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Doctorat de l'Université de Toulouse

préparé à Toulouse INP

Contribution à la production d'énergie électrique pour les zones rurales isolées utilisant composants de seconde vie et énergies renouvelables: faisibilité pratique et analyse du cycle de vie

Thèse présentée et soutenue, le 4 juin 2024 par

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Dedicated to the sweet memories of my dear MUM, Nuratu Adenike Aliyu

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Abstract

The ever growing demand for electricity has always been a burden which has continued to inspire the need for development and evaluation of new sources for generating electricity. Besides the current challenge of high cost, the effect of ecological footprint and the global warming concerns have further made deployment of novel ideas a bit more difficult. The possibility of adapting a reuse solar-pico hydro energy generation system to a rural apartment for economic and ecological advantage was the key motivation for this thesis. This reuse system was made from old materials and e-waste components such as old lead acid battery, power supply unit from desktop computer, an old induction machine and so on. This thesis thus answers three main research questions; is it feasible to apply and deploy the reuse system based on available e-waste components and second life materials? Is the reuse system efficient and adaptable to the energy needs of a typical rural household? Is the environmental impact contribution of the reuse system smaller than that of a new system over the same lifetime? The investigations commenced by exploring the effect of deploying the reuse system on electricity access. A load model was developed for a typical rural household taking a case study in Nigeria while optimal component sizing was done based on the developed load model for both the reuse and new systems. Techno-economic analysis was performed and a comparison between the new system and the reuse system indicated about 65% and 15% decrease in the initial capital cost and cost of energy respectively. From the sizing results, three different possible scenarios of combining old solar panels and the reuse hydro turbine were presented and further analyses were done based on these scenarios. Afterwards, a feasibility study of adopting the reuse system in Nigeria based on annually generated e-waste within the country was performed. The results showed that an average of about 127 thousand households can be electrified annually if the reuse solar-pico hydro generation system was adopted for energy generation in households. The second phase of the research was to develop a battery energy management algorithm to ensure maximum power supply to the loads irrespective of weather conditions and load demand. To achieve this, an Autoregressive Integrated Moving Average (ARIMA) algorithm was developed for forecasting solar irradiance vis-a-vis a battery energy management algorithm incorporating a combination of load shifting and load curtailment. The application of the energy management algorithm successfully reduced the possibility of having zero battery state of charge during a typical rainy day by 82%. After achieving a desirable energy management for the reuse system, the last step was to evaluate the environmental impact contribution of the system as compared to a new hybrid system of a similar configuration. To achieve this, life cycle assessment was performed with the aid of Simapro software and EcoInvent database. The ISO 14040/44 standard was strictly adhered to and the result indicated that for the reuse system, only six out of the fifteen impact categories had significantly visible impact scores. The normalised impact score for all the impact categories were less than 0.005 Daily Adjust Life Years (DALY) with aquatic acidification and eutrophication having zero impacts score. Furthermore, sensitivity analysis was performed to see the influence of critical parameter on the environmental impact contribution. This revealed that battery lifetime was the most sensitive parameter which resulted in the highest change in impact contribution when varied. In conclusion, this thesis has proven the technical, economic, and ecological advantage of adopting the reuse solution for rural electrification.

Resumé

La demande croissante en électricité constitue depuis toujours un défi. Développer de nouvelles sources de production d'énergie durables devient une nécessité et un enjeu sociétal majeur afin de diminuer l'empreinte carbone du secteur. La principale motivation de cette thèse réside dans la possibilité d'adapter un système de production d'énergie solaire-pico hydraulique de deuxième vie, construit à partir de composants électroniques. Ce système a été conçu en utilisant des matériaux réutilisés et des composants électriques mis au rebut tels que des batteries au plomb, une alimentation d'ordinateur, une vieille machine à induction, etc. La thèse explore trois questions clés : est-il possible et de mettre en œuvre le système de seconde vie en se basant sur des déchets électroniques, la ressource locale est-elle suffisante ? Le système de réutilisation est-il efficace et adaptable aux besoins énergétiques d'un ménage rural standard ? L'impact environnemental du système de réutilisation est-il inférieur à celui d'un nouveau système sur la même durée de vie ?

Les recherches ont débuté par l'étude de l'impact du déploiement du système de réutilisation sur l'accès à l'électricité. Un modèle de charge a été élaboré pour représenter un ménage rural typique au Nigeria, tandis que le dimensionnement optimal des composants a été réalisé en se basant sur ce même modèle pour le système de réutilisation ainsi que pour le nouveau système. Une analyse technico-économique a été conduite, révélant une réduction d'environ 65% du coût d'investissement initial et une diminution d'environ 15% du coût de l'énergie pour le système de réutilisation par rapport au système neuf sur toute la durée de vie.

Les résultats du dimensionnement ont généré trois scénarios combinant d'anciens panneaux solaires et une turbine hydroélectrique réutilisée, soumis à des analyses approfondies. Une étude de faisabilité basée sur la quantité annuelle de déchets électroniques au Nigeria a révélé qu'environ 127 000 foyers pourraient être électrifiés annuellement avec le système de production solaire-pico-hydraulique réutilisé.

Ensuite, deux algorithmes ont été développés. Un algorithme type « Autoregressive Integrated Moving Average » (ARIMA) a été élaboré pour anticiper l'irradiation solaire et un autre algorithme de gestion de l'énergie de la batterie, intégrant des stratégies de déplacement de la consommation et d'effacement a aussi été élaboré. L'application de cet algorithme a conduit à une réduction de 82 % de la probabilité d'un état de charge nul de la batterie au cours d'une journée de pluie typique.

La phase finale consistait à évaluer l'impact environnemental du système par rapport à un système hybride neuf de configuration similaire. Enfin, une analyse du cycle de vie a été effectuée en utilisant le logiciel Simapro et la base de données EcoInvent, en stricte conformité avec la norme ISO 14040/44. Les résultats ont montré que, pour le système de réutilisation, seules six des quinze catégories d'impact présentaient des scores significativement visibles. Le score d'impact normalisé pour l'ensemble des catégories était inférieur à 0,005 « Daily Adjust Life Years » (DALY), avec absence d'impact pour l'acidification aquatique et l'eutrophisation. De plus, une analyse de sensibilité a été réalisée et a mis en évidence que la durée de vie de la batterie constituait le paramètre le plus sensible, entraînant la modification la plus significative de la contribution à l'impact lorsqu'il était ajusté.

En conclusion, cette thèse a réussi à démontrer la faisabilité de l'adoption d'un système de production solaire-picohydraulique réutilisé pour générer de l'énergie dans une zone rurale typique. Les avantages techniques, économiques et écologiques de l'adoption de ce système par

rapport à un nouveau système ont été clairement établis, positionnant cette solution comme une réponse immédiate pour améliorer l'accès à l'électricité dans les zones rurales et isolées.

Abbreviations and Symbols

AC	Alternating Current
ACF	Auto Correlation Function
Ah	Ampere-hour
AIC	Akaike Information Criteria
AMMC	Aluminium Metal Matrix Composite
ARIMA	Auto Regressive Integrated Moving Average
AR	Autoregression
ARMA	Autoregression Moving Average
BIC	Bayesian Information Criteria
CAPEX	Capital Expenditure
CO ₂	Carbon dioxide
DC	Direct Current
DOD	Depth of Discharge
ECN	Energy Commission of Nigeria
E-waste	Electronic waste
GDP	Gross Domestic Product
GHG	Green House Gas
Gt	Giga tonne
GW	Gigawatts
GWP	Global Warming Potential
HOMER	Hybrid Optimization of Multiple Electric Renewables
IEA	International Energy Agency
IMFT	Institut de Mécanique des Fluides de Toulouse
ISO	International Organisation for Standardisation
J	Joules
kg	kilogram
kW	Kilowatts
LAPLACE	Laboratoire Plasma et Conversion d'Énergie
LCA	Life Cycle Assessment
LCOE	Levelised Cost of Energy
MA	Moving average
MPPT	Maximum Power Point Tracking
MW	Megawatts
NEPA	National Electric Power Authority
NERC	Nigeria Electricity Regulatory Commission
NPC	Net Present Cost
₦	Nigerian Naira
OAITI	One-Isolated-And-Two-Isolated-Inputs
P	Power
ρ	Density
PACF	Partial Auto Correlation Function
PSU	Power Supply Unit
PV	Photovoltaic
RE	Renewable Energy
REA	Rural Electrification Agency

REEE	Reuse Electrical and Electronic Equipment
REMP	Renewable Energy Master Plan
SoC	State of charge
STC	Standard test conditions
\$	US Dollars
T	Tonnes
TSCAOI	Two-Series-Connected-And-One-Isolated
TW	Terrawatts
UEEE	Used Electrical and Electronics Equipment
UNDP	United Nations Development Programme
UPS	Power Supply
V	Voltage
W	Watts
WEEE	Waste from Electrical and Electronic Equipment
Wp	Watt peak
Wh	Watt-hour

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General Introduction

The need for stable, reliable and efficient electricity is one important aspect that is required to improve the quality of life of a common man. The constant and continuous advancement in technology which is aimed at making living easier and simpler has made electricity to become a vital aspect as most of the devices are dependent on this source of energy for functionality. However, the lack of electricity would automatically translate to lack of availability of technological applications, which would in turn have a negative effect on the economic aspect of both individuals and communities. Most developing countries are characterised by rural areas which have no or insufficient access to electricity. This makes the economic activities of those areas quite low and thus they have little or no input to the overall economy of the nation. In recent times, the reliance on energy consuming devices such as phones, computers, radios, television, heaters amongst other have made electrical energy access an important aspect. In addition, electricity, if generated from renewable sources have proven to reduce emission of poisonous gases which are as a result of use of fuels for different purposes as it has been able to provide different equipment for different usage. For example, a simple gas cooker or kerosene stove can now be replaced with an electric hot plate; a kerosene lantern can be replaced with rechargeable bulbs and solar lamps and so many more. The fact that there is urgent need to reduce emission of poisonous gases so as to avoid global warming has encouraged most government to embrace use of renewable energy for generation of electricity. Also these renewable energies are freely available in nature and are not used up which makes it some added advantages besides the zero emission advantage it gives.

It is quite true that provision of electricity is an expensive investment when compared to the profit accrued after electrification. This is the reason why a lot of developing nations have been unable to provide adequate electricity to most part of their countries and most of them still depend on conventional ways of energy generation which have seemingly been overstretched and require grid expansion as well as introduction of new generation stations to meet the ever growing demand. The lack of technological manufacturing industries has made these countries to depend on importation of technology, as such they solely depend on importation of electrical and electronic equipment and components to function and catch up with current trends.

A combination of lack of manufacturing industries and high importation of technology translates to high cost of purchase, and generation of used electrical electronics waste within the countries. These electronic wastes can be prudently re-used and/or recycled to serve new purposes as most of these equipment have components with long residual lifetime. This would however require innovative ideas and high level skills to use these e-wastes for adequate and sufficient products which can further intervene in the economy while improving the quality of lives of rural dwellers. The reuse of e-waste can promise a reduced cost of production and also reduce emission of toxic compounds which would normally be the issue if electronic components are abandoned to rot. Also, several components such as copper and gold can be extracted from e-waste which is another investment opportunity. Lastly, the components can be frugally combined to provide more useful resources which would improve the living of individuals within the locality.

The status of electrical energy access and availability serves as a justification to seek new ideas for generating and providing electricity to rural areas with no supply or insufficient access. The status and amount of e-waste and used electrical electronic equipment which can be reconditioned and repurposed for frugal energy generation will be analysed and discussed to achieve a basis for providing electrical energy to rural areas while staying in conformity to renewable energy policies and guidelines.

This thesis is in its entirety divided into four main parts; The first chapter which is devoted to discussing the fundamentals of energy generation, rural electrification, renewable energy, e-waste, frugal innovation and their respective statuses as it relates to Nigeria and a few surrounding west African countries in certain instances.

The second chapter builds upon the background information of renewable energy status and electronic waste to investigate the feasibility of adopting a frugal innovation based technology for energy generation in a rural household using a reuse hybrid solar-pico-hydro system which was inspired based on the work of [1]. A daily load duration curve was modelled for a typical residential rural household and components sizing was done using HOMER software. The feasibility study based on number of components required and the amount of e-waste generated annually was performed and the impact of this solution on electricity access in Nigeria was presented. Finally, an economic analysis was done to compare the reuse solution against a conventional/new renewable energy generation solution based on the current technology available in the Nigerian market.

In the third chapter, time series analysis was introduced for renewable energy data and a real-time Auto Regressive Integrated Moving Average (ARIMA) model was developed to forecast time series data which can be customised or adopted to the reuse model. A battery energy management scheme was then developed to ensure that maximum energy is delivered to the load at every point in time while protecting the battery and ensuring the maximum load demand is met. The fourth chapter shows a final investigation on the life cycle impact assessment of the reuse hybrid solar-pico-hydro system. Life cycle assessment was performed based on the ISO 14040/44 standard using SIMAPRO software to evaluate the environmental impact contribution of the reuse system if deployed and used over a five-year lifetime. The impact contribution of the reuse system was also compared to a new/conventional system with similar characteristics. Finally, a sensitivity analysis was performed on some critical parameters that constitute the model of the reuse system to see their influence on the impact contributions.

CHAPTER ONE

GENERAL BACKGROUND AND CONTEXT OF ENERGY SITUATION IN NIGERIA

1.1 Electrical Energy Generation

Electricity or electrical energy is a premium form of very useful energy which is characterised by voltage and current. This form of energy is derived from conversion of other forms of fundamental energy types to electrical energy. The electrical energy consumption sector is the fastest growing form of energy which was estimated to be about 16TW as at in 2006 and would grow up to 60% more by 2030. Several areas of usage ranging from science and technology, transportation, agriculture, manufacturing and household usage amongst others are responsible for this high net energy consumption. Furthermore, continuous investigation and research have been introducing new areas of application for electrical energy usage.

Several ways can be used to generate electrical energy from other existing energy sources that are available. These include Nuclear, Coal, Gas, Oil, Renewables and so many more. Conventional power stations such as coal-fired, gas and nuclear powered plants as well as hydroelectric power stations are the most widely used means of generating electricity. However, as the world is considering more economical and environmental friendly alternative energy generation systems, the global energy mix is becoming more complex [2]. The factors forcing these considerations are [3]:

- i. the increasing demand for electric power,
- ii. many developing countries lacking the resources to build power plants and distribution networks,
- iii. losses due to transfer of electrical energy from generation through transmission to the distribution lines,
- iv. greenhouse gas emission and climate change concerns.

This leads to the idea of energy sectors using widespread alternatives to deal with increase in electrical energy demand, because population growth affect energy demand and so many other factors.

Several ideas have been introduced to cater for alternative means of generation such as Distributed Generation, Renewables, Microgrids and so on. These all aim at ensuring that the power needs of consumers are met at a reasonable and cost effective model. Most rural consumers are characterised by low density of load consumption and poor financial situation which is another reason why the generation solution for rural areas has to even be targeted to be as cheap as possible. This reason has brought about frugal ideas of generating smaller units of energy by minimising cost of production as much as possible. The use of electrical energy after being generated has been divides into different categories shown in Figure 1.01.

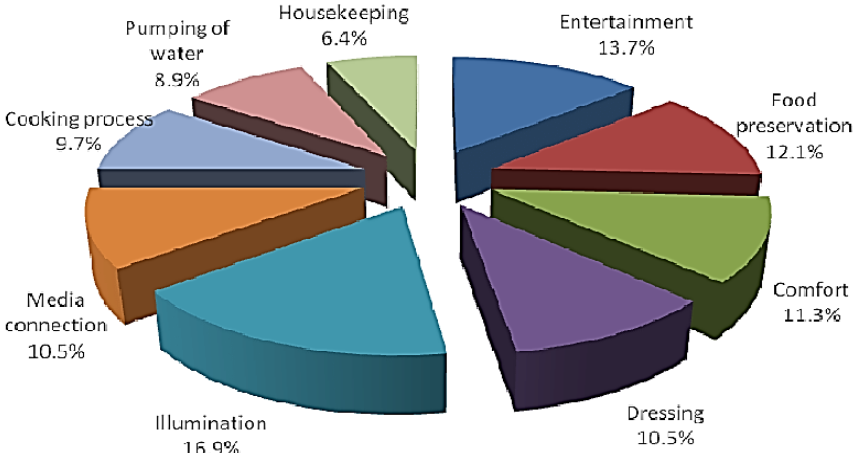


Figure 1.01: Different usage of electricity [4]

The lack of adequate electricity is probably not a new scenario to majority of Nigerians. This is because millions of Nigerians do not have access to grid electricity, thus relying instead on polluting lighting sources such as kerosene lanterns, candles, and rechargeable lamps and torches. According to World bank SDG report in 2020, Nigeria is not amongst the top ten countries with electricity access in Africa, with Egypt, Algeria, Seychelles and Morocco having 100% access to electricity while Tunisia, Mauritius, Cape Verde, Gabon South Africa and Ghana have more than 80% access to electricity. Nigeria on the other hand has 56.5% of the population with access to electricity even though majority of these individuals don't have constant supply. The situation in rural areas is particularly acute with only 41.1% grid access rate. And even among those who have access to the grid, 40% are 'under-electrified' meaning they have less than 12 hours of grid electricity per day. Some areas do not have access to electrify at all and have only depended on other toxic and poisonous sources of fuel for their day to day activities. Most of them depend on firewood for cooking and use kerosene lantern for illumination at night. A summary of the energy situation in Nigeria which is shown in Figure 1.02 indicates that on the average, electricity costs \$0.24 per kWh and an installed generation capacity of 12,522MW serves the entire country.

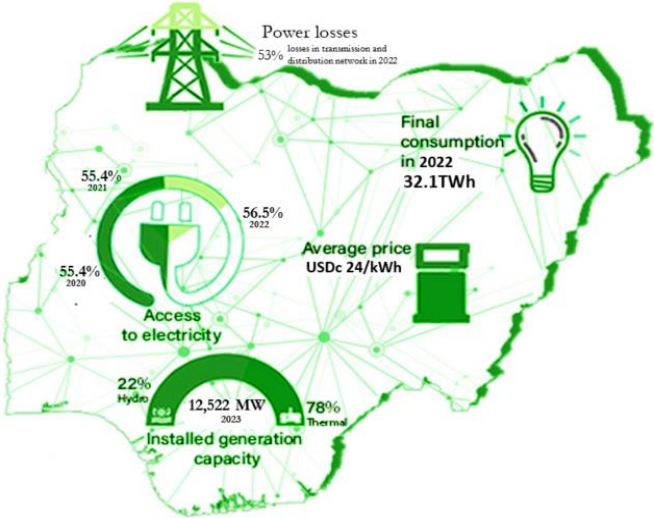


Figure 1.02: A pictorial summary of the Nigerian energy situation [5–7]

1.2 Rural Electrification

The word “rural” is a relative terminology which compares two different scenarios based on a specific baseline. This is why the understanding of rural areas may differ from country to country because the baseline for one country’s definition of rural area may be different from another’s. However, according to the Food and Agriculture Organization of United Nations, three common benchmarks define rurality; sparse settlement, land cover and use, and remoteness from urban cities. Generally, condition of livelihood is a major factor in determining what is rural and what is urban. Rural electrification on the other hand is much easier to define and understand because it fundamentally involves electrifying or bringing electrical energy to the rural or remote areas. The effect of rural electrification is to positively reduce the burden of overpopulation in urban areas as availability of electricity will grossly improve condition of living of rural dwellers, reduce mass migration to cities thereby reducing population imbalance and improve the economy of rural areas. This will in turn have a positive effect on the per capita income and gross domestic product of these areas because most of the rural areas will begin to become less dependent on urban cities [8]. Rural electrification will further reduce the emission of poisonous gases into the atmosphere due to the fact the use of fossil fuel will reduce. The

term ‘rural electrification’ has proven to show a lot of advantages which is why most countries and governments have been encouraged to concentrate on electrifying rural areas.

