fact that the **Fix FiT** is independent on market price whereas the **Feed-in Premium (FiP)** is strongly dependent on market price. On extension, the major differences are given in the table below:

***Table 57:*** *Distinction Between Fixed Feed-in Tariff (FFiT) and Feed-in Premium (FiP)*

| **Fixed Feed-in Tariff (FFiT) / FiT** | **Feed-in Premium (FiP)** |
|---|---|
| • Payment level is independent of market price of electricity, and with a guaranteed payment for a specific period of time based on the specific development cost of the concerned technology.<br>• Higher level of cost efficiency, resulting from lower investor risk and higher transparency<br>• Can be challenging for policy makers to implement. Tariffs set too low may be ineffective at encouraging investment, while tariffs set too high may be over generous, possibly leading to over-subscription and budgetary constraints.<br>• Allows flexibility and digression for the promotion of different goals on the basis of numerous considerations, such as:<br>✓ Type of technology<br>✓ Size / Capacity of a project<br>✓ Location of the project (onshore/offshore)<br>✓ interconnected/non-interconnected system. | • Electricity Payment level is based on a premium offered above the market price of electricity. The FiP can either be constant (i.e. Market Price + Fixed Premium), or can vary based on a sliding scale (i.e. Market Price + Variable Premium: The higher the market price, the lower the premium).<br>• Premium price can be differentiated according to technology type and project capacity or size<br>• Developers can enjoy high rewards when market prices increase, but also with an accompanied risk when there is a decrease. In order to avoid large divergence between profits and losses, it can be designed with payment caps and/or floors. |

Source(s): Georgopoulos and Issaias, 2012; Centre for Clean Air Policy, n.d; Couture and Gagnon, 2010

The Market Price = Fixed Capital Costs + Variable Fuel and Operation Costs + Return on Investment ------------- (23)

The Advantages and the disadvantages of the 2 Feed-in Tariff Models are as outlined in the below table:

***Table 58:*** *Advantages and Disadvantages of Fixed Feed-in Tariff and Feed-in Premium*

| FiT Models | Advantages | Disadvantages |
|---|---|---|
| Fixed Feed-in Tariff | • Lower Average per kWh costs for the state<br>• Higher transparency and stability of payment levels reduces investor risk and encourages infant technologies<br>• Payments are more closely related to actual costs of RES generations | • Lower average per-kWh cost benefits for the producer<br>• Is costly over time, especially when the FIT is adjusted for inflation<br>• No incentive to develop RES in areas where mostly needed<br>• No incentive to adjust supply to demand |
| Feed-in Premium | • Higher average per-kWh cost benefits for the producer.<br>• More compatible with liberalized electricity markets.<br>• Supply more likely to adjust to demand | • Higher average per-kWh costs for the State.<br>• Greater investor risks, with no purchase guarantee and the inability to utilize the hedge value of a fixed FIT. |

Source: Georgopoulos and Issaias, 2012

- **Net Metering (NM):** Net metering is sometimes referred to as Net Feed-in Tariff, and considered an alternative to feed-in tariff but applicable specifically to small scale utility companies with grid supply who are consumers at the same time. In this regulation, a meter is used to record both electricity production and consumption by the consumers such that when production exceeds consumption, payment is made at for instance wholesale or retail market rate or beyond per kWh of the excess energy (Njeri, 2005; BMZ, 2012). Moreover, success in attracting participants to net metering strongly depends on the following viz.: capacity limits sets, attractive financial incentives, the grid connection standards and charges, and lastly the level of awareness among participants (Njeri, 2005). Under the Net-Metering scheme comes another scheme that is termed **Net-Billing** as obtained from literatures and practiced in some countries unfavourably. The **Net-Billing** arises or is referred to when the scheme is not based on parity pricing to the whole sale or retail market or premium pricing (payment above the whole sale or retail market rate) but on the fact that distribution utilities pay lower for consumer-produced electricity, but charge higher for utility-produced electricity (Verzola, 2016).

In a summary, regarding the Feed-in tariff and Net-metering discussion, some extended conditions or charge principles apply as practiced in some countries of the globe. These conditions or further classification regarding the charges applicable to either the Feed-in tariff or the Net-metering scheme or both as presented in the table below:

*Table 59: Utility Bill Charging Principles for FiT and Net-metering Schemes*

| Charging Principle | Description | Scheme applicable to |
|---|---|---|
| Fixed charge increase | Fixed rate charging plus extra cost of maintaining the grid-infrastructure | Both FiT and Net-metering |
| Non-By-passable Charge | Charges built in to electric utility rate, adding up to about 2-3% per kWh, and it's towards funding energy efficiency, low income customer assistance, and other related programs | Both FiT and Net-metering |
| Time Varying Rate (includes Time of Use rate (TOU), Variable Peak Pricing, and Critical Peak Pricing) | Charging depending on the time of the day the energy is consumed (i.e. either peak hours or base load hours and the likes) | Both FiT and Net-metering |
| Residential demand charge | Charging based on consumer's energy demand capacity | Net-metering only |

Source: NREL (2017)

- **Electric Utility Quota Obligations (EUQO/RPS):** This is also termed renewable purchase obligations or renewable portfolio standards (RPS) in some other texts. In this instrument, the government set a framework within which power production, distribution and consumption has to take a certain share of renewable sources or in other words, an imposition is done on a certain minimum share of renewables in the overall electricity mix (BMZ, 2012; Dijk et al., 2003). It must also be noted that the instrument is usually traded from one utility company to another to avoid market distortion and hence may incorporate the need for tradable green certificates in the undertakings (Dijk et al., 2003). The green certificate serves as instrument also on its own for the Quota system for accrediting and monitoring the production of renewable based electricity and trade facilitation. To conclude on this, a penalty may or may not be applied for non-compliance to the Electric Utility Quota Obligations.

- **Tradable Renewable Energy Certificate (TREC):** This is also referred to as the Tradable Green Certificates. The tradable green certificates having seen previously under the Electric Utility Quota discussion is also a special instrument that is used in the Quota obligations as an additional feature in stimulating cost-efficient solutions among Quotas (BMZ, 2012). To expand a bit, utilities usually generate green certificates for amount of kWh of produced such that on exceeding the minimum required electricity of the quota obliges selling the extra certificates to the other utilities that have not yet met their quota targets (BMZ, 2012). As a final note, green energy certificates incorporate all renewable and environmental attributes for electricity generation but with the exception of emission reduction credits (Gabriela and Luiz, 2011).

- **Tendering (TN):** This instrument is also called **Competitive Bidding, Tender, Demand Auction or Procurement Auction,** which could take 2 directions namely: **Forward and Reverse**. The rationale behind the **Forward Auction** is procurement of mechanism based on financial offer such that buyers of electricity per kWh compete for purchase of which the highest price offeror wins and gets involved in the contract (Gabriela and Luiz, 2011). On the other hand, i.e. on an occasion of **Reverse Auction or Bidding**, producers and suppliers of energy competitively bid for selling the energy service such that the lowest price offeror wins and get solicited for the contract (REN21, 2017; Gabriela and Luiz, 2011). There are some further classifications regarding the tendering process as observed from literatures and practiced in some jurisdictions are being presented in the table below:

***Table 60:*** *Tender/Auction Classification*

| **Auctions / Tenders** | **Brief Description** |
|---|---|
| Price-only Auction | Price is considered the only award criteria |
| Multicriteria Auction | Price being the main criterion with additional prequalification criteria such as local content rules, impact on R&D, environmental impacts etc. |
| Static Bid | Prices remain fixed throughout bidding processes |
| Dynamic (Ascending Price) | Sequential bidding phases with increasing prices by auctioneers (Service offerors or providers) to the purchasing parties (i.e. service offerees or receivers) over time based on quantities of supply specifications |
| Descending Clock Auction | Sequential bidding phases with decreasing prices by auctioneers to the purchasing parties over time based on quantities of supply specifications |
| Sealed Bid | Auction system where price offers are submitted in sealed envelopes in response for an invitation to bid, and is opened for selecting the winners on the stipulated date. |
| Pay-as-Bid | Auction system where multiple homogenous items (i.e. multiple electricity produced from different technologies in this context) are sold at different prices |
| Uniform / Clearing Bid | Auction system where multiple homogenous items sold at same prices |
| New Energy Auction | Auctions set aside to satisfy the demand of a distribution company based on its load growth specification |
| Reserve Energy Auction | Arises on the government willingness or choice to contract extra energy beyond the demand |

Source: Wigand et al., 2016

- **Transport Obligations /Mandates:** This policy instrument is in other words referred to as biofuels obligations / Mandates. In this kind of policy instruments, producers and suppliers of fuels are mandated to ensure that a certain share of their fuels is from renewable source, specifically biomass for biofuels. This also incorporated the requirement for blending some specified share of biofuels (Biodiesel and Bioethanol) with the fossil fuel for energy service (REN21, 2017). As a final note, this Policy instrument is similar in principles to the Renewable Portfolio Standards (RPS) only that the RPS applies to power while this policy applies to fuels. This instrument is completely out of the scope of the policy research in the dissertation.

- **Heat Obligations / Mandates:** This policy instrument mandates the area of heat generation and supply to incorporate some chare of renewable sources mainly solar and bioenergy, coupled with energy efficiency for buildings domain (Energy Korea, 2011). This also incorporates the aspect of cogeneration where producers generate both heat and power for distribution although heat being the area of interest (Energy Korea, 2011). It must be stated further that this policy instrument is similar in principles to Renewable Portfolio Standards (RSP) just like the Transport Obligations having said earlier. This instrument is also completely out of the scope of the policy research in the dissertation.

- **Investment or Production Tax Credit / Tax Relief / Tax Exemption / Tax holiday (I/PTC):** This being the first on the set of instruments under fiscal incentives and public financing. According to the International Renewable Energy Agency (2012), this kind of policy instruments provides energy investors or producers with an annual income tax credit based on the amount of money invested on the energy production or based on the amount of kWh of the energy produced on a yearly basis. Hence this allows energy investors or energy producers to be credited against the tax obligations on an annual basis (REN21, 2017). It sometimes comes in other forms depending on countries specifications and principles, such as **Tax Relief, Tax Exemption / Waving, or Tax holidays** however, for the **Tax holiday** case, the exemption to the tax levy is only for a certain period of time in the contract design.

- **Reduction in Sales, Energy, VAT or other Taxes (R/S, E, VAT…):** This is a special instrument also under the fiscal incentives and public financing that guarantees some percentage reduction in taxes to renewable energy or its associated technologies purchase or production (International Renewable Energy Agency, 2012). These taxes could be in form of value added, sales, energy, carbon credit etc.

- **Energy Production Payment (EPP):** This is another sub classification that specifies the direct payment from the government per unit of renewable energy produced hence reducing the costs of a project with respects to size or capacity in production (IRENA, 2012b; BMZ, 2012). To conclude, the 2 key features of this scheme as suggested by The Federal Ministry of Economic Cooperation and Development (BMZ) (2012) are: “Simple and direct additional funding of projects and its incentives for producing a maximum of renewable energy (Power, Heat, and Fuel)”.

- **Public Investment, Loans, Grants, Capital Subsidies or Rebates (PI, L, G, C.S or R):** This is the last incentive mechanism where government aids in form of loans, grants, capital subsidies or rebates for the deployment of renewable energy systems hence facilitating investments in renewable energy projects (REN21, 2017; BMZ, 2012).

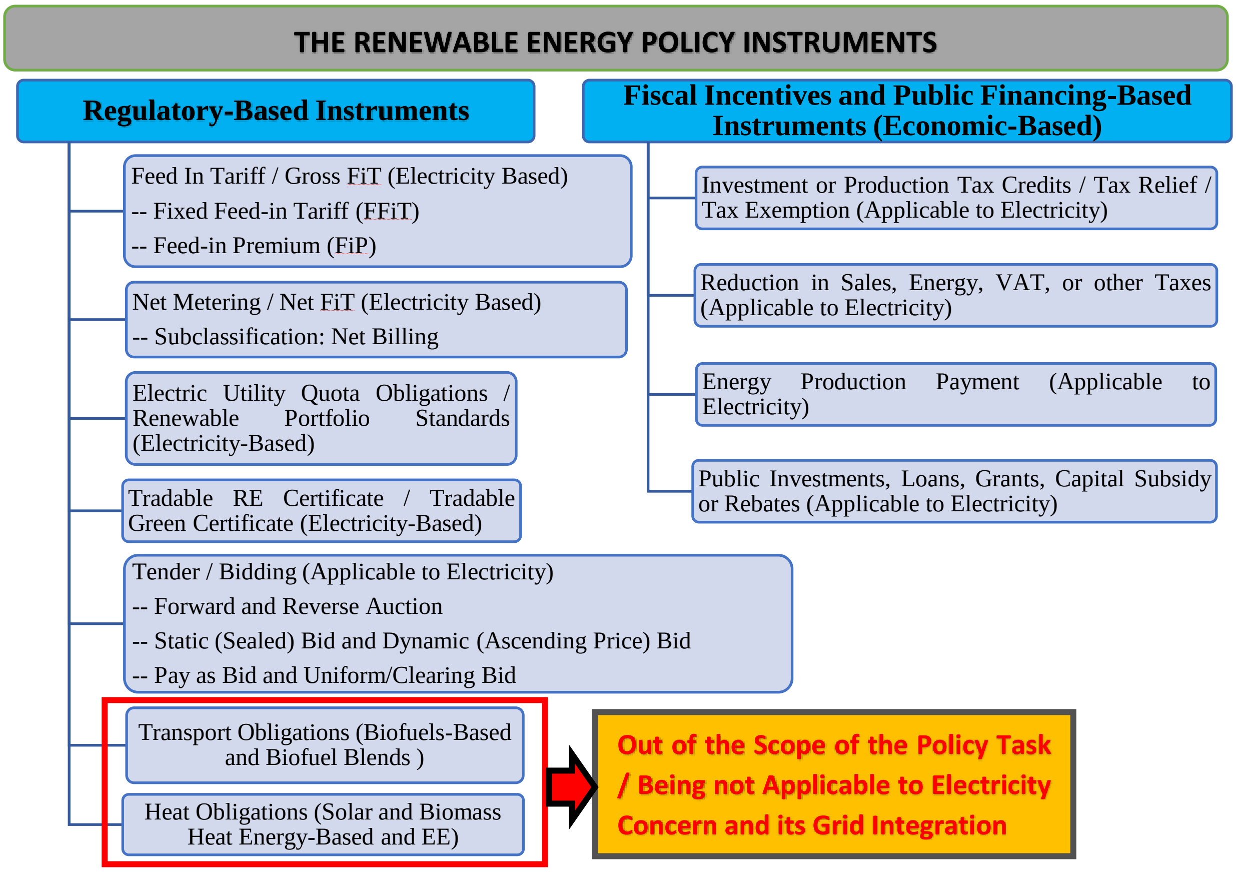



***Figure 41:*** *Summary of the Renewable Energy Policy Instruments*

Note that the Economic Policy as specified in the second category / column of the above figure basically comes in 2 forms viz. **monetary policy** and **fiscal policy.** The monetary policy could be perceived as the public financing-based instruments that are related to investments, loans securing, grants, subsidies etc whereas, fiscal policy could be perceived as the fiscal incentives-based instruments that are related to taxations.

Furthermore, the table below gives the advantages and the disadvantages of the discussed renewable energy policy instruments while excluding the out of scope policies i.e. those with no relation to the power / electricity sector.

***Table 61:*** *Advantages and Disadvantages of the RE Policy Instruments*

| **Instruments** | **Advantage(s)** | **Disadvantage(s)** |
|---|---|---|
| Feed in Tariff (FiT) | • High effectiveness<br>• High investment security<br>• Strong market dynamics | • Higher electricity prices<br>• Difficult policy-design (e.g. difficult control of penetration speed; false design may lead to over- or under-estimated expansion rates |
| Renewable Portfolio | • Strong market-orientation<br>• Less government intervention<br>• Easier policy-design than FiT | • Lower effectiveness than FiT particularly in case of a weak penalty system<br>• Not necessarily cheaper than FiT |

| | | |
|---|---|---|
| Standard (RPS / EUQO) | • It provides a clear investment signal<br>• For long term target, it can facilitate the establishment of industry infrastructure and capacity<br>• It can promote compensation between different types of renewable energy and leading to greater efficiency and innovation and cost lowering | • They are complex to establish and operate<br>• There may be high transaction cost associated with creating, trading and buying certificates coupled with ensuring compliance |
| Capital Subsidy, Grants, and Rebates (C.S, G, R) | • Facilitate Investments in R.E Projects<br>• They are simple to implement and understand<br>• They are transparent and aid boosting market confidence | • They contain no reference to market performance<br>• There are less incentives to maintain systems over time |
| Investments or other tax credits (I/PTC) | • Reduces investment cost<br>• Suitable for utility-scale investments | • May keep power producers from operating plant if tax credits are only available for investment (not for operation)<br>• Less attractive to small-scale investors |
| Tradable Renewable Energy Certificates (TREC) | • Allows power producers achieve higher share of RE in their electricity mix through trading<br>• Helps green power producers receive additional benefits | • May keep power producers from investing in RE themselves |
| Energy production Payments (EPP) | • Fair to high effectiveness<br>• Can complement investment tax credits | • Lower investment security than FiT as weaker legal basis |
| Net Metering (NM) | • Less complex than FiT<br>• Lower cost than FiT | • Lower financial benefit than FiT<br>• Not suitable for utility-scale installations |
| Public Competitive Bidding / Tender (TN) | • Strong market-orientation<br>• Competitive prices<br>• Checks on capacity addition<br>• It is a simple process<br>• It is done in a transparent manner | • Applicants may bid too low to win the tender; may lead to non-completion of project or bankruptcy<br>• Bidding process may have a high administrative cost<br>• Transaction costs for bidders may be high |

Source(s): BMZ (2012); IT Power Group (2014)

Focussing on the Risk associated to the renewable energy policy instruments, from my opinion coupled with insight obtained from literatures such as from study conducted by Shrimali et al. (2016), the following risks categorizations could be attributed to policy designs, which are expected to be addressed effectively during the management phase of the formulated appropriate policy instruments in support and realizations of the set policy objectives and obligations for the Case-study country in favour of the grid-integration of renewable energy power plants.

***Table 62:*** *Risks with Subdivisions for Renewable Energy Policy Instruments*

| S/N | Risks | Sub Factors Considered | Principal Targets |
|---|---|---|---|
| **1** | Project/Technology Risk (Linked to [2] and [3]) | • Information Dissemination Issue/Gap<br>• Acceptability / Against Fossils<br>• Project Completion / Time Factor<br>• Specific Technology Favoring<br>• Competition (Auction based)<br>• Tariff Fluctuation / Staticity<br>• Resource Availability and Variability | Project/Technology Effectivity and Sustainability |
| **2** | Economic/Financial Risk (Linked to [1]) | • Rate of Return Impacts<br>• Money Locked-in / Payback Impact | Financial Viability and Sustainability |
| **3** | Environmental Risk (linked to [1]) | • Greenhouse gas Emissions<br>• Pollution<br>• Associated Penalties | Environmental friendliness and safety |

## 4.2 Analysis of the Existing Global Power Policy Instruments (Continental Clusters)

***Background Information on the Power Policy Analysis***

***Note 1:*** *The existing power policy findings for the Clusters were on the basis of highly performing and top countries in global RE Ranking as follows:*

1. *Asia Cluster: China, India, Japan, Turkey, Russia, Philippines, Indonesia, Malaysia*
2. *Europe Cluster: Germany, France, Spain, Italy, Denmark, Sweden, Finland, Iceland*
3. *North America Cluster: USA, Canada, Mexico*
4. *South America Cluster: Brazil, Chile, Argentina*
5. *Australasia Cluster: Australia, New Zealand*

***Note 2:*** *The quantitative summary of the* ***''Power Policy Instruments''*** *findings have been presented in the* ***''Appendices Section''****. All the details of the policies' statements, objectives and targets, as well as the accompanied instruments operational principles (both regulatory and economic-based) were skipped in the document due to their bulk nature.*

***Note 3:*** *Countries skipped in the process of the selected continental cluster analysis are basically few and has been due to reliable data not found for their cases.*

The performance analysis of the existing power policy instruments compiled in general is another key concern, and could be based on some fundamental parameters according to our opinion. These parameters could effectively be looked in to as the in-depth searches are done regarding the successes, failures, phase-out and challenges of policy instruments in the global perspectives. The fundamental parameters or indicators are as outlined in the below bullet points:

- Capacity installed for the Energy Systems and Projects **(Effectiveness-Indicator)**
- Amount of energy produced from the projects installed under the policy program **(Effectiveness-Indicator)**
- Reduction in technology and production costs over time (Digression / learning rate) **(Efficiency-Indicator)**
- Number and distribution of renewable energy (power) businesses established during the lifetime of an incentive program **(Equity-Indicator)**
- Number of participants / stakeholders' involvement **(Equity-Indicator)**
- Measurement of performance on social favour relative to program goals (e.g. electrification rates, electricity consumption per capita, economic energy use in total final consumption etc.) **(Equity-Indicator)**

The most commonly-used or existing regulatory policies for electricity are feed-in tariff/premium payment and tendering. Whereas, on the fiscal incentives and public financing, it was observed that the most frequently existing are the taxation-based incentives with loans and grants based on the experience obtained from the literature searches.