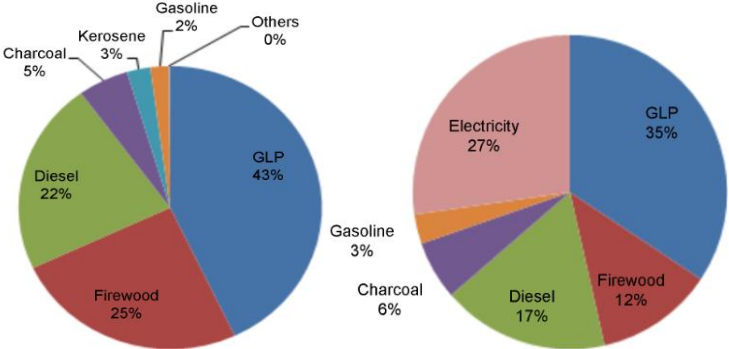


Figure 1.03: Effect of electrification on the energy consumption profile of a typical rural household in Brazil [9]

1.2.1 The Impact of Rural Electrification

The contribution of stable electricity supply cannot be overemphasized in the daily activities of man. This availability of constant electricity supply will have a positive impact of healthcare, education, economy, technological development as well as the social welfare of man. In most developing countries, the major efforts of continuous development are concentrated on the urban cities while the rural areas lack basic fundamental amenities. Based on data reports from International Energy Agency, the population of rural dwellers without electricity supply will be about six times higher than those in urban cities by 2030 [10]. This will effect to imbalance in quality of life as well as increased migration to urban cities thus most rural cities will lag in development and Urban cities will become overcrowded. In order to avert these issues, the best solution is to create and implement policies that would increase rural electrification and provide basic amenities for rural areas. Another feasible solution is providing alternative energy which are cheap, easy to install and cost efficient since most of these rural areas have been said to consume less amount of energy.

The positive effect of providing electricity for rural inhabitants can be seen in so many areas. These improvements have been manifested of general quality of life, greenhouse gas emission reduction, reduced migration as well as job creation.

1.2.1.1 Impact on Lighting

Before intervention and electrification, most rural dwellers use non-environmental friendly methods for artificial lighting at nights. Despite their toxic and health hazardous effects, these methods of lighting as also very inefficient as their illuminance is very poor, they generate a lot of heat and emit toxic gases. Some of the lighting techniques are even associated with high risks as any mistake could lead to fire outbreak, burns and so on. These lighting methods included the use of hurricane lamps, traditional can lamps, wax candles, firewood, battery torches. The electrification of areas depending on these lighting techniques will positively improve the quality of the night life in association with a few other related factors such as health, environment and cost [11]. The effect on health is a reduction of inhalation of toxic gases being released from the use of conventional fuel lighting methods and also better eyesight while for the environment, the release of greenhouse gases will be grossly reduced. Furthermore, the need for continuous purchase of fuels and dry-cell batteries will also be eliminated which ends up being cost efficient for the end-user.



Figure 1.04: Lantern, firewood, wax candle and traditional wick lamp used as sources of lighting [11,12]

In Nigeria, the World Bank Lighting Africa-Nigeria project has so far affected about 1.8million rural dwellers between 2014 and 2018 with an approximate reduction of 162 thousand tonnes of greenhouse emission. The impact of electrification has encouraged users to discard these fuel-based lighting sources for more efficient and cost-effective alternatives. It worthy of note that candles emit an average of 11 Lumens while electrically powered AC lamps emit an average range of 150 to 1000 Lumens depending on the technology. This difference in output of lumens is one significant factor for widespread acceptance of electric bulbs as well as positive impact of electrification for nightlife [12].



Figure 1.05: Samples of LED lamps [13]

Even in the advent of power outage, rechargeable lamps have become very popular and has replaced the sources of lighting shown in Figure 1.05. Majority of users now prefer rechargeable lamps which can be charged with electricity supply and be used at nights if there is an outage or as emergency lighting. This impact has also favoured the led technology market which has gone as high as 90% penetration in countries like Senegal where houses that have electricity supply prefer to buy these rechargeable lamps to use when there is outage [14]. In 2009, data from some parts of Senegal showed that only 7% were still using fuel based sources for lighting while the remaining 93% were already using other sources in which electric lamps make up 85% of the entire data set. Furthermore, data from some countries like Burkina Faso and Rwanda have also shown that rural electrification will impact the choice of lighting as there was significant reduction in the use of fuel based sources of lighting over a period of two years as shown in Figure 1.06.

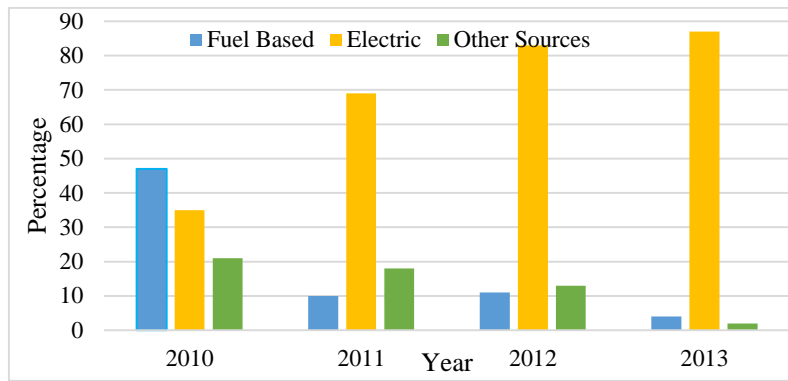


Figure 1.06: Impact of electrification on lighting for Rwanda and Burkina Faso [13]

1.2.1.2 Impact on Education

The availability of electricity also has a positive effect on education as it will extend possible study time. This is directly related to the lighting impact as most school goers can have extended study time at nights compared to using candles and lanterns at night. Bright electricity powered bulbs offer a more efficient alternative for reading and studying as there is no harm to the eyes. For children mostly below teenage, daily activities can be categorised in four aspects; education /learning and studying, house chores, leisure or play time. The studying and learning aspect can be grossly improved by sufficient supply of electricity even if the time invested is not increased, there is guarantee of improved outcome as the quality of lighting would surely bring comfort and reduce fatigue. Most children spend about 40% of their time on studies which may slightly increase if the night time lighting is improved. However, there is a relative distraction as provision of electricity also means access to leisure devices such as televisions and radios, thus, this effect may vary from household to household. Studies have shown that 90% of parents have agreed that the provision of electricity would increase the study time of children while 55% also agreed that leisure time would also increase if the electricity is available [15]. In 2009, a study in Senegal was able to prove an increase in study time after nightfall from 21minutes to 30minutes [14]. This indication may not be consistent in every other part of rural Africa but is a sign that with the right resources and discipline, electrification would hopefully have positive impact on education and in turn improve performance of school children in their academic activities. Furthermore, this caused an inquisitive idea whereby it was assumed that these extended reading hours should further translate to improvement in academic performance at school.

A study was performed on the effect of available extended hours of lighting on the academic performance of some rural dwellers in Zambia by distributing solar lanterns to some households. It was first established as shown in Figure 1.07 that majority of these students' own flashlights which are obviously not suitable for reading at night and thus may need to increase their night time activity if there is adequate and sufficient artificial source of lighting.

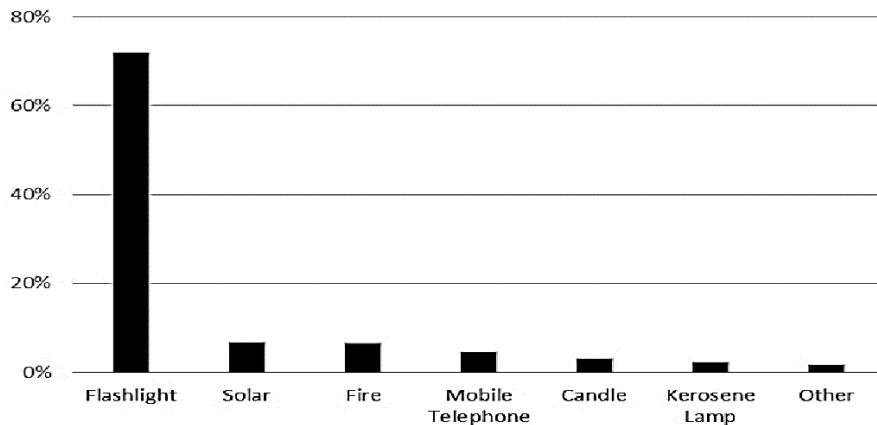


Figure 1.07: Types of lighting used by students in rural areas [16]

These solar lamps can also be assumed to be a form of electrification lighting source at nights and could well show the impact of extended hours of lighting on the behaviour of rural dwellers. However, the results obtained in [17] showed that extended lighting hours did not affect the academic performance of students or cause an improvement in grades. Other factors such as age, gender and socioeconomic status were the only factors that affected performance in examinations. However, it is believed that over a longer period of time, extended hours of lighting may have little impact on examination performance.

1.2.1.3 Economic Impact

The effect of electrification on the economy is related to labour, employment, agricultural outputs, productivity and overall development which is certainly a positive. Also, there is a direct relationship between rural electrification and income, especially for newly connected homes. This is likely linked to possibility of increased business opportunities from home such as commercial operation of milling or electric grinding machines for profit. The increase in working hour is another index for improved profit because there is more productive time as a result of electrification [14]. This, on the long run may in turn have a positive effect on the Gross Domestic Product (GDP) or per capita income as shown in Figure 1.08 where a thirty-year survey was carried to see the inter-correlation between rural population, rural electrification, rural/urban electrification and GDP per capita.

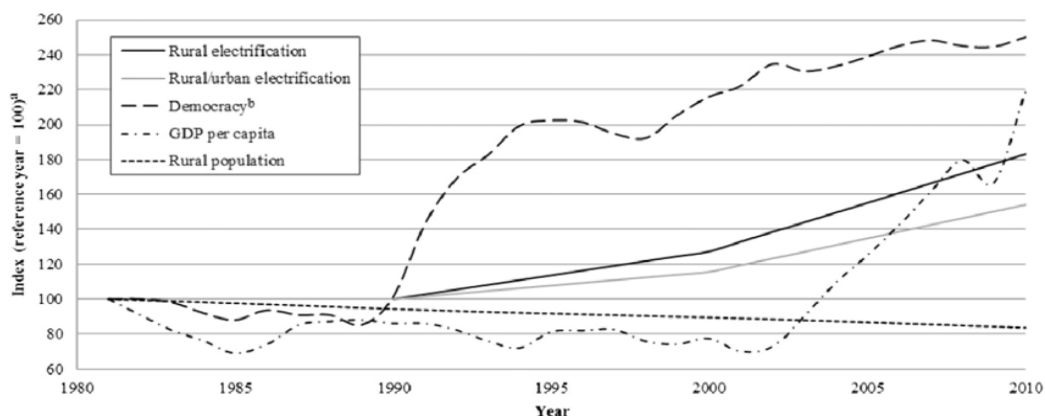


Figure 1.08: Relationship between rural electrification and GDP per capital [18]

From Figure 1.08, it is obvious that increase in rural electrification is correlated with GDP per capita but there is no significant effect on rural population. According to the world bank data [19], average population growth rate in sub-Saharan Africa was about 2.5% which indicates that the only explanation for the decline in population observed in Figure 1.08 is as a result of the usual mass migration from rural areas to urban cities.

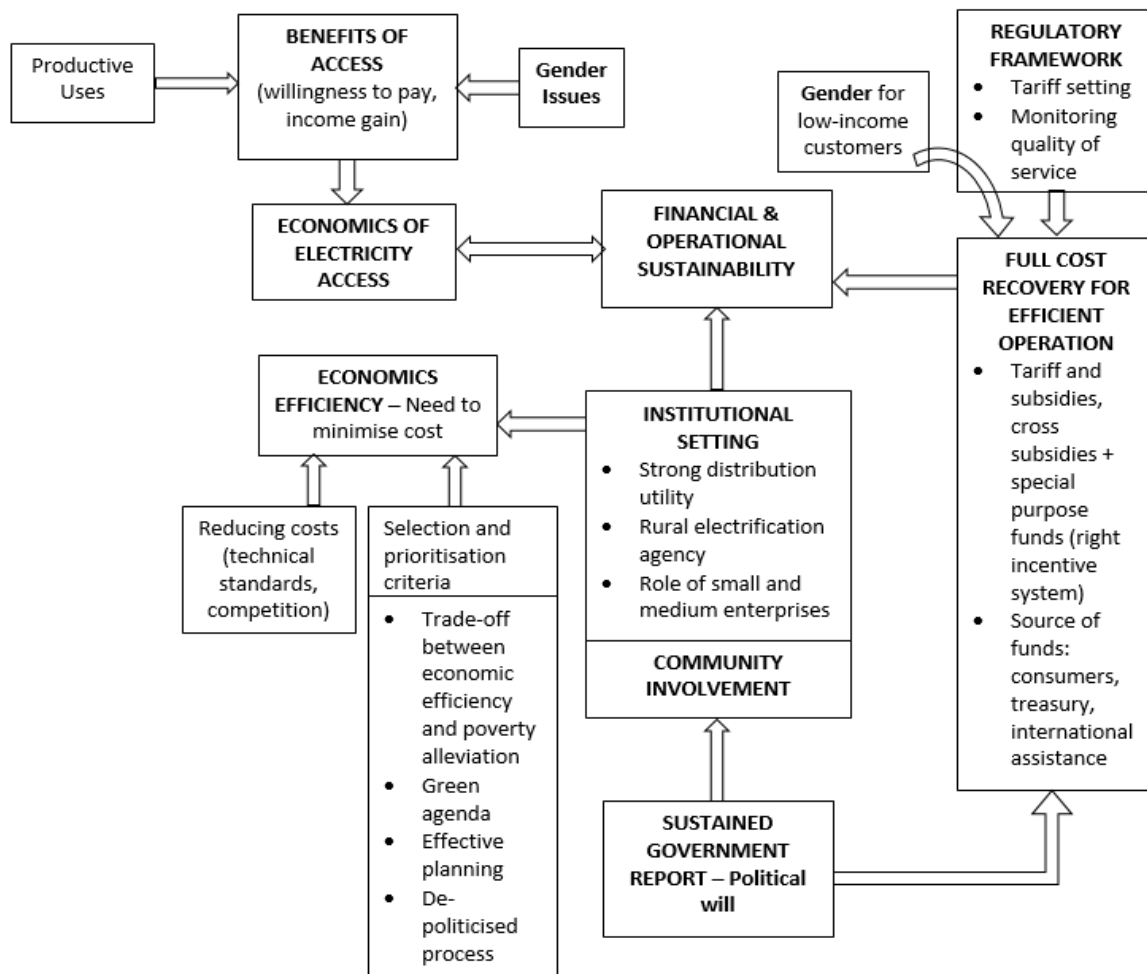


Figure 1.09: Interwoven challenges of electrification [20]

Research evidence have shown that electrification of rural areas can be directly related to some sustainability metrics which have certain factors such as technological, economic and financial, social or societal, environmental factors, regulatory factors health, safety, gender and security. Thus it is important to plan, design, implement and manage the process of rural electrification appropriately so as to fully harness the positive effects of these factors on the population [20]. The interrelationship between these factors is shown in Figure 1.09 whereby the challenges of electrification is depicted and it can be seen that when any of these factors is inadequately considered, it could become a risk to the entire outcome thus have a negative effect on the economic impact. For example, [17] studied the impact of extended lighting on the performance of youth in schools. The result evidently showed that the distributed lamps had a positive effect on attendance in schools at the initial stage but this did not directly translate to improvement in performance of the youths academically. This is an indication that fulfilling one factor (i.e. provision of solar lamps to the youths) may achieve an aim in one direction (i.e. extended hours of lighting) but does not necessarily mean the global challenge of positive economic output would be solved.

Another study evaluated and investigated the impact of rural electrification in Niger-Delta area of Nigeria via grid extension was able to establish the positive effect of rural electrification on average income of different enterprises in the community as shown in Table 1.01. Significant increase in profit margin was observed for most of the businesses that were interrogated and this was possibly due to increase in quality of service as a result of availability of electricity.

Table 1.01: Improved profit of electrified enterprises

S/N	Enterprise	Annual Percentage Increase in Profit due to Electrification
1	Agriculture and Agro-related	123.8%
2	Health	99.3%
3	Artisans (e.g. Barbers, Welders etc.)	157.8%
4	Relaxation Spots	83.5%
5	Mini-grocery Retailers	95.1%

The results showed in Table 1.01 evidently shows that electrification increases the profit of small and medium enterprises which will in turn have an effect on the economy at large. Generally, enterprises in communities connected to grid electricity have been shown to be 16.2% more profitable than their counterparts in communities not connected to electricity [21].

The impact of electricity, and not just rural electrification alone, on the economy of any nation is a very important factor. Most developed nations have been able to generate and supply electrical energy to rural areas in order to boost their GDP per capita and continue to move a stable economy. This is evident as discussed in [22] where it was agreed that the development of modern economies is dependent on the delivery of reliable and affordable electricity.

1.2.1.4 Greenhouse Emission Impact

As at 2013, indoor air pollution was the third risk factor ranked as a global disease burden after high blood pressure. This is basically caused by use of fuel sources in various activities in the house such as kerosene stove for cooking, candle and local lamps for lighting and many other [23]. Several sources such as Carbon dioxide, Ammonia, Nitrogen IV oxide and many more contribute to the release of greenhouse gases as shown in Figure 1.10 with their percentage contributions as well observed.

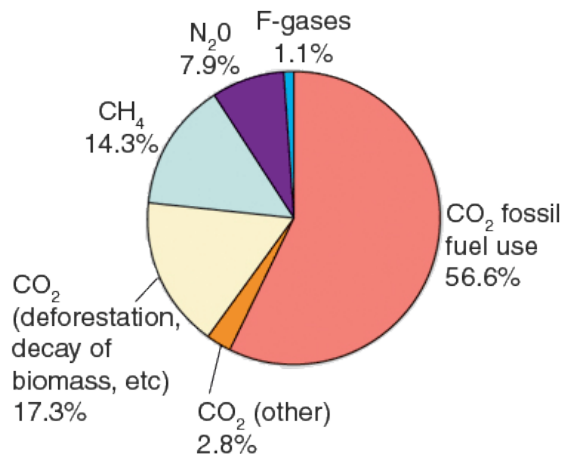


Figure 1.10: Sources of Green House Gas contribution [24]

These activities cause the release of toxic gases which are not friendly to the human system nor the environmental thereby causing disease to humans and further being released into the atmosphere are unwanted wastes. Any major source of greenhouse emission is the use of back-up generators by houses and companies. Most small unit generators are powered by either petrol or diesel which comprises an Internal Combustion or Compression Engine and releases a lot of toxic gases during operation.

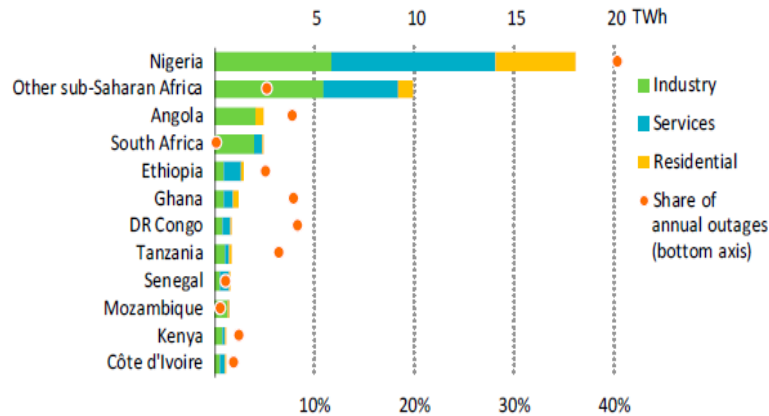


Figure 1.11: Electricity demand served by back-up generators in 2018 [5]

The total amount of energy generated from back-up generators in 2018 (as shown in Figure 1.11) for Africa amounted to about 40TWh which translates to hundreds of metric tonnes of emission. Africa alone, contributed about 4% of the world’s energy-related CO₂ emission in 2018 which majorly comes from the power sector, transport and industry, fuel based cooking and lighting and so many more. Several households in Nigeria for example, still depend on Firewood and kerosene as sources of cooking. Figure 1.12 shows the percentage of households that still depend on firewood for cooking in each state of Nigeria. This method of cooking doesn’t only cause release of poisonous gases into the atmosphere but will also cause deforestation in the long run.

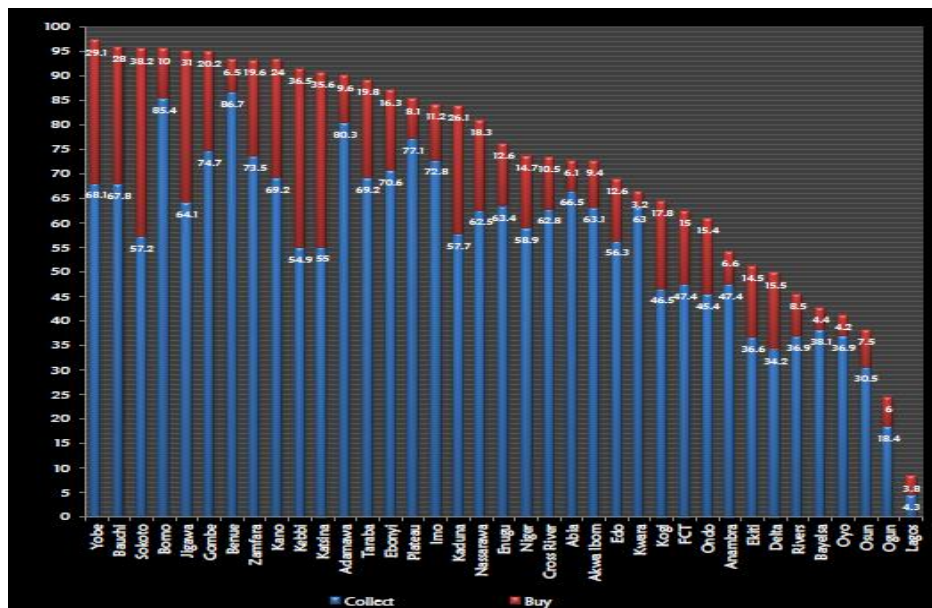


Figure 1.12: Households depending on firewood for cooking in Nigeria (per state) [25]

The complicated part of emission reduction is that electrification may not necessarily cause reduce in greenhouse poisonous gas emission except if the source of generation is clean and renewable. The world is presently moving towards higher global temperature which would mean increased land ambient temperature, melting of arctic regions and rise in nominal sea levels.