To complement the preceding discussion with the tender instrument that is also practiced globally to a greater extent, there are a lot of short comings or bad lessons generalised and reported by the European Wind Energy Association (2015) as outlined below:

- Investors uncertainties on the price affected/hindered investments
- Investors bidding too low with the target of winning the tender were mostly not able to develop the project as the system economics affected the returns negatively
- Complex tender proceedings coupled with financial risks discouraged low income or small players from partaking in the process
- Sites selection disregarding environmental impacts resulted in public rejections and undesired environmental consequences leading to projects being annulled
- Sites considered with little regard for territorial distribution resulted to certain locations being over-solicited whilst others ignored
- Areas with negligible or zero competitions experienced zero incentives for price lowering.

It must be noted that some of these points could be or must have probably been threats to other instruments as well in electricity deals of the global concerns. Looking at the analysis for successes and failures regarding the already reviewed existing policy instruments globally and on a continental basis is necessary. This shall be carefully addressed based on the preceded and outlined analytical indicators.

### 4.2.1 Europe Renewable Power Policy Analysis

The top highly performing countries in Europe have been analysed of their existing power policy instruments. The table below begins the analysis of the policy instruments, which shows the main instruments in boosting the renewable power supply in the selected countries.

***Table 63:*** *Main Instruments Boosting RE (Power) in the Selected EU Member States*

| Selected EU Member States | Main Instruments |
|---|---|
| Germany | Feed-in Tariff (FiT) |
| Spain | Feed-in Premium (FiP) |
| France | Feed-in Tariff (FiT) |
| Denmark | Price Premium (Fixed or Variable: Element of FiP) |
| Italy | Green Certificate (Tradable RE Certificate) |
| Sweden | Green Certificate (Tradable RE Certificate) |
| Finland | Feed-in Tariff (FiT) |
| Iceland | Nil |

Source: Muranen, 2012

Since the 90s, FIT instruments have greatly stimulated renewable energy investments, particularly in Europe, as well as in many other regions globally (Centre for Clean Air Policy, n.d). It was also reported by Centre for Clean Air Policy (n.d) that the FiT instruments are the most widely used policy tools for hastening the deployment of renewable energy, and nearly around 65 countries and 27 states and provinces around the globe have considered the instruments into effect as at 2012.

Starting with Germany, being the precursor of energy transition in Europe, the country employs fixed-price tariffs for a range of technologies, and the FiTs are fundamental to its target of securing 35 percent of its electricity from renewable sources by 2020 (Centre for Clean Air Policy, n.d). The first German feed-in law of 1991 as clearly mentioned previously was based on fixed percentage of retail electricity price and had been effective at deploying coastal wind and hydropower electricity price but unfortunately failed to encourage investments in more cutting-edge technologies such as the solar-based generations (Centre for Clean Air Policy, n.d). Moreover, other disadvantage observed by the scheme was the fact that there was no time limitation in considering gradual reduction in feed-in payment with accompanied incentives for the cost reduction and technological innovations (Sijm, 2002). But on a positive note, the wind technology impact from the law had been observed from the more than doubled increase in the wind annual capacity, of which in absolute terms, the wind capacity has been reported to expand greatly from 1100MW in 1995 to 6100MW in 2000 making the country the leading in wind energy deployment (Sijm, 2002). Due to the highlighted negative impacts of the scheme, there was a shift to the actual model-based on the actual cost of renewable energy generation rather than a market-based rate in 2000, hence offering a competitive advantage to a variety of renewable technologies with varying generation capacities and being the most successful instrument in the country (Centre for Clean Air Policy, n.d). The FIT program in Germany has resulted in a drastic increase in the production of renewable electricity, which grew-up from 3% of total electricity production in 1990 to 20% by the first half of 2011 (Centre for Clean Air Policy, n.d). Moreover, Electricity generation from projects supported by FIT schemes rose from approximately 38.5TWh in 2004 to about 75TWh in 2009 i.e., about 79 percent of all renewable electricity generated at that base year, and lastly to 91TWh in 2011 (Centre for Clean Air Policy, n.d).

It must be stated further that the successful FiT in the country i.e. Germany helped tremendously in surmounting many barriers to RE deployments viz.: ‘’distorted playing field due to existing infrastructure and support measures for conventional sources of energy, high initial capital costs for renewable technologies, lack of legal framework for IPP, difficulty in having access to grid, and perceived technology performance uncertainty and risk’’ (Centre for Clean Air Policy, n.d). Moreover, in 2006, energy producers supported by the German FIT system generated revenue aggregating to over USD 17 billion, that represented over 60 percent of total domestic renewable energy revenue (Centre for Clean Air Policy, n.d). More so, from 2004 to 2008, the number of jobs (human empowerment) in the German renewable energy industry augmented by 75%, from about 160,000 in 2004 to 280,000 in 2008 (Centre for Clean Air Policy, n.d). Also, shifts in electricity generation resulting from the FIT helped reduce greenhouse gas emissions by approximately 70 million metric tons in 2011 as also reported by the Centre for Clean Air Policy (n.d).

Germany had been very successful in the renewable energy arena based on further reasons aside from the policy and the fact that it is one of the first countries to have realized the necessity of renewable energy, is that there is a fact-based monitoring process, known as the Energy of the Future (Mahmure et al., 2015). The scheme or process made sure that the energy reforms are being realized, while also promoting public participation and acceptance

(Mahmure et al., 2015). It is also said to be due to the increase in retail electricity prices over the few years due to surcharge enforcement to customers for remitting/subsidizing renewable energy producers, hence, leading to the sharp rise/expansion of the renewable capacity in the country (NREL, 2017). Further analysis on Germany's Fixed FiT success story has been put forward as follows: Since 2000 the RES Act had increased the share of RE sources within Germany's electricity mix from 6.3% to 14.8% of final electricity consumption in 2008, which also led to an increase in non-hydro RE generation from 9.2TWh at the end of 1999 to a sum of 70.5TWh by the end of 2008 (Couture and Gagnon, 2010). Further expressed in terms of installed capacity, the scheme had represented an addition of beyond both 4900 MW of grid-connected solar PV capacity and 19000 MW of wind power in the period of 2000 to 2008 (Couture and Gagnon, 2010). These success stories are strongly and frequently attributed to the high level of investment security provided by Germany's FiT framework, which probably represents the most recognized and highly cited example of a successful FiT policy in the globe (Couture and Gagnon, 2010).

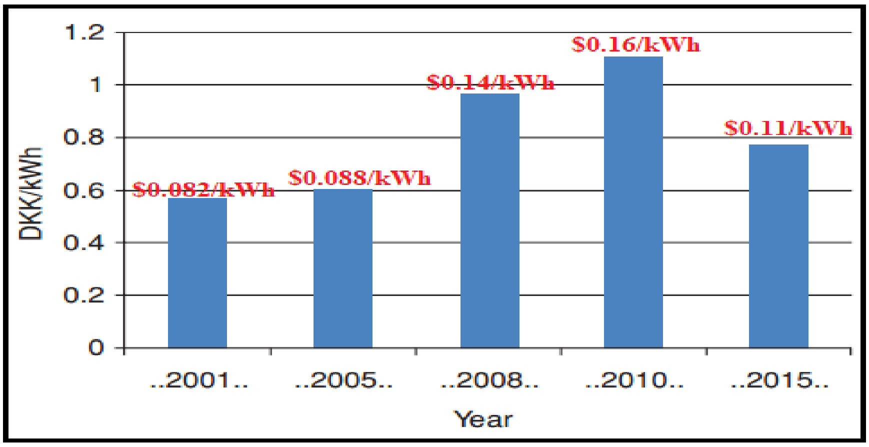
Germany again in another narrative had secured sustainable FIT support for solar PV, onshore wind, and other renewables since the Stromeinspeise-Gesetz (Electricity Feed-in Law) of 1990, with feed-in rates for solar and wind originally pegged at 90% of retail electricity rates (Felix et al., n.d). However, this first FiT delivered only limited renewable energy deployment, and was not until the emergence of Erneuerbare-Energien-Gesetz (Renewable Energy Sources Law) of 2000 that decommissioned the feed-in rates for renewables from the initial retail rates basis to calculations based on the respective generation costs of eligible renewable energy technologies that resulted in German renewable energy bloom-up (Felix et al., n.d). All FIT rates have built-in, technology-specific annual "digression rates" that reduce the tariff by a set percentage every year in an attempt to anticipate and account for technology learning and cost improvements (Felix et al., n.d). To date, all of the targets set by Germany in electricity scale-up have been met well ahead of targeted date, being that the goal of 12.5% by 2010, set in 2004, was achieved three years early, in 2007, and in complement, the goal of 20% by 2020 was attained nine years early, in 2011 resulting from the aggressive FiT uptake in most of the cases (Felix et al., n.d).

Basing on the policy impacts to cost successes in what is known as the digression measure, the feed-in tariff instrument accompanied by the guaranteed grid connection and priority grid access proved successful in the German concern. It was successful in a manner of being instrumental to reducing the cost of wind and solar power in the range of 50-90% over a decade, and the costs are presently as low as US$0.04–US$0.05 per kWh, making them the cheapest choices for new electricity generations (Deger et al., 2018). Apart from the FiT success in Germany, the economic-based policy instrument, specifically the loan provision by banks also helped tremendously in scaling up the supply of renewable power. This was obtained as reported by Sonia et al. (2012) that wind turbine-based projects were made possible with high capacity.

There are a number of different reasons why FIT policies designed as a percentage of the retail price have fallen into un-favour for some EU member states with such schemes, leading to going for other alternatives in-line, as put forward by Couture and Gagnon (2010) as follows:

- In Germany, the change to a fixed-price model based on RE project costs was brought forth to augment investor security through more stable prices, also to accelerate RE development, and to enhance diversification of technologies.
- In Denmark, the transitions were driven mostly by the need from the new government side, to navigate to what is seen to be more "market-based" support mechanism, i.e. one that would make use of tradable green certificates, and surmounting the decline in government interest in renewable energy.
- In Spain the percentage-based model was ignored primarily due to concerns over costs, as the percentage-based payments led to highly volatile payments when electricity increase was experienced in 2005-2006. Additionally, the problem of over or under compensation for renewable energy projects remains under the premium option provided the premium offered remains unchanged. This last point is considered the major reason to why certain jurisdictions in Spain are beginning to move away from fixed premiums and toward variable premium designs in line with the Feed-in Premium of the country.

Additionally, it was obtained from Wigand et al., 2016) that countries like Denmark, France, Germany, and Italy operate **static (sealed bid) auction**. This could be differentiated with the **Dynamic (Ascending) auction** which is a form of sequential bidding phases with increasing prices. It was further stated that **Price-only auctions** have been the most common method of bid evaluations in EU countries, which is without considering any other criteria in the selection of winning bid other than the price (Wigand et al., 2016). Looking at the case of Denmark as a further evaluation, The Danish / Denmark scheme on a further note operates as a **static (sealed-bid)**, **pay-as-bid auction**, in which sliding feed-in premiums (FIPs) are paid for a fixed volume of produced electricity for about 12-15 years (Wigand et al., 2016). Furthermore, all the auctioned Danish offshore wind projects have been realised successfully, which assists tremendously in increasing its installed capacity from 455.2 MW before the auctions to currently 1271.5 MW, at an average price of €99.5/MWh (Wigand et al., 2016). It must be further mentioned that the retarding force regarding the Tender instrument rapid expansion where High penalties for delays and a very strict time plan, among other external factors, which has resulted in low interest in the Anholt tender in Denmark and a low competition level to some extents (Wigand et al., 2016). Furthermore, it was observed that technological wise, offshore wind prices in the auction scheme increases from 2001 to 2010, where further penetration then results in cost reductions as an efficiency indicator (David et al., 2015). The below figure describes the trend.




Source: David et al., 2015

***Figure 42:*** *Auction Scheme with Prices indication trend for Offshore Wind in Denmark*

In Denmark also, the existing feed-in tariff had impacted positively on wind power generations to which the total reimbursement secured by the power producers resulted in IRR for average 600 kW wind turbine in a range of 5-22% after tax payment, depending on locations (Sijm, 2002). The high IRR for wind power in the 90s had triggered and encouraged venturing in to such initiative resulting in the realization of a total installed capacity of 343 MW in 1990 with a rapid increase up to 2300 MW in 2000 (Sijm, 2002). Further experience regarding the Denmark Net-Metering instrument existence now in this perspective have shown clearly the retail price exceeding that at the production to some renewable energy systems and hence, the decision makers decided to restrict their netting principles on hourly basis, in countering excessive rise of deployments which they feel could be to their advantage as well (IEA, 2015a).

Moving further to the specific case of Spain as a further evaluation, other narratives had its illustrative case study of FIT/FiP failure, where a modified FIT/FiP was launched in 2007 and ended with misfortunes. Hence, the Spanish case has since served as a negative example of how not to do FIT. It must be stated that although the country took its scheme pattern from the German FIT, Spain decided on a few changes of its own, and the changes turned out to be a disadvantage: The Spanish government came up with a decision to pay for the premiums itself, rather than passing on the cost of the program / scheme to consumers. Also, the high FIT rates were also locked-in, and the digression provisions skipped (Verzola, 2016). However, a measurable amount of success existed on the scheme despite the mistakes, and was reported in some literatures regarding the case of wind power. For this technology, the installed capacity obviously almost doubled annually from 114 MW in 1995 to beyond 2800 MW in 2000 (Sijm, 2002). Regarding the capacity cap specifications in the Spanish perspective, there was initially no caps / limits to installation and participation in their FiT scheme. However, it was observed that due to highly favourable FiT for solar PV, the solar market gets overheated from 2007 to 2008, and capacity was realised to be higher than the expected target required to keep the country on track as par the targets and ratepayer impacts (NREL, 2011). This resulted in capping the capacities for technologies especially the solar PV in 2008, in keeping the policy away from deformation and ensuring predictable policy outcomes (NREL, 2011). Spain's FiT policy was design with a downward adjustment to subsequent payment amount. This was made possible or triggered if 75% of the capacity target of preceding calls were made and was followed by a formula as reported by the NREL (2011) as follows:

Percentage adjustment to actual FIT payment (if triggered) =

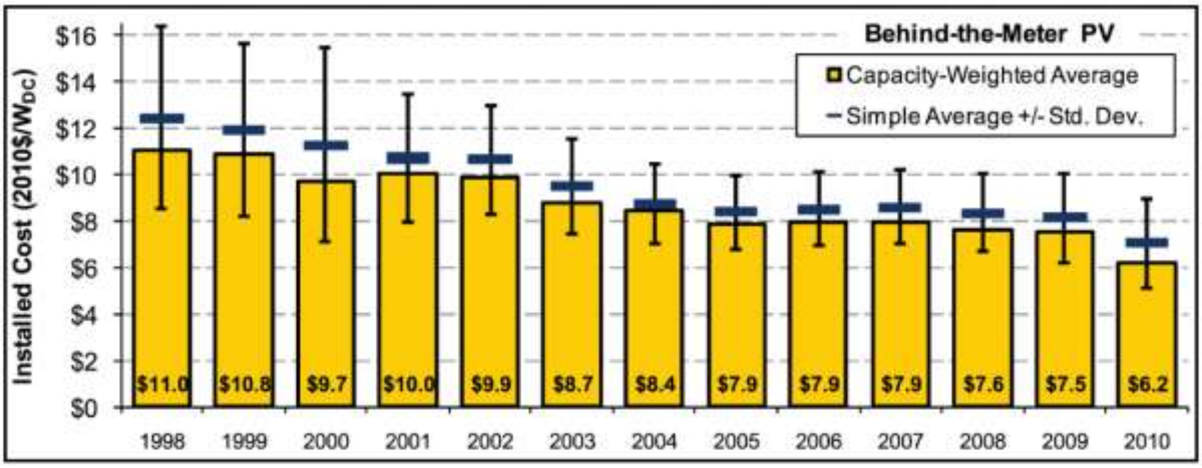
$$[(1 - 0.9^{1/m}) \times (P_o – P) / ((0.25 \times P_o) + 0.9^{1/m})] \text{ ------ } (24)$$

Where: $P_o$ - the capacity target for the given call, p – pre-registered capacity signed up during the previous call, m – number of annual calls

Looking at the case of Italy as a further evaluation, the Auction scheme in the country had prescribed floor (-30%) and ceiling (-2%) deductions for all technologies in order to prevent under- or overbidding with strong effects (Wigand et al., 2016). It must be stated that on the French perspective, being successful in renewable energy adoption arising from the policy support schemes has got some few challenges in the process as outlined by Centre on Regulation in Europe (2015). The first being that regardless of the considered policy support scheme, the main issue to the deployment of the renewables has been lack of stability as obvious from the moratorium / suspension on FiT for Solar in 2010/2011 coupled with the uncertainty over the legality of FiT for Wind Power during 2014. Secondly was the fact that high level of deployment risk has been obvious due to high financing costs for the renewable technologies in the country. Hence, implementation of a better and more favourable financing scheme could strongly be necessary such as the kind of Soft Loans provided by the Kreditanstalt fur Wiederaufbau, KFW, for renewable-based projects in Germany. Thirdly was on the fact that the administrative procedures linked to the renewable energy projects deployment in the country was really complex, which usually results in increased delays and slow developments. A perfect example is the fact that the lead-time for Wind Power project could take say 7-8 years as compared to 2-3 years in Germany.

### 4.2.2 North America Renewable Power Policy Analysis

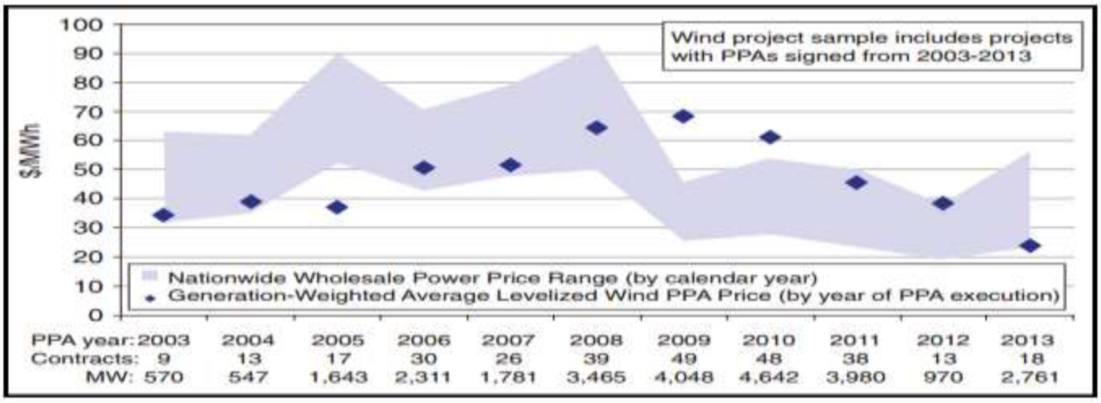
For this continent however, beginning with the United States, regarding the Net-Metering existing instrument, experience in some of its states/regions have shown the fact that capacity limits introduction of between 0.1 to 20% of total generation was set to the advantage of the policy makers (IEA, 2015a). This was considering the fact that some technologies rewarded at the retail prices exceeds the value of their production and hence that will prevent the excessive rise of the deployment by the investors which could be at the policy makers disadvantage. Additional impact of the Net Metering scheme was for example, the installation of on-site solar systems in the service territory of California by around 77,000 residential and non-residential customers, where about 99% the state customers were for solar PV (Steven and Nathaniel, 2012). Based on this, many installations were realised in the state as an effectiveness measure. This has helped tremendously in ensuring job opportunities as an equity measure. A rough estimate of around 100,000 workers were employed in the solar industry in the whole country as at 2011, of which 26,000 were from California (Steven and Nathaniel, 2012). On the basis of cost reduction from the rapid penetration of the solar PV systems in the California state, the figure below gives the details as an efficiency measure to the Net Metering instrument.




Source: Stephen and Nathaniel, 2012

***Figure 43:*** *Installation Cost Trend for Customer Site Solar PV System in California State*

Furthermore, going in to the different practices of the tariff / charges schemes regarding distributed generation customers compensation, falling under either Net-metering or Feed-in tariff or both instruments have been for instance, the Net-Billing (reduced compensation as compared to retail rate). This is seen to have been practiced by some US states such as the Arizona, Maine, New Hampshire, and others (NREL, 2017)). Another charge specification termed Fixed Rate Increase (i.e. fixed rate plus extra charge for grid maintenance) had been proposed to many utilities in about 25 states and the District of Columbia (DC) based on defined percentages (NREL, 2017). Moreover, charge principles like Non-By-passable Charges, included by only one state so far, which was California, and lastly the Time Varying Rate, considered by California and Colorado (NREL, 2017). More so, regarding the U.S FiT, capping / upper limits were ensured owing to some technical reasons and lessons. The reasons behind such specifications behind the instrument were to maintain grid integrity/quality, reliability, and stability depending on the grid nature of different locations and their challenges; and also, in controlling the costs of the RE policies and projects (NREL, 2011). The PPA for the tariff system has been effective in terms of cost reduction over years due to the analysis done for the case of onshore wind as reported by David et al. (2015) in the below figure. This is an efficiency indicator showing the price peak with ultimate fall in the technology penetration.




Source: David et al., 2015

***Figure 44:*** *Onshore Wind Contract Prices with Signed PPAs*

Nevertheless, the existing net metering of the country has got some problems. The problems are structural rate design, in which determined prices fail to incorporate the local knowledge that would be reflected in market responses to price signals or modifications in prices when system conditions alter (Kiesling, 2016). Net-metering rates also made ambiguous cross-subsidies associated in traditional utility regulation, which often reveal themselves when new technologies change the energy-market opportunities that are obviously of interest to consumers (Kiesling, 2016). Also, looking at the Auction in USA, according to the study conducted by McConnel and Saretto (2009), Auction Rate Security (ARS) failed to some extent, and the failure was attributed to level of bond maximum auction rates as investors rationally declined to bid for bonds in which the required market yields was beyond their maximum auction rates. They further found that Auction Rate Securities (ARS) yields were normally in excess of outcomes of different cash equivalent investment choices inclusive of treasury bills (T-bill), certificates of deposits (CD), money market funds (MMF), and Variable Rate Demand Obligations (VRDO). Moreover, McConnel and Saretto (2009) classify ARS by the type of max rate, and they found that auctions for those with floating maximum rates failed at a much higher frequency than the auctions for bonds with fixed maximum rates. For instance, during the tumultuous second week of February 2008, the rate of auction failures for bonds with floating maximum auction rates was 93%, while the rate of auction failures for bonds with fixed maximum auction rates was 13.4% as predicted.

***[Note: An Auction Rate Security (ARS) is a debt security (Bond-based) that is sold through a Dutch auction at an interest rate that will clear the market at the lowest yield possible (Investopedia LLC, 2018)].***

Additionally, the Auction System in some states like California is double fold i.e. **Static (Sealed bid) Auction and Pay as bid** (Wigand et al., 2016). The pay as bid auction is an auction system where multiple homogenous items (i.e. multiple electricity produced from different technologies in this context) are sold at different prices in contrast to **Uniform Price or Clearing price auction** where multiple homogenous items are sold at same prices. Furthermore, the Incentives scheme in various states of the U.S has significantly assisted in augmenting the share of grid-connected renewable systems capacity installed, particularly the Photovoltaic systems (NREL, 2002). However, lessons derived in the various states regarding the negative impacts to incentives program for renewable energy adoption are the varying levels of difficulties in view of integrating renewable energy systems to the utility grid (NREL, 2002). It is noted that in scenarios where the grid-interconnection is worrisome and expensive, the effectiveness and worth of incentive programs that encouraged the installation of grid-connected renewable system is seriously on menace. Secondly is the Weakness of the power plant infrastructure (NREL, 2002). Note that Offering generous incentives to increase demand before an adequate distributor and installer infrastructure is in place can frustrate potential participants and delay or discourage installations. The most significant developments in the policy arena in the U.S are the commencement of the American Recovery and Reinvestment Act (ARRA) (2009), in which the Department of Energy (DOE) invested more than $31 Billion in energy infrastructure, energy efficiency and clean energy projects (Mahmure et al., 2015).

To proceed further, inadequate understanding of the types and benefits of renewables in general is still considered a major barrier to technology adoption hence putting a threat to the incentive schemes (NREL, 2002). It must be mentioned further that in States like Florida in USA, the Rebate incentive scheme has also helped to some extent in boosting capacity of the renewable electricity supply, and specifically, from 1999 to 2001, a total of 173kW installed capacity has been put to record, where 54% of recipient are Residential and 46% public facilities (NREL, 2002). Renewable energy deployment (Particularly in Electricity domain) in both California and Texas relies heavily on federal tax incentives, such as tax credits and accelerated depreciation rates (Felix et al., n.d). Also, The Investment Tax Credit (ITC) has been obviously successful, aiding the U.S. sector growth by more than 70%/year (Verzola, 2016). Furthermore, in Illinois, a combination of Rebate and Grant proved to be effective, leading to renewable capacity installation of up to 28kW and 24MW respectively also from 1999 to 2001 for a wide range of renewable technologies and the recipients were residential, public facilities and commercial (NREL, 2002). Lastly, in Iowa, the Loan-based incentive proved to be effective in ensuring annual generation of about 477235MWh from 1996 to 2001 also for a wide range of technologies viz. hybrid system, solar, hydro, wind and biomass with the recipients being Residents, Businesses, Schools etc. (NREL, 2002). Basing on the Renewable Energy Certificate Instrument (REC) in the whole country as practiced also state-wise, there has been a tremendous success stories based on 2 different market orientations (i.e. Compliance market and Voluntary market). The compliance market is linked to the Renewable Portfolio Standard (RPS) instrument in ensuring compliance to the set target or meeting of the mandatory quota requirements whereas, the voluntary market has nothing to do with that. The below table shows clearly the RECs sold with the corresponding market values during 2004 as obtained from NREL (2005).

***Table 64:*** *Table of Successes / Effectiveness of REC in US Member States during 2004*

| **Market Nature** | **RECs Sold (Million MWh) (Market Size)** | **REC Market Total Value (Million USD) / based on $/MWh Values** |
|---|---|---|
| Compliance Market | 13 | 140 |
| Voluntary Market | 3 | 15 – 45 (range value) |
| Total | 16 | 155 – 185 |

Source: NREL (2005)

According to NREL (2005), despite the effectiveness of the REC policy instrument, a number of challenges exists that need to be addressed in increasing the effectiveness of the instrument in the member states with such. These challenges were: lack of upfront or direct guaranteed revenue stream to obtain financing for new projects, which can come from long-term sell of either the bundle energy and RECs or energy and RECs sold separately; Communication inefficiency or barrier to the consumers on the clear distinction between RECs and Renewable Electricity; Lack of electronic database that could track the movement of RECs at the whole sale level, which could strongly improve the integrity of REC market; REC market hinderance by question about ownership, Emission market participations among others.

On the social impact of the renewable energy policy in the United States (U.S) being another indicator of success i.e. Equity, many jobs were created as a measure of human empowerment.

According to Deger et al. (2018), there was an increase in citizens working in Energy Efficiency jobs by 7% from 2015 to 2016, 24.5% increase in workers in solar electric generation companies from 2016 to 2016, 32% increase in workers in wind power generation companies and so on. Further to this, costs have fallen especially in the solar electricity domain due to the rapid capacity scale-up influenced and driven by the policy designs in many states of the country (Deger et al. 2018).

On a final note, the primary policy instruments drivers in the US Federal as well as in some states namely California and Texas as already stated and with comparison to Germany is as summarised in the Table below:

***Table 65:*** *Policy Drivers Comparison for US in Comparison to Germany*

| **Jurisdiction** | **Major Policy Driver** | **Mandate / Goal / Cap** |
|---|---|---|
| U.S Federal | Investment Tax Credit (Solar)<br>-Residential<br>-Commercial | Phases down to 22% by 1/1/2021, Expires 1/1/2022, Drops to 10% by 1/1/2022 |
| | Production Tax Credit (Wind) | Phases down to 40% by 1/1/2019, Expires 1/1/2020 |
| | Accelerated Depreciation | Permanent |
| California | Renewable Portfolio Standard | 50% by 2030 Mandate |
| | Reverse Auction Mechanism | 1,299MW Cap |
| | Feed-in Tariff | 750MW Cap |
| | California Solar Initiative | 1,940MW by 2016 Goal |
| | Net Energy Metering | 5% of Peak Load Cap |
| Texas | Renewable Portfolio Standard | 5,000MW by 2015 mandate,<br>10,000MW by 2025 goal,<br>500MW non-wind goal |
| | Competitive RE Zones | N/A |
| Germany | Feed-in Tariff | 80% by 2050 goal,<br>52,000 MW solar cap |

Source: Felix et al. (n.d)

In Canada, a lot of success stories exist from the existing policy instruments in the country. The summary of the existing net metering success in different regions of the country which covers both the effectiveness and equity indicators is as given in the below table:

***Table 66:*** *Net Metering Projects with Capacities Raised in Different Regions in Canada*

| Regions | Generation Type | Number of Projects | Capacity |
|---|---|---|---|
| Central Interior | PV | 11 | 21 |
| | Wind | 1 | 2 |
| | Wind & PV | 1 | 7 |
| East Kootenay | Hydro | 1 | 25 |
| | PV | 10 | 29 |
| Kelly / Nicola | Hydro | 2 | 8 |

| | | | |
|---|---|---|---|
| | PV | 14 | 47 |
| Lower Mainland | Biogas | 1 | 20 |
| | Hydro | 3 | 75 |
| | PV | 71 | 366 |
| | Wind | 2 | 5 |
| | Wind & PV | 1 | 5 |
| North Coast | PV | 11 | 29 |
| | Wind | 1 | 3 |
| Peace River | PV | 7 | 29 |
| South Interior | Hydro | 2 | 62 |
| | PV | 21 | 78 |
| | Wind | 2 | 11 |
| | Wind & PV | 1 | 8 |
| Vancouver Island | Hydro | 1 | 11 |
| | PV | 61 | 287 |
| | Wind | 1 | 3 |
| | Wind & PV | 2 | 7 |
| Total | | 228 | 1138 |

Source: Fraser, 2013

Furthermore, looking at the Net Metering customers uptake for the whole North American continent, comprising of some states from Canada and the United States. The table below provided an update to that effect. This is considered an equity indicator as a job opportunity measure and social welfare.

***Table 67:*** *Customers Uptake for Net Metering Programs in Different States in N/A Continent*

| Jurisdiction | Net Metering Customers | Total Customers (Million) | % Uptake |
|---|---|---|---|
| California / US | 139000 | 11.8 | 1.18 |
| Vermont / US | 1000 | 0.3 | 0.40 |
| New Jersey / US | 12000 | 3.3 | 0.36 |
| Oregon / US | 4200 | 1.4 | 0.31 |
| Washington / US | 1250 | 1.0 | 0.12 |
| Florida / US | 4000 | 9.7 | 0.04 |
| Ontario / Canada | 22521 | 4.8 | 0.47 |
| Saskatchewan / Canada | 400 | 0.5 | 0.06 |
| Alberta / Canada | 400 | 1.2 | 0.03 |
| BC Hydro / Canada | 228 | 1.8 | 0.01 |

Source: Fraser, 2013

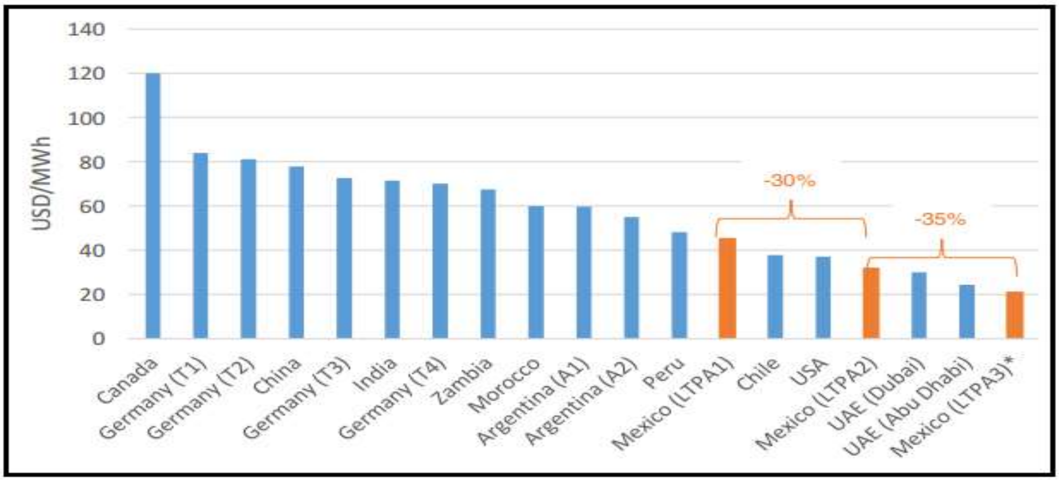
Additionally, the Tradable Electricity Certificates (TREC) instrument in Canada had significant success based on different programs with 2007 analysis as follows:

*Table 68: Customers Uptake for Net Metering Programs in Different States in N/A Continent*

| **Bundled Electricity and Environmental Attribute Programs** | **Price** | **Sales in 2007 (MWh)** | **Eco-logo Certified Product** |
|---|---|---|---|
| ENMAX Greenmax | Did not disclose | 549,000 | Yes |
| SaskPower GreenPower | $25/MWh | 30,000 | Yes |
| Oakville Hydro Green Light Pac | $60/MWh | 217 | No |
| Maritime Electric Green Power | $2.5/MWh above market price | 570 | No |
| Select Power's Selectwind | $87/MWh | Not operational in 2007 | No |
| Stand-alone Environmental Attributes Programs | Price | Sales in 2007 (MWh) | Eco-logo Certified Product |
| BC Hydro Green Power Certificates | Varies | 67,084 | No |
| Canadian Hydro Developers REC | Varies | 600,000 | No |
| Bullfrog Power REC | $30/MWh | 176750 | Yes |

Source: Sustainability Prosperity, 2011

Mexico is the next country to be looked into. It has been analysed for its existing power policy instruments in the North American continent as among the highly performing global countries in renewable power. It must be noted that the electricity market in the country has been redesigned based the Locational Marginal Pricing (LMP) model. The existing auction performance in the country has been analysed from the literature, of which has been found among the lowest in terms of price in the world. The Auction (i.e. Long-Term Power Auction (LTPA)) specifically for solar PV technology in terms of massive adoption and price reduction trend is showcased in the below figure being an efficiency indicator.




Source: Carlos, 2018

***Figure 45:*** *Solar PV Prices Reduction Trend in the Auctions Practice in Mexico as Distinguished*

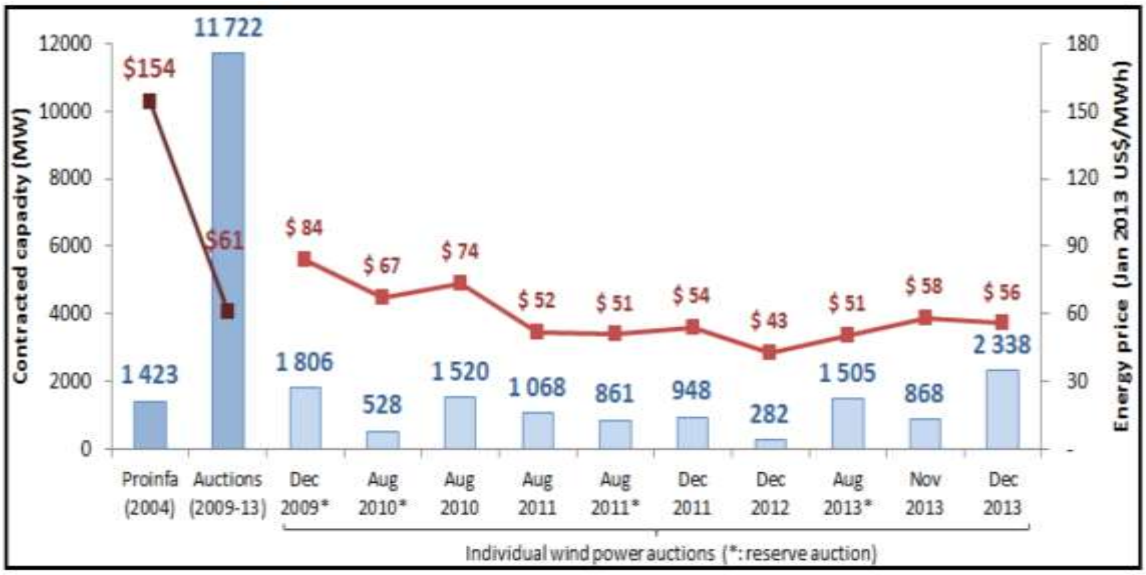
The challenge regarding the Auction process (i.e. LTPA) in Mexico has been due to the fact that there has been a delay in obtaining the construction permit in various states of the country hence, endangering PPA's development (Carlos, 2018). Also, as reported by Carlos (2018), some of the Permits are expensive to secure, making the investors so reluctant in paying for such permits prior to the awarding of the contract.

### 4.2.3 South America Renewable Power Policy Analysis

Brazil's Alternative Energy Source Incentive Programme (PROINFA) enacted in 2002 had become the main programme operating to promote electricity generation from renewable energy sources (Chou et al., n.d). Note that the **PROINFA** comprised of 2 stages viz.: Stage I: 3300 MW of RE from wind, Biomass and Small Hydro will be brought through a system of Feed-in Tariff coupled with Subsidies and incentives until 2006; Stage II: Once the 3300 MW is met, scaling will be done through Tendering / Bidding (IEA, 2018). The realised final contraction in the PROINFA program in the first stage was 3298MW, split in to Biomass (685 MW), Small Hydro (1191 MW), and Wind (1422 MW) (Chou et al., n.d). Note that Unfortunately, there was no evidence that PROINFA was effective in its management of CDM revenues, and in general, it was criticized to some extent in failing to provide economic signals for efficiency and technological improvement as put forward by Gabriela and Luiz (2011).

According to Wigand et al. (2016), Brazil operated a system of both **static (sealed bid) auction** and **dynamic ascending auction**. Moreover, the challenge of access to transmission infrastructure has delayed and hindered the realization of many projects in line with the Auction / bidding scheme being the most highly performing (Wigand et al. 2016). To mentioned further, in Brazil, two general types of auctions have been used for the development of RES viz.: **New Energy Auctions and Reserve Energy Auctions** (Wigand et al., 2016). **New energy auctions** are dedicated to supplying the demand reported by distribution companies according to their expected load growth, and aggregated by the auctioneer, having the Auctions technology neutral in line; while **Reserve energy auctions** are carried out occasionally or at regular intervals, usually at government's discretion to contract surplus energy, it is peculiarly a technology-specific, and has been strongly used to promote RES-E (Wigand et al., 2016). Onshore wind has been participating in both technology-specific (since 2009) and technology-neutral auctions (since 2011) (Wigand et al., 2016). Furthermore, it was mentioned from experience that the procurement of renewable energy through the Reserve Energy Auction has been more successful than through the New Energy Auction. The First New Energy Auction was launched in 2007 although participation in the auction was unexpectedly low, and the lack of interest has been attributed to the following factors viz: RE developers have obtained higher prices in the free market because of the attractiveness of the T&D discount (which is offered only to RE of less than 30 MW), It is often more difficult for RE to comply with the Firm Energy Certificate (FEC) coverage obligation, since intermittent generation faces a higher risk of penalization, and lastly The upper limit for the remuneration level in the auction was set at a rate lower than the FITs previously offered by PROINFA (Gabriela and Luiz, 2011). Notwithstanding, since 2005, a total of 62 GW was contracted by 25 Auctions that include 9 RE-based power generation auction all via the new energy auction and reverse energy auction (IRENA, 2013). Furthermore, the tender instrument strong impact in the Brazil energy jurisdiction led to about 16 long-term contract auctions carried between 2004 to 2009, contracting both new and existing generators in average of 37000 MW (NREL, 2011). Also, at the same time, with records from 2008 to 2014, more than 20,000 MW capacity was acquired hence, confirming the effectiveness and power of the instrument (NREL, 2011). In specifics, first alternative energy auction was launched in Brazil in 2007, where it resulted in 541 MW for biomass contracts (average of USD 82.6/MWh) and 97 MW for small hydro (average of USD 81.7/MWh) (IRENA, 2013). First biomass only auction occurred in 2008, that resulted in 2,379 MW for 31 plants using sugar cane and elephant grass-based bagasse, where the winning bid was settled at average price of USD 36.50/MWh (IRENA, 2013). Moreover, the first wind only auction occurred in 2009 where 71 projects were selected, resulting in 1,806MW based on the final average reached price of USD 84/MWh (IRENA, 2013).

In summary, the Auction scheme in Brazil has been successful in attracting enormous capacities of renewable power with a substantial cost reduction in the technology over time, especially the wind power being the fastest growing in the country (IRENA, 2013). Auction between 2008 to 2011 covering small hydro, wind, and biomass resulted in a renewable power capacity of about 10 GW, which is in contrast to the PROINFA scheme of 2002 that enabled installed capacity of 2,889 MW from 2002 to 2011 of mostly wind power (IRENA, 2013). To show clearly the impact of the wind project penetration with the cost reduction advantage over time as an efficiency indicator has been showcased in the figure below:




Source: Gabriela et al., 2014

***Figure 46:*** *Auctions Involving Wind Power Performance (Capacity and Price)*

### 4.2.4 Australia / Australasia Renewable Power Policy Analysis

As a result of the strong policy impacts targeted at saving the environment significantly, Australia had tremendously increased its share of clean energy in its overall electricity mix. It was reported according to NREL (2017) that the share of renewable electricity in 2015 was 14.6% of the total generation and is valued at 35 TWh (40.1% Hydro, 33.7% Wind, 17% Solar, and others). Favourable policies set in place such as the rebate, state-level FiT, REC, and taxation-based instruments have significantly fuelled the excessive deployment of PV technologies particularly the Distributed Generation based (DG) (NREL, 2017). Basing on the success of the TREC of the country, the country has got 2 separate trading TREC, namely the small-scale technologies TREC such as solar, and the large-scale technologies REC like wind (Shrimali and Tirumalachetty, 2013). Additionally, solar credit scheme was launched in favour of the TREC, which led to 5 times the usual number of the TREC for solar power systems, hence, making a huge influx in the market for the TREC in 2011 (Shrimali and Tirumalachetty, 2013). Furthermore, on the rebate specific instrument success, the program linked stimulated over 130,000 renewable systems installation worth $0.68Billion, with a growth of around 80 new solar panel installation businesses per month towards the end of the program (Sonia et al., 2012).