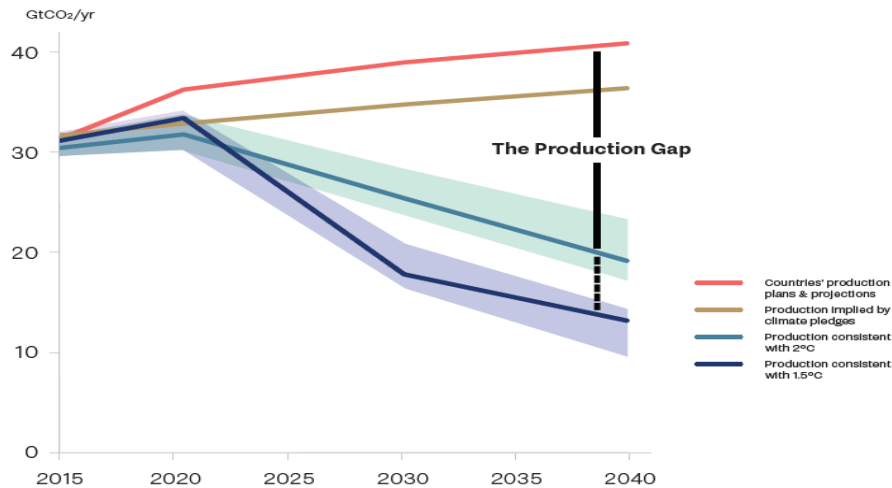


Figure 1.13: Planned CO₂ emission from fossil fuel production [26]

The causative factors of these issues have been critically analysed and burning of fuels in rural areas have been identified as one of the major reasons why greenhouse gases are contributing to global warming. This justifies the need to provide clean and reliable electricity for rural areas so as to slow down the rate at which the climate temperature increase by reducing the contribution of rural dwellers to emission of greenhouse gases. The Paris agreement of 2017 aims at participation of all signature countries in effectively reducing the emission of CO₂ and hold it beyond 2 degrees in 2040 by encouraging energy generation via clean sources [27]. The effect of the planned fossil fuel production to 2040 would translate to a production of about 40 Gt of CO₂ and thus would cause serious global challenges. The agreement if strictly followed will consequently grossly reduce the projected emission of CO₂ to averagely 20Gt or even 12Gt depending on compliance and dedication. Figure 1.13 shows the current and projected trend of CO₂ emission as it affects production to hold increase in global warming between 2015 and 2040. It is evident that most countries are not committed to the emission reduction agreements because there is a wide gap between the production that will keep the temperature at 2°C below the present average global temperature and future productions till 2040. Also, the reduction of greenhouse emission and provision of energy for all has been captured in the Sustainable Development Goal because of their interrelationship which has shown over time that availability of electricity will reduce the burning if fuel sources for various activities and as such reduce the emission of certain gases into the atmosphere [12].

1.2.2 Rural Electrification Policy

Rural electrification policies can be termed as general guidelines which are set to address or mitigate the specific needs of rural communities based on their peculiarities. They can further be termed as rules or principles that are set and strictly followed to decide on how electrification of rural areas would be achieved. Therefore, there is no specific global form of defining rural electrification policy except to follow the peculiar challenges of each rural community to develop such policy. However, there are common challenges which is general to every rural community all around the world and these form the background of any rural electrification policy. Thus it is safe to say that generally, rural electrification policies are channelled towards the energy needs, specific challenges and projected benefits of each and every rural community. The fundamental problem being faced by rural communities is inaccessibility to the central grid due to conditions like distance, high cost of grid expansion associated with low average energy demand making the communities to be less under the priority for energy investment.

The choice of policy for rural electrification may include reasons like low literacy level, low average load demand except during peak hours of evenings which in turn relates to low revenue. These issues can form a bedrock of objectives which can be grouped into four categories; economic, social political and environmental objectives [28]. The objectives would become the benefits of the policy in the long run. Most developing countries experience massive migration from rural areas to urban areas, thereby causing imbalance in the population growth indices between the rural and urban settlements [29]. This reason could be another basis for creation of rural electrification policy to try and reduce the migration of rural indigenes [30]. Some other countries may try to base their rural electrification policy on improvement of social conditions while discouraging grid expansion and sub-standard power systems. This normally involves government trying to balance the disparity between rural and urban settlements by improving the standard of living of rural areas. Most at times, development of rural electrification requires long term financial commitment which can only be guaranteed by government support. In essence, the triumph and influence of any rural electrification policy is hinged on its basic objectives [28].

The introduction of power sector reforms which include commercialization, structural changes and privatization has played an important role in electricity expansion and access to energy especially for pioneer countries. However, [31] was able to argue that this reforms may reduce the rate of rural electrification in many developing countries especially in the aspect of privatization. This is in line with the most economical beliefs because World bank and International Monetary Funds (IMF) have lending agreements with developing countries. These funds may be seen as investments which will be channelled to areas where it could be recouped as soon as possible, thus putting rural areas at a disadvantage because of peculiarities such as low energy demand and consumption consequently causing a longer pay-back period [31]. The rural electrification policy can therefore be independent of power sector reforms because electricity cannot be treated as a commodity when it should be seen as an integrated service. In the contrary, Government and a few other institutions have big roles to play in the successful achievement and implementation of policies and guidelines that will be judiciously used as a benchmark for rural electrification. These intuitions which include the government and other assigned institutions (an example shown in Figure 1.14) would not only create the policies based on peculiarities but also monitor and implement them for successful achievement of the objectives

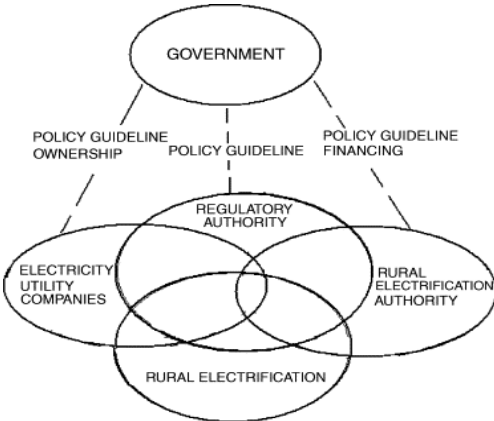


Figure 1.14: Institutions responsible for rural electrification policies [31]

Since it has been established that the impact of rural electrification can have effect in areas such as education, health and sustainable welfare, several governments of individual countries have created different policy which is peculiar to their model and problems of rural electrification. Although these policies mostly have some common baseline theme with everyone, they are

aimed at addressing rural electrification issues in their locality. Rural electrification policies such as the “*Luz Para Todos*” (Light for All, LPT) implemented by the Brazilian government, the Rural Electrification Plan (REP) and Rural Electrification Law (REL) implemented in Peru, National Policy of Cambodia, The Build Own Operate (BOO) and Build Own Transfer (BOT) financing models in Turkey, the National Energy Policy in Malaysia via PETRONAS, the Indian “Rajiv Gandhi Grameen Vidyutikaran Yojana” policy amongst many others for different countries [10]. As of 2013, most European countries have used more renewable energy sources to reduce fossil fuel and electrify rural areas while some Scandinavian countries like Norway and Sweden created policy to use hydro generation. This is largely evident in countries like France and Spain where about 90% of the entire country is supplied via the National grid [32].

African countries have also been proactive in terms of policy making to improve rural electrification. The creation of rural electrification authorities has been widely accepted and implemented by many African countries as a follow up to the privatisation of some sectors of the government owned electricity infrastructure. These rural electrification authorities are to be guided by specified rural electrification policies thus they would work in cooperation with regulatory bodies and utilities. As at 2015, countries have created policies which have started yielding positive results; Zambia achieved about 15% growth in rural electrification after the creation of policies monitored by Rural Electrification Authority (REA), the Mozambique Master plan policy which had a 20% increase in electrification, the Kenya rural electrification master plan which targeted electrification of 40,000 rural households in four years, the 2020 target policy of Rwanda which aims at increasing electrification by 35% and many others [31]. One of the reasons why achieving this has been a challenge so far is the lack of understanding, and proper monitoring of the responsibility of each sector in the rural electrification interweave shown in Figure 1.14. From the government to the authorities and agencies, each unique institution must ensure there is no lag in its area of jurisdiction so as to achieve the set target of reducing rural households without electricity supply. A sample of focus and responsibilities of all actors in the rural electrification scheme is shown in Table 1.02.

Table 1.02 Responsibilities of institutions in rural electrification [31]

Responsibility or Collaborators	Activities/Issues	
Government	Policy Reform	Rural Electrification
		Power Sector Reform and Regulation
	Legal Framework	Establishment of Rural Electrification Mandate
		Establishment of Regulatory Mandate
		Establishment of Mandate for Utilities
	Financial Arrangement	Rural Electrification
Regulatory Activities		
		Management of Rural Electrification Resources
		Capacity building for Rural Electrification
		Preparing Country Rural Electrification plans
		Integrating Rural Electrification plans with development
		Financing of Rural Electrification
		Develop and Implement Subsidies for Rural Electrification
	Regulatory Authority and Utilities	Recommend policies for Rural Electrification
		Design mechanisms for developing Rural Electrification
		Development of Rural Electrification technologies
		Promotion of Decentralised electricity supply technologies
Regulatory Authority		Open and transparent regulatory process
		Balancing interest of consumers, utilities and government
		Obligation of utilities to serve all consumers
		Approving electricity tariffs and connection fees
		Enforcement of license conditions
		Enforcement of performance standards
	Rural Electrification and Utilities	Design mechanisms for operation of rural electricity systems
		Development of performance standards for rural systems
		Determination of fees for connection to rural electricity supply systems and to the grid
		Determination of tariffs for supply to rural areas
		Transparency costs for generation, transmission and distribution or supply
		Billing and settlement procedures for rural systems
	Rural Electrification Authority	Develop supportive entry and exit rules
		Develop licensing process for rural electricity operators
		Monitoring performance of rural electricity operators
	Utilities	Investment in nation and/or regional network expansion
Provide non-discriminatory and open access to the network		
Utilities		Operation of rural electricity systems
		Collection and remittance of Rural Electrification consumer levies
	Rural Electrification Authority	Investment in system expansion
	Regulatory Authority	Investment in generation and electricity network expansion
		Ensure optimum network costs

In Nigeria for example, rural dwellers just like most Sub-Saharan African countries has been experiencing poor quality of life due to lack of electricity not because there is no plan for rural electrification but because these policies have not been judiciously accomplished. This lack of electricity supply in rural areas has aided mass migration to urban cities where even still, the instability of supply has marred continuous development. In order to solve this problem, government unbundled the entire Power Holdings Company of Nigeria (PHCN) by privatization as advised by the World Bank. Two policies were created which were Renewable Energy Master Plan and the Vision 20:2020. The target of these plans is to develop grid extension to rural localities, generation diversification to include renewable resources and development of decentralized hybrid microgrid plants [33]. The current policies are also being expanded to a large-scale strategy so as to accelerate implementation of grid extensions and renewable mini-grid development for markets, manufacturing centres, educational institutions and healthcare facilities. These implementations mostly involve the use of solar or hybrid solar-diesel generation systems.

Similarly, most countries around the West-Central region of Africa have also taken initiatives to one way or the other improve rural electrification. Examples include the Cameroon-Chad Electricity Interconnection Project (PERICT) which targets electrification of about 8.9 million rural dwellers. The policy created by the collaboration of these two countries involve electrification of rural areas along the corridors of the transmission lines via an interconnected power grid. Benin republic have adopted some policies together a few other African countries like Burkina Faso and Ethiopia to provide 50% of electrical energy investment costs for non-governmental organisations so as to effectively improve grid expansion and rural electrification. These subsidies are targeted at reducing the burden of high investment cost and encourage private investors who would not have to bother about their immediate return on investments [5]. Also, Niger republic which is partially reliant on Nigeria for supply of electricity have put in place, such as the National Energy Policy and other certain policies which are aimed at ensuring the creation of an Energy Commission which shall be the sole unit to monitor and ensure strict adherence to the implementation of the National Policy [34].

It is clear as seen that most African nations with a low rural electrification system have created one policy or the other to ensure rural electrification through grid expansion and/or integration of renewable energy. However, the major task has always been ensuring that these policies are adhered to, which is a responsibility of the government. A focus of Nigeria has shown its similarities with its neighbours in terms of policies for rural electrification. Not only is there a need to strictly adhere to these policies but also there is a need to ensure that these policies finally translate into the aim and objectives as to which they were created

1.2.3 Rural Electrification Policies in Nigeria

Rural electrification in Nigeria can be traced back to as far as 1981 when it was proposed that about 301 local government headquarters should be connected to the national grid. The implication of this decision translates to vailing electricity to a few neighbouring towns and communities that were close to the headquarters which translated to electrifying some rural areas [28]. The target was to reduce economic disparities and empower local government secretariats to enable them discharge their constitutional duties diligently which was not a policy per say but a move to accommodate and ensure all tiers of government independently carry out their functionalities. This was surely the beginning of Energy and Electrification Policy in Nigeria which was strictly implemented and monitored by National Electric Power Authority (NEPA), a government funded agency in charge of electricity management under the federal ministry of power and steel.

By 1999, the number of local government headquarters have grown to 774 which was incomparable with the achieved rural electrification and expansion projects which had a target of approximately 1100 projects but has only been able to achieve a mere 300 electrifications while others have been abandoned. An Implementation Committee on Rural Electrification was then inaugurated and as at 2003, about 600 local government headquarters were connected out of the total 774. This was not a significant progress as local government headquarters don't depict rural areas as a whole and the main dwellers of the rural areas were still in darkness. Also the population growth rate was faster than the electrification rate as evidently shown in Figure 1.15 where a period of 20 years data obtained from [5] was analysed to indicate the relationship between annual population growth and electrification access. In some years, there was reduction in the percentage growth in electricity access was due to damage of some major generation stations connected to the electricity grid. Thus instead of improving electricity access, there was a decline thereby causing blackouts to some people who already had access to electricity. Loss of generation and grid collapse is a frequent scenario that has been a challenge in the Nigerian electricity grid [35]. An emergency solution to reduce that could obviously improve the situation is the adoption of microgrids (either as standalone or islanded) to avoid reduction in access to electricity and avoid further complications in the national grid

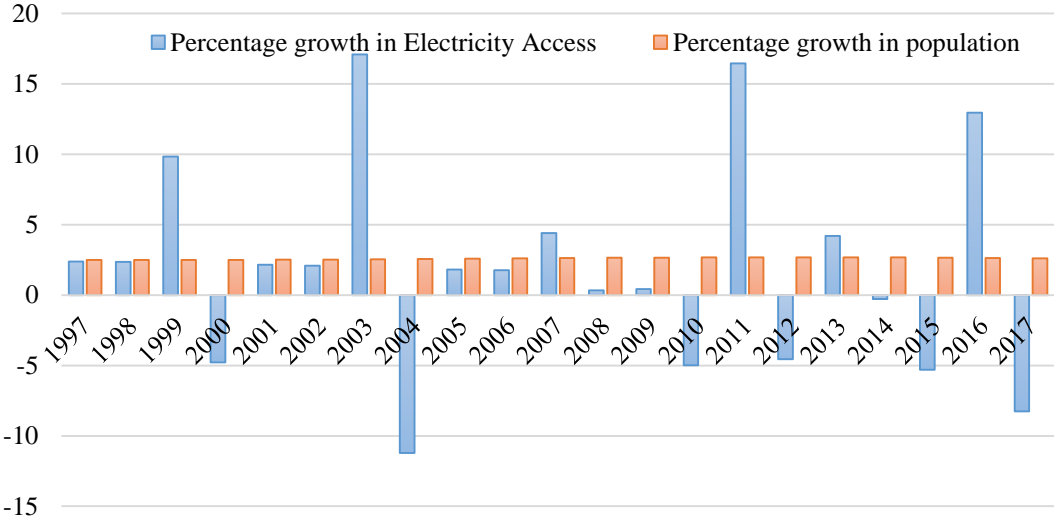


Figure 1.15: Annual percentage growth in population as against annual growth in electrification access for Nigeria

In 2005, the rural electrification program was giving and overhauling reform thereby giving birth to new policies with specific targets, time frame and monitoring and implementation agencies under the Rural Electrification Agency with the supervision of the Energy Commission and Ministry of Power. The national energy policy which was drafted in 2003 was adopted in 2005 in which several objectives which included rural electrification, grid expansion, renewable energy generation and grid decentralisation amongst others were outlined. Some strategies in the overall energy policy of 2005 which was widespread is notably summarized below as it affects rural electrification:

- a) Establishment of Rural Electrification Fund to facilitate electrification of rural areas under the electrical energy utilization policy
- b) Development of small hydropower plants for provision of electricity for rural areas and remote settlements under the hydropower policy
- c) Extension of electricity to rural and remote areas through the use of mini and micro hydropower schemes under the hydropower policy

- d) Incorporation of small scale hydropower plants in the development plan of rural electricity boards under the hydropower policy
- e) Inclusion of solar energy as a complementary source of generation in rural and urban areas under the Solar PV policy
- f) Inclusion of wind energy for provision of power to rural areas and remote communities that are far from the national grid under the wind policy
- g) Development and Implementation of appropriate packages to enhance the utilization of renewable energy to solve rural energy problems and to make possible the extension of commercial energy and associated technology to the rural sector under the short term policy.
- h) Stimulation of industrialization in rural areas to minimize rural-urban migration

The reformed policy which was tagged “National *Energy Policy*” was drafted to serve as a blueprint for future economic and sustainable development, supply and utilization of energy resources, and for use as a guide during international trade and cooperation which will address issues of energy manpower development, energy sector financing, domestic self-reliance, and private sector partnership amongst others. The overall policy had five broad objectives which are [28]:

1. To enhance energy security in the nation through diversifying the energy supply mix
2. To increase energy access especially in the rural and semi-urban areas
3. To facilitate employment creation and empowerment
4. To protect the environment and mitigate climatic change
5. To build local capacity

With regards to electrification and rural sector development, the Electricity Power Sector Reform Act of 2005 was officially released which mainly targeted at restructuring the entire underperforming power sector of Nigeria. The aim of the act was to allow the formation of companies to take over the assets, liabilities and staff of the existing National Electric Power Authority (NEPA). This was more of an incomplete privatisation channelled towards the development of a competitive electric market comprising of Generation, Transmission and Distribution entities, while an overseer named Nigeria Electricity Regulatory Commission (NERC) was established by the act to license, regulate and enforce performance standards, consumer rights and obligations, regulation and determination of fair tariff structure.

Some institutions were also incorporated, in line with global best practices to oversee and get involved in implementation of the Energy policy in Nigeria under the act, which was where the establishment of the Rural Electrification Agency (REA) was introduced in Nigeria. Also the Rural Electrification Strategy and Plan was set up to achieve the following:

- a) Expansion of main grid
- b) Development of isolated and mini-grid system
- c) Renewable energy power integration

The REA is to set up and manage the Rural Electrification Fund (REF) which shall be used to support, promote and provide rural electrification programmes through public and private sector participation in order to function as follows:

- a) Achieve more equitable regional access to electricity

- b) Maximise the economic, social and environmental benefits of rural electrification subsidies
- c) Promote expansion of the grid and development of off grid electrification
- d) Stimulate innovative approaches to rural electrification; provided that no part of the rural electrification fund shall be used as subsidies for consumption.

The Rural Electrification Strategy and Plan was later named Rural Electrification Strategy and Implementation plan was approved in 2006 with the main goal of setting rural electrification targets and achieving them using the independent Rural Electrification Fund. The 2020 target was to reach an electrification rate of 75% by electrifying 471,000 rural households each year from 2007 to 2020 and to reach 100% electrification by 2040, by connecting 513,000 households each year from 2020 to 2040. However, as of 2018, according to world bank data, the electrification access in Nigeria is just 54.4%.

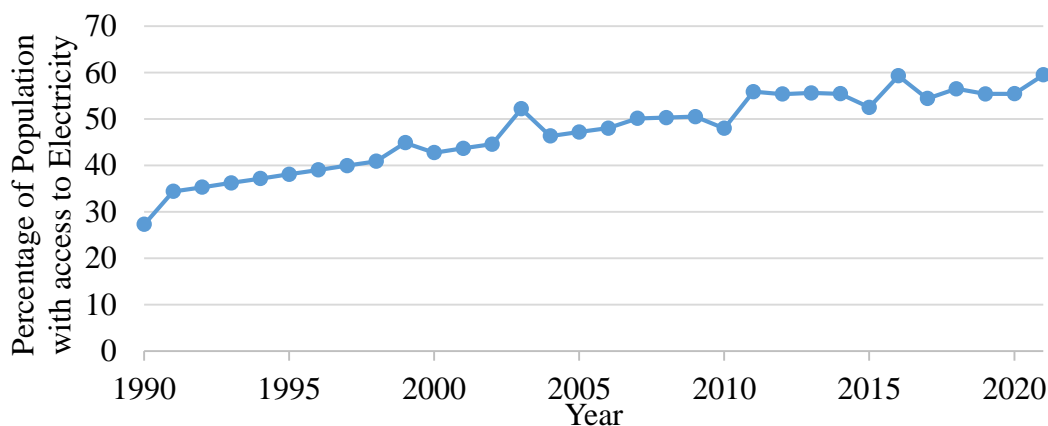


Figure 1.16: Percentage of population with access to electricity in Nigeria [5]

It is evident that rural electrification in Nigeria still has a long way to go so as to be able to achieve the set goals. Although, efforts have been put in place to achieve these goals, there is need for innovation and novel ideas to improve and increase the pace of rural electrification. The introduction of renewable energy which is also an aspect of the policy of rural electrification in Nigeria is an immediate solution which avails itself for implementation due to its safety and availability.

1.3 Renewable Energy

Renewable energy is a kind of energy that is normally replenished by nature. Thus, any form of energy which is continuously available, naturally occurring and cannot be used up is termed under this definition. They could be derived directly or indirectly from the sun and other natural and mechanisms of the environment (e.g. wind, rivers, underground earth movements, oceanic water and tidal flows etc.). Harnessing these forms of energy to generate electricity is a major bonus as there is no need to worry about diminishing of the source and it provides a safe and feasible option for the provision of a clean and environment friendly energy. This form of energy generation also has several advantages such as availability, natural distribution and free raw materials. Examples of renewable sources include wind, solar, hydro, geothermal and bioenergy thus, another nomenclature for renewable energy is sustainable energy because they are readily available and do not diminish (i.e. they cannot be used up) [36]. Although they have some drawbacks such as intermittent disruptions due to their dependency on climate, high generation cost and technological complexity but however, they are the future of solving the continuous growing energy needs of the world. Each of the forms of generation have their

specific advantages and disadvantages but they all have a common and collective advantage of zero emission of greenhouse gases and they are expected to reach as high as 31% of primary energy sources by 2040 as these costs are rapidly reducing [22]. However, as of 2023, only 14% of the world energy generation are from renewables [37].

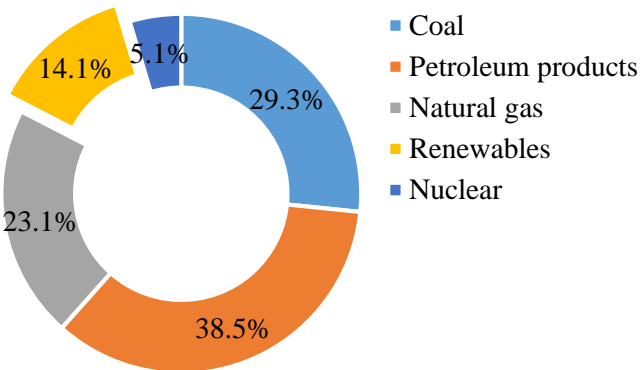


Figure 1.17: Percentage of world renewable energy generation as at 2023 [37]

Wind energy generation involves harnessing the power from speed of wind to drive turbines of generators so as to generate electrical energy. The process is as a result of air in motion having kinetic energy and thus when any device comes in contact with the stream of moving air, some energy can be extracted to do other works whose output power is a function of the wind speed. The Wind Energy Conversion System (WECS) is gradually becoming a renowned system for generation intervention in developing countries where there is limited or no supply of electricity. The system has a few operating design principles used for electricity generation such as the self-excited induction generator, doubly-fed induction generator, wound-rotor induction generator and so on; which operate based on different schemes such as constant-speed constant frequency, variable-speed constant frequency, double output induction generation and variable-speed variable frequency. The wind generation scheme is a promising system for standalone and hybrid energy generation as continuous research has shown it has a sustainable future [36].

Solar energy generation is the process of harnessing energy directly from sunlight. Just like the wind energy system, solar systems can also be either stand-alone or grid connected thus making it a good alternative/option for developing countries with insufficient or zero electricity supply. Generally, a Photovoltaic PV module converts energy from sunlight into Direct Current (DC) electric power which can be turned to Alternating Current (AC) power using a suitable and appropriate inverter. However, unlike the WECs, sunlight is not available all day long thus solar systems always have a backup arrangement or hybrid combination for continuous operation and generation. It is expected that by the year 2040, the solar energy generation system would provide a minimum of 11% of the world’s primary energy generation sources which is about 4100 TWh in totality [22,36]. Some pictures of installed wind and solar panel photovoltaic systems taken in different locations are shown in Figure 1.18



Figure 1.18: Pictures of installed wind turbine and solar panel samples

Geothermal energy sources involve harnessing the energy trapped within the earth crust in form of steam, hot water or hot molten rocks for electrical energy generation. The geothermal energy source is also inexhaustible always available at any point in time thus it possesses an advantage of non-stochastic behaviour when compared to some other renewable energy sources. As at 2016, 13.2 GW of geothermal energy generation plants have been installed worldwide which is available in well over 25 countries in the world [38]. This unpopular source of renewable energy is quite promising and has numerous potentials around the world which mostly requires drilling of underground wells to approximately 3km where the reservoirs are located. The type operating plant which are flashed steam, dry steam, binary power or hybrid power plant is a dependent on the kind of reservoir [36].

Hydro and ocean generation of energy deals with the use of water movement for electricity generation. The ocean energy generation technologies include tidal power generation, Ocean Thermal Energy Conversion (OTEC), wave power, ocean winds, ocean currents and salinity gradient whereas the hydro energy uses the kinetic energy of water bodies falling from a specific height in a behaviour related to wind energy. In as much as there is a close river, the hydro generation is always available for continuous generation, a main reason why it is mostly used to cater for base load demands in most developing countries. The amount of electric power generated is used to generally classify hydro power stations into six based on their peak power capacity while the head (i.e. the height of falling water) can also be used to classify them in low, medium and high head hydro power stations. The OTEC is the most popular amongst the six types of ocean generation and just like the hydro station, it is available for continuous generation of electrical energy and is only limited by availability of oceans. In summary, the ocean and hydro generation are available for continuous energy generation but are only limited to the presence of water bodies unlike the wind and solar systems that can be located anywhere. Furthermore, most of the sustainable energy technology asides hydro, need further improvement to reduce their cost and improve efficiency but this is not a hindering factor for adopting and implementation of these schemes in developing countries where they serve as immediately available solution to rural areas with limited or zero power supply.

1.3.1 Renewable Energy in Nigeria

Nigeria is highly endowed with sustainable energy resource assets like sunlight based, biomass, hydropower and wind. Hydropower sources which is the most significantly used sustainable power source has potentials which add up to 10,000 MW for large hydropower and 734 MW for small hydropower. Wind energy with a capability of 150,000 land joule for every year, created by a normal breeze speed of 2.0–4.0 m/s. Solar radiation evaluated at 3.5 – 7.0 kWh/m² daily, and biomass at 144 million tons for each year [29]. However, these resources are yet to be explored and thus the global mindfulness of the phenomenon of climate change together with the anticipated scarcity of conventional energy resources have incited numerous nations around the globe to build up some progressively feasible energy frameworks to cater for development and growth. Demographic change, dramatic population increase and industrial growth are part of the major trends coming up in Nigeria. In line with broad international consensus and the policies of most developed countries to embrace renewable energy resources as a better source of energy, the Government of Nigeria needed to re-evaluate its own energy strategies. There exists a huge biomass potential as bio-harvests and fuel wood, biogas, wind, sun based and little hydro in Nigeria, though being horribly underutilized. As observed in quite a number of successful countries in promoting renewable energy such as Denmark, Germany, USA, China and Japan, a strong and long-term commitment from the government is crucial in implementing any kind of policies which will lead to a sustaining renewable energy development.

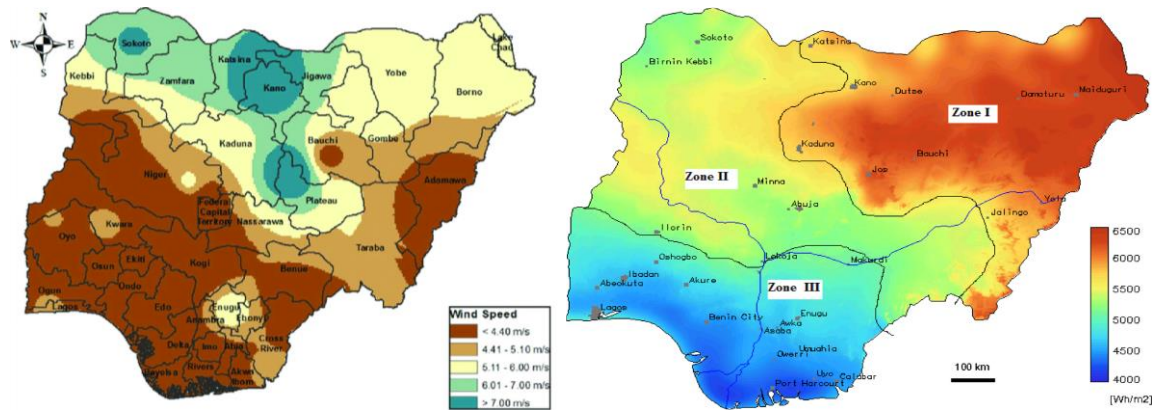


Figure 1.19: Wind and solar radiation potential in Nigeria ranging from 4000-6500Wh/m² [39]

Nigeria has a few large scale hydro power generation stations located at Jeba, Kainji and Shiroro which are all located in Zone II as shown in Figure 1.19 very close to Minna. They serve as a major source of electricity supply to the population besides other non-renewable energy sources. This is an indication that despite the huge potentials of renewable energy in Nigeria, the exploitation and utilization of the renewable energy resources in the country is very low as compared to their potentials. Recent efforts by private investors and some individuals have led to an increase in the use of small stand-alone and grid-connected solar generation sources but others like wind and biomass are currently limited largely to pilot and demonstration projects. Also, several initiatives have been introduced to have meaningful intervention in the renewable energy sector of Nigeria over the years. This include the Vision 20:2020 renewable energy plan, Renewable Energy Master Plan (REMP), the ECN/UNDP intervention, Sustainable development goals 2030, Renewable Energy and Energy Efficiency Project (REEEP) and many others. In summary, the key objectives of these initiatives in line with the Vision 20:2020 renewable energy plan are as follows [40]:

1. To increase generation, transmission and distribution capacity for adequate and sustainable power supply. Generation of 16,000 MW by 2013 was envisaged.
2. To have an optimal energy mix of gas fired plants (12,730 MW), coal (900 MW), hydro (2250 MW) with other renewable i.e. wind, solar and biomass that could give a total of 16,000 MW by 2013 – using appropriate technologies.
3. To encourage local production of inputs for power sector development using local materials.
4. To reduce wastage of electricity by promoting efficient practices through introducing demand side management, publicity, encourage use of energy saving equipment.
5. To promote effective utilization of coal to complement the nation’s power needs and ensure the much-needed power generation mix.
6. To harness a significant contribution of hydropower potential for electricity generation with the development of mini and micro hydropower schemes for electricity extension to rural and remote areas.
7. To ensure a significant contribution of the wind energy to the electricity generation mix in the areas feasible.
8. To make effective use of the solar energy resources for electricity generation, particularly in the rural and remote areas.

Though, the timeline was between 2000 and 2013, only a few of the projects have been developed in this regard and until now, hydroelectric power is still the only main source of

renewable energy and the second largest source of power in the nation after gas-fired plants with little or no input from other sources [40,41].

Table 1.03: Renewable energy generation projections in Nigeria [39]

Resources	2008 Projection (MW)	2015 Projection (MW)	2030 Projection (MW)
Hydro (Small, Medium and Large)	14759	23360	59900
Solar PV	5	120	500
Biomass	-	100	800
Wind	1	30	40
Total	14765	23610	61240

Thus, the introduction of other ideas was adopted over time because the projection for 2030 is clearly not achievable as indicated in Table 1.03 since the current status is still way behind the 2015 projections. Presently, there is a total installed capacity of 2380 MW of hydropower generation, 2.2 MW of wind generation, 17 MW of solar (mostly stand-alone) and none currently from biomass.

1.3.2 Renewable Energy Potential in Nigeria

The exploration of renewable energy sources in Nigeria is still underutilised as there is a very high potential for some of these sources of generation especially Solar and Oceanic. This is one of the reasons why Nigeria signed the 2015 agreement in Paris Conference of Parties to the United Nations Framework Convention on Climate Change (COP-UNFCCC) where the Intended Nationally Determined Contribution (INDC) framework of Nigeria was presented and tagged as “Reduction from Business as Usual”. The main aim of COP21 agreement was to reduce emissions by 2030 while adopting renewable or sustainable alternatives in the aspect of energy generation. With the renewable potential of Nigeria in mind, it is expected to integrate 13GW off-grid solar energy system into its energy generation network while also improving the electricity grid [42].

Table 1.04: Sources of renewable energy in Nigeria [29,43]

Resources	Availability	Current Utilization
Hydro (Small, Medium and Large)	11600 MW	1968 MW
Solar	3.5-7.0 kWh/m ² /day	5GWp
Biomass	Over 1.2 million ton/day	0.12 million ton/day
Wind	Average of 2-4m/s at 10m height	-

1.3.3 Hydro Electric Energy

The ability to use water for ceaseless energy production is one of the oldest form of renewable energy which is still growing till today. It is projected that by 2030, the world would be having about 4903 TWh of hydropower energy production. Asia is presently the biggest utiliser of projected and ongoing hydro energy generation with about 84GW capacity as compared to Europe having 2GW, North and Central America with 1GW and Africa having about 2.4GW.

Nigeria is vastly rich in hydropower possibility with its multiple network of rivers having a possibility of about 70 micro dams, 126 mini dams with a total potential of 11,250MW of energy capacity. Only 17% percent of this capacity is being explored at the moment while there are few ongoing hydro power plans under construction [44].



Figure 1.20: A 30MW small hydro development in Jos, Nigeria [44]

Furthermore, several sites have previously been located and analysed based on their capacity to generate energy via small hydro dams. Besides the currently existing Kainji and Shiroro dams which are currently used in generation of electricity in Nigeria, some of other sites which have the capacity of small hydro dams are listed in Table 1.05 which further shows the hydro potential in Nigeria.

Table 1.05: Some potential hydro sites in Nigeria [45]

Location (See Figure 1.19)	River Basin	Total Capacity
Sokoto (Zone II)	Sokoto-Rima River	30.6 MW
Katsina (Zone I)	Sokoto-Rima River	8 MW
Niger (Zone II)	River Niger	117.6 MW
Kaduna (Zone II)	River Niger	59.2 MW
Kwara (Zone III)	River Niger	38.8MW
Kano (Zone I)	Hadejia-Jamaare River	46.2 MW
Borno (Zone III)	Chad Basin Rivers	20.8 MW
Bauchi (Zone I)	Upper Benue River	42.6 MW
Gongola (Zone II)	Upper Benue River	162.7 MW
Plateau (Zone II)	Lower Benue River	110.4 MW
Benue (Zone III)	Lower Benue River	69.2 MW
Rivers (Zone III)	Cross River	28.1 MW

It is important to note that more than 3 MW capacity small hydro scheme have been developed in various sites and analyses have shown that about 277 sites can be developed for generation of electricity using small hydro [44,45]. This is an indication that there are several sites where small hydro can be developed and thus the system can be tapped to encourage adoption frugal innovation solutions and energy generation mix.

1.3.4 Solar Energy

The abundance of sunshine in Nigeria has made its solar potential very high when compared other sources of renewable energy. This abundance however has not been harnessed over the year until recently when the popularity of Solar panels as an alternative source of energy was being adopted by medium and high income earners for standalone or grid connected backup

systems during grid failure. Figure 1.19 showed the solar radiation distribution in Nigeria which is fairly balanced having an average of 19.8 MJ/m²/day with an average sunshine hour of 6 daily. Several analyses have supported claims that Nigeria has a solar potential of about 42.7 GW if only about 5% of the northern part is dedicated to energy generation using solar.



Figure 1.21: A solar PV powered base transceiver station [44]

Most telecommunication Base Transceiver Stations have now been migrated from the use of stand-alone diesel generators to solar system (an example is shown in Figure 1.21) which has proven to be a more economical and environmental friendly means of generating power for their equipment. Even though the potentials of solar energy are glaring high, their no large scale solar farm serving the national grid at the moment but it is hoped that with the rural electrification policy and the National Energy Policy, this potential will soon be harnessed fully.

1.3.5 Wind Energy

The wind energy generation potential, just like solar is yet to be harnessed in Nigeria despite its abundance especially in the mountainous regions of the country. As at present, there is no single wind energy farm contributing to the existing national grid. However, a climatic assessment showed that Nigeria has an estimated wind potential of 19 GW capacity with an average wind speed 4 to 5m/s in the extreme northern part of the country while the southern part ranges from 1.4 to 3m/s. The Energy Commission of Nigeria once reported that total explorable wind energy in some parts of northern Nigeria varies from 8MWh/yr in Yola (Zone I) to 51MWh/yr in the mountainous areas of Jos (Zone II) as well as 97MWh/yr in the desert areas of Sokoto (Zone II) [46,47].

Currently, efforts are being made to explore the benefits of wind energy in Nigeria. For example, a picture displayed in Figure 1.22 shows an ongoing project of a 10 MW wind farm located in Katsina which will be the first grid-connected wind energy generation farm in the country. Even though the average wind speed across the entire country is not very high as compared to solar energy, there are areas where adequate energy can still be extracted from wind especially with the current improvement in the generator design. A summary of some few sites where wind energy can be sufficiently used for generation is shown in Table 1.06 which was published as a Nigeria climate assessment report in 2011 [48].



Figure 1.22: Pictures of Katsina wind farm project near completion in Nigeria

Table 1.06: Wind energy potential as shown by 2011 Nigeria climate assessment report [48]

Location (See Figure 1.19)	Average Wind Speed at 25m Hub Height (m/s)	Energy at 10m Blade Diameter (kWh)	Energy at 25m Blade Diameter (kWh)
Benin City (Zone III)	2.135	2,18.81	13,673.78
Calabar (Zone III)	1.702	1,053.69	6587.53
Enugu (Zone III)	3.372	7375.75	46,097.96
Ibadan (Zone III)	2.62	3909.70	24,436.19
Ilorin (Zone III)	2.078	1157.06	7230.57
Jos (Zone II)	4.43	15,129.60	94,559.98
Kaduna (Zone II)	3.605	936.81	58,355.08
Kano (Zone I)	3.516	8078.61	50,491.28
Ikeja, Lagos (Zone III)	2.671	4099.78	25,682.52
Lokoja (Zone II)	2.235	4451.23	15,320.17
Maiduguri (Zone I)	3.486	7933.61	49,583.17
Minna (Zone II)	1.589	989.60	6185.01
Makurdi (Zone II)	2.689	4183.51	26,148.85
Nguru (Zone I)	4.259	14,645.19	85,284.42
Oshogbo (Zone III)	1.625	1006.60	6288.09
Port Harcourt (Zone III)	2.64	3925.48	24,533.88
Potiskum (Zone II)	3.636	8894.35	55,591.46
Sokoto (Zone II)	4.476	15,525.75	97,035.94
Warri (Zone III)	2.027	19,00.66	11,879.15
Yelwa (Zone II)	3.36	7314.88	45,714.59
Yola (Zone I)	1.824	1,361.88	8511.75
Zaria (Zone II)	2.891	5,017.26	31,357.02

With the promising values shown in Table 1.06, the use of wind energy for small scale energy production is obviously a good intervention which should be explored especially in terms of hybrid energy as well as consideration for other innovative ideas using wind energy.

1.3.6 Biomass and Biogas Energy

The biomass and biogas are expected to replace diesel, charcoal, fuel wood and the likes in the nearest future due to its abundance and excess availability. The biomass resource is estimated at 800 MJ which includes about 227,500 tonnes of fresh animal and annual municipal solid waste of 20kg per capita which makes a capacity of 6.3 million cubic meter of biogas per day.