### 4.2.5 Asia Renewable Power Policy Analysis

Beginning with China, initially, the country's bidding process was a straightforward lowest-bidder gets the contract, however, it later became clear that underbidding could be an issue due to the prestige that was gained from winning one of its large projects (Cozzi, 2012). Therefore, in response to that, in 2007, the NDRC reformed its policy, and modified the contracts in such a way that the new agreement would be for the average bidding price, rather than the lowest bid (Cozzi, 2012). Additionally, China's Wind Power Concession Programme, implemented in 2002, has been the main programme to develop large-scale on-shore wind projects for grid-connection, of which as of 2005/2006, the installed capacity for wind has risen drastically to around 1260MW nationwide (Chou et al., n.d). Furthermore, from 2003 to 2009 being the year the Wind Power Concession Program i.e. onshore wind (for tendering process, being technology specific) ended, wind capacity in China increased significantly from 0.57 GW to 25.83 GW, which was an increase of more than 4,400% and hence, the most significant cause of massive expansion of China's Wind Power Capacity (Cozzi, 2012). Furthermore, the concession program appeared to impact strongly to bringing down the price of wind energy in the country: A comparison of concession and non-concession projects in 2006, as an instance showed that on average, concession projects were significantly cheaper than their Approved Price counterparts, with concession projects costing an average of 0.43 RMb/kWh ($0.063/kWh) to an average cost of 0.71 RMb/kWh ($0.10/kWh) for non-concession projects (Cozzi, 2012). China with respect to tendering instrument or bidding, according to Wigand et al. (2016) operates a static (sealed bid) auction. Regarding the Wind Concession bidding of China, realization of 3.5GW capacity was certain specifically in 2007 (Wigand et al., 2016), which shows in overall, the effectiveness of the concession bidding. Further technology specific auctions for Solar PV, CSP, and Offshore wind following 2009 to 2011 resulted in a total contracted volume of 1,340MW at an average contract prices of USD160/MWh, USD140/MWh, and USD116/MWh respectively (IRENA, 2013).

China's FiT scheme in effect from 2009 was found to be effective as well, of which specifically for wind power as an instance had stimulated the interests of the developers in wind farm investment. Record has shown that from 2010 to 2012, the wind installed capacity under the strong influence of this instrument had continued to grow rapidly making the country the leader of wind installed capacity globally for 3 the consecutive years in specific values of 44,733 MW, 44,733 MW and 75,324 MW, accounting for 22.7%, 26.2% and 26.7% of the global total (Zhang et al., n.d). These have tremendously impacted the wind turbine industries in terms of production and sell as well as technological advancements via research and development. Furthermore, on the basis of subsidy as well as the concession programs on solar PV technology, china has recorded a massive success as well. According to Zhang et al. (n.d), the cumulative capacity of the technology had risen drastically from 300 MW in 2009 to 8300 MW in 2012, representing 4.6% and 8.1% of the global total for the respective years. This had concurrently led to the solar PV market strong growth in terms of improved facilities production and sell from industries.

Successes recorded regarding the policy instruments implementations in general for China being the highest renewable energy developer and implementer globally were: numerous energy-saving renovations are put into effect, efforts ensured to support renewable energy developments being a new aspect, improvements ensured in civil energy utilization conditions (energy service level, access to natural gas and electricity, combined heat and power projects, etc.), and lastly environmental protection has been augmented (Mahmure et al., 2015).

Moving on to India, Currently, a combination of policy instruments - Renewable Portfolio Standard and feed-in tariffs, at the state level, is the main market mechanism as stated by Chou et al. (n.d). Moreover, some existing policies in the power sector of the country (India) are considered to be negative on the development of RETs being that the overall electricity tariffs structure for the end users has been severely distorted by the cross-subsidisation such that Agricultural and residential electricity prices have been heavily subsidized being that the government considers universal access to electricity a social and political objective (Chou et al., n.d; UNEP, 2011). By contrast, industrial consumers are charged more to subsidise agricultural and residential consumers. Owing to strong political compulsion, the situation of cross-subsidy is unlikely to be phased out in a short or medium term at the national level, and it has shown significant negative economic impacts (Chou et al., n.d; UNEP, 2011). To expatiate on the impact, the low prices, especially for the residential and agricultural sectors, leave utilities without sufficient finances to improve the quality and reliability of electricity supply, of which for instance, the state utilities are operating with heavy financial deficits (around €3.95 Billion a year) (Chou et al., n.d). Secondly, these cross-subsidies benefit mainly those who are economically better off, whereas the majority of really poor people have no access to electricity due to the high connection fee to electricity as well as low electricity consumption (Chou et al., n.d). Thirdly, owing to high cost and unreliable supply of electricity, industrial consumers have chosen to have their own back up supplies, mainly diesel generators. It is evident that numerous stand-alone diesel generators contribute to more GHG emissions (Chou et al., n.d). Below Table gives the Electricity Subsidies Breakdown:

***Table 69:*** *Electricity Subsidies in India*

| Sector | Average Price ($/kWh) | Supply Cost ($/kWh) | Rate of Subsidy (%) |
|---|---|---|---|
| Residential | 0.02 | 0.048 | 57.9 |
| Agricultural | 0.0034 | 0.046 | 93.0 |
| Industrial | 0.047 | 0.048 | N/A |

Source: Chou et al., n.d

Furthermore, on India, regarding the set Renewable Purchase Obligation (RPO) as a contemporary name for Renewable Portfolio Standard (RPS) instrument of the country that was set, many success stories exist in states on meeting up with the RPO target as shown in the Table below:

***Table 70:*** *Successes Stories / Compliance with the RPO in India, 2009*

| State | Target Introduced from 2006 | Achievement in 2009 | % Extent of Target Achievement |
|---|---|---|---|
| RPO Andhra Pradesh | 5% (1% from Wind) | 4.52% (Target on Wind not met) | 90% |
| RPO Gujarat | 2.0% | 2.10% | 105% |
| RPO Haryana | 3% | 0.01% | ~ 0% |
| RPO Karnataka | 7 to 10% | 9.47% | 95-135% |
| RPO Kerala | 5% | 1.22% | 24% |

Source: Gabriela and Luiz (2011).

The use of Feed-in Tariff Policy (FITPs) in combination with fiscal and financial incentives in India has efficiently promoted the deployment of different types of RE systems and capacities, especially on-shore wind (Gabriela and Luiz, 2011). Yet, the strengthened market growth was not accompanied by standard levels of operational efficiency—especially in wind-based generation partly because of abnormal incentives driven by the policy mix as explained before (Gabriela and Luiz, 2011).

Regarding the Renewable Energy Certificate (REC) existing though has been falling short from the decision makers experience in the country, some factors have also been attributed to such low efficiency in the instrument. It was reported according to Shrimali et al. (2013) that the short falling of the market for the instrument has been due to overdependence on state level policies and compliance of which there are not strict compliance laws and enforcements to renewable energy targets as well as insufficient inceptive mechanisms. The authors mentioned further that lack of reliable long-term pricing signals and long-term yearly target is considered also a discouraging factor to the bloom of the market for the instrument. Notwithstanding, the REC led to some milestone in the trading for both solar and non-solar technologies. Commissioning of 7,500 MW renewable energy capacity was done since the introduction of the REC in January, 2010, of which 2,256 MW (30%) got registered under the REC scheme (Sushanta et al., n.d). Further records regarding the penetration of the instrument based on the number of certificated issued and redeemed has been provided in the table below:

***Table 71:*** *RECs Issued and Redeemed in India for Some Defined Periods*

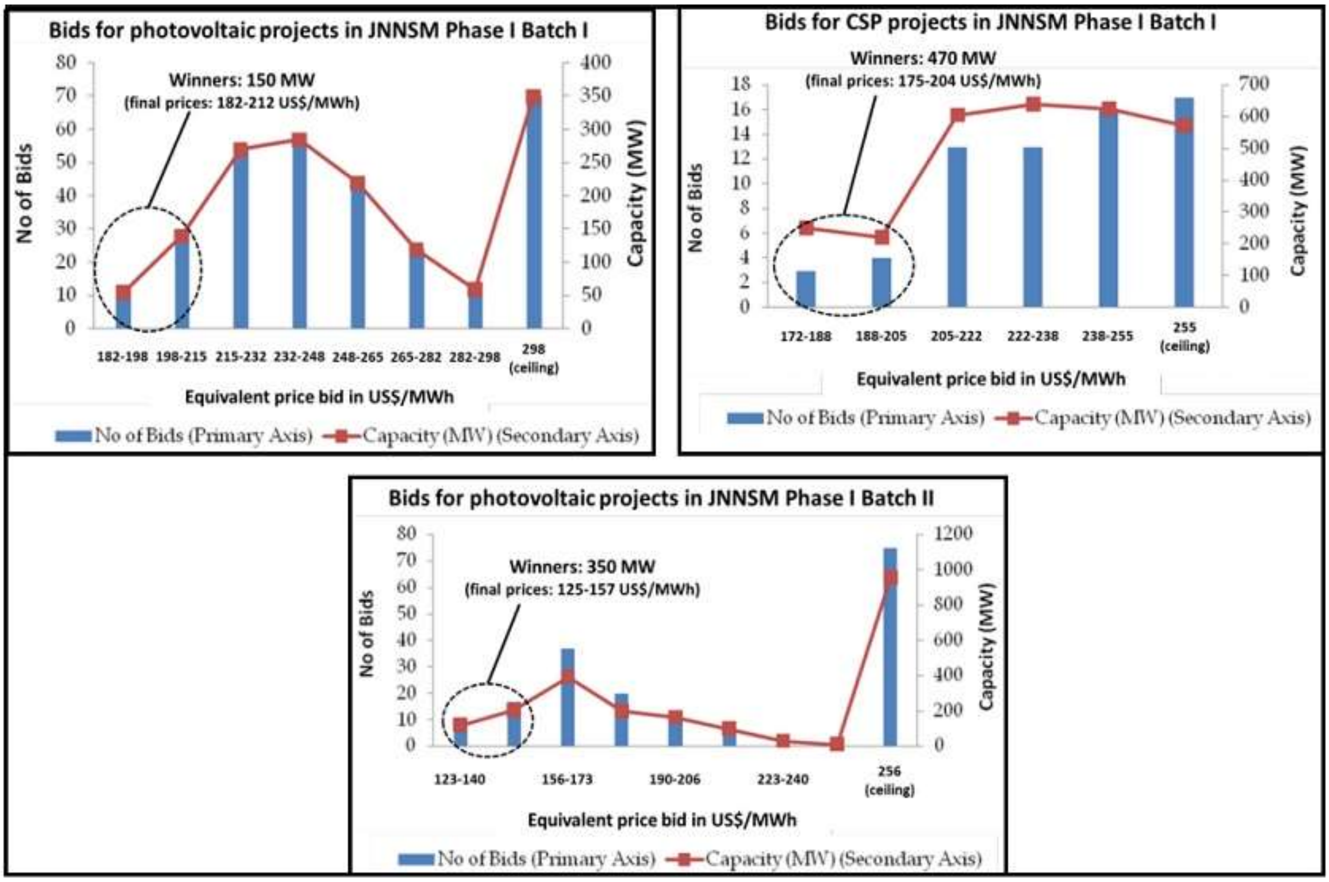
| Period | Opening Balance | RECs Issued | RECs Redeemed | Closing Balance |
|---|---|---|---|---|
| March, 2011 | - | 532 | 424 | 108 |
| April, 2011 | 108 | 4,503 | 260 | 4,351 |
| May, 2011 | 4,351 | 28,270 | 18,502 | 14,119 |
| June, 2011 | 14,119 | 27,090 | 16,385 | 24,824 |
| July, 2011 | 24,824 | 30,224 | 18,568 | 36,480 |
| August, 2011 | 36,480 | 31,813 | 25,096 | 43,197 |

| | | | | |
|---|---|---|---|---|
| Sept., 2011 | 43,197 | 74,612 | 46,362 | 71,447 |
| Oct., 2011 | 71,447 | 126,544 | 95,504 | 102,487 |
| Nov., 2011 | 102,487 | 135,697 | 105,527 | 132,657 |
| Dec., 2011 | 132,657 | 88,055 | 111,621 | 109,091 |
| Jan., 2012 | 109,091 | 102,348 | 171,524 | 39,915 |
| Feb., 2012 | 39,915 | 200,736 | 206,188 | 34,463 |

Source: Shrimali and Tirumalachetty, 2013.

Also, at the Indian regulation, a key government policy that fails the renewable energy sector in general is the distortion of energy prices; Energy pricing policies in India tend to favour fossil fuel-based energy sources (electricity, kerosene, LPG, petrol, diesel, etc.) (UNEP, 2011). Since the conventional technologies are also supported by subsidies, there is no level playing field for the new technologies that compete with them (UNEP, 2011). One example of policy-induced energy inefficiency relates to the low agricultural tariffs (subsidies are as high as 80%–90% in most states) as stated previously, which has resulted in gross overuse of both electricity and groundwater (UNEP, 2011).

On the existing auction instrument in the country that takes phases and batches, solar-based technology performed greatly. The National Solar Mission (NSM) of the country phase 1 auction performance has been summarised in the below figure. It gives the number of bids received, the winners and the capacities realised in the practice.




Source: Gabriela et al. (2014)

***Figure 47:*** *Bids Received with the Accompanied Capacities Obtained for NSM*

Turkey on the other hand has only one universal feed-in tariff, ranging between €5-5.5 cents/kWh as mentioned already in the existing policies review, which was provided by the government, hence, leaving completely the market to decide which technology by its cost advantage and future prospect will develop (Chou et al., n.d). It turns out that, the tariff is only sufficient for wind power energy; however, it is noted by the World Wind Energy Association that this tariff is still much lower than the average remuneration in the leading European wind markets. By contrast, the tariff is not sufficient to promote the development of other renewable energy technologies such as solar energy, small hydro, and biomass (Chou et al., n.d). Further on Turkey, since 2005, the Turkish Government efforts to improve the energy efficiency and develop RES through many outlined laws viz.: the Law on Utilization of RES for the Purpose of Generating Electrical Energy (2005), the Energy Efficiency Law (2007), accession to the International Renewable Energy Agency (IRENA) in June 2009, the adoption of the Ministry of Energy and Natural Resources (MENR) Strategic Plan (2010–2014) and the Energy Efficiency Strategy Paper published in February 2012 have ultimately all resulted in total energy savings of 40,300 TOE between 2009 and 2013 (Mahmure et al., 2015). Furthermore, it must strongly be noted that the sustained growth of on-shore wind capacity additions was largely attributed to the introduction of a Feed-in Tariff Policy (FITP) in 2005 (Gabriela and Luiz, 2011).

Switching to the case of Japan, the Japanese government once more initiated what they referred to as the “New Sunshine” project, under its subsidy scheme, which subsidized 50% of the installation cost of residential PV systems (Verzola, 2016). The goal being to create a market for PV systems for the Japanese solar industry, and the subsidy was set to 33.3% in 1997, of which by 2001, Japan boasted of more than 77,000 “solar roofs” as a success story (Verzola, 2016). It must be noted that the program reached its apex in 2004, having subsidized a total of 400,000 homes, and later on, the subsidy was down to 3%, and was phased out finally in 2005 after its significant roles (Verzola, 2016).

Looking at Philippines success story regarding policy instruments, the FiT has been very active especially the solar-energy-based FiT, which had led to the installation of about 500 MW of solar plant in its first round of the solar FIT projects (Verzola, 2016). Additionally, many contradicting views exist in Net-Metering instruments globally, of which some countries such as the case of Philippines in this regard considered using other terminology under the Net-Metering called Net-Billing as their unfair experience (Verzola, 2016). The Net-Billing arising for these countries such as the case of Philippines as stated above is when the scheme is not based on parity pricing but on the fact that distribution utilities pay lower for consumer-produced electricity, but charge higher for utility-produced electricity (Verzola, 2016). The Philippine FiT system has several features of the successful German FIT system, but it does not have the friendliness of the latter to small players in the system, instead, the bureaucratic FIT requirements are closer to the unsuccessful Spanish model, which also kept the small players out of the FIT system (Verzola, 2016). Additionally, Risk reduction was the key to the success of the German FIT system, the Philippine FIT design increased the investors' and lenders' risks, instead of reducing them as pointed out clearly by Verzola (2016). Still on the Philippines success story, a report according to USAID (2017) showed that Feed-in Tariff and incentives measures like the soft loans and tax incentives have been more successful with an impact indicator of power capacity growth rate of around 5% (excluding large hydro) from 2006 to 2016.

Regarding Indonesia story line for success measures, the country has not been able to develop its RE market consistently or sustainably when Standardized Power Purchase Agreements (SPPAs) for FiT scheme were offered from 1993, but it was not until after 2002 that they actually started to attract investments (Gabriela and Luiz, 2011). This has been largely attributed to contextual factors such as the effect of the Asian financial crisis and governance issues, among others (Gabriela and Luiz, 2011). In its practice, the use of SPPAs based on tariffs levels below avoided costs of power generation has been largely unsuccessful (Gabriela and Luiz, 2011). It must be stated that a combination of Feed-in Tariff (FiT) and incentives measures such as soft loans and tax incentives existing have been proven to be the most successful in the country with impact on the power capacity scale-up to an estimated growth rate value of 7.6% from 2006 to 2016 excluding large hydro (USAID, 2017). Another issue was reported of the country's bidding process where some bidders apply for a bidding process without adequate financial capacity accompanied by the challenge that some of the financial institutions do not have full knowledge of the ventures to risk securing loans (International Institute for Sustainable Development (IISD), 2012). This is centred at the country's inadequate and uneven sensitizations regarding the need and impact of the renewable energy adoptions. Another notable challenge also linked to the bidding process was the fact that the bidding rounds are run by the local governments at the projects' locations (International Institute for Sustainable Development (IISD), 2012). It is evident that these bodies may not possess sufficient human resources and technical capabilities to deal with the process efficiently.

In general, three issues affect the scale-up of RE in Indonesia namely: high levels of regulatory uncertainty in the power sector; lowering avoided costs of power generation, especially in the islands that have switched from oil- to coal-based generation (and thus the existing policy is becoming even more ineffective); and lack of clarity as to how the government will cover incremental costs (there is a high off-take risk) (Gabriela and Luiz, 2011).

Moving to Malaysia, the policy instruments especially the Feed-in Tariff (FiT) and with incentives measures such as soft loans and tax incentives have been thriving significantly in augmenting the capacity of power supply. The average annual growth rate of installed power capacities from renewable sources (excluding large hydropower) has been around 22.9% in a decade from 2006 to 2016 resulting from the intervention of such instruments (USAID, 2017).

Note that in general, Market conditions in some ASEAN countries have enabled a transition from FITs to an auction mechanism for certain technologies, which is expected to help reduce the cost of renewable power procurement (USAID, 2017). Specifically, Indonesia and Malaysia have both conducted solar auctions.

### 4.3 Overall Energy Policies for the Case Study Country (Nigeria)

Nigeria as the case study country with aggressive and massive uptake of fossil energy specifically the Natural gas in its electricity generation where its share is presently beyond 80%

in the mix have some background policy measures for energy executions and expansions. There has been the National Energy Policy (NEP) developed by the Energy Commission of Nigeria (ECN) and approved by the federal government of the country in 2003 (Emodi, 2016). This policy measure addresses diverse issues namely research and development, energy pricing and financing, legislation, energy efficiency, environment and so on, with an overall goal of optimal energy resource utilization of the country for sustainable development (Energy Commission of Nigeria, 2003). The specific objectives of the energy policy as put forward by the Energy Commission of Nigeria (2003) are as highlighted below:

- ‘’To ensure the development of the nation's energy resources, with diversified energy resources option, for the achievement of national energy security and an efficient energy delivery system with an optimal energy resource mix.
- To guarantee increased contribution of energy productive activities to national income.
- To guarantee adequate, reliable and sustainable supply of energy at appropriate costs and in an environmentally friendly manner, to the various sectors of the economy, for national development.
- To guarantee an efficient and cost-effective consumption pattern of energy resources.
- To accelerate the process of acquisition and diffusion of technology and managerial expertise in the energy sector and indigenous participation in energy sector industries, for stability and self-reliance.
- To promote increased investments and development of the energy sector industries with substantial private sector participation.
- To ensure a comprehensive, integrated and well-informed energy sector plans and programmes for effective development.
- To foster international co-operation in energy trade and projects development in both the African region and the world at large.
- To successfully use the nation's abundant energy resources to promote international co-operation.’’

### 4.3.1 Renewable Energy Policy Guide for Nigeria

Nigeria is blessed with abundant renewable energy resources such as solar, biomass, wind, and hydro however, only hydro is obviously performing in the country’s national grid with a share of roughly around 20% for decades. However, it must be noted that other projects exist in the country outside the hydropower in small scale and off the national grid network, mainly for activities such as street lighting, water pumping, electricity generations for domestic and industrial activities and so on. The potentials of the different resources have already been addressed in the research background section.