The estimated biomass resources that is readily available in Nigeria as at 2014 is shown in Table 1.07 [29] (1Wh equals 3600Joules).

Table 1.07: Biomass resources and estimated quantities in Nigeria [29]

Resources	Quantity (10 ⁶ ton)	Energy Value (10 ⁶ J)
Fuel Wood	39.1	531
Agro-waste	11.244	147.7
Saw dust	1.8	31.43
Municipal Solid Waste	1.075	-

In as much as biomass and biogas may become key resources in the nearest future, there is need to understand the sustainability of the production needs before dwelling into its utilization.

Finally, the solar and wind energy which are currently the most popular forms of energy generation available today are affected by environmental changes that cannot be controlled but can be predicted in certain scenario. This has necessitated the need for combination of more than one resource in areas where there is no room for loss of generation to such that each source complements one another during individual downtime. The introduction of renewable generation mix which was motivated from hybrid energy generation with grid connection is therefore a solution where there is inadequate or zero grid supply. Several novel ideas on how to combine these sources of energy in a cost efficient manner need to be explored to achieve a lasting solution which should be cost effective and highly efficient.

1.4 E-Waste

Electronic Waste (E-Waste) or Waste from Electrical and Electronic Equipment (WEEE) is used to describe all discarded items of electrical and electronic equipment which are no longer used by the owners and have been dumped either in parts or in full without the intent of reuse. Used items or gadgets which are bound for repair, reuse, resale, rescue reusing through material recovery or removal are likewise viewed as Reuse Electronic Equipment under e-waste. With the usage of electrical and electronic equipment on the rise, the amount of electrical and electronic waste (e-waste) produced each day is equally growing enormously around the globe. Across the world, electronic or electrical devices have become indispensable in our daily lives. This developing significance and interest for electronic or electrical gadgets combined with rising outdated nature because of quick innovative progressions and diminishing lifetime of electrical and electronic equipment has prompted an exponential increment in the volume of e-waste produced. Comprehensively, in 2017, around 45 million metric tons were created, and about 52 million metric tons could be produced by 2021 [49].



Figure 1.23: Global projected e-waste generation [50]

Recycling of valuable elements contained in e-waste such as copper and gold has become a source of income mostly in the informal sector of developing or emerging industrialized countries. However, primitive recycling techniques such as burning cables for retaining the inherent copper expose both adult and child workers as well as their families to a range of hazardous substances. E-waste-connected health risks may result from direct contact with harmful materials such as lead, cadmium, chromium, brominated flame retardants or polychlorinated biphenyls (PCBs), from inhalation of toxic fumes, as well as from accumulation of chemicals in soil, water and food. In addition to its hazardous components, being processed, e-waste can give rise to a number of toxic by-products likely to affect human health [50]. Furthermore, recycling activities such as dismantling of electrical equipment may potentially bear an increased risk of injury to both the workers and the general populace entirely. Thus, based on the knowledge of the status of e-waste, a simple procedure to reuse some of these components as being applied in this research can positively benefit the general populace.

The entire continent of Africa currently generates about 2.2 million tonnes (Mt) of electronic waste annually, as the United Nations' 2017 Global E-Waste Monitor reveals which is equivalent to 1.9 kilogrammes per inhabitant. In comparison, 44.7 Mt of e-waste were produced globally in 2016, with core materials valued at about €55 million (£49 million). Africa is one of the world's leading destinations for large-scale shipments of electronic wastes from the United States and Europe. In West Africa, Ghana and Nigeria are major recipients of this waste, but high volumes also go to Cote D'Ivoire and the Republic of the Congo. Nigeria is particularly burdened by WEEE, with over 1.1 million tonnes of e-waste every year stemming from both local and imported electrical and electronics equipment [51].

The utilization of imported WEEE is a significant problem in Nigeria as most of the imported equipment may no longer be reused but is often dumped thereby exposing toxic elements to the environment. E-waste in Nigeria can be divided into two; the waste from new imported products and the waste from already used imported products. In 2015, Nigeria saw 56,000 tonnes of imported e-waste; in 2017, this amount increased to 288,000 tonnes, more than four times higher than two years earlier. This high amount of e-waste provides a wide opportunity for Reuse Electrical and Electronic Equipment (REEE) which may involve innovations from old and discarded materials.



Figure 1.24: Dumping of electronic waste in Nigeria and some recycling processes [49,51]

The amount of e-waste internally created in Nigeria is expanding as more individuals utilize electrical gadgets and equipment. In Nigeria, numerous individuals own more than one data and correspondence innovation (ICT) gadget, for example, cell phones, PCs, TVs, and different gadgets and their substitution cycles are getting shorter, consequently the reason for huge amount of e-waste produced in Nigeria. There are existing informal e-waste recycling places in Nigeria but these are hardly documented as there are weak enforcement of laws which guide the recycling of e-waste at the moment. This indicates that there is abundant amount of reuse materials which can be converted to other innovative gadgets based on frugal or jugaard ideas and a potential market for cheap REEEE.

1.5 Frugal Innovation

Frugal innovation could be termed as a prudent invention. It implies “*delivering more with less*” which involves being cost-conscious when creating, manufacturing and assembly products by using either discarded materials, or converting a specific item into an entirely different product thus involving smaller amount or cheaper raw materials [52]. Frugality further implies associating limitations to use of resources, regardless of finance, material or institutional availability but incorporating a scope of strategies which turns these constraints to an advantage. Through these limitations, frugal innovations result in dramatically low cost of products which outperforms alternatives, availability and affordability to low income earners especially those in less developed areas. In reacting to the call for global sustainability, the concept of frugal innovation is presented as a design innovation process in which the needs and context of citizens in the developing world are put first so as to develop appropriate, adaptable, affordable and accessible services and products for emerging markets. The core competences of frugal innovation should comprise; ruggedness, lightweight, simplicity, adaptation, use of local resources, green technology, affordability, human centric design and so on [53].



Figure 1.25: Electronic waste usage and recycling by an artisan [49]

In developing countries like Nigeria, frugal innovation from used electrical electronic equipment is very much available but in an informal setting. This is because there is no formal setup which documents or regulates such ideas and developments. However, artisans and local technologists have a lot of waste used electronic and electronic equipment in which they pick components and parts to do repairs and sometimes fabricate new equipment. These fabrications can be termed as frugal innovation but have received low visibility because they are mostly developed for local consumption and receive little or zero documentation and publicity.

1.6 Frugal Innovation for Energy Generation Purpose

The concept of frugal innovation is gradually becoming an adoptable alternative to which sustainable development can be measured and used to reduce waste, premature disposal of items and products [53]. Several investigations are currently ongoing in different applications of frugal innovation to achieve numerous goals. With regards to this thesis, the use of frugal innovation for renewable energy generation was initialised by and conceptualised in [54] where waste component such as an old three phase induction machine was modelled as a single phase induction generator. A control technique for this induction generator was explored for the purpose of electricity generation in rural areas using renewable energy sources with the presence of an old car battery and Uninterruptible Power Supply (UPS) system. This system was further improved in [1] where a Power Supply Unit (PSU) from an old computer was repurposed to serve as Maximum Power Point Tracking (MPPT) charge controller in solar photovoltaic system applications. A life cycle assessment of the reuse solution integrated with a solar photovoltaic system was performed to compare the impact contribution of the solar based reuse system with a conventional system. Furthermore, a new model called One-Isolated-And-Two-Isolated-Inputs (OAITI) was introduced as an improved alternative to the already existing Two-Series-Connected-And-One-Isolated (TSCAOI) topology of the repurposed induction machine.

Thus the adoption of the combination of these reuse component for rural energy generation was analysed in [55] and the direct and indirect connection of the frugal innovation based generators, with the repurposed PSU, old batteries and microcontroller for the purpose of delivery and control of electrical energy was presented. Since this system has been shown to be feasible, there arouse the need to investigate the possibility of adopting the reuse hybrid solution in a typical and practical rural household and the need to see the impact contribution of this system. It is in view of this that a typical rural area in Nigeria (Northern part of Africa) was selected for the purpose of investigating the environmental impact advantages and feasibility of deploying and adopting the reuse hybrid solar-pico-hydro system in a rural household.

1.7 Conclusion

The need for quality, constant and efficient supply of electrical energy cannot be overemphasized which is the main reason why several alternative solutions have been constantly developed for ease of access to electricity. An overview of the energy situation of Nigeria has shown the high potential of renewable energy sources. On the contrary, there is very little benefit as these potentials have been underexplored for the purpose of electricity generation. It has been put in evidence that there has been little or no significant improvement in access to electricity over the past ten years. Thus, there is a need for adoption of alternative solutions to improve the electricity situation in Nigeria. These alternatives may include microgrid development, distributed generation, renewable energy mix, storage and emergency back systems and many more. Furthermore, the high cost of developing conventional energy generation stations as well as grid expansion is another hindering aspect which has constantly been calling for attention as manufacturers have been constantly trying to reduce the cost of production of all components in the energy generation sector.

The quest to explore alternative solutions resulted in the introduction of reuse of waste electrical and electronic components based on frugal innovation to solve three lingering issues; the emission problem, the high cost of generation, and the availability of electrical energy. This concept can be adopted in Nigeria since there is abundance of renewable energy and sufficient amount of e-waste. Thus the possibility of adopting a renewable energy generation system

based on reuse materials will be explored in the next chapter. The purpose is to serve households in rural and remote areas thus a sample load consumption model will be developed to represent a typical household. A techno-economic analysis will be carried out to see the actual size required by each household and economic comparison will be discussed. Using the sizing results as a guide, a feasibility study to see the impact of adopting the reuse solution on electricity access based on existing e-waste materials will be discussed.

CHAPTER TWO

SIZING AND TECHNO-ECONOMIC ANALYSIS OF REUSE HYBRID SOLAR-PICO HYDRO GENERATION SYSTEM

2.1 Introduction

The current status of electricity access in Nigeria based on the evolution of energy generation over the recent years and delivery of electricity to consumers have been analysed in the first chapter. The information has shown that access to electricity is seriously lagging (especially in rural areas with little or no supply) and there is need to provide emergency solution in the area of energy generation. One of the easiest and fastest solution to this problem is the adoption of renewable energy resources for electricity generation at an affordable cost. Thus in this chapter, the load model of a rural household is developed for a few selected essential loads and the concept of the reuse hybrid solar-pico hydro generation solution is introduced. The aim is to optimally size the reuse hybrid solar-pico hydro generator developed based on reuse materials for a rural household to power essential load. However, the first step was to investigate the feasibility of adopting the reuse solution in a developing country, thus an example of a typical rural area in Nigeria, West Africa was adopted as a case study.

Some questions answered in this thesis include the following; Is this solution feasible? Can it be adopted in a typical rural household? Are the required devices available in a sufficient number locally and at an affordable price? Thus, we present the results of the investigation assuring that the amount of e-waste and old lead acid batteries as well as Power Supply Units (PSUs) disposed annually are sufficient to have a positive significant impact on energy access of rural dweller. Then, the next step was to optimally size the required components for the proposed reuse solution. To achieve this, two different load models of daily energy consumption (based on critical/essential equipment in a single household) were adopted for Renewable Energy (RE) sizing using a commercially available software called Homer. For the purpose of comparison, alongside the reuse solution, components sizing was also done for a new conventional RE solution and the result were compared. Finally, an economic analysis was done to see the difference between the reuse solution and a new solution over their lifetime while serving the same load.

2.2 Rural Household Load Description/Analysis

Previous studies on the consumption behaviour of rural dwellers (Nigeria inclusive) has shown that most individuals living in the rural areas do not have high load demand compared to people living in the cities [56]. As long as essential loads in residential apartments are served, most rural consumers can continue to have their daily routine without any disruption. In order to achieve a simple, economical and less expensive solution, the load model only focused on the basic essential loads that can be found in residential homes of rural dwellers. The equipment (and their ratings) were determined based on what is obtainable in Nigeria and can be found in most homes, which are televisions, radios, light bulbs, mobile phones and fans. Thus, the daily load duration curve for a typical rural home is modelled based on these loads only, which are clearly highlighted in Table 2.01.

Table 2.01: Essential loads details

S/N	Appliance	Ratings (W)	Daily hrs of usage	Energy (kWh)
1	Television	65	5	325
2	Radio	5	7	35
3	CFL Lightings (x5)	26 x 2	15	780
		26 x 3	6	468
4	Rechargeable (Mobiles, lamps) (x3)	5 x 3	4	60
5	Fan1	40	14	560
6	Fan2	120	7	840
	Total	375		3068

The information in Table 2.01 is used for the development of the load duration curve, which is basically an hourly load consumption pattern of a user in a day. Two techniques were considered which are the analogue technique also known as the 24-hour method and the standard rural consumer model [57]. The analogue technique involves manually predicting the user's load usage behaviour at every hour (on or off) for 24 hours in a day. On the contrary, the standard rural load daily load consumption pattern was developed by [57] after monitoring and recording the load utilisation behaviour of a typical rural area in Zimbabwe. The average data was used to predict an hourly percentage of the total installed load which can be adopted to any household once the total load is known. It is therefore assumed that all rural dwellers have the same behavioural load utilisation pattern, irrespective of their location. This is also one of the reasons why it is easier to apply this model to only essential loads for the case study considered (i.e. a rural home in Nigeria). The data of the hourly behaviour of both models are shown in Annex B.

The information in Table B1.1 is derived based on intuition and at the sole discretion of the designer, whereby for each hour of the day, each component is assumed to be ON or OFF. An assumption that most users are out for work during the day is made thus drastically reducing load consumption at daytime. On the contrary, for Table B1.2, a percentage of the total load which is active at every hour is already fixed and as such, the only required variable is the total load connected or considered. In both scenario, there no point in time when the load demand equals the total load.

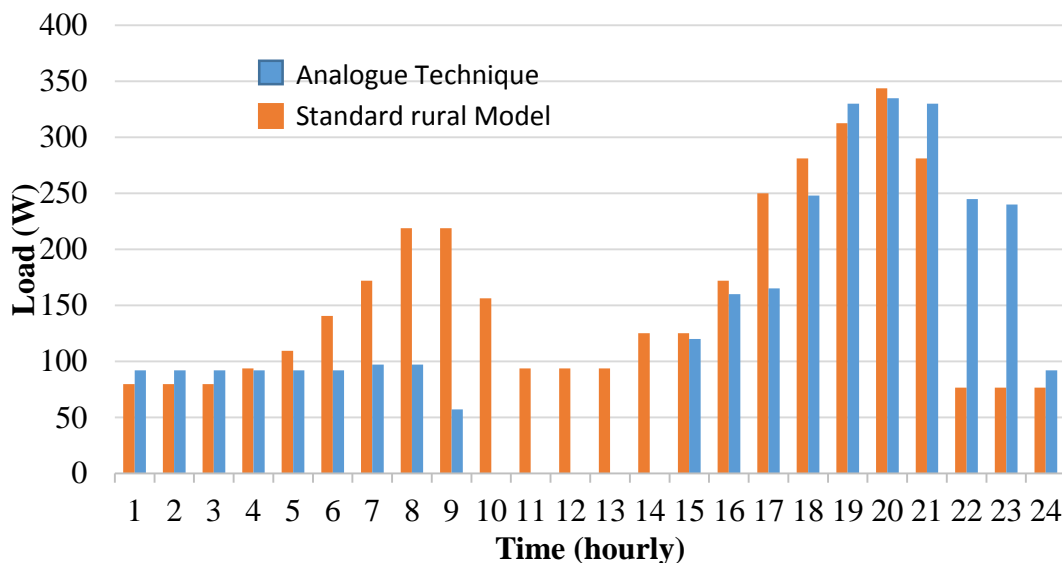


Figure 2.01: Load duration curve for essential loads in a rural home

It can be observed that the load distribution follows the generalised form of daily load duration curve in any typical household. However, for the analogue technique, the consumption between 10h00 and 14h00 is zero due to the assumption that the consumers will generally not be at home during this period. This assumption may not be completely safe and may also vary during weekends as the true behaviour of electricity consumers cannot be completely predicted.

2.3 Description of Solar and Hydro Generation Systems

In general, two energy generation systems are considered to serve as solution to satisfy the load model described earlier. The use of a combination of solar and hydro generation systems which will incorporate a hybrid solution for energy generation with batteries storage elements is considered. In other countries, other circumstances, wind energy could be considered rather than hydro energy. The main aim is to satisfy the consumer load at reduced cost and reduce the global footprint of the solutions as much as possible while adopting the reuse solution based on frugal innovation. This will consequentially result in reducing e-waste and carbon emission in the long run while improving energy access to rural dwellers. Generally, the type and technology considered are based on the availability in the Nigerian market, so as to typically localise the solution to rural dwellers in Nigeria in the case considered.

For the solar panels and its components, the technology has evolved over the past couple of years with different technologies varying from monocrystalline panels to polycrystalline panels from different manufacturers being available in the Nigerian market. Whereas, for the hydro generator, there are fewer varieties available since most of the hydro generation projects can be customised based on unique design. However, the concept of reuse technology for the pico-hydro generator and hybrid solar-hydro system is briefly explained subsequently.

2.3.1 Reuse hybrid solar hydro solution

The reuse solar-hydro generation system as the name implies is made up of mostly second life components which have been repurposed for application in renewable energy generation. All the components used in the system are components that can be easily found in most developing countries (Nigeria inclusive). Besides availability of the components, cost factor was also considered when proposing the reuse solution because the target consumers are expected to be rural dwellers who are in the lower income margin.

The reuse system which has been designed in a previous work between LAPLACE and IMFT [58], comprises of old parts recovered from discarded equipment and products such as :

- old 3 phase 4 poles induction machine,
- lead-acid batteries discarded from thermal car engine automobiles,
- Uninterruptible Power Supply (UPS) systems
- Power Supply Unit (PSU) from desktop computer,
- 200-litre oil canister drums, the rim of an old bicycle, and a few other peripheral components as shown in Figure 2.02 [58,59].

The oil canister is split into several parts which are connected to circular plywood to form a wheel turbine that turns when it comes in contact with the moving waterbody. This turbine wheel is subsequently connected to the bicycle rim which in turn drives the induction machine via a belt [58].



Figure 2.02: Reuse hydro turbine based on plywood, oil canister and bicycle wheel [55]

Due to the fact that the components need to be repurposed, [4] and [5] proposed the operation technique of the reuse hydro generator whereby the induction machine is directly connected to AC loads as shown in Figure 2.03(a). However, the direct connection means that there is need to have a very large speed multiplier because the reuse water turbine rotates at only 0.3rev/s. Consequently, Figure 2.03(b) shows an indirect connection of the induction machine through a rectifier, whereby all the AC loads are supplied through an inverter (UPS in this case) while both the hydro and solar panels charge the batteries. In addition, a simple derivative feedback control strategy is implemented in a micro-controller to control the DC bus voltage and the battery charging current [55,59,60].

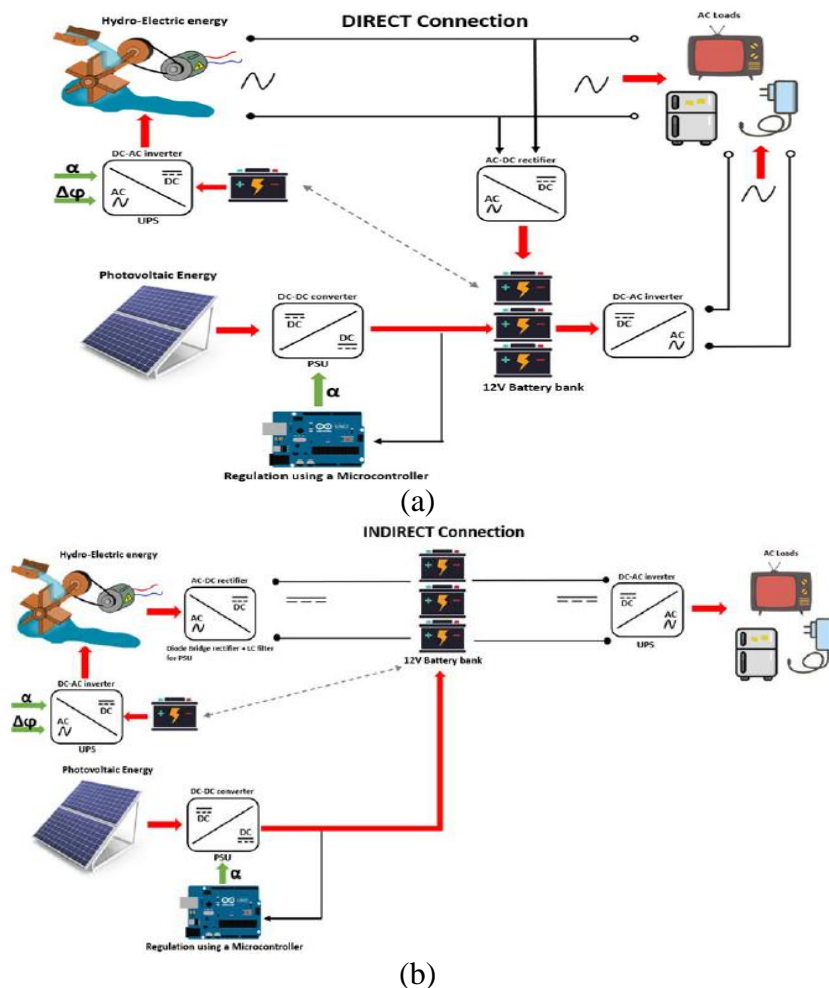


Figure 2.03: Direct and indirect connection of reuse hybrid solar-hydro turbine system [55]

Generally, hydropower plants classification is done based on the power capacity of the installed system. Just like every power generation system, classification is done based on peak output power capacity of the system. Table 2.02 shows the different classifications based on peak output power of the hydropower generation system [61].

Table 2.02: Types of hydropower plants with respect to power output

S/N	Hydropower	Capacity
1.	Large hydro	>100 MW
2.	Medium hydro	15-100 MW
3.	Small hydro	1-15 MW
4.	Mini hydro	100 kW-1 MW
5.	Micro hydro	5 kW-100KW
6.	Pico hydro	<5kW

Based on the classification shown in Table 2.02, the reuse hydro-system can be classified and treated as a pico-hydro generation system because the energy generation is in a few tens of Watts. In fact, the system is best described using the explanation of “Run-of-river” installation because damming is not necessarily needed to deploy the turbines.

In addition to the reuse hydro turbine, solar panels are added for electricity generation from the sun. Just like the case of the hydro turbine, the solar system also comprises reuse components such as a second life solar panels (mono-crystalline panels locally available in Nigeria in big numbers), the PSU and the UPS. There is a microcontroller in the system for the purpose of control and regulation which is the only new component in the entire system [55]. The PSU has been repurposed to serve as DC-DC converter having a minimum input voltage of 100V and a maximum unit power of 350W for each PSU [59]. Thus, in order to use the PSU in a solar module, certain constraints need to be met as shown in equations (2-01) and (2-02).

$$V_{PV_{total}} > V_{PSU_{min}} \quad (2-01)$$

$$P_{PV_{peak}} \approx P_{PSU_{total}} \quad (2-02)$$

where $V_{PV_{total}}$ is the sum of voltage for the combination of PV panels in a serial connection,

$V_{PSU_{min}}$ is the minimum design input voltage for one PSU, $P_{PV_{peak}}$ is the peak power output

of the PV panel and $P_{PSU_{total}}$ is the total input power to the combination of the PSUs. The possibility of connecting multiple PSUs as well as hydro turbines as described in equations (2-01) and (2-02) is shown in Figure 2.04 for the reuse hybrid solar-pico-hydro system.

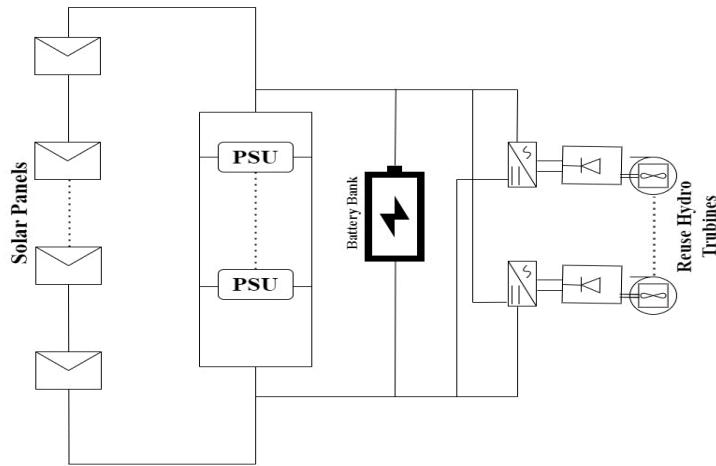


Figure 2.04: Reuse hybrid solar-hydro generation system only

2.3.2 Conventional Hybrid Solar Hydro System

For a conventional system description, the hybrid system will comprise of new components which are state-of-the art and readily available in Nigeria. This is to be able to successfully compare the reuse system with a similar system that will satisfy the same load conditions. The conventional system employs the use of a more recent solar PV panel (polycrystalline), lithium-ion battery, conventional charge controller and inverters as the case may be. The hydro system on the other hand is a small 50W output embedded hydro turbine shown with an example depicted in Figure 2.05 which conceptualised for applications in mostly small rural areas and run-off river application [62,63]. The choice of this micro hydro turbine is based on the fact that it is easily comparable with the reuse pico-hydro turbine in terms of peak power output and operation mode. Furthermore, it does not require construction of a dam and is assumed to be treated as a run-of-river hydro generation system.



Figure 2.05: A 50W DC hydro generator [64]

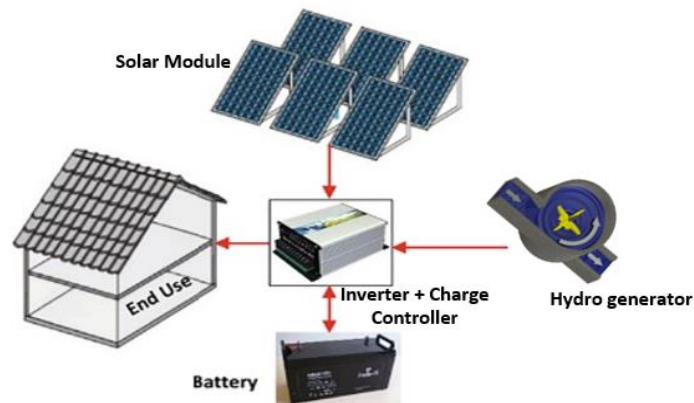


Figure 2.06: A representation of the conventional hybrid solar-hydro generation

2.4 HOMER Software for Sizing of Hybrid Solar-Hydro Generation based on Reuse Component

Homer software which is acronym for Hybrid Optimization of Multiple Energy Resources is a microgrid design and optimization software which is used for technical and economic analysis of renewable energy, distributed generation and microgrid systems [65]. The choice of this software was based on simplicity and widespread availability to ensure easy adoption of the reuse technique. The software involves the process of load modelling by inputting the load data as described in subsection 2.3. Historical solar irradiance data is directly available based on location and the possibility of modelling solar modules and its components based on requirements explained. Similarly, other kinds of generators (such as hydro in this case) can be modelled with their required resource components for any respective case.

The results of the optimization which technically works based on worst case scenario is outputted to propose the optimal size and cost of the generation mix that satisfies the load. The size of each component, cost of energy per kilowatts-hour, and net present cost are one of the many results and metrics that can be obtained from the analysis.

The generation of electricity from hydro turbine requires a river flow rate data, which is used to obtain the kinetic energy that drives the turbine. In this case, volumetric flow rate of a river was obtained from [66] which was adopted for use in this analysis. The river is a small river located in Katsina (Lat. 12.98°N, Long. 7.62°E) in Nigeria, the same geographical location selected for siting the proposed reuse solution. The average monthly flow rate is shown in Table B1.3 of Annex B.

2.4.1 Hybrid solar-pico-hydro generator

The load details were used to optimally size the reuse solar system and pico-hydro generator previously described. The sizing steps are based on general arithmetic calculations which ensures energy balance using worst case scenario to optimally size renewable energy sources. All possible configurations are explored using the grid search algorithm and a proprietary derivative-free algorithm to obtain the optimal result. This takes into consideration the load to be served, available generation and defined costs respectively. The PV output power is calculated based on the average solar irradiance and the output of the array is obtained by [65]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G}_T}{\overline{G}_{T,STC}} \right) \left[1 + \alpha_p (T_c - T_{c,STC}) \right] \quad (2-03)$$

Where;

- Y_{PV} is the rated capacity of the PV array under standard test conditions in kilowatts (kW)
- f_{PV} is the PV derating factor in percentage (80%) [which are factors such as environmental conditions, ageing and so on causing reduction in the expected output power [67]]
- \overline{G}_T is the solar radiation on the PV array in kilowatts per square metre (kW/m²)
- $\overline{G}_{T,STC}$ is the incident radiation under standard test conditions (1kW/m²)
- α_p is the temperature coefficient of power (%/°C) [-0.46 for monocrystalline and -0.48 for polycrystalline]
- T_c is the PV cell temperature (°C)
- $T_{c,STC}$ is the PV cell temperature under standard test conditions (25°C)

Just as the case of solar PV array model, the electrical output power of the hydro turbine generator is also calculated based on specific input parameters [65,68]:

$$P_{hyd} = \frac{\eta_{hyd} \rho_{water} g h_{net} Q_{turbine}}{1000} \quad (2-04)$$

Where; η_{hyd} is the hydro turbine efficiency (%)
 ρ_{water} is the density of water (1000kg/m³)
 g is the acceleration due to gravity (9.8 m/s²)
 h_{net} is the effective head in metres(m)
 $Q_{turbine}$ is the hydro turbine flow rate (m³/s)

The hydro turbine flow rate is based on the design of the reuse turbine which is considered to be the flow rate at which the turbine operates at maximum efficiency. It is also assumed that the turbine can be arranged in multiples without any loss or depletion in efficiency and functionality.

Finally, the battery model is based on the kinetic battery model [68], which is used to determine the amount of energy that is received or withdrawn from the bank of batteries at every point in time. This description of Lead acid battery behaviour is used to the amount of power that is discharged or absorbed during each time step (which depends on the available of energy from generation sources). These power can be nomenclated as $P_{batt,abs}$ and $P_{batt,dis}$ which are modelled as follows:

$$P_{batt,abs} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (2-05)$$

and
$$P_{batt,dis} = \frac{kcQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (2-06)$$

It is important to note that the total storage capacity of the battery is defined as $Q = Q_1 + Q_2$

Where; Q_1 is the available energy (kWh) at the beginning of the time step
 Q_2 is bound or extractable energy (kWh) available at the beginning of the time step
 P is the power into or out of the bank of batteries (kW)
 Δt is the length in time step (60 mins) based on the hourly load duration curve
 c is the storage capacity ratio (0.445) i.e. the actual storage capacity per rated capacity of the lead acid battery adopted from [65,68]
 k is the storage rate constant (0.627h⁻¹) which is the battery's ability to quickly deliver power during charging or discharge cycle [65,68]

In addition, the daily amount of energy obtained from the load model is used to calculate the required number of batteries based on the specified days of autonomy and maximum depth of discharge. Thus, for a typical 12V lead acid battery, the number of batteries required will be:

$$N_{bat} = \frac{Autonomy * \left[\int_0^{24} \left(P_{load} * \frac{1}{\eta_{inv}} \right) dt \right]}{12 * DOD * C_{bat}} \quad (2-07)$$

2.4.2.1 Analogue Method

Based on the load duration curve in Figure 2.01, the daily energy demand can be obtained as approximately **3.07kWh** daily with a peak load of **0.34kW**. This load detail is used to simulate and obtain the sizes of hybrid solar-hydro generation with battery storage. In order to include some realistic certainties which is peculiar to consumers in northern Nigeria and areas with only 2 seasons in a year, a day-to-day variation of 10% was randomly introduced into the model to reflect some changes in the peak load demand per day. The load demand pattern which includes this random variation is shown in Figure 2.08. This random variation sets daily and hourly variability to synthesize the load data so as to avoid having a constant peak or minimum demand all year round. Thus the peak demand (which in this case becomes **0.44kW**) changes after inclusion of random variability in the load data.

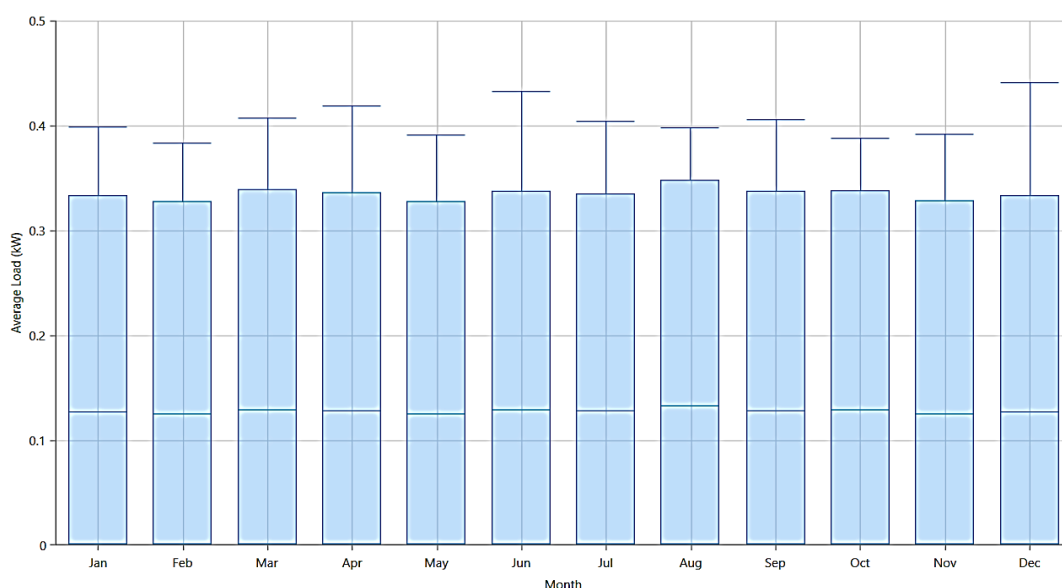


Figure 2.08: Average monthly load demand (analogue method) after 10% random variation

Since it is almost impossible to perfectly predict the consumption behaviour of a typical electricity consumer, the random variation can help to give a bit of change to the load behaviour from time to time. This is justifiable as to the fact that only one-day load pattern was modelled in Figure 2.01 but based on this demand, the average load can be randomly changed within the 10% interval thus trying to make it more realistic than repetitive. Therefore, the plot in Figure 2.08 is the sum of daily load consumptions including 10% random variations indicated by the lines on each bar for each month, with minimum average and maximum values of the load demand with variations.

— Photovoltaic sizing

The sizing of the PV panel is generic when compared to other components. This is because as shown in equation (2-07), global irradiance data is inputted for the desired location and based on the derating factor (which was selected as **80%**), the total required output of PV power under standard test condition is obtained whereby, number of PV panels required can be obtained using

$$N_{PV} = \frac{P_{PV}}{\text{peak power rating of one PV panel}} \quad (2-08)$$

Similarly, given the value of PV power and efficiency, the required surface area of PV can be obtained as [1]:

$$A_{PV} = \frac{P_{PV}}{\mathfrak{S}_{PV}} \quad (2-09)$$

Where; \mathfrak{S}_{PV} is the conversion efficiency of each PV panel.

— **Lead Acid battery**

The use of lead acid battery will serve as energy storage and backup system for supply of energy during low or zero generation periods from the solar and pico-hydro generators. Investigations into the Nigerian market showed that three common SLT car batteries can be found in the used batteries' market and these are rated **44Ah**, **52Ah** and **75Ah** respectively. The most abundantly available size is the 52Ah battery thus it is considered for the sizing scenario in this research. In order to size the battery, parameters and properties such as efficiency, nominal voltage, maximum capacity (C_{bat}) and many more which can be found in the battery datasheet of HOMER software with respect to the nominal capacity were considered as shown in Table 2.03.

Table 2.03: Re-used lead acid battery details [69]

1.	Nominal Voltage	12V
2.	Maximum Capacity	52Ah
3.	Lifetime	1 year
4.	Efficiency	70%
5.	Capacity ratio	0.445
6.	Depth of Discharge	20%

The maximum capacity is the most important parameter which is used to select the number of batteries required and can also be used to perform sensitivity analysis on the effect of battery rating on the entire system. In conclusion, the number of battery can be obtained using equation (2-07).

— **Pico-hydro generator**

The hydro turbine is easily sized since it is assumed that the P_{hyd} is the output power from the pico-hydro generator thanks to an MPPT system which is supposed to work well. This implies that the number of hydro generators can be obtained using the power of the reuse pico-hydro generator which is 55W:

$$N_{hyd} = \frac{P_{hyd}}{0.055kW} \quad (2-10)$$

For sizing the hydro turbine consequently, the properties/parameters that are considered in the choice of model are shown in Table 2.04.

Table 2.04: Pico-hydro turbine details

1.	Available head	0.5m
2.	Design flow rate	25L/s
3.	Minimum flow ratio	0.50%
4.	Maximum flow ratio	75%
5.	Efficiency	45%
6.	Pipe head loss	15%

The available head is assumed to be minimal because the river considered is a small river and as such, it is easier to treat the hydro generator as a run-of-river system with a small head. Generally, for small head, low flow hydro systems, the pipe head loss ranges from 10-20%, for

which in this case an assumption of 15% was made. Also the design flow rate and efficiency were selected based on laboratory models already described in [58].

— **Other Components**

The converter is easily sized since it represents a 300W power supply unit and by default two pieces will be required to cater for a load model having a peak load on 340W. Also, a load following control technique is chosen to ensure that whenever a generator is operating, it produces the power to meet the load demand such that at every time ‘t’;

$$P_{gen} = P_{load} \pm P_{bat} \tag{2-11}$$

Where;

$P_{gen} = P_{PV} + P_{hyd}$ is the output power generated at any time ‘t’ from PV and/or hydro,

P_{load} is the load demand at any time ‘t’

P_{bat} is battery power output (when charging) and power demand (when discharging)

— **HOMER sizing results**

The optimisation technique used by HOMER is based on trying all possible combinations and choosing the optimal solution that satisfies load demand, economic cost, sensitivity and any other criteria specified by the user. The sizing result in this scenario is summarised in Table 2.05.

Table 2.05: HOMER sizing results for analogue method

	No. of Hydro Generators (55W)	PV Peak Output Power (kW)	No. of Batteries (52Ah)	Number of Converters (0.3kW)
Scenario 1	1	2.58	10	5
Scenario 2	2	1.83	8	6
Scenario 3	3	0.854	7	7

Three different scenario can be observed in the solution shown in both Table 2.05 and Figure 2.10. The change in the number of hydro generators will consequently affect the size of all other components. It is assumed that the hydro generator can be connected in parallel up to a maximum number of three units as shown in Figure 2.09.

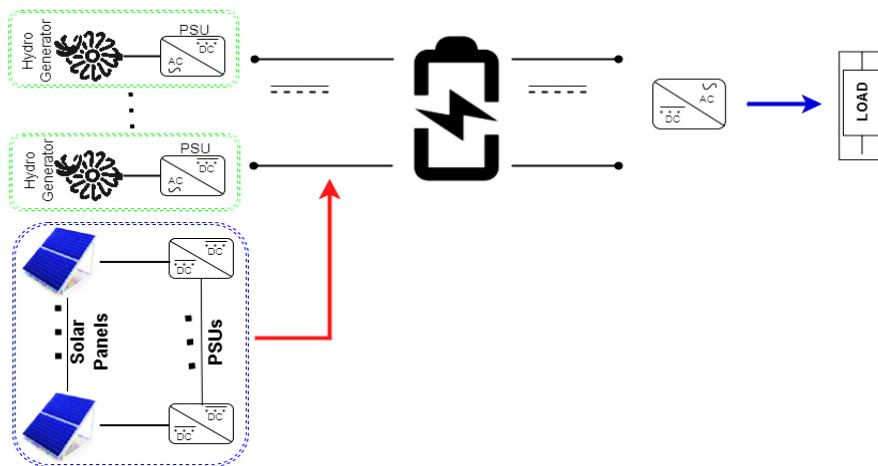


Figure 2.09: Components sizing architecture

The maximum number of 3 hydro turbines was selected due to the constraint of river width and parallel connections are not considered, because experimental observations have shown the kinetic energy of the water will not be sufficient to efficiently drive another turbine connected directly in front. Thus each reuse hydro generator is treated as one whole unit having its turbine, generator and PSU respectively while the solar panels and PSUs are treated as a whole unit in series-parallel connection.