In terms of policy measures regarding the renewable energy resources, the country had established the National Renewable Energy and Energy Efficiency Policy (NREEEP) that was developed by its ministry of power in 2014 (Emodi, 2014). This was mentioned clearly in the African regional renewable power policy review for the case of Nigeria, of which most of the policy instruments for the renewable energy operations discussed were in line with the achievement of the objectives of this policy measure or are committed within the frame of this policy measure. The overall objectives of the National Renewable Energy Policy separately as put forward by the Federal Ministry of Power (FMP) (2015) are presented below:

- ‘’To ensure the development of the nation's energy resources, with diversified energy resources option, for the achievement of national energy security and an efficient energy delivery system with an optimal energy resource mix.
- To guarantee adequate, reliable, affordable, equitable and sustainable supply of renewable energy at cost-reflective and appropriate costs and in an environmentally friendly manner, to the various sectors of the economy, for national development.
- To accelerate the process of acquisition and diffusion of technology, managerial expertise and indigenous participation in the renewable energy and energy efficiency sector industries, for stability and self-reliance.
- To guarantee efficient, location-specific and cost-effective consumption pattern of renewable energy resources and improved energy efficiency.
- To promote increased investments and development of the renewable energy and energy efficiency sector, with substantial private sector participation.
- To ensure a comprehensive, integrated and well-informed renewable energy and energy efficiency sector, with plans and programmes for effective development.
- To foster international co-operation in trade and project development, in the ECOWAS, African Region and the World at large.
- To successfully use the nation's abundant energy resources to promote international cooperation.
- To bring abundant electricity access to almost half of the Nigerian population that is currently electricity abstinent, including more sustainable provisions for domestic use and cooking.
- To develop the nation’s renewable energy and energy efficiency resources through the establishment of appropriate financing mechanism that support private investment in the sub-sectors.
- To ensure effective coordination and collaboration among all players in renewable energy and energy efficiency activities in Nigeria.‘’

On shifting to the Energy Efficiency bit of the NREEEP developed in the 2014 year, it is crucial to mentioned the fact that renewable energy adoption alone is not sufficient for sustainability however, the manner in which the resources are harnessed is equally significant. Hence the energy efficiency ensures the judicious and effective utilization of the renewable energy sources both at supply side level and at demand side level. In line with this brief insight, the outlined policies, set objectives and strategies for the Energy Efficiency segment of the whole policy idea having obtained from the Federal Ministry of Power (FMP) (2015) is presented below:

❖ **Policies**

- ‘’The nation shall promote the adoption of energy saving appliances and devices through a nationwide energy campaign and training sessions.

- The nation shall provide incentives for consumer adoption of energy saving technologies.
- The nation shall provide incentives for retailers and importers of energy efficient products and promote local manufacturing of such products.
- The Federal Government shall take the lead in implementing the replacement of inefficient devices with energy efficient ones and promote the same at the state and local levels.
- The nation shall monitor the progress being made in the adoption of energy efficiency.''

❖ **Objectives**

- ''To ensure the prudent exploitation of the nation's energy resources.
- To enhance energy security and self-reliance.
- To reduce the production cost of energy-dependent goods and services.
- To reduce adverse impacts of energy utilization on the environment.
- To eliminate avoidable investments in energy supply infrastructure.''

❖ **Strategies**

- ''To declare energy efficiency as a source of energy that can be bought and sold. This will include tariff provisions for Distribution Companies (DisCos) that promote and achieve high efficiency within their customer base.
- Providing institutional arrangements and incentives for the promotion of energy conservation and the use of energy efficient technologies and processes for domestic, industrial use and services as well as the transport sector and urban planning
- Developing energy efficiency building codes so that buildings are designed to take advantage of climatic conditions in order to reduce energy consumption.
- Ensuring the importation of the more energy- efficient equipment and machinery.
- Promoting Research and Development activities in energy conservation and efficiency, including the development and manufacture of energy- efficient equipment and machinery under consideration of standards and labelling.
- Encouraging the production and use of improved and more-efficient cooking stoves.
- Tasking the Nigerian Electricity Regulatory Commission (NERC) and other responsible agencies to implement the tariff and rule changes that will form the basis for more meaningful renewable energy electricity policy targets.
- Promoting public awareness about the benefits of improved energy efficiency.
- Promoting efficiency improvements with regard to electricity transmission and distribution.
- Mandating the deployment of energy saving light fixtures in federal government offices and facilities.
- Ensuring that the National Building Code requires every new house design in Nigeria must incorporate energy saving measures such that the energy use in the building is at the barest minimum by using light emitting diode (LED) and other efficient devices and equipment.

- Encourage all building in Nigeria to install renewable source of energy as much as possible e.g. roof top solar PV modules, solar water heaters, small wind turbine, biogas system and energy efficient wood stoves.
- Implementation of energy audit programme nationwide and enforcement of various standards for efficient energy use.''

Having seen the summary of the energy policies and the renewable energy policies in general, it is of great benefits to also see the sub-energy policy measures specifically the policy for the electricity sector as a major concern and as an area with multiplying impacts on the rest sectors of the economy of the country. In 2001, the National Electric Power Policy (NEPP) was developed, as a step towards the reformation of the electricity sector of the country (Gopa – International Energy Consultants GmbH, 2015; Emodi, 2016). This policy measure according to statement put forth by GIZ (2015) defined 3 basic principles or steps namely: privatization of the National Electric Power Authority (NEPA) and introduction of Integrated Power Producers (IPPs) and Private Emergency Power Producers (PEPPs), increasing the competition between market participants, reduction of subsidies, and selling of excess power to distribution company of the country (DisCos), and lastly intensifying the markets and the competitions by full cost pricing of supply and liberalization in selection of supplier beyond the local DisCos by larger customers with full competitive market trading. It must be noted that the NEPP had some critical objectives for the country's electric power sector as put forward by Emodi (2016) as follows:

- ''Ensure that the power sector attracts private investments both from Nigeria and Abroad
- Drafting of a new electricity law to provide the legal framework for the reform agenda
- Establishment of an Independent Regulatory Agency
- Development of a whole sale electricity market
- Establishment of a consumer assistance fund to ensure the efficient and targeted application of subsidies to less privileged Nigerians
- Establishment of Rural Electrification Agency (REA) to manage the rural electrification fund''

### 4.3.2 Existing Renewable Power Policy Instruments in Nigeria

The policy instruments with focus on the power sector for the country ranging from regulatory to incentives based were strongly committed within the framework of the NREEEP, and are discussed next. Beginning with the regulatory intervention tools, the National Electricity Regulatory Commission (NERC), established a pricing framework called Multi Year Tariff Order (MYTOI) in 2008 and superseded by MYTOII in 2012) (NERC, 2012). The central goal of the MYTO was regulating the prices to be paid to licensed electricity generation companies (GenCos) in providing power to distribution and retailing companies (DisCos) without compromising the ROI (Nnamdi et al., 2017). The MYTO provided 15-year tariff path however, the slight difference between the 2 structures were annual review for MYTOI and bi-annual review for MYTOII (NERC, 2012; IEA, 2018). The Tariff structures cover multiple renewable resources viz. hydro, wind, solar, and Biomass. The MYTOII that superseded the MYTOI got finally superseded by the Feed in Tariff (FiT) that was approved in 2015 and put to force in 2016 covering bioenergy, solar, Small Hydro, and wind as targeted renewables (IEA, 2018). The objectives of the regulatory instrument were to boost power supply with renewables incorporation in to the national energy mix, enhance national RE target attainment, enhance power investment security and market stability amongst others (NERC, 2015). Under the FiT framework, the government of the country obliged DisCos to purchase electricity from renewables of at least 50% of their total procurement at fixed rate by NERC with the remaining 50% to be sourced from the Nigerian Bulk Electricity Trading Company (NBET) (IEA, 2018).The framework also defined project capacity ranges for the renewable electricity allowed to sell to grid at transmission or distribution network, of which capacities between 1-30 MW will automatically be integrated as renewable energy whereas, above 30 MW will require some COMPETITIVE BID or AUCTION in the regulation (Sustainable Enterprise Media Inc., 2016). The FiT assigned prices as of 2016 were solar PV ($177/MWh), wind ($125.47/MWh), small hydro ($154.72/MWh), and biomass ($154.71/MWh) (Bloomberg New Energy Finance, 2017). Additionally, comes the simplified licensing measures for Independent Power Producers (IPP) (i.e. private sector based) selling electricity from renewables to the Grid of maximum 50MW (Nigeria Energy Future, 2018). Note that the NBET could purchase power from GenCos or IPP based on Power Purchase Agreement (PPA), whereas the DisCos could purchase power from NBET based on Vesting Contract, and from GenCos or IPP based on PPA. Furthermore, Nigeria has an existing Electric Utility Quota Obligation or Renewable Portfolio Standards (RPS) in effect from 2005, which clearly defines the mix share of power generation that must come from renewable sources based on a targeted year. According to the Nigeria Energy Future (2018), the NREEEP sets 18% targets by 2020 with marginal rise to 20% electricity mix target translated to around 23,000 MW. This total has a breakdown of 6830 MW from solar, 4600 MW from large hydro, 8170 MW from small hydro, 3200 MW from Biomass, 291 MW from Wind.

Nigeria has a number of existing incentives-based policy instruments in line with the NREEEP. The first being the power investment or production tax credit made in effect in 2014 where the government commits to ensuring widespread of renewable energy which also included that specific to power generation. The instrument is in form of a tax incentives i.e. 5-year tax holidays to energy producers from the production commencement date, 5-year tax holidays on dividend incomes from investors in renewables, as well as 2-year 0% custom duty on importation of RE and EE equipment and materials (Nigeria Energy Future, 2018). Moreover, regarding the reduction in sales, energy, VAT etc. policy instrument, there was a deduction on VAT for power sector operators based on the agreement made between the Federal Inland Revenue Service (FIRS) and Nigeria Electricity Regulatory Commission (NERC) in adding motivations to power producers or investors (NERC, 2012). Finally, comes the existence of public investment, grants, or loans policy instrument set up to provide access to finances for renewable energy and energy efficiency projects, including generation, transmission, and distribution with grid extensions as well as off-grid and mini grid systems which was in force from 2014 (Nigeria Energy Future, 2018; FMP, 2015; Bloomberg New Energy Finance, 2017).

**CHAPTER FIVE**

# 5. POLICY AND REGULATORY FRAMEWORK FORMULATION

## 5.1 Introductory Information

Development and promotion of renewable energy in Nigeria is having some level of success based on the already mentioned progress in renewable-based off-grid mini projects in the research background discussion of **CHAPTER TWO**. However, the contribution level to the socio-economic growth and development is almost insignificant comparing with the huge resources available. The expansion, diffusion and capacity improvement specifically in electricity generations, grid-integration and boosting, as the central focus is quite below expectation due to so many challenges or barriers. These barriers are discussed in the different bullet points below:

- Policy and Regulatory Framework Issue: The country has no adequate and appropriate policies both regulatory based and incentives based with lack of political will at the highest level that could favour the bloom of renewable energy in improving final energy service. The existing policies have not been in to full implementation and also needs arises for their thorough revision in line with market regulations and overall best practices lessons. Moreover, the institutional framework is quite weak due to the fact that the coordination between government ministries and agencies in favour of renewable energy is underperforming unlike for oil and gas.
- Affordability: Having known that renewable energy systems have low operation and maintenance costs, the challenge are however based on the fact that their initial costs are usually high with uncertainties associated in comparison with the conventional energy systems. The uncertainties were basically due to lack of trials and risk taking in investments to the technologies to ascertain the misconceptions.
- Capacity Building: This is a strong area that has been weakened as far as renewable energy deals are concern both human and institutional based. The capacity building areas are mainly manpower training for installation, operation and maintenance of renewable energy systems, manufacturing skills, capacities for efficiency and optimization in energy systems. These are all dedicated to scientists, engineers and economists in view of risking investment decisions by private sector and government.
- Public Awareness: Awareness regarding the potentials, opportunities, and benefits of renewable energy technology is poor in the country. This could be seen on the fact that the technologies are not yet matured as compared to the conventional based technologies.
- Competition with Food / Energy-Food Nexus: This aspect is for the first-generation biomass to biofuels technologies and utilizations inclusive of the power generation aspects.
- Intermittency: The intermittency challenge is based on the fact that some renewable energy resources are found not to be stock in supply but fluctuating. This calls for twinning as the case with the hybrid system solution put forward in the extensive decentralized power system design of chapter three.
- Infrastructural barrier: This relates to the grid infrastructure weakness, inefficiency and insufficiency.

Based on all these barriers, it must be stated that they are almost all complementary and hence, linked to the policy concerns, with the appropriate solutions set to be provided in the policy and regulatory framework formulation process with its wider scope.

The fundamental policy targets basing on the numerous policy statements and the energy status quo of the case study country as well as the global experience are summarised and simplified in the below bullet points:

- ✓ Improved research and development in the energy domain, especially the renewable energy for power generation
- ✓ Renewable energy integrations for boosting electricity generation at all levels
- ✓ Ensuring the energy efficiency operations from both demand and supply side of energy systems execution
- ✓ Greenhouse gases and pollutants emissions reduction and environmental saving
- ✓ Ensuring economic growth and development with their sustainability. This incorporates GDP growth maintenance as well as overall impacts to different sectors inclusive of social favours.

Based on this brief information, the policy support instruments in line with achieving the outlined targets as well as overcoming the already stated barriers are summarized in the two broad divisions below:

- ✓ Supply Push: R&D-based.
- ✓ Demand Pull: Targeting the diffusion of the technologies and impacts via intervention tools.

## Learning Rate Incorporation

Regarding the learning rate guide, which is a crucial tool or model in digression analysis or technology costs reduction forecasting for the demand pull-based instruments design. It is briefly given by the below model i.e. one-factor-based, indirectly related to R&D progress, and reported by Rubin et al. (2015).

$$Y = aX^{b} \text{ -------------------- } (25)$$

Where: Y = Unit Cost of the Technology, X = Cumulative Experience (i.e. Cumulative Capacity or Cumulative Energy Production), a = constant, and the unit cost of the first unit, b = constant, and the rate of cost reduction as a learning by doing based.

$$\text{Hence, } \operatorname{Log} Y = a + b \operatorname{Log} X \text{ -------------- } (26)$$

The fractional reduction in cost associated with a doubling of capacity experience is termed the Learning Rate (LR) and is given by the model below:

$$LR = 1 - 2^{b} \text{ ------------------- } (27)$$

Where the factor $2^b$ is the progress ratio (PR), b = fractional cost reduction after a doubling of cumulative capacity or production as a learning by doing-based.

In incorporating additional parameter, the model becomes a two-factor based, where strong and direct linkage with the R&D component is established. It has been put forward by Rubin et al. (2015) as follows:

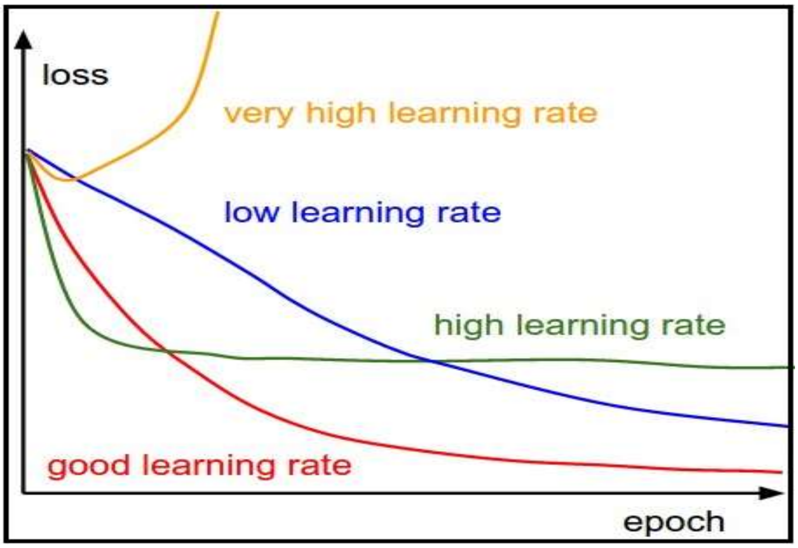
$$\operatorname{Log} Y = a + b_{lbd} \operatorname{Log} X + b_{lbr} \operatorname{Log} (R) \text{ -------------- } (28)$$

Where R = cumulative R&D investment or knowledge stock, $b_{lbd}$ = learning by doing-based cost reduction parameter, $b_{lbr}$ = learning by researching-based cost reduction parameter.

Note that the fundamental learning effects in the energy technologies and costs forecasting as appeared in the 2-factor model are described below:

- Learning by doing: Repetitive manufacturing of the products leading to improvements in the production process (Trial and error method)
- Learning by Researching / Searching: Improvement in technologies arising from R&D with innovations.

The figure below gives different patterns of the learning or experience curve as an analytical guide. This was obtained from Zulkifli (2018).




Source: Zulkifli, 2018

***Figure 48:*** *Different Learning or Experience Curve Patterns*

The range of reported learning rates based on one factor and two factor models for electric power generation focussing on the renewables is given in the below table as reported by Rubin et al. (2018).

***Table 72:*** *Range of Learning Rates for Different Renewable Electricity Generation Technologies*

| **Technology** | **One-factor Model** | | **Two-factor Model** | | | | **Years Covered** |
|---|---|---|---|---|---|---|---|
| | LR Ranges | Mean LR | Ranges of rates for LBD | Mean rate for LBD | Ranges of rates for LBR | Mean rate for LBR | |
| Wind (Onshore) | -11 to 32% | 12% | 3.1 – 13.1% | 9.6% | 10 – 26.8% | 16.5% | 1979 – 2010 |
| Solar PV | 10 – 47% | 23% | 14 – 32% | 18% | 10 - 14.3% | 12% | 1959 – 2011 |
| Biomass | 0 - 24% | 11% | - | - | - | - | 1976 – 2005 |
| Hydroelectric | 1.4% | 1.4% | 0.5 – 11.4% | 6% | 2.6 – 20.6% | 11.6% | 1980 – 2001 |
| Hybrid System Case to be Analyzed | $LR_{H.S} = X\%*LR_a + Y\%*LR_b + Z\%*LR_c$ + --- (where: $LR_{H.S}$ is the LR for the Hybrid Case, X%, Y%, Z%, --- are shares of technologies concerned, $LR_a$, $LR_b$, $LR_c$, --- are the selected LRs corresponding to the technologies) | | | | | | N/A |

Source: with data from Rubin et al. (2015).

## Derived Power Policy Lessons Summary

- Supply Push based Instruments (R&D Focus): Driven from the lessons obtained especially from China, and some EU Countries. **One factor model** for digression analysis being most widely used.

- Regulatory Instruments Lessons (Demand Pull)
  - ✓ FiT: Fixed FiT not FiP / With digression rates specification via learning or experience-based monitoring analysis. Lessons from Germany and Spain
  - ✓ Net Metering: Lessons from Canada, U.S, and Argentina. Digression rates specification and learning based monitoring inclusive.
  - ✓ Tender: Reverse Auction / Static Sealed and Pay as bid. Lessons from Brazil, Some EU Countries, the US, and China
  - ✓ RPS with linkage to TREC in some of the regulations, based on the lessons from Brazil, US, Canada, Australia, and India.

- Economic-based Intervention Tools Lessons (Demand Pull)
  - ✓ Fiscal-incentives: Linkage to the regulatory instruments and the supply push-based instruments. Such as Tax Credits/Exemption/Holidays proven to be effective in US, Philippines, Indonesia, Malaysia. Reduction/Deduction in some Taxation Schemes proven to be effective in Philippines, Indonesia, Malaysia.

  - ✓ Public Financing Based: Linkage to the regulatory instruments and the supply push-based instruments. Such as the rebate incentives proven to be effective in countries like US and Australia. Loans/soft loans proven to be effective in countries like US, Philippines, Indonesia, and Malaysia. Subsidies proven to be effective in countries like Japan.

## 5.2 Policy Instruments Design Process

### 5.2.1 Supply Push-based Instruments (Research and Development Shaping)

Targeting Technological Transfer, Capacity building, Innovation and status quo improvements as R&D components. This is in view of the improved manpower in the energy sector, long-term profitability target, patents and trademarks securing etc. The levels in the R&D could be described in the below outlines:

1. Basic research level (by researchers / scientists / engineers): This aspect being a knowledge seeking and expansion-based solely is paramount and should be intensified especially in the energy related aspects, particularly the renewable energy for power generation in this regard. This should strongly incorporate technology transfer on strong liaison with highly performing countries such as China, and some EU countries.

2. Applied research level (by researchers / scientists / engineers): This being a linkage to the fundamental basic research is worthy of expansion. This is possible provided capacity building and technology transfer are given strong considerations on an international cooperation-based just like the basic research, ultimately leading to the innovation aspect and linked to the next phase below.

3. Development / implementation and demonstration level (site engineers / technicians / technologists): This level being linked to applied research provided all the requirements are met becomes easy and wide spread. In line with the development also comes the need for more researches in view of efficiency improvement and piloting for certainty of outputs in view of wider replications and the strong impacts.

4. Business incubation level (entrepreneurs nurturing on business skills): In line with the previously mentioned levels, the ultimate goal has always been on the pre-commercialization, commercialization and mass diffusion in an effective manner. This is where the incubation centres are very necessary in nurturing the entrepreneurs and equipping them with the market confidence and entrepreneurial spirits. In view of stronger impacts of this stage, international collaborations and strong liaison is also necessary.

The Parties to be involved in the joint intervention and intensifying the already existing states are government and financiers, research centres and universities, customers and suppliers.

Lastly, benefits of the supply push-based instrument having all the protocols and conditions met are potential costs reductions, improved technologies diffusion and market breakthrough, improved competitiveness, enhanced international business participation and economy building.