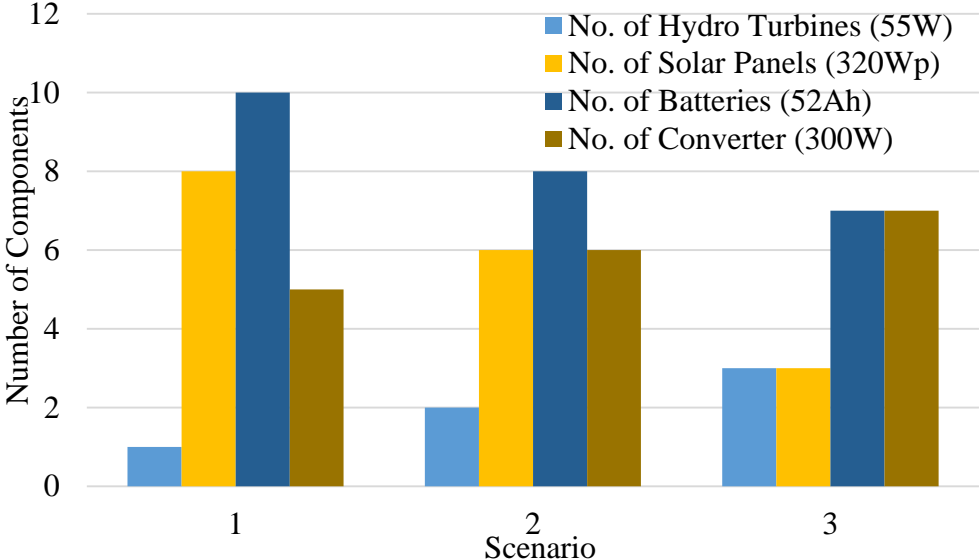


Figure 2.10: Sizing results (analogue method)

2.4.2.2 Standard Method

Based on the load duration curve in Figure 2.01, the daily energy demand can be obtained as described in the work of [57] using the standard rural household consumption pattern. The same processes were repeated on HOMER using the load data and results are as follows.

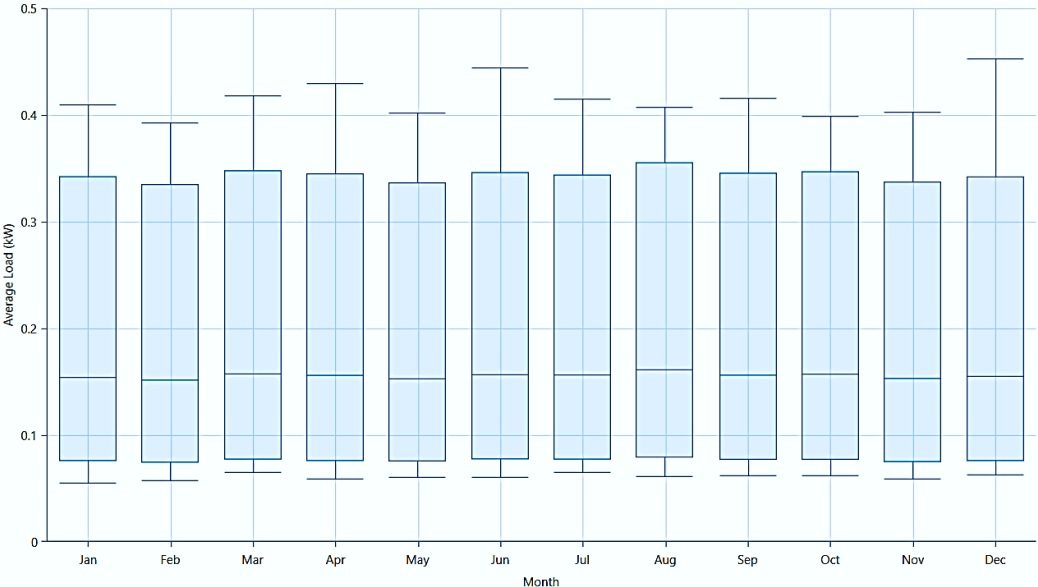


Figure 2.11: Average monthly load demand (standard method) after 10% random variation

Contrary to what was seen in Figure 2.08, it is important to note that the absence of zero values in the Figure 2.11. This is due to the fact that there is no point in time during the day that load demand is zero. Thus, just as explained for Figure 2.08, this figure shows the monthly

minimum, average and maximum values based on random changes in load data with 10% random variability indicated by the straight lines on each bar.

Just as done previously, the simulation was run and the sizing results obtained are shown in Table 2.06 and Figure 2.12 respectively

Table 2.06: HOMER sizing results for standard method

No. of Hydro Generators (55Wp)	PV Output Power	No. of Batteries (52Ah)	Number of PSU/Converter (0.3 kW)
1	3.10 kW	9	5
2	2.31 kW	7	6
3	1.67 kW	5	7

The number of also components based on the three different scenario discussed for Figure 2.10 are also obtainable here, and they are presented in Figure 2.12.

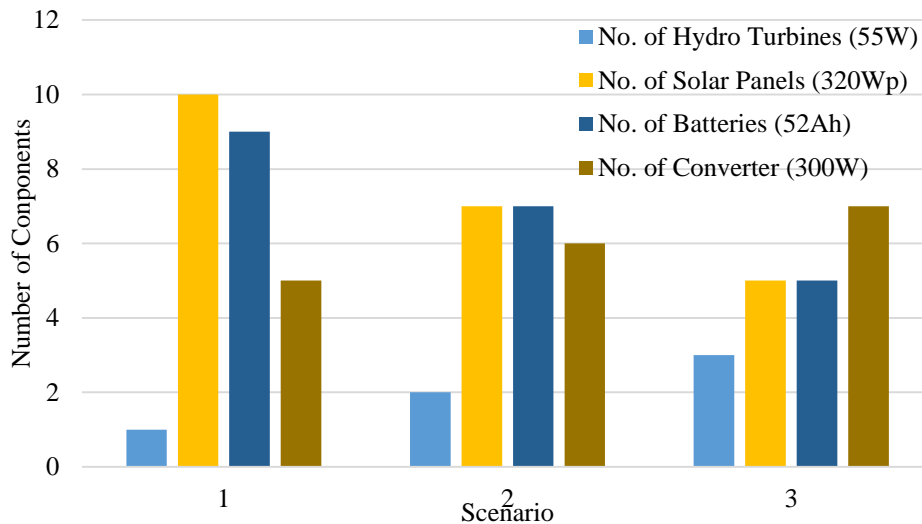


Figure 2.12: Sizing results (standard method)

It can be observed that for the scenario in Figure 2.12, the average sizes of PV reduce progressively as the size of hydro generator increases. This is unsurprising as the need to keep the battery charged during dark hours is definitely improved and thus reducing the time the battery gets fully charged during sunlight hours. Similarly, the number of converters remains the same for the architecture in all cases (5 units) as the minimum number of converter selected to be 300W is sufficient with the modified PSUs serving as converters connected to supply the load, one for the hydro generator side, one set for the PV side and the last one between the induction machine and the pack of batteries. Finally, a comparison of both sizing results (Analogue and Standard methods) is provided in Table 2.07.

Table 2.07: HOMER sizing results for rural household

No. of Hydro Generators (55Wp)	No. of Solar Panels (320Wp)		No. of Batteries (52Ah)		No. of PSU/converters (300W)	
	Standard model	Analogue model	Standard model	Analogue model	Standard model	Analogue model
1	10	8	9	10	5	5
2	7	6	7	8	5	5
3	5	3	5	7	5	5

In conclusion, an economic analysis which will be presented in subsection 2.7 based on market survey in Nigeria to determine the price of the reuse components. The comparative results shown in Table 2.07 can be interpreted in numerous ways especially considering the fact that load demand is the most important factor in decision making. This signifies that the peak demand period does not coincide with peak energy generating period and thus maximum backup is required. For instance, during the sunshine hours, the load demand for the analogue technique has some zero values and thus the battery gets fully charged, but at nights when there is no solar generation, the load demand is at its peak thus causing the need for more backup which in turn causes an increase in the size of the solar panels. This is one of the reasons which justifies the choice of scenario 3 (with 3 hydro turbines) as the most optimal of all the three cases since the hydro generator is available continuously and offers a reduced size for all the other associated components.

2.5 Sizing for conventional solution

Sizing of a conventional solution was necessitated for the purpose of comparison with the reuse solution. For cost effect and life cycle assessment comparison, components sizing was done for the conventional/new solution using the same load data described in subsection 2.2. Contrary to the reuse solution, in this case, a polycrystalline PV panel is selected and lithium ion batteries as well as other recent components as described in subsection 2.3.2. The randomised load demand shown in Figures 2.08 and 2.11 for analogue and standard techniques respectively were also adopted for the conventional solution and the optimal size is displayed in Table 2.08. Thus the number of new components obtainable in the market are determined and the results are presented accordingly.

Table 2.08: Sizing of conventional pico-hydro generator

	No. of Hydro Generators (50Wp)	No. Solar Panels (345Wp)	No. of Li-Ion Batteries (52Ah)	No. of converters (600W)
Standard model	3	5	3	1
Analogue model	5	5	5	1

It can be observed that there is a difference in the number of hydro generators and batteries for both methods of load modelling. This is due to the fact that the analogue technique has more load demand during the night hours as compared to the standard technique as evident in Figure 2.01. As a result, more batteries will be required to cater for this difference consequently resulting in more generators.

2.6 Economic analysis

In order to perform economic analysis for the systems, a local market survey was carried out to obtain the current price of the components used for the solutions described. This survey was generic and was done solely for the purpose of this investigation and to see the possibility of deploying the reuse solution in a developing country like Nigeria while comparing the cost with a new conventional solution. Thus, most of the components selected initially are based on the what is obtainable in Nigerian local market. For the components of the reuse solution, the retail prices are listed in Table 2.09 as obtained in the local currency (Naira, ₦) and the prices were converted to dollars (\$) for universal understanding based on the official conversion rate as at

when the survey was conducted. The standard rural load model was selected at this point for further analyses since it has a precedence from long term data of a typical rural household as shown in [57] and its origin is more applicable than the analogue technique for load modelling

Table 2.09: Cost of reuse components

S/N	Component	Cost	
		Naira (₦)	Dollars (\$)
1.	Bicycle wheel	3000	6.50
2.	Induction Machine	7500	16
3.	Plywood	7000	15
4.	Oil canister	3000	6.5
5.	Solar Panel (used)	45500	98
6.	Old Battery (Lead acid)	16000	35
7.	Old UPS	5000	11
8.	Old PSU	4000	9
9.	Microcontroller	8000	17
10.	Auxiliaries	3000	6.5
Conversion rate (\$1 = ₦462)			

Table 2.10: Cost of new components

S/N	Component	Cost	
		Naira (₦)	Dollars (\$)
1.	Mini hydro generator (50W)	160000	347
2.	Li-Ion battery (156Ah)	249000	540
3.	Solar panel	70000	152
4.	Inverter	20000	43
5.	Charge controller	10000	22
6.	Miscellaneous	4600	10
Conversion rate (\$1 = ₦462)			

The prices of components listed in Tables 2.09 and 2.10 were used to inputted as the capital costs in Homer for each specific component and the economic analysis was done based on three (3) major parameters: Initial Capital Expenditure, Levelised Cost of Energy and the Net Present Cost. The total net present cost (NPC) is the present value of all the cost the system incurs over its lifetime (including maintenance costs). Initial Capital Expenditure (CAPEX) is the total initial cost of all components and expenditure during the beginning of the project. Finally, the Levelised Cost of Energy (LCOE) is the average cost of useful energy produced per kWh by the system. This is obtained by dividing the annualised cost by the total energy served to the electrical load in a year [65].

$$LCOE = \frac{C_{ann_tot}}{E_{served}} \quad (2-12)$$

where; C_{ann_tot} is the total annualised cost (\$/year)

E_{served} is the annual electric load served (kWh/year)

The results of the economic comparison between the reuse solution and the conventional solution is shown in Figure 2.13 where the values of CAPEX, LCOE and NPC are compared

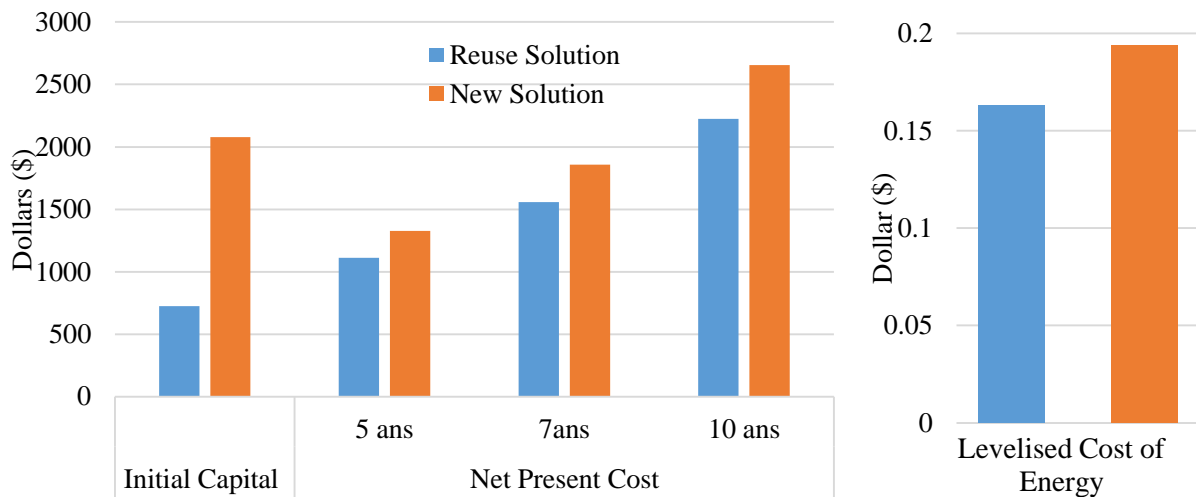


Figure 2.13: Comparison of costs for reuse and new solutions over 5 years

Table 2.11: Replacement of components

S/N	Components/Parts	Component Lifetime	Number of replacements		
			5 years	7 years	10 years
Reuse System					
1.	Reuse hydro generator	5 years	-	1	1
2.	Reuse turbine	5 years	-	1	1
3.	Power Supply Unit	1 year	4	6	9
4.	Solar Panel	10 years	-	-	-
5.	Inverter	2 years	2	3	4
6.	Lead acid battery	1 year	4	6	9
New/Conventional System					
7.	New hydro generator	20 years	-	-	-
8.	Li-Ion battery	5 years	-	1	1
9.	Solar Panels	25 years	-	-	-
10.	Inverter	5 years	-	1	1
11.	Charge controller	3 years	1	2	3

From Figure 2.13, it can be observed that the initial cost of installation of the reuse solution is almost four times lower than the cost of a new solution. Unsurprisingly, the initial capital cost and cost of energy remain the same even after the five years of initial lifetime. This is because the costs of replacing components as shown in Table 2.11 were assumed to be the same and inflation is not considered in the economic model. This trend is also the same as in the case of the net present cost thereby showing the dominance of the reuse solution in all aspects of the economic comparison. The low initial capital expenditure is a great advantage especially since the target consumers of the reuse solution are low income rural dwellers and thus offers a great advantage for the reuse solution. Thus, it is easy to conclude that the reuse hybrid solar-pico-hydro system offers a competitive economic advantage with guarantee of user satisfaction.

2.7 Feasibility Study for Adoption of Power Supply Units in Nigeria

The goal of feasibility study is to investigate the possibility of adopting the reuse solution proposed by [70] for the sole purpose of energy generation in rural and remote areas. In as much as there is doubt about the availability of reuse components for renewable energy generation, conversion and management in developing countries, it is therefore necessary to see if the

number of Power Supply Units (PSUs) and used car batteries available in the local market of each country (Nigeria in this study) will be sufficient to have an effect on the ever growing population. In the feasibility study, the number of PSUs and reuse lead acid batteries that are available in the Nigerian market are investigated based on available data. As explained earlier in subsection 2.2, a market survey was carried out during the economic analysis in order to obtain the prices of available components and their corresponding sizes. Some assumptions were made before commencing these investigations which basically aids the possibility of obtaining the minimum amount of individuals or number of households that could benefit from the reuse renewable energy generation system (if adopted). The assumptions are:

- Besides the battery and PSUs, all other component of the reuse generation system are abundantly available in the market,
- For every discarded desktop computer, one PSU is available for reuse,
- Only three different sizes of lead acid battery were considered for the proposed feasibility study (i.e. 44Ah, 52Ah and 75Ah). This selection was based on popularity and availability in the market,
- The average weight of used lead acid battery is 14kg,
- The weight of a desktop computer is 29kg (i.e. assuming e-waste is based on old technology computers which are widely available in Nigeria nowadays),
- All the PSUs available can be repaired and adopted to the solution,
- Only 20-50% of the old lead acid batteries from cars are adopted for this solution
- A rural household in Nigeria contains an average of seven (7) persons.

These assumptions were basically used, to as much as possible, create the most realistic scenario based on information and data available in the Nigerian e-waste and renewable energy markets. The first step was to obtain the sizes and number of the components that are required by each household based on the load duration curve shown in Figure 2.01. Since our focus in this case is the number of PSUs and batteries, the summary of the average number of PSUs and batteries required for one household is shown in Table 2.12.

Table 2.12: Average number of components required for each household

S/N	Component	No. of Units	
		PSUs	Battery
1.	44Ah Batteries	5	10
2.	52Ah Batteries	6	8
3.	75Ah Batteries	7	7

The repurposed Power Supply Units and used batteries are the major determining factors which are proposed to be the independent variables. They would be used to determine the possibility of deploying the reuse solution for energy generation in rural households. Thus, two subsections are presented; one for the number of available old batteries and the second, for the number of available PSUs that can be adopted for each household. Also, all analyses in these subsections are done based on the weight of the (Computers and Batteries) because the data readily available in [71] only gives the weight of these materials. Thus, each component is represented by its approximate weight obtainable in a generalised form.

As stated in the list of assumptions, solar panels and other components are assumed to be readily available as the solar panel market in Nigeria is oversaturated with different types of solar panels from numerous manufacturers. In fact, the inconsistency in grid supply and unavailability of reliable and quality electricity supply is the main reason for the boom in renewable energy components as most households who can afford it are considering standalone

RE generation for electricity supply. The solar panel market is oversaturated and readily available with a total worth of about 2.9 billion dollars [19]. This makes it quite easy to conclude that availability of solar panels will not be a constraint in adopting the reuse solution. Before proceeding, some important parameters used in describing each situation or components are defined as follows;

- M_{avail} Weight of used lead acid batteries discarded annually
- M_{LAB} Weight of used lead acid batteries that can be recycled or reused
- M_{rep} Weight of used lead acid batteries dedicated for reuse energy solution
- $N_{M_{rep}}$ Number of used lead acid batteries that can be recycled or reused
- $N_{BAT_{hh}}$ Number of households that can be served with used lead acid batteries
- M_g Total annual weight of e-waste/UEEE generated annually in Nigeria
- M_{im} Total annual weight of imported e-waste/UEEE in Nigeria
- M_{lo} Total annual weight of locally generated e-waste/UEEE in Nigeria
- $M_{PC_{avail}}$ Weight of desktop computers readily available annually
- N_{PSU} Total number of PSUs available
- $N_{PSU_{hh}}$ Total number of PSUs available per household
- $N_{EA_{hh}}$ Total number of households that can be equipped by both power supply units and batteries simultaneously

2.7.1 Availability of used batteries

The total amount of used lead acid batteries annually generated in Nigeria hovers around 106 thousand tons [72], and 90% of these used batteries are either repaired, resold or illegally recycled [73]. The used battery market in Nigeria is highly competitive due to the abundance of buyers of old batteries for either export to recycling plants abroad, or for second life uses within the country. This indicates that there is an enormous availability of used batteries within the Nigerian market and thus the possibility of easily obtaining these batteries. Based on this observation, the total amount of used lead acid battery annually available can be obtained as:

$$M_{LAB} = 0.9M_{avail} \quad (2-13)$$

On the other hand, not all these batteries will be available for the reuse energy generation solution, because some would end up being used for other purposes such as export, recycling, reuse in cars, and miscellaneous purposes or because their State of Health (SoH) is not high enough. Different solutions test of the SoH for reused batteries could be found in [74]. Without any existing data, it is assumed in our study, that a range of 20-50% of the available old batteries could be used for the purpose of energy generation in rural households. This gives a margin of range of available batteries which can be deployed into the proposed reuse solution in order to evaluate the feasibility of this solution. For the purpose of clarity and simplicity, an interval of 5% each is considered in this analysis, for the reuse energy generation;

$$M_{rep} = y * M_{LAB} \quad \text{for } y=0.2:0.05:0.5 \quad (2-14)$$

The amount of batteries available for the dedicated purpose of reuse energy generation will be an array of seven (7) possible solutions as indicated by equation (2-14). For a typical SLI (Start, Lighting and Ignition) lead acid car battery, weight of the batteries is not fully specific to their Ah ratings but varies from different manufacturers, components and technology. Because of this constraint, it is quite difficult to ascertain a specific weight to each battery size based on their capacity. Therefore, another assumption was made to keep use a uniform average weight for all the batteries since the weight of a typical car battery mostly ranges between 12 kg to 22 kg depending on the manufacturer. Based on popularity, an average weight of a 14 kg was used

for one battery whereby the total weight of battery (M_{rep}) is used to obtain the total number of batteries available annually as;

$$N_{M_{rep}} = \frac{M_{rep}}{14} \quad (2-15)$$

In order to obtain the total number of households that can be served, three different scenarios are considered based on the information presented in Table 2.11. Depending on the size of battery being used in the solution, each case is considered independently (i.e. 7 units, 9 units and 10 units of batteries) to obtain the total number of households that can be served as:

$$N_{BAT_{hh}} = \frac{N_{M_{rep}}}{nb} \quad (2-16)$$

where; nb is the number of units of battery (i.e. 7, 9, or 10 respectively). It is important to note that for the result obtained from equation (2.16), the number of batteries only considers one battery size at a time. This means that the results from this part analysis assumes that all the households are adopting one size of battery for their reuse solution at for every scenario and there is no possibility of mixing battery size.