### 5.2.2 Demand Pull-based Instruments (Intervention Tools Formulation)

The accompanied demand pull-based intervention tools selection criteria for the formulation process are as follows:

- Based on wider diffusion and successes in the global context in line with the outlined indicators for the global policy finding analysis

- Based on the nature of hybrid energy system design proposed in the research
- Based on the ambitions and future targets for renewable energy in the country, of which scaling might be required
- Based on the need to overcome market barriers (i.e. renewable energy market)

Based on the above criteria, the policy instruments / intervention tools to be considered in the formulation process (i.e. with linkage to the successes around the globe) are as follows:

- Regulatory intervention tools of interest
  - ✓ Feed-in Tariff (Reformulation to more appropriate)
  - ✓ Net Metering (New Formulation, due to its non-existence)
  - ✓ Tender / Competitive Auction (Reformulation to more appropriate)
  - ✓ Renewable Portfolio Standard (RPS) (Reformulation to more appropriate)

- Economic-based intervention tools of interest
  - ✓ Taxation-based (Reformulation to more appropriate)
  - ✓ Financing (Reformulation to more appropriate)

**5.2.2.1 The Regulatory Intervention Tools Formulation**

**1. Renewable Portfolio Standard (RPS) Reshaping**

This instrument existed having seen from the Nigerian holistic energy policy review of chapter 4 conducted. It reads as follows: The NREEEP sets 18% targets by 2020 with marginal rise to 20% electricity mix target translated to 23,091 MW (with Solar: 6,830 MW, Large Hydro: 4,600 MW, Small Hydro: 8,170 MW, Biomass: 3,200 MW, and Wind: 291 MW (Nigeria Energy Future (2018)).

Extrapolation to 2030 is really necessary in giving more time for seeing the effectiveness of the overall policies reformulation. In view of that, the 2015 renewable energy capacity generation in the electricity mix reaching final consumers was found to be 756 MW constituting solely hydropower performance (Energypedia, 2019). Using this data as a baseline with the intermediate 2020 targets above, the extrapolated results reads as follows: 2030 – 67,761 MW (with Solar: 20,042.77 MW, Large Hydro: 13,498.79 MW, Small Hydro: 23,975.03 MW, Biomass: 9,390.46 MW, and Wind: 853.95 MW).

In this opinion, the feed-in tariff and net metering should go hand in hand based on a defined RPS i.e. set targets of 2030 to be accomplished within a given time period with no capacity limits all through. When the capacity target is met, further participation in the feed-in tariff and net metering contracts then should be based on capacity limit, of which capacities beyond 30MW (i.e. the set capacity in the previously designed Auction scheme of the country) have to undergo tendering / competitive bidding process for the feed-in tariff in selecting the appropriate participants. For the net metering auction, residential users of up to 30 kW under three-phase connections, or 5 kW under single-phase connection, and industrial, commercial or productive users of up to 150 kW in low voltage (LV) or 300 kW in medium voltage have to undergo competitive bidding in selecting the winning parties for the contract. The idea has been obtained from Brazil and Argentina schemes' lessons with some modifications done. Proper specifications of the feed-in tariff, net metering, and the auction / competitive bidding follows:

## 2. Feed-in Tariff (FiT) Reformulation

The feed-in tariff reformulation process has been achieved based on different design parameters with the clear specifications of what is seen to be appropriate in the process as follows:

- Initial Conditions (Eligibility parameters: Technology, Size of Project, Quality of resource, location etc.)
  - ✓ Technology: Solar PV, wind, biomass and hydropower have been briefly specified as eligible technologies in the existing FiT scheme. As emphasis, all solar PV technologies (i.e. mono-crystalline, poly-crystalline, amorphous, organic-based et c.), all biomass technologies (i.e. direct combustion of solid biomass and power generation inclusive of biomass value addition chain, wastes conversion of a broader range to biogas and to power generation, gasification with synthesis gas production and use for power generation (i.e. BIGCC) etc. involved), wind power technologies (i.e. both vertical and horizontal axis-based onshore involved), all hydropower technologies (both small, medium, and large scale hydro dams, inclusive of surface water turbine).

  - ✓ Size of Project: All sizes should be allowed until the RPS target is met before the size restriction is imposed. In the size restriction, project capacities of beyond 30MW will undergo competitive bidding for selecting the winning parties.

  - ✓ Quality of Resources: Quality of the resources should be assessed for qualification on projects execution

  - ✓ Location: All locations with high quality and high potential for the resources linked to any of the qualified technologies.

- Specified Approach to Set Overall FiT Payment
  - ✓ Previously, the FiT payment design was technology-specific or dependent, based on different components of the LCOE and plants' capacity (NERC, 2012). Updates here should be based on the global LCOE ranges for any of the technologies qualified, where the upper cap should be considered. This will ensure improved fair pricing and motivations.

- Payment Design Alternative by Market Pricing
  - ✓ In line with the above specification, fixed price FiT payment approach is the most appropriate due to the lessons obtained from the global perspectives such as Germany. The fixed FiT should be the Upper cap of the global ranges for the LCOE of the different technologies as specified above, plus additional incentives for better return

and motivations to the investors. This should incorporate additional costs of transmission losses and transmission congestion costs depending on locations and to be borne by the consumers. The incorporation of the additional costs of the transmission losses and transmission congestion costs then results in the locational marginal pricing (LMP) for the different technologies and the power generation for the grid-integration as applicable on a general perspective. The transmission congestion entails power dispatch based on economic merit order.

- Charging Principle (Extra cost incurring) in the Redesign
  - ✓ Fixed Charge increase (i.e. Fixed rate plus extra cost of maintaining grid-infrastructure) should be incorporated. Additionally, Non-by-Passable Charge (i.e. for funding other independent programs like EE, Low-income customers assistance etc.) is strongly necessary and should also be incorporated. However, Time Varying Rate that could be in the form of Time of Use Rate, Variable Peak Pricing, or Critical Peak Pricing should be of less priority in the extra costs incurring principle.

- FiT Implementation Option Design
  - ✓ Utility Role Specification: Energy production and grid connection at transmission and (or) distribution networks as well as respecting the rules and guidelines of the contract over the PPA duration.

  - ✓ Contract duration / PPA Specification: Of the opinion that it should be for 5 years in each of the qualified technologies with Continuous extension up to the life span of the project/technology depending on performance

  - ✓ Caps / Ceiling / Roof for Program (i.e. Lower and upper limits of what is allowed in the program(s)): Program cost (total allowable program cost) should be an optimal costing based on the qualified participants/Investors in the contract. There should be no limitation for the energy production just like the capacity specification.

  - ✓ Forecasting and adjustments (i.e. future capacity and price allocations with digression rates / learning rate description: Digression rate should be specified showing the reduction of the costs with time owing to the hope of massive adoption and diffusion, with lessons from the successes of the German perspective. This should be analysed based on learning rates appropriate assumptions with the analysis as already described briefly in the introductory information. However, the one-factor model is considered the most widely applied according to the study conducted by Rubin et al. (2015).

  - ✓ Penalties specifications (e.g. for non-compliances on the contract): Warnings will be given and if proved abortive, termination of the contract might apply and banning for some years before being entitled for the next application.

  - ✓ Funding and managing the policy (funders specifications): The government organizations involved with power/energy issues specifically the Federal Ministry of

Power (FMP) and its sub-divisions/parastatals as well as the Energy Commission of Nigeria (ECN).

- Network Specifications: Decentralized generations apply to the project's executions, in ensuring efficient performance and long transmission challenges curbing

**3. Net Metering (NM) New Formulation**

The Net Metering being non existing so far in the country is seen to be crucial especially in view of the grid-connected power system design and execution such as what was put forward in chapter 3. This will serve as a strong motivation to the energy producers that are consumers at the same time to venture in to the business for dividends. Hence, that ensures energy scaling as well. The different parameters in the design of this instrument were put forward with the appropriate specifications for the case study country below:

- Eligible Technologies Specifications: All the technologies specified in the Teed-in Tariff scheme are eligible for the Net Metering Scheme.

- Participating Sectors Specifications: Residential, commercial, industrial, and institutional sectors be allowed to equally participate.

- Size Cap Specifications: This should be based on installed capacity limit as follows. No size cap should be imposed in the instrument execution, except after the RPS target specification is met. At the met target, the capacity limit then applies with competitive bidding applications as follows: Residential users of up to 30 kW under three-phase connections, or 5 kW under single-phase connection, and Industrial, commercial or productive users of up to 150kW in Low Voltage (LV) or 300 kW in Medium Voltage have to undergo competitive bidding in selecting the winning parties for the contract. These limits specifications have been seen to be clear and more logical and proved to be effective in Argentina.

▪ Network Specifications: Decentralized generations apply to the project's executions just like the feed-in tariff case.

- Roll Over Specifications (Payment deferring/holdback for a given period with decisions on how the rate will be for the sum of all the payments of the past periods): Of the opinion that payments should be made at the end of the months to the investors without any deferring. The deferring may discourage the investors ultimately affecting the capacity targets.

- Payment for excess electricity specifications
  - ✓ FiT levels - This may be more appropriate and logical in line with the specifications given in the FiT discussions that incorporates the transmission losses costs and transmission congestion costs in obtaining the overall LMP. Digression should be

applied to the pricing over time as specified in the FiT based on the lessons from the German perspective. This is in view of diffusion of the technologies, capacity improvements and ultimate costs reduction. Learning rate should be applied as a monitoring criterion in predicting the costs reductions in a similar manner to the FiT description.

- Charging principles (Extra Cost Incurring) specifications in the design: This should be similar to the specification presented for the case of Feed-in Tariff previously.

- Considerations for implementation
  - ✓ Business Models: Leasing / Third-party ownership model (i.e. r/ship between the energy system developer (lessee) and the site host (lessor) must be checked and verified prior to the initiation of the contract. Also, PPA defining (Years of validity of the contract) has been on the opinion of 5 years first, and with further extensions depending on the performance of the investors and the compliance levels up to the defined life span of the concerned technologies.

Basing on the Levelized Cost of Electricity (LCOE) pricing baseline having specified in the feed-in tariff and net metering schemes, below gives the guidelines on the global perspective. It has been based on extrapolations or costs updates forecasted specifically for the year 2020 based on the baseline 2012 LCOE values. This has been obtained according to IRENA (2012a).

***Table 73:*** *Global LCOE Ranges for Different Renewable Energy Technologies for 2012 and 2020 Forecasting. (Rough Estimates)*

| **Technologies** | **2012 Baseline LCOE ($/kWh)** | ***2020 Projection ($/kWh)*** | **Remark** |
|---|---|---|---|
| Wind Power (Onshore) | 0.055 - 0.150 | ***0.055 – 0.130*** | Decision be made by the policy makers regarding technologies difference in the onshore, in line with the upper cap of the range. |
| Solar PV | 0.125 – 0.360 | ***0.085 – 0.300*** | Decision be made by the policy makers regarding the technologies differences in the solar PV in line with the upper cap value of the range. |
| Biomass Stoker Bubble Fluidized Bed (BFB)/Circulating Fluidized Bed (CFB) | 0.070 – 0.215 | ***0.060 – 0.195*** | Upper caps considerations as the baseline for the total price evaluations. |
| Biomass gasification | 0.080 – 0.250 | ***0.075 – 0.210*** | |
| Biomass Anaerobic Digestion (AD) | 0.070 – 0.150 | ***0.060 – 0.140*** | |
| Biomass Co-firing | 0.055 – 0.130 | ***0.055 – 0.110*** | |

| | | | |
|---|---|---|---|
| Hydropower | 0.025 – 0.150 | ***0.025 – 0.150*** | Decision be made by the policy makers regarding the technology sizes in line with the upper cap value of the range. |

Source: IRENA, 2012a.

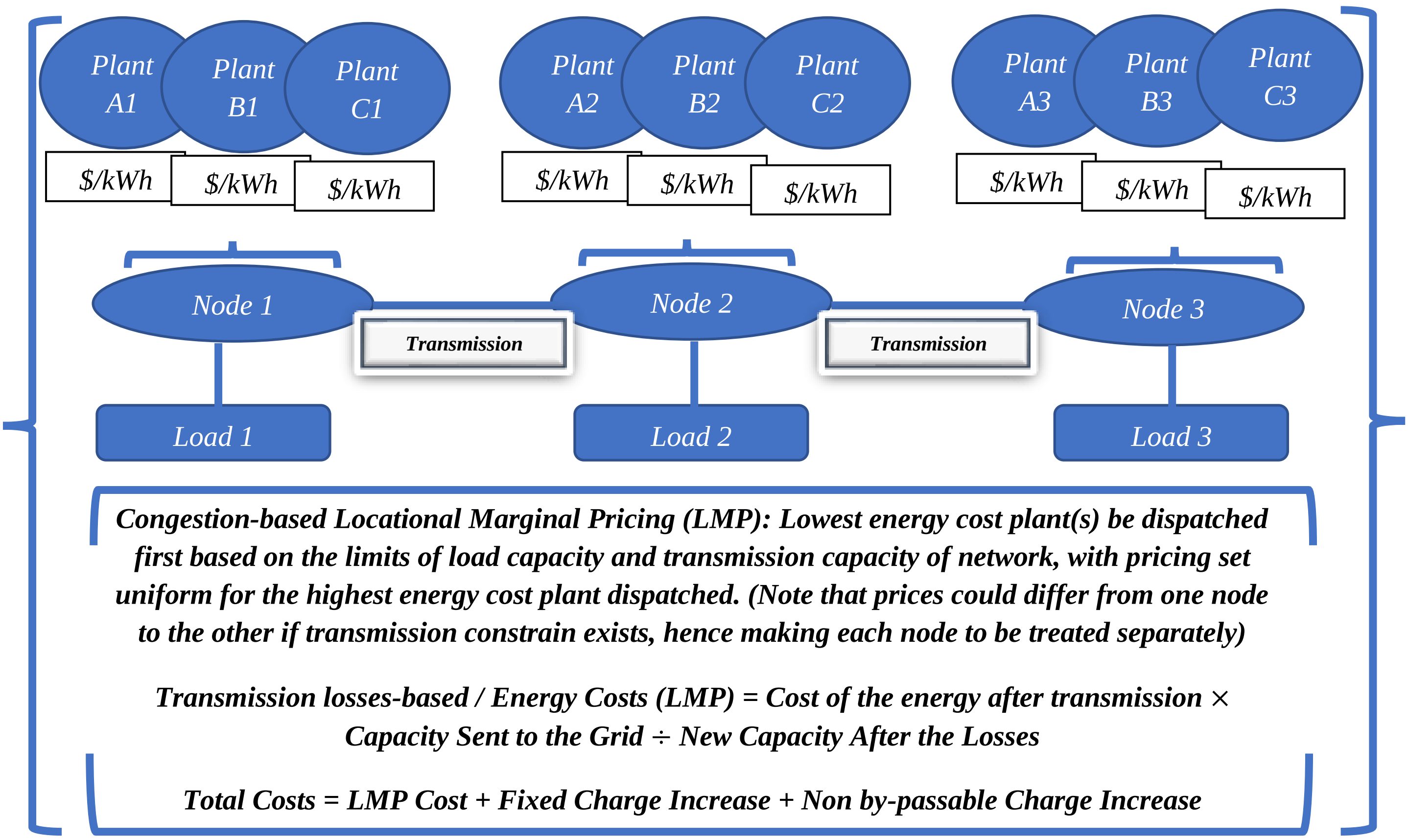
Based on the LCOE ranges put forward in the above table, for **Hybrid System** ventures as an important aspect of consideration is worthy of evaluations. The opinion or argument proposed is the fact that the specified upper caps of the 2020 projections considered as the baselines for the final prices evaluations of each technology can be considered. Thereby, the overall price determination can then be based on the energy production weight or fraction of each technology participating in the hybrid as can be seen from the below expression.

**FiT and NM Charges for Hybrid RE System = X%*A + Y%*B + Z%*C + …----(29)**

Where: X% = Percentage / Fraction of Generation from Technology A, A = The Specified Upper Cap LCOE Plus the Intended Return for Technology A, Y% = Percentage / Fraction of Generation from Technology B, B = The Specified Upper Cap LCOE Plus the Intended Return for Technology B, Z% = Percentage / Fraction of Generation from Technology C, C = The Specified Upper Cap LCOE Plus the Intended Return for Technology C and So on.

**Note that X% + Y% + Z% + …... = 1.0**

**<u>Summary of the Overall FiT and NM Payments by Final Consumers (DGs)</u>**



**4. Auction / Competitive Bidding Reformulation**

The existing auction or competitive bidding in the country has been reformulated with the linkage to the feed-in tariff, net metering, and the renewable portfolio standard having specified in the beginning of the policy instruments discussion. However, the considered parameters for the further reformulation are as discussed below.

- Tender Structuring and Site/Network Selection
  - ✓ Forward or Reverse Auction Specification - Reverse auction / bidding is the concerned case for the execution.
  - ✓ Centralized and (or) Decentralized Approaches Decisions - Decentralized approaches is more appropriate just like for the feed-in tariff and the net metering case, for efficiency and effectiveness of the implementation at all levels.
  - ✓ Standalone and (or) Grid-connected Systems - Applicable to both network concerns, however, the grid-connected system projects are the most appropriate and of highest priority.

- Supply and Demand Specification
  - ✓ Who can participate in the Auction scheme? - All winning parties that have been investigated and found worthy and appropriate for the contracts.
  - ✓ Quantity specification to be contracted – It should be based on the already specified quantities for the feed-in tariff and net metering schemes that requires the Auction scheme.

- Pre-qualification Criteria
  - ✓ Multicriteria Auction - This category is more appropriate with further specifications as follows. Incorporation of material (e.g. license, land permit, grid-connection etc.), financing / economic criteria, technology and impact, local content rules, and environmental impacts.

- Penalties for non-compliance and delay specification
  - ✓ A warning shall be given, and if proved abortive will then lead to the termination of the contract and considered for next participation only after a number of years.

- Remuneration specification
  - ✓ Energy ($/kWh) is appropriate, with the pricing based on the specifications of the winners in the bidding / lowest price selection based

- Band Choices with specification
  - ✓ Technology Neutral (i.e. Based on group of eligible technologies) is considered appropriate based on the eligible technologies provided in the feed-in tariff and net metering schemes. Also, there should be no restrictions on the minimum number of bidders. Hence, any party can apply for the reverse auction/bidding scheme within the time limit having met the pre-qualification criteria already described.

- Price Finding Mechanism Different Choices
  - ✓ ‘’Static Sealed Auction’’ as well as ‘’Pay as Bid’’ strongly considered due to lessons obtained from Brazil, some EU countries, the US, and China, where it is being practiced and proved to be effective.

- Winner Selection Process – This should be based on least cost bid as seen to be more appropriate.

#### 5.2.2.2 Economic Intervention Tools Formulation

1. **Taxation Credits (Reformulation)**

This could be seen in the form of tax exemption or tax holidays. It is obvious that the country has got this instrument as obtained from the literature. The instrument is in form of a tax incentives i.e. 5-year tax holidays to energy producers from the production commencement date, 5-year tax holidays on dividend incomes from investors in renewables, as well as 2-year 0% custom duty on importation of RE and EE equipment and materials (Nigeria Energy Future, 2018). This design principle having incorporated both investment and production concerns is quite interesting owing to what has been seen from the global economic policies in the review task done, and proven to be effective in countries like US, Philippines, Indonesia, Malaysia, India etc. However, a slight modification that could be done is as follows:

This instrument is expected to link-up with the taxation reduction instrument that will come up next. But regarding the tax credit here, the opinion is on the fact that the investments and production related renewable energy affairs specified should be subjected to same number of years for the tax holidays i.e. 5 years. This ensures balance in operation such that all the investments and production related businesses can grow at close pace in boosting the energy supply. To add further, this tax-free all through should be applied to the R&D related investments as a critical area and the engine of growth for the renewable energy operations. This covers the R&D impacts resulting in the local manufacturing of the renewable energy and energy efficiency equipment and the innovations associated at all levels. In addition to the custom duty holiday specification for the renewable energy and energy efficiency equipment importation that should be changed to 5 years for the uniformity, this should also apply to the exportation in the long run arising from the effectiveness of R&D and further economy building through the exports.

2. **Taxation Reduction (Reformulation)**

This instrument exists in the country, however, only the VAT specification has been found from the literature. From the Indian experience, the production and investment tax credits with its highlighted areas of focus should be closely linked to the taxation reduction, such that at the end of the 5 – year holidays, reduction in the taxation can be by 50% for another 5 years. Immediately after the second 5 – year specification for this instrument, normal tax rates then apply up to the end of the contracts. The reason is because as the technologies get matured, capacity is boosted and the costs of both the investments and productions related concerns ultimately get lower and with improved dividends to the owners of the businesses. Hence, this motivates the investors and producers and leave them with no boredom regarding the tax payment after wards.

### 3. Public Financing-based Instrument(s) (Reformulation)

A specification regarding the finance provision for renewable energy and energy efficiency related operations has been obtained from the literature. To emphasize further, the financing instrument areas of major focus should be rebate incentives, soft loans, and subsidy. This should be applied to all the qualified renewable technologies project executions and equipment related investments and supply especially to the low-income personnel who are strongly willing and committed to contributing to the power supply boosting of the country. Such aid should be channelled via a venture capital fund, of which the low-income investors can be supported for at least 2 years via either rebate or subsidy, and the moderate-income owners be supported with soft loans also for at least 2 years. Regarding the loan provisions, payment should be allowed over a long period of time and with possibility of making it on instalments basis and without any interest rate imposed. It must be noted that the rebate incentives have proven to be effective in countries like US and Australia; the soft loans have proven to be effective in US, Philippines, Indonesia, Malaysia etc.; and the subsidy proven to be effective in the case of Japan. This was seen as a lesson from the global renewable power policy review and analysis conducted.

### 5 Energy Efficiency Policy Practice Criteria (Re-shaping)

The energy efficiency policy practice is a crucial aspect of consideration at different sectors of the country, namely the domestic, industrial, commercial, to institutional sectors of development. The impact of the energy efficiency practice has been clearly seen in the power system design task of chapter three, where switching of appliances was considered and analysed at the demand side residential energy concern. It is of great interest that the energy efficiency provisions have been set in the NREEEP document provided by the Federal Ministry of Power (FMP). To that effect however, strengthening of the energy efficiency practice in the policy design is of great relevance on the uptake level of energy resources. Strong motivations are necessary regarding the wider diffusion and use of the most efficient energy consuming devices in the different sectors of the economy asides the importation aspect addressed in the economic / taxation-based instrument discussion. The specific motivation or incentive in this opinion could be on a certain percentage reduction of tariff for one or two years to the consumers/customers provided all conditions on the energy efficiency appliances are met. This should be combined with a white certificate as an indication of energy consumption reduction. Furthermore, in view of the rapid implementation, proper sensitization on the relevance of such transition is also necessary. This should be combined with continuous consultations of the energy appliances used as well as monitoring and evaluations of the progress of the practice and energy consumption in the different sectors with time.

### 5.3 Risks Management of the Formulated Power Policies.

Risks are aspects associated with any kind of project and policies in an implementation process. Therefore, it is strongly considered here while offering some strategic measures in managing the associated risks. The risk management employed in this regard are the technical or technological related risk factors, economic and financial risk factors, as well as the environmental and climate related risk factors. The different classifications and measures to be put in place in the management process have been provided in the table below.

***Table 74:*** *Risks Evaluation for the Renewable Power Policy Instruments*

| S/N | Risks | Sub Factors Considered | Principal Targets |
|---|---|---|---|
| **1** | Project/Technology Risk (Linked to [2] and [3]) | • Information Dissemination Issue/Gap: This gap is surmounted by ensuring effective and efficient communication to the masses regarding the need for the renewable energy integration and the benefits of such ventures owing to the packages covered which ensures favorable return on investment.<br>• Acceptability / Against Fossils (Oil and Gas Operations): It is evident that the fossil fuels dominated the power sector, which makes the renewable energy acceptability somewhat difficult. However, this is addressed through proper sensitization regarding the need for such transition and the demerits of the fossil fuels the country is blinded with based on the sustainability indicators.<br>• Project Completion / Time Factor: This risk factor is overpowered by ensuring proper monitoring and evaluation of the project developers in terms of their finances, motivations and so on, prior to awarding the contracts. All the conditions for project executions should be met with endorsements and making provisions for sanctions on failure to execute or complete the projects.<br>• Specific Technology Favoring: This risk has been taken care of, as the pricing mechanism for all the qualified technologies has been on LCOE basis hence, investor can put forth any technology for the power generation with full confidence of return, and without any doubt of imbalance payment in favor of any of the technologies.<br>• Tariff Fluctuation / Staticity: This risk has been addressed by making provisions for digressions in | Project/Technology Effectivity and Sustainability |

| | | | |
|---|---|---|---|
| | | the different projects and policies execution hence, serving as advantage to both the project developers and the clients / government). This is in view of the maturity and diffusion impacts on economics.<br>• Resource Availability and Variability: This risk hardly comes in to place considering the fact that provisions have been made in the policies' designs on evaluation and screening of project developers regarding their locations and the resources potentials prior to awarding the contracts on any of the qualified technologies. This hardly put the project developers on dubious concerns regarding the systems performances in boosting supply). | |
| **2** | Economic/Financial Risk (Linked to [1]) | • Rate of Return Impacts: This is an important element in the projects and policies executions and the pricing system hardly puts the project developers in to risk of non-dividends irrespective of the technologies putting forward.<br>• Money Locked-in / Payback Impact: Payback is certain regarding the pricing criteria set in place and the government are strongly expected to be committed to the payments to the investors / project developers in order not to ruin the contracts and damage the reputation of the policy practice. | Financial Viability and Sustainability |
| **3** | Environmental Risk (linked to [1]) | • Greenhouse gas Emissions / with linkage to fossils: This risk never applies to the renewable energy projects since they are clean and carbon neutral, with even further opportunities of making them carbon negative in the process. Hence, integrating the renewable energy systems to the utility grid and lowering the fossil energy adoption levels ensure massive reduction in greenhouse gas emissions in favor of the environment / climate. The carbon neutrality specified relates to their direct emission impacts solely having analysed in the environmental life cycle assessment conducted in chapter three.<br>• Pollution / with linkage to fossils: This risk factor is also surmounted by the promising nature of the renewable energy systems to be integrated as compared to the fossils existing in the mix. The only exception is on the biomass related technologies. However, the impact is less as | Environmental friendliness, safety and sustainability |

<table>
<tr><td></td><td></td><td>compared to the fossil fuels on direct consequence basis, namely the acidification potential (AP) related gases i.e. NOx, Sox, etc. The human toxicity potential (HTP) substances on indirect consequences has also been majorly associated with the biomass systems, that is measured in 1,4 – dichlorobenzene (DCB) having analysed extensively in the environmental life cycle assessment task conducted in chapter three. However, its impact is less as compared to that in the analysis of the fossil fuels.<br>• Associated Penalties (Not applicable)</td><td></td></tr>
<tr><td colspan="4">This ensures effectiveness in the policy practice, yielding dividends to the country and placing it among the highly performing countries in the globe regarding the renewable power performance. This ensures an improved joint climate action and energy access in view of sustainability.</td></tr>
</table>

### 5.4 Supplementary Power Grid Infrastructure Overview and Assessment

Having addressed the renewable power system design and the accompanied appropriate power policies formulation and reformulation, the utility grid is also a major component of concern in view of the grid-integration of the renewable systems. The Nigerian grid system covers three sectors viz.: Generation, Transmission and Distribution. The Nigerian Electric Power Authority (NEPA) used to be the governing body for utilities operation, and was later replaced by the Power Holding Company of Nigeria (PHCN) that comprises of some successor companies as subsidiaries at all the sub-sectors levels.

The Generation sub-sector comprises of the Generation Companies (GenCos) as the successor companies in the PHCN which has been privatized, the Independent Power Producers (IPPs), which are owned and managed by private sectors with licenses even prior to the privatization process, and lastly the National Integrated Power Projects (NIPP), which is in government efforts to complement the efforts of GenCos in addressing power shortages across the country (KPMG, 2013). The existing IPPs included the Shell – Afam (642 MW), the Agip – Okpai (480 MW), and AES Barges (270 MW) (KPMG, 2013). It must be noted that some of the power plants are not operational and most of the operational ones operate below their installed capacities. The successor GenCos include Afam Power Plc (987 MW), Egbin Power Plc (1,320 MW), Kainji / Jebba Hydro Electric Plc (1,330 MW), Sapele Power Plc (1,020 MW), Shiroro Hydro Electric Plc (600 MW), and Ugheli Power Plc (942 MW) (KPMG, 2013). Lastly, the NIPP also consists of many generation companies of mostly gas power plants.

The Transmission sub-sector consist of the Transmission Company of Nigeria (TCN), which is also a successor company in the Power Holding Company of Nigeria (PHCN), and fully owned and operated by the government (KPMG, 2013; NERC, n.d). The TCN Comprises of 3

Operational Departments as obtained from the NERC (n.d) and Oxford Institute for Energy Studies (2019) as follows:

- Transmission Service Provider (TSP): Responsible for Developing and maintaining the transmission Infrastructure
- System Operations (SO): Responsible for managing the flow of electricity throughout the power system from GenCos to DisCos (Grid Codes Operation)
- Market Operations (MO): Responsible for electricity market administration and efficiency promotion in the market

The transmission capacity operates at 330 kV and 132 kV high voltage levels, of which as of 2010, 12,000 km transmission lines operations were split into 5523.8km and 6801.49 km linking about 32 of the 330 kV and 105 of the 132 kV respectively (GOPA – International Energy Consultants GmbH, 2015). As of 2014, the transmission network had a total (theoretical) capacity of 6,500 MW, but can handle a wheeling capacity of 4,500 MW (GOPA – International Energy Consultants GmbH, 2015). The total (theoretical) capacity and the wheeling capacity figures have been updated to 7,500 MW and 5,300 MW respectively as reported by NERC (nd).

The distribution sub-sector (DS) operates at voltage levels of 33 kV / 11 kV medium voltage (MV) to low voltage (LV) (GOPA – International Energy Consultants GmbH, 2015). The 33 kV has got a connection distance of 23,753 km, with 19,226 km for the 11 kV, and with 679 substations on the rating 33 kV/11 kV (Nigerian Federal Ministry of Power and Steel, 2006). The DisCos have a joint distribution capacity of 24,457 MW, with injection capacity of 13,571 MW (Oxford Institute for Energy Studies, 2019). The distribution capacity is constrained by the injection capacity; as the injection capacity is constrained by the transmission capacity, hence, none of the specified upper limits have ever been reached. The DS comprises of about 11 successor electricity distribution companies (DisCos) in the PHCN, managed by private sectors as a result of the privatization. The DS are distributed to the different regions of the country on service to a range of customers viz. residential, commercial, industrial and special ones in line with the different power phase descriptions.

The generation, transmission and distribution chain with the accompanied losses have been summarised in the table below:

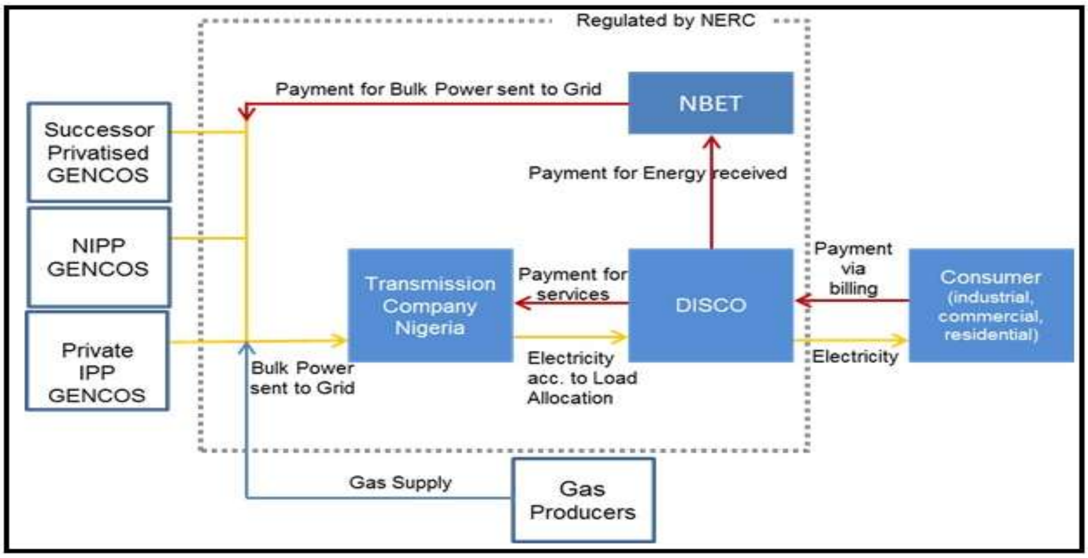
***Table 75:*** *Installed and Generation Capacity Across the Power Value Chain in 2015*

| Capacities | Specification | Losses Breakdown |
|---|---|---|
| Installed Capacity (IC) | 12.5 GW | Capacity Losses / Unutilized (IC to OGC): 8.6 GW / 69% |
| Operational Generation Capacity (OGC) | 3.9 GW | Transmission Losses (OGC to TC): 0.3 GW / 7% |
| Transmission Capacity (TC) | Supplied: 3.6 GW<br>Installed: 5.3 GW | Distribution Losses (TC to DC): 0.45 GW / 12% |
| Distribution Capacity (DC) | Supplied: 3.1 GW<br>Installed: 7.2 GW | |

Source: PWC, 2016

*NB: Emerging countries transmission losses benchmarks is 2-6% (NERC, n.d). The emerging countries include: Brazil, Chile, China, Colombia, Czech Republic, Egypt, Greece, Hungary, India, Indonesia, Korea, Malaysia, Mexico, Morocco, Qatar, Peru, Philippines, Poland, Russia, South Africa, South Korea, Taiwan, Thailand, Turkey, and UAE.*

The Overall structure of the grid-system with all the parties involved, including the Nigerian Bulk Electricity Trading (NBET) company is found below. This has been followed by the networks mapping for the generation, transmission and distribution of the electric power.




Source: GOPA – International Energy Consultants GmbH, 2015

***Figure 49:** Structure of the Nigerian Grid-network on Post Privatization*

On moving to the challenges, it must be stated that around 15.3 million households, mostly from rural areas, making up to about 60% of the Population are not connected to the grid (Kelechi, n.d). T&D infrastructure currently reaches 50% of the Nigerian population according to another narrative from International Trade Administration (ITA) (n.d). Moreover, the Nigerian Federal Government estimates that an additional 26.6 GW of supply will be required to meet electricity demand by 2020 (International Trade Administration (ITA), n.d). The Different challenges associated with the grid system have been summarised in the table below:

***Table 76:** Challenges Associated with the Utility Grid of the Country*

| **Category** | **Challenges** | **Specifications** |
|---|---|---|
| Anthropogenic | Technical | • Long transmission lines / Networks and feeders, making voltage control difficult and reducing the maximum power transfer capability. Some of the lines include Kainji - Birnin Kebbi (310km), Jebba – Shirro (244km), Oshogbo - Ikeja West (235km), Jos - Gombe (265km).<br>• Few mesh network / Duplicated lines / Nodes network: Responsible for efficient service delivery to the clients.<br>• Line losses ($I^2R$ Inherent in all Conductors): Lengthy distance covered attributes to the high losses and other technical issues.<br>• Dielectric losses: Due to the heating effect of dielectric material between the conductors. |

| | | |
|---|---|---|
| | | • Induction and radiation losses: Due to the electromagnetic fields surrounding the transmission line conductor<br>• Transformer losses (Winding losses and core losses)<br>• Inadequate spare parts and poor technical staff<br>• Inadequate modern technologies for communication and monitoring in the system.<br>• Transformer overloading, resulting in load shedding<br>• Ultimate frequent grid collapse: Annual average of 35 between 2000 and 2009 though was found to decrease to an average of 23 between 2010 and 2016. mainly due to insufficient maintenance and lack of modern and comprehensive Supervisory Control and Data Acquisition (SCADA). |
| | Geographical and Geo-technical | • Rural Communities located far from the Utility Grid, and being mostly with low population densities and widely separated |
| | Economic | • Costs associated with the Grid Systems activities and the associated investments |
| | Socio-cultural | • Land letting issues (land tenure system) due to cultural heritage<br>• Vandalization<br>• Fallen lines due to vehicles hitting and the likes. |
| Natural | Climate-related / Extreme Weather | • Lightning effect due to inadequate lightning arrestor<br>• Extreme Heat<br>• Rainstorm and Windstorm |

Source(s): with information obtained from Akpojedje et al., 2016; Kelechi, n.d; Oxford Institute for Energy Studies, 2019

### 5.4.1 Qualitative Measures on Improving the Power Grid Status Quo

Based on the challenges encountered by the utility grid (T&D networks) of the case study country and the summarised basic information of the grid system, qualitative measures are necessary in improving the status quo. It is obvious that the challenges have been broadly categorised into anthropogenic (i.e. technical, economic, geographical/geo-technical, and socio-cultural) and natural (climate-related), for ease of analysing the solutions to be offered. These qualitative measures which are obviously interwoven regarding the different challenges stand in support of the grid-integration of the renewable power systems as a complementary aspect to the policy instruments broadly evaluated.

#### 1. Technical Concerns to the Technical Challenges

The technical aspects with the associated challenges having highlighted requires the following measures:

- Regarding the long transmission lines and fewer mesh networks with their associated impacts, the aspect of power decentralization as well as the grid decentralization is very critical in addressing this challenge. This serves to underpin the kind of power system design put forward in **CHAPTER THREE**, i.e. the decentralised power system design. This lowers the excessive energy losses associated, and having the ease of other technical controls as well as ease of troubleshooting in the system. The mesh networks in ensuring effective service delivery to the clients is also addressed via the decentralization of the power and the grid.

- Concerning the technical losses in the system operation, it is obvious also from the overview of the grid system, the huge losses at the different levels of the power delivery in the system. Regarding the transformer losses, it could be obvious that proper sizing of the transformer is necessary in line with the power systems. According to Grid Cure (2019), transformers operates efficiently at 80 - 100% of maximum capacity of power plants linked. On the conductors or cable losses, the sizing issue might be the problem associated, hence proper sizing is necessary depending on the voltage levels at different stages of the power wheeling. It must be noted that where high amperage is anticipated due to voltage lowering, larger conductors are strongly required.
- The energy efficiency aspects already analysed and discussed in the power system design is considered also a key component in the grid network for stress lowering due to the huge energy demand or consumption lowering.
- The utility grid operations needed to be as smart as possible by incorporating improved intelligence or information technology for greater flexibility and improved communications in the system for energy efficient operation and uncontrolled losses minimization.

**2. Appropriate Actions to the Geographical / Geo-technical Challenges**

Regarding this challenge for the utility grid network, which was further specified as remote based locations of low population densities and widely separated, the standalone renewable based systems could successfully be used in addressing their energy concerns. The standalone systems are seen also to be of interest despite its economic and policy disadvantages over the grid-connected system as discussed previously. This will ensure improved penetration of the renewable systems at all levels and locations.

**3. Appropriate Measures to the Economic Challenge**

On the investment bit for equipping, replacement of old and dilapidated components, extension for power capacity increment, and maintaining the effectiveness in the operation, a strong political will is required. This should be tied up with the proper awareness regarding energy access and development linkage, as to why such spending is necessary and never considered a waste. Hence, in view of that, proper management and repositioning of resources is necessary in prioritising where qualitative spending matters the most.

**4. Appropriate Measures to the Socio-cultural Challenges**

Regarding the socio-cultural aspects of the challenge, the reference has been to the land tenure system issues, vandalizations, fallen lines due to human activities and the likes. Cultural heritage issues and the likes, affecting land utilizations for the utility grid expansions and upgrade needs reviews, enlightenment, and policy shaping. Vandalization aspects require close and continuous monitoring using improved intelligence, with sanctions to any party engage on such. Also, strong concern applies to the resilience of the grid infrastructure in ensuring its reliability against possible challenges such as the human activities that may unintentionally temper or affect the infrastructure such as the fallen lines scenarios. The resilience aspect that is strongly important due to its impact on other challenges asides this, shall be discussed later on the climate-related challenges.

### 5. Appropriate Measures to the Climate-related Challenges

The climate change being a real issue has resulted in many negative impacts such as the aspects mentioned in the climate-related challenges associated with the grid infrastructure. The appropriate measures to be set in place are as highlighted below:

- Reduction of greenhouse gas emission is first of all a major key to addressing the climate change challenges impacting the grid infrastructure. Therefore, the renewable energy systems adoption having put forward in this research work as an alternative to the conventional systems is seen to be very fundamental in ensuring the low carbon development and ultimately combatting the climate change and its impact to the utility grid.
- Ensuring a better resilience to the grid infrastructure. Resilience in this context relates to three fundamental aspects that are key to sustaining the grid system. These are the withstanding capability or resistance or robustness of the grid network, the resourcefulness of the grid network, and lastly the recovery. On the resistance pillar, it is necessary to ensure toughness for the system such that shocks or agitations experienced as a result of the extreme weather condition will still maintain the operability of the system. This can be achieved via necessary measures on improving the design limits of the system. Otherwise, its ability to quickly and easily troubleshoot on occasions of failure to regain fitness. The troubleshooting aspects could then be considered the resourcefulness pillar of the system resilience. The recovery aspect relates to the necessity of the system to get back to normal after being distorted or affected by different climate impacts. These require continuous research and development as well as continuous collaborations.
- Aging of the infrastructure is observed to be also a challenge regarding the resilience of the system. Therefore, special attention is needed regarding the operational span and commitments towards replacement of old ones.

### 5.4.2 Quantitative Measures and Evaluations on Improving the Power Grid

The quantitative measures with strong linkage to the optimization results of the proposed grid-connected hybrid power system of **CHAPTER THREE** has been of great concern. This is because, the integration of the renewables cannot prevail without looking at the utility grid status quo and coming up with quantifications in view of the successful implementation. The optimization results inclusive of the energy efficiency (EE) impacts focussing on the capacities have been brought forth in the below table:

***Table 77:*** *The Optimized Capacity Results of the Grid-integrated Hybrid RE System*

| **Hybrid System Optimization Components (Major)** | **Results for the Site Considered (Prior to Extrapolation Assessment)** | | **Extrapolations Results for the 50 Decentralized Systems (Load Multiplier)** | |
|---|---|---|---|---|
| | **Capacity** | **Capacity on EE** | **Capacity** | **Capacity on EE** |
| Wind Turbine (WT) | 30 * 330 kWp | 30 * 330 kWp | 3,500 * 330 kWp | 2,000 * 330 kWp |

| | | | | |
|---|---|---|---|---|
| Photovoltaics (PV) | 2,000 kW | 400 kW | 5,000 kW | 1,200 kW |
| Bio-genset (BIGS) | 2,500 kW | 800 kW | 120,000 kW | 60,000 kW |
| **Total Capacity** | **14.4 MW** | **11.1 MW** | **1,280 MW** | **721.2 MW** |

The power grid wheeling capacity conventional model consideration in view of the integration of the proposed hybrid system can be clarified as follows. This is in view of the networks' expansion for the renewable systems integration as the grid wheeling capacity is currently not sufficient to such proposed actions.

$$\sum_{n=1}^{n=N} P_{C.S_n} + \sum_{n=1}^{n=N} P_{P.H.S_n} \leq P_{W.C} \gtrsim \sum_{n=1}^{n=N} P_{L.D_n} ------(30)$$

Where: $P_{C.S_n}$ = Power Supplies to the Grid for the Conventional System, Currently Around 4,000 MW Cumulative; $P_{P.H.S_n}$= Power Capacities of the Proposed Hybrid System (Extrapolated Results); $P_{W.C}$ = Expected Wheeling Capacity for the Utility Grid on Integration of Proposed System; $P_{L.D_n}$ =Load Demands.

Furthermore, the rule of thumb as a strong pillar for the quantitative analysis, together with the economic components baselines for cost evaluations can be found in the below tables:

***Table 78:*** *Rule of Thumb (RoT) and Cost Baselines for Grid Integrated Power System*

| **Case** | **Principle** | **Implication** |
|---|---|---|
| Case I | $\frac{\text{No of Connections (N)}}{\text{Average Distance (Dav.)}} < 2 \text{ Connections/km}$ | Grid extension likely unviable |
| Case II | $\frac{\text{No of Connections (N)}}{\text{Average Distance (Dav.)}} > 30 \text{ Connections/km}$ | Grid extension likely viable |
| Case III | $\text{N} \times \text{Dav.} < 1{,}500 \text{ km}$ | Single-phase appropriacy |
| Case IV | $\text{N} \times \text{Dav.} > 10{,}000 \text{ km}$ | Three-phase appropriacy |
| Case V | $\text{N} > 100$ | Isolated grid likely viable |
| Case VI | $\text{N} < 100$ | Isolated grid likely unviable |
| **Cost Baseline** | | |
| **Cost** | **Specifications** | **Remark** |
| Total Capital Cost | € (1,364 – 5,142)/MW.km | Evaluated based on obtained different total investment costs with their corresponding multiples of capacities and cable length factors (MW.km) |

Source: Energypedia, 2019a; Ea Energy Analysis (2014)

Based on the specified rule of thumb with respect to Cases II, III, IV, and VI in the above table, the following analysis table stand in support of the integration of the renewable power systems to the grid system.

***Table 79:*** *Quantification Table for the Grid Integration of the Renewable Power System*

| **<u>Applied Parameters in the Analysis to the Rule of Thumb (RoT)</u>**<br>**N = 50 (for the 50 Decentralized Systems Proposed of Chapter Three)**<br>**$C_{Extrapolated}$ = 1,280 MW; $C_{Extrapolated + EE}$ = 721 MW (Chapter Three Optimized Capacity)**<br>**Current Grid Wheeling Capacity = 4,500 MW**<br>**Conventional Generation Capacity Integrated to the Grid ~ 4,000 MW** | | |
|---|---|---|
| **Grid Network** | **Extension Specifications** | **Remark** |
| Case II Compliance | $D_{av.}$ = (0.5 – 1.6) km | Ensuring a ratio of N to $D_{av.}$ greater than 30 connections/km. (Minimum case) |
| Case III & IV Compliance Issue | $D_{Total}$ = (25 – 80) km | Multiples of the number of connections specified and the connection distance on average (D) in respect to case II. (This is a minimum case for the 1-phase compliance, and with continuous expansion in getting to the 3-phase rule) |
| Capacity of Distance ($CoD_1$) / Extrapolation Case | $CoD_1$ = (32,000 – 102,400) MW.km | Based on the extrapolated capacity of the proposed decentralized system and the $D_{Total}$ of case III & IV. (Minimum case with expansion capability) |
| Capacity of Distance ($CoD_2$) / Extrapolation + EE Case | $CoD_2$ = (18,025 – 57,680) MW.km | Based on the extrapolated capacity on EE for the proposed decentralized system and the $D_{Total}$ of case III & IV. (Minimum case with expansion capability) |
| New Grid Wheeling Capacity on Extension (Extrapolated System Integration) | 5,780 MW | Summation of the conventional and current wheeling capacity and the capacity of the proposed extrapolated decentralized system on extension. (Minimum case with expansion capability) |
| New Wheeling Capacity on Extension (Extrapolated System + EE Integration) | 5,221 MW | Summation of the conventional and current wheeling capacity and the capacity of the proposed extrapolated decentralized system with EE on extension. (Minimum case with expansion capability) |

Regarding the economic implications of the extension analysis, the cost evaluations have been successfully determined in the below table.

***Table 80:*** *Cost Evaluation of the Grid Extension for the Proposed RE System Integration*

| **Proposed System** | **Investment Costs ($I.C_s$) for the Grid Network** | **Limits** |
|---|---|---|
| Extrapolated System Concern | €43.6 Million | Lower Limit |
| | €218.6 Million | Mid Value |
| | €526.5 Million | Upper Limit |
| Extrapolated System + EE Concern | €24.6 Million | Lower Limit |
| | €123.1 Million | Mid Value |
| | €296.6 Million | Upper Limit |
| **Remark: Evaluations based on the baseline cost range of capital cost for every MW.km and the impact of the evaluated capacity of distance (CoD) valued ranges for the proposed grid-integrated system and its EE measure** | | |

## CHAPTER SIX

# 6. CONCLUSION, RESEARCH CONTRIBUTIONS AND FUTURE WORK

## 6.1 Conclusion

The overall research dealt with the grid-integration of renewable energy power plants in the African context looking at the case of Nigeria. In the process, technical aspects specifically the decentralised hybrid power system design covering the physical components modelling and optimization, adequate sensitivity assessment and control evaluations, energy efficiency assessment, economic benefits evaluation of systems switching, extrapolation assessment at bigger capacity and lastly the environmental life cycle assessment of the grid-integrated renewable energy system has been successfully offered. In complementing the technical aspects, in-depth renewable power policies analysis in the global context has been offered, all assisting in successfully deriving appropriate lessons for the policy instruments that have been properly redesigned, as well as the supplementary grid-infrastructural assessment all in favour of integrating renewable energy systems to the utility grid of the case study country.

On implications to the successfully obtained results, it is evident that the proposed grid-integrated system is seen to be appropriate due to the optimized sizing reduction, and economic impacts from the standalone systems, owing to the advantage of the utility grid impacts and negligence of storage concerns. The demand side energy efficiency incorporation to the proposed system is observed to be very necessary due to massive reduction in energy resource extraction and optimized system components sizing, with ultimate reduction in energy consumption and net economic benefit. Extrapolation at bigger capacity is also observed to be very necessary in covering more geographical areas and taking the advantage of economy of scale while in the transition process to the renewable energy integration to the utility grid. The environmental impact on life cycle ground for the renewable system integration in the case study country, which ensures reduction in the uptake level of fossil fuels, is an indicator of sustainability. This is owing to the outstanding features offered based on minimization of the global warming potential (GWP), human toxicity potential (HTP), acidification potential (AP), and abiotic depletion potential (ADP) impacts from the conventional scenario path. The hybrid system idea in linking the different renewable systems to the grid to allay possible drawbacks on any environmental impact inherent in one is worth doing especially on giving preference to any of the scenarios that appeared with the lowest contributions in one or some of the impact categories by decision makers, all in line with the proposed photovoltaics (PV) / wind / biomass gasified hybrid system.

Integrating the renewable systems to the utility grid owing to the distinguishing features has been seen not to be viable unless the utility grid infrastructure is qualitatively improved tremendously, coupled with appropriate quantified extensions. Also, as a complement, it has been properly clarified the necessary policy instruments' appropriate shaping or reformulation while also addressing the possible risks in the implementation process of the policy instruments. These are in view of the prevalence of the renewable power systems, especially the hybrid power systems in the case study country, coupled with wider replications and capacities expansions at different sectors of development.

## 6.2 Originality of the Research Contributions

Within the limit of this research work, some strong components are believed to be the novel aspects or research contributions to knowledge. Beginning with the technical component of the research, the following aspects must be highly acknowledged:

- Demand side energy efficiency assessment uniquely addressed.
- Economic benefits evaluations of the switch from standalone hybrid power system to the proposed grid-connected system and to the proposed grid-connected system with the energy efficiency incorporation uniquely addressed.
- The extrapolation assessment based on load multiplier approach and resource variability uniquely addressed.
- The unique linkage of the power system design with the environmental life cycle assessment, and most uniquely the uncertainty analysis addressed as a data curation approach in the life cycle assessment work.

Regarding the policy component of the research, it is extremely important to stress on the fact that shaping the courses of actions or principles regarding the renewable energy operations for power generation and grid-integration has been a great success and a great contribution to knowledge. This has been solely the policy instruments redesign. Although it has been driven largely from the different lessons gathered around the world regarding best practices. As a supplement to the policy instruments redesign aspect, the grid-infrastructural assessment task that covered both qualitative and quantitative measures is worthy of mentioning here as another strong and original contribution. This is especially the quantitative evaluations, having direct linkage to the power system optimization results, with some unique quantifications for the grid extensions, for the successful integration of the proposed hybrid renewable power system.

## 6.3 Future Work in Line of the Research

Based on the extensive research work done, it is however, strongly noted that some follow-up research works in the case study country as a supplement to this research are highly necessary. These research works are highlighted below:

- The impact on the renewable power integration for huge oil and gas operations of the country. Although this aspect was touched briefly in the risk assessment part of the policy instruments formulated, specifically under the acceptability sub-heading. However, a broader research in this context is necessary because of the country being largely endowed with this huge fossil resources and being blindly and largely dependent on it for the power generations and beyond.
- The area of Electric Vehicles (EV) integration to the renewable power generations as a supplement to the conventional fossil-based transportation system is an area of priority for research as well. This is because EVs are becoming widely applied in the global context and hence, stands to be the future of Africa and potentially to the case study country.
- The area of renewable power generation to gas conversion systems integration is seen to be a strong research area in line. The gas considered in this regard is the hydrogen,

considered very unique and fundamental, with diversifying impacts, cutting across the power sector, transport sector, domestic and industrial sector. The hydrogen technology from power generation, of which renewable-based power is considered more appropriate is attracting great attention in the global context, hence, the future of Africa and potentially to the case study country.

## Publications in the Research Work

### Articles

- 2020: **Ismail Abubakar Jumare**, Ramchandra Bhandari, Abdellatif Zerga. Assessment of a Decentralized Grid-connected Photovoltaic (PV) / Wind / Biogas Hybrid Power System in Northern Nigeria. Energy, Sustainability and Society (Springer Nature), 10:30, DOI: 10.1186/s13705-020-00260-7

- 2019: **Ismail Abubakar Jumare**, Ramchandra Bhandari, Abdellatif Zerga. Environmental Life Cycle Assessment of Grid-Integrated Hybrid Renewable Energy Systems in Northern Nigeria. Sustainability (MDPI), 11 (21) 5889, DOI: 10.3390/su11215889

### Conference Papers

- 2020: **Ismail Abubakar Jumare**, Ramchandra Bhandari, Abdellatif Zerga. Energy Supply with Photovoltaics/Wind Hybrid System: A Reliability Assessment in Northern Nigeria. Energy Proceedings, 11th International Conference on Applied Energy (ICAE, 2019 - Elsevier), 4, Link: http://www.energy-proceedings.org/energy-supply-with-photovoltaics-wind-hybrid-system-a-reliability-assessment-in-northern-nigeria/

- 2018: **Ismail Abubakar Jumare**, Ramchandra Bhandari, Abdellatif Zerga. Decentralized Grid-Connected Hybrid Renewable Energy System Design in Nigeria: Case Study of Zaria Municipal. SSRN E-Journal (Elsevier – Repository), PAUWES Research to Practice Conference, DOI: 10.2139/ssrn.3224175

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## Appendices

***Appendix 1:*** *Summary of the Renewable Power Policy Instruments in the Case Study Country*

| | Regulatory Policies | | | | | Fiscal Incentives & Public Financing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | FiT / PP | EUQO / RPS | N-M | TREC | TN | I / PTC | R / S, E, VAT.. | E.P. P | PI, L, G, C.S or R |
| Nigeria | √ / 2016 | √ | X | X | √ / 2016 | √ / 2014 | √ | X | √ / 2014 |
| Regulatory-Based Policy Instruments in the Region and % Share | | | | | | 03 | | 50% | |
| Fiscal Incentives Policy Instruments in the Region and % Share | | | | | | 03 | | 50% | |
| Total number of policy instruments in the Region | | | | | | 06 | | 100% | |

## General Quantitative Summary for the Global Power Policy Findings (Clusters)

***Appendix 2:*** *Summary of the Renewable Power Policy Instruments for the ASIAN Cluster*

| | Regulatory Policies | | | | | Fiscal Incentives & Pub. Financing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | FiT / FiP | EUQO / RPS | N-M | TREC | TN | I / PTC | R / S, E, VAT.. | E.P. P | PI, L, G, C.S or R |
| China | √/’09/’10/’11/’12 | √ | X | X | √/’10/’16 | √ / 2013 | √/’08/’13 | √ / 2006 | √ / 2007 |
| India | √/’10/’15/’16/[Sub.] | √ | √/’14/[Sub.] | √/’11 | √/’14/[Sub.] | √/’19[Future] | √ | √ / 2008 | √/’06/’13 |
| Japan | √ / 2012 | √/’03/’07 | X | √/2000 | √ | X | √ | X | √/’98[Exp.]/’99 |
| Turkey | √ / 2010 | √ | X | X | √/’16/’17 | √ | X | X | √ |
| Russia | X | √ | X | X | √ / 2013 | √ | √ | X | √ |
| Philippines | √/’12/[Rev.]’15 | √ | √ / 2013 | X | √ | √ | √ | √ / 2011 | √ / 2011 |
| Indonesia | √/’14[Exp.]/’15[Exp.]/’16 | √ | X | X | X | √ / 2010 | √ | X | √ / 2012 |
| Malaysia | √ / 2011 | √ | X | X | √ / 2017 | √ | X | X | √ / 2010 |
| Total | 07 | 08 | 02 | 02 | 07 | 07 | 06 | 03 | 08 |
| % Extent | 87.50% | 100% | 25.00% | 25.00% | 87.50% | 87.50% | 75.00% | 37.50% | 100% |
| Regulatory-Based Policy Instruments for the Cluster and % Share | | | | | | 26 | | 52.00% | |
| Incentives & Financing Instruments for the Cluster and % Share | | | | | | 24 | | 56.00% | |
| Total number of policy instruments for the ASIAN Cluster | | | | | | 50 | | 100% | |

***[Note: Sub.: Instruments Existing at Subnational Level; Rev.: Instrument Revised; Exp.: Instrument Expired / Inactive; Future: Instrument Planned for Future]***

***Appendix 3:*** *Summary of the Renewable Power Policy Instruments for the Selected EU Cluster*

| | Regulatory Policies | | | | | Fiscal Incentives & Pub. Financing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | FiT / FiP | EUQO / RPS | N-M | TREC | TN | I / PTC | R / S, E, VAT.. | E.P. P | PI, L, G, C.S or R |
| Germany | √/91/[Rev.]’00 | √ | X | √/2013 | √ / 2017 | √ | √ | X | √ / 2009 |
| France | √/06/[Rev.]’16 | √ | X | X | X | √ | √ | X | √ / 2016 |
| Spain | √/90s/Ccl. | √ | X | X | √ / 2015 | √ | X | X | √ / 2015 |
| Italy | √ / 2012 | √ | √ /2008 | √/1999 | √ / 2013 | √ | √ | X | √ / 2012 |
| Sweden | √ / 1998 | √ | √ | √/2003 | X | √ / 1991 | √ | X | √ /’05/’09 |
| Finland | √ / 2011 | √ | X | √ | X | X | √ | X | √ /’99/’02 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Iceland | X | X | X | X | X | √ / 2012 | X | X | √ / 2003 |
| Denmark | √/90s/[Rev.]'00 /'08 | √ | √ /2012 | √ | √ / 2004 | √ / 2012 | X | √ / 2009 | √ / 2009 |
| Total | 07 | 07 | 03 | 05 | 04 | 07 | 05 | 01 | 08 |
| % Extent | 87.5% | 87.5% | 37.5% | 62.5% | 50% | 87.5% | 62.5% | 12.5% | 100% |
| Regulatory-Based Policy Instruments for the Cluster and % Share | | | | | | 26 | | 55.32% | |
| Incentives & Financing Instruments for the Cluster and % Share | | | | | | 21 | | 44.68% | |
| Total number of policy instruments for the EU Cluster | | | | | | 47 | | 100% | |

***[Note: FiP Existence: France, Spain, Italy, Denmark, and Germany (Through Tender); Rev.: Revised Instrument; Ccl: Instrument Later Annulled]***

***Appendix 4:*** *Summary of the Renewable Power Policy Instruments for the Australasia Cluster*

| | Regulatory Policies | | | | | Fiscal Incentives & Pub. Financing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | FiT / PP | EUQO / RPS | N-M | TREC | TN | I / PTC | R / S, E, VAT.. | E.P. P | PI, L, G, C.S or R |
| Australia | √/2009[Sub] | √ | √/2009[Sub] | √ | √ [Sub] | X | X | X | √ / 2004 |
| N. Zealand | X | √ | √ [Sub] | X | √ | √ | √ | X | √ /1995 |
| Total | 01 | 02 | 02 | 1 | 02 | 01 | 01 | 0 | 02 |
| % Extent | 50% | 100% | 100% | 50% | 100% | 50% | 50% | 0% | 100% |
| Regulatory-Based Policy Instruments for the Cluster and % Share | | | | | | 08 | | 66.7% | |
| Incentives & Financing Instruments for the Cluster and % Share | | | | | | 04 | | 33.3% | |
| Total number of policy instruments for the Australasian Cluster | | | | | | 12 | | 100% | |

***[Note: Premium Net FiT / N-m Existence: Australia; Sub: Instrument Existing at Sub-national or Regional Level]***

***Appendix 5:*** *Summary of the Renewable Power Policy Instruments of North American Cluster*

| | Regulatory Policies | | | | | Fiscal Incentives & Pub. Financing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | FiT / PP | EUQO / RPS | N-M | TREC | TN | I / PTC | R / S, E, VAT.. | E.P. P | PI, L, G, C.S or R |
| USA | √/1978[Sub] | √ [Sub] | √/1982[Sub] | √/2002[Sub] | X | √ | X | X | √ / 1997 |
| Canada | √/2009[Sub] | √ [Sub] | √/2005[Sub] | √ | √ [Sub] | √ | X | √ | √ |
| Mexico | X | √ | √ / 2010 | √ | √ / 2015 | √ | X | X | V / 1982 |
| Total | 02 | 03 | 03 | 03 | 02 | 03 | 0 | 01 | 03 |
| % Extent | 66.67% | 100% | 100% | 100% | 66.67% | 100% | 0% | 33.33% | 100% |
| Regulatory-Based Policy Instruments for the Cluster and % Share | | | | | | 13 | | 65% | |
| Incentives & Financing Instruments for the Cluster and % Share | | | | | | 07 | | 35% | |
| Total number of policy instruments for the N.A Cluster | | | | | | 20 | | 100% | |

***[Note: Sub.: Instrument Existing at Subnational or Regional level]***

*Appendix 6: Summary of the Renewable Power Policy Instruments of South American Cluster*

| | Regulatory Policies | | | | | Fiscal Incentives & Pub. Financing | | | |
|---|---|---|---|---|---|---|---|---|---|
| Country | FiT / PP | EUQO / RPS | N-M | TREC | TN | I / PTC | R / S, E, VAT.. | E.P. P | PI, L, G, C.S or R |
| Brazil | √ / 2004 **Exp.** | √ / 2010 | √ /2012 | X | √ / 2007 | √/'11/'12 | √ /2011 | X | √ / 2015 |
| Chile | X | √ | √ | X | √/'13/'15/'17 | √ | √ | X | √ |
| Argentina | √/'98/ Rev. '06 | √ / 2006 | √ **Sub** /'14 | X | √ / 2009 | √ / 2009 | √ / 2009 | X | √ / 1998 |
| Total | 02 | 03 | 03 | 0 | 03 | 03 | 03 | 0 | 03 |
| % Extent | 66.67% | 100% | 100% | 0% | 100% | 100% | 100% | 0% | 100% |
| Regulatory-Based Policy Instruments for the Cluster and % Share | | | | | | 11 | | 55% | |
| Incentives & Financing Instruments for the Cluster and % Share | | | | | | 09 | | 45% | |
| Total number of policy instruments for the S.A Cluster | | | | | | 20 | | 100% | |

***[Note: FiP Existence: Argentina; Exp.: Instrument Inactive / Expired; Rev.: Instrument Revised; Sub.: Instrument Existing at Subnational or Regional Level]***

*Appendix 7: Quantitative Summary of the Policy Instruments Assessment for the Globe*

| **Indicators** | **Regulatory Policy Instruments** | | **Fiscal Incentives and Public Financing Policy Instruments** | | **Total Policy Instruments** |
|---|---|---|---|---|---|
| **Continents** | **Instruments** | **% Weight** | **Instruments** | **% Weight** | **Instruments** |
| Asia Cluster | 26 | 52.00% | 24 | 48.00% | 50 |
| Europe Cluster | 26 | 55.32% | 21 | 44.68 | 47 |
| North America Cluster | 13 | 63.16% | 07 | 36.84% | 20 |
| South America Cluster | 11 | 55.00% | 09 | 45.00% | 20 |
| Australasia Cluster | 08 | 65.00% | 04 | 35.00% | 12 |
| Total | 84 | 55.78% | 65 | 44.22% | 149 |