The number of households that can be served using the available batteries for each value of y is shown in Figure 2.14. Depending on the capacity of battery adopted, the blue, green and red bars represent the 44Ah, 50Ah and 61Ah batteries respectively.

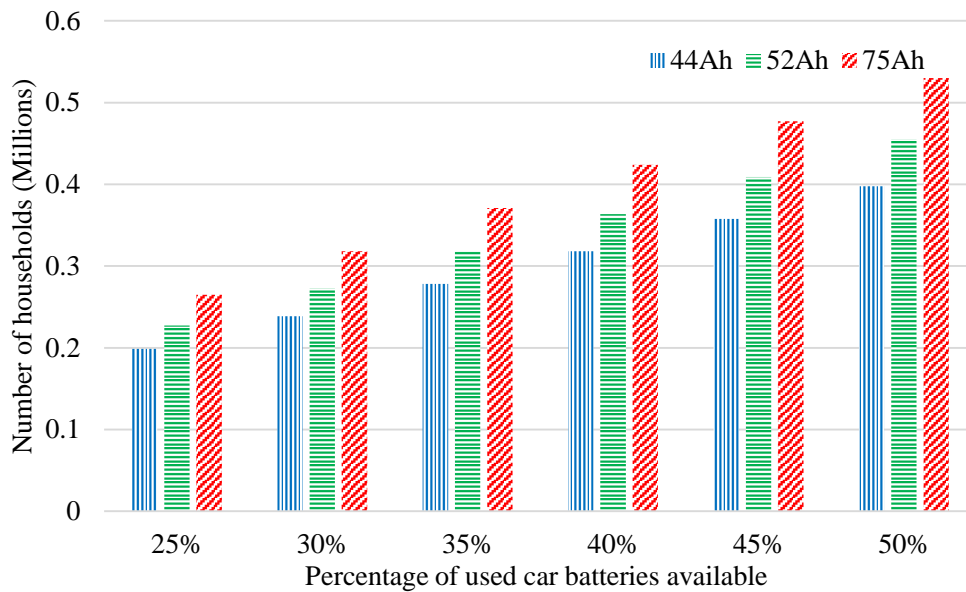


Figure 2.14: Number of households (1 house for 7 persons) that can be served by used batteries only

2.7.2 Availability of Power Supply Units

Just as explained in subsection 2.7.1, the for number of old batteries available for the reuse solution, the number of PSUs available can be analysed using annual weight of PSUs obtained from Used Electrical and Electronics Equipment (UEEE) obtained in Nigeria. Because the weight of a PSU cannot be directly applied in this case since it should normally be embedded inside the desktop computer, it is assumed that one PSU can be found in each discarded desktop computer. Thus, the number of PSU being mentioned is literally referring to the number of desktop computers in the general bulk of e-waste.

In Nigeria, there are two main sources of UEEE or e-waste which are the e-waste generated within Nigeria and e-waste imported into Nigeria from other countries. Nigeria internally generates between 260,000 to 500,000 tons of e-waste annually [75]. According to the data obtained from [71] out of approximately 15,600 tons of UEEE that are imported into Nigeria annually, desktop computers comprise 7% of them. 30% of these UEEE are immediately discarded due to one fault or the other while the remaining are reintroduced into the used electronics market. Based on these data, it is possible to estimate the possible number of PSUs that could be available annually in Nigeria based on the amount of desktops discarded annually.

$$260,000T \leq M_g \leq 500,000T \quad (2-17)$$

Expression (2.17) is from the internally generated e-waste while the total mass of e-waste annually available in Nigeria is the sum of imported mass of UEEE (labelled as imported e-waste) locally discarded e-waste within the country (titled local e-waste). The total mass of e-waste generated can be obtained as:

$$M_g = M_{im} + M_{lo} \quad (2-18)$$

Since 30% of the imported UEEE are immediately discarded, it is safe to say that they have become e-wastes also and 7% of them could be desktop computers. Thus, 7% of the immediately discarded imported e-wastes plus the available amount of desktop computers from the locally generated e-wastes form the total amount of computers having one PSU readily available. The total number of desktop computers can be obtained as;

$$M_{PC_avail} = 7\% \times 0.3M_{im} + x\% \times M_{lo} \quad (2-19)$$

In order to be less optimistic about the amount of desktop computers available annually, a range of values are considered to be $x\%$, i.e. the percentage of locally generated e-waste available. Since it is already established that desktop computers make up 7% of the e-waste generated, there is every possibility that this value is not feasible. This is why a variation is also considered for the percentage of desktop computers in locally generated e-waste.

An assumption that a minimum of 2% of the local e-waste generated are desktop computers is considered. Thus, it is assumed that the value of x in equation (2-19) ranges from 2% to 7% since there is no data stating the minimum amount of desktop discarded locally. This is a safe assumption because desktop computers comprise 7% of the annual importation data and thus, if the cycle of life is consistent, then it is quite possible to have the same amount of desktop computers, (or less) in the local e-waste. Based on the amount of computers available, the number of available PSUs can be obtained. We have already established earlier that one desktop computer weighs approximately 29 kg so the amount or number of PSU available can be obtained based on this value. Since one of the assumptions earlier listed in subsection 2.7 was that one PSU can be found in every desktop computer, then the number of PSUs which corresponds to the number of computers can be obtained as:

$$N_{PSU} = \frac{M_{PC_avail}}{29} \quad (2-20)$$

The number of PSUs required per year in each household is five since it is assumed that the lifetime of each PSU is one year and it will be replaced annually. It is important to notice that no data is available to evaluate the duration of the second life PSU which leads us to these assumptions. Thus, the total number of households that can be served each year by the reused solution based on PSUs only can be estimated by dividing the total number of PSUs available

by 5. This gives an estimate of the total number of households and the result can also be used to determine the total number of persons/individuals that will have access to electricity. Based on this, the total number of possible households that can be served based on the number of available PSUs are:

$$N_{PC_hh} = 0.2 * N_{PSU} \tag{2-21}$$

For each value of x , the results of the number of households that can be served/supplied annually based on number of PSUs is shown in Figure 2.15. Apart from the six possible cases that are obtainable based on the variation in the value of x , three (3) different scenarios are considered based on the amount of e-sate generated annually. Using (2-07) as a factor to be considered, the minimum value of 260,000T, an average value of 380,000T and a maximum value of 500,000T are considered to see the influence on the total number of PSUs available and consequently, the number of households that can be equipped.

Thus, from Figure 2.15, the green bars represent the minimum value of e-waste generated annually (M_g), average value of M_g are represented by the blue bars and the red bars represent the maximum values of M_g respectively. The variation in the value of is on the horizontal axis while the number of households that can be served for each of the scenario is on the vertical axis.

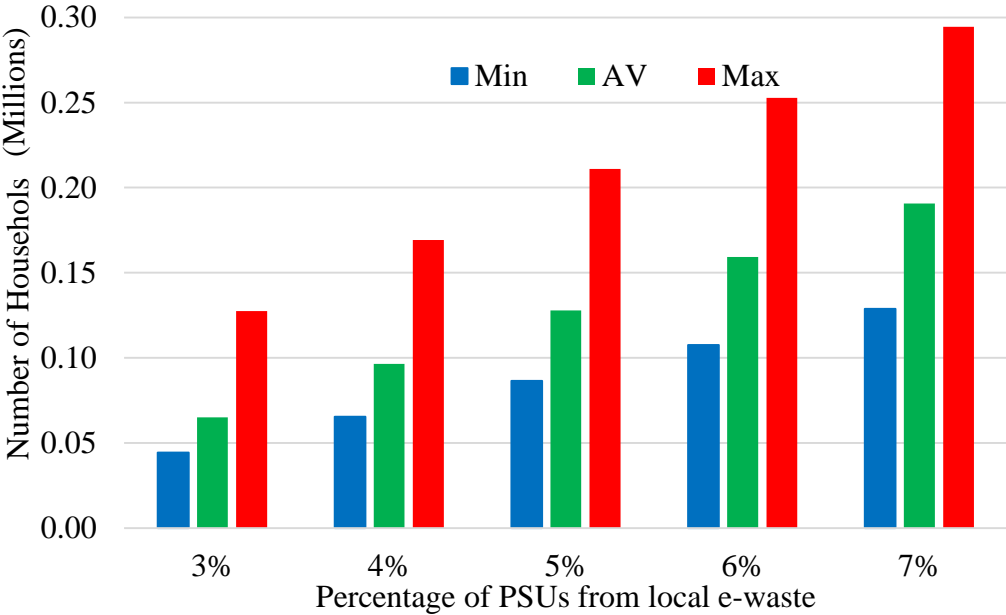


Figure 2.15: Number of households (1 house for 7 persons) that can be served by PSUs

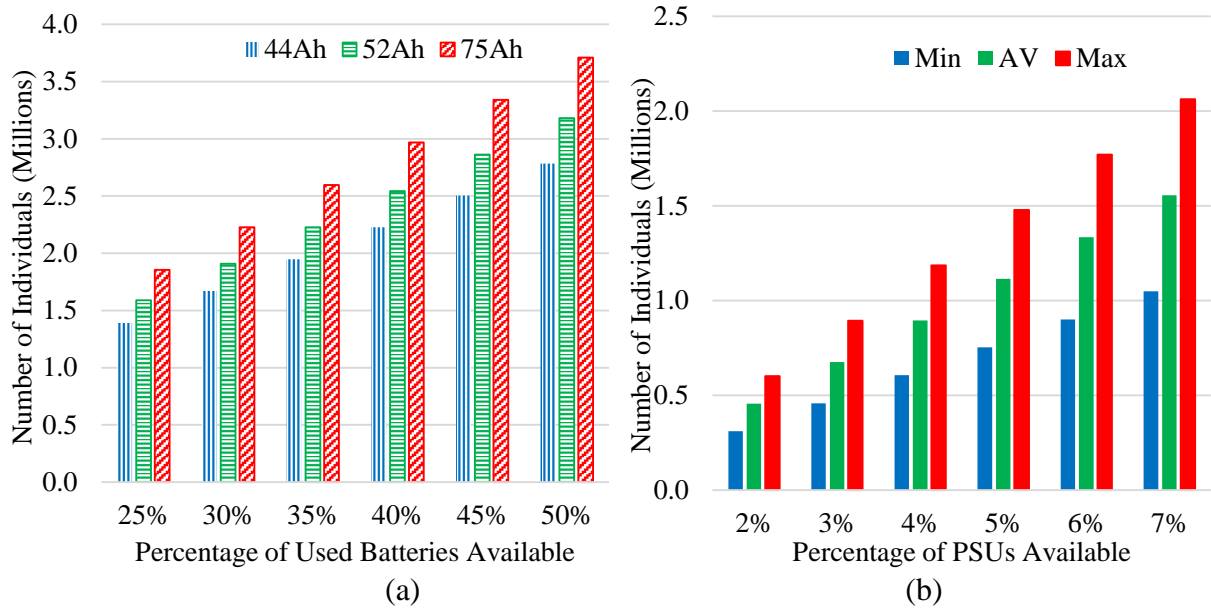


Figure 2.16: Number of individuals/persons that can be served by used batteries and PSUs

Since the last assumption of the number of people comprising one rural household in Nigeria (7 people), Figure 2.16 shows the number of individuals that will have access to electricity thanks to our solutions, based on the number of used batteries and PSUs available within the country for the purpose of reuse energy generation. These two analyses (i.e. battery and PSU) cannot be used yet to finally conclude on the total number of households that can have access to electricity using the re-use idea.

A final step is to describe different scenarios to establish a point of intersection between both cases with respect to the number of households or individuals that can benefit from the reuse solution. Thus, the total number of households that can be served annually will be based on three different scenarios which are described using equations (2-22), (2-23) and (2-24) respectively. This makes it possible to visualise the possible number of households that can be powered based on both the availability of PSUs and old batteries together. Because an intersection of both components are required to complete the solution, the minimum, average and maximum number of households that can be served will be based on availability of both components (PSUs and old lead acid batteries) assuming other required components are abundantly available. The corresponding feasible value between the total number of Power Supply Units and number of batteries available is used to conclude on the total number of households that can be supplied. Similarly, the average and maximum values are also selected based on these conditions so as to conclude the possible number of households and corresponding population respectively.

$$\text{Scenario 1: } N_{EA_hh} = \min[N_{PSU_hh}; N_{BAT_hh}] \quad (2-22)$$

$$\text{Scenario 2: } N_{EA_hh} = av.[N_{PSU_hh}; N_{BAT_hh}] \quad (2-23)$$

$$\text{Scenario 3: } N_{EA_hh} = \max[N_{PSU_hh}; N_{BAT_hh}] \quad (2-24)$$

The results from three scenarios expressed by (2-12) to (2-14) are summarised in Table 2.13. The total amount of households that can be energised in one year by the proposed reuse solution based on availability of components is shown. These values are expressed as a percentage of the entire population and the number of people currently without access. Recall that about 38% of the population in Nigeria do not have access to electrical energy and this amounts to approximately 78 million individuals.

Table 2.13: Results of households that can be energised based on re-use solution

	Minimum	Average	Maximum
Number of households	44,397	127,914	294,570
Population	310,780	895,401	2,061,988
Percentage of Total Population	0.15%	0.43%	1%
Percentage of Population without Energy Access	0.40%	1.15%	2.64%

From these results, it can be concluded that based on worst case scenario, 0.4% of the population without access to electricity can be electrified and have their basic appliances powered by the reuse solution, which does not seem much, but this translates to 310,780 persons in the worst scenario. If the solution is aggressively adopted, the best case scenario shows that 2.64% of the people currently without electricity access can be energised (little bit more than 2 millions)

In conclusion, the overall results have shown that the adoption of the reuse solution is feasible in a developing country like Nigeria. One-year data has shown the possibility of electrifying between 44 thousand to 294 thousand households. It is not a very big number for a country with very large population like Nigeria but will provide electrification benefits to thousands or millions (depending on the scenarios) of people. If this solution is adopted as an immediate backup plan while developing long term solution plans for rural areas without electricity, it will go a long way in reducing the amount of people without access to electricity annually.

2.8 Conclusion

This chapter has highlighted the use and adoptability of a frugal innovation based hybrid (solar and pico-hydro) electricity generation system based on reuse of local materials and e-waste for improving access to energy in rural areas. The concept of the reuse hybrid solar-pico-hydro generator was discussed and the possibility of adopting it for energy generation in a rural household was presented. Two rural load model for essential loads (based on analogue and standard methods) were described and Homer software was used for sizing of components of the reuse system. The standard method was preferably adopted for further analysis due to its realistic pattern and a comparison was done between the components sizing results for the reuse system and a new/conventional system. To complete the techno-economic analysis, a cost comparison was done between the reuse system and a new system serving the same load. The results highlighted the advantage of the reuse system which had an initial capital cost that was 65% cheaper and a cost of energy that was about 15% cheaper than those of a new system.

After obtaining the required components sizes to power a typical rural household, a feasibility study was presented to establish the positive contribution of adopting the proposed reuse solution on energy access in Nigeria. The results have shown that a substantial part of e-waste and UEEE can increase the annual energy access in a developing country like Nigeria for a minimum of 44 thousand households and a maximum of 294 thousand households. This corresponds to a minimum of 310 thousand individuals and a maximum of 2 million individuals that can be electrified annually. This confirmed the possibility of adopting locally sourced materials to improve electricity access in a developing country like Nigeria. Besides improving the electricity situation of rural areas without electricity access, it is also cheaper and more economical with materials that can be assessed locally.

Thus, the next step is to ensure that there is zero or minimal loss of power supply during operation of the reuse system. This will be done by adopting a battery energy management system algorithm which will maximise the benefits of the available renewable energy resources

during peak generation periods. This is to ensure that the reuse system generates electricity to the consumer at every time required, irrespective of the weather conditions so long as it is within the stipulated load demand.

CHAPTER THREE

TIME SERIES FORECASTING AND BATTERY ENERGY MANAGEMENT

3.1 Introduction

In this chapter, time series modelling is introduced and tested on a typical historical data before it is used to perform forecasting. However, the choice of forecasting was to see the possibility of introducing an energy management plan for the reuse hybrid solar-pico-hydro system which was discussed in the second chapter. Since the feasibility study for the adoption of this system has been presented and adequate sizing was done, the possibility of introducing an energy management schedule to maximize the potentials of the components and satisfy as many load as possible is presented. This management was done based on the battery State of Charge (SoC) being the main parameter that determines the final output of the management plan.

3.2 Time Series Modelling and Forecasting

Time series analysis can be defined as a mathematical and statistical approach use to analyse, interpret and process data which are collected over a specific period of time with constant time interval [76]. Time series data can be explained as a set of observations that are measured or recorded over a specified time interval, either continuously or in a discrete form. They are a sequential set of data points which are available at a recurrent, constant time interval [77] which can be classified as either continuous or discrete time series.

In general, any set of data having regular time intervals and making a sequence which can uncover presence of trends, seasonality, cyclic pattern and stochastic irregularities all embedded in it can be classified as time series data and can be analysed based on time series modelling and forecasting [78,79]. The decomposition of times series data into various components helps in better understanding underlying patterns for analysis, prediction and forecasting.

Based on these components, the data can be used for statistical characterization to extract specific features and descriptive information that can be used to perform numerous analyses using the information deduced from the data points [80]. In the long run, the aim is to represent these data as time series models. According to [6] and [7], time series model can be defined as a kind of joint distribution (or possibly just the mean and covariance) of a sequence of random variables representing a realistic scenario.

Decomposition of time series is an important step which is used to treat or analyse the data. This can be observed from a preliminary assessment of the time series data, even a visual observation of the data can give some ideas on the properties. Initial data analysis always shows either three or four properties. These are called trends, seasonality or seasonal variations, cyclic variations, and irregular fluctuations or random components. A trend is constant upward or downward growth observable over a successive period in time while seasonality is a specific repetitive pattern or behaviour constantly observable after a length of time. Similarly, cyclic variations are a rhythmic pattern over a longer period other than more year while random components are basically haphazard patterns which is left after removal of trends, seasonality and other components. A time series model is either additive or multiplicative respectively, depending if;

- i. The observed data series has: trends + seasonality + irregular or random components,
- ii. The observed data series has: trends \times seasonality \times irregular or random components

The use of prediction models and forecasting has been practiced for several purposes such as planning, control and exploration of future decision making considerations. In fact, as long as

there is a consistent historical pattern for any kind of information, it is subjectable to prediction which leads to forecasting. Forecasting is not limited to specific situations but can be generalized as a way of preparing for possible unforeseen circumstances. This justifies the fact that, before any prediction or forecasting can be done, previous knowledge or history of the behaviour of the system is sufficiently required. Similarly, the need to ensure that the data to be processed possesses the characteristics of a typical time series data is pertinent. In this case, the use of normality test can be deployed to determine whether the set of data under investigation follows the Gaussian or normal distribution. The normal distribution is characterised by a symmetric bell-shaped curve indicating important properties such as mean and standard deviation [82,83]. Some popular techniques used in performing normality tests are listed in Table 3.01 [84–86]. The choice of technique used for normality test is highly dependent on the kind of data, size and/or the desired reason for carrying out normality test.

Table 3.01: Methods for normality test

S/N	Test	Characteristic
1.	Kolmogorov-Smirnov (K-S)	More sensitive near the centre than the tail
2.	Shapiro-Wilk	Rejects null hypothesis for large data with small differences
3.	D'Agostino Pearson Omnibus	Used for data higher than 20 elements
4.	Jarque-Bera	Used for very large sample sizes of greater than 2000
5.	Anscombe-Glynn	It may not be accurate for large tail skews as it mostly returns acceptance of null hypothesis
6.	Anderson-Darling	Used where a multiple cluster related of data distribution is considered
7.	Cramer-von Mises	An alternative to the K-S but mostly used when two samples cases are to be estimated as one

Generally, time series data models can be in several forms and structures, and can be used to analyse different stochastic processes. Examples of forms of time series data are: regularly spaced/continuous data, irregularly spaced/discrete data, univariate time series, multivariate time series, event time series, seasonal time series, financial time series and many more [87]. The analysis of times series models can be done using several techniques ranging based on the desired procedure and expected outcomes. Statistical models such as ARIMA (Auto Regressive Integrated Moving Average), Exponential Smoothing and GARCH (Generalised Autoregressive Conditional Heteroscedasticity) can be adopted for modelling in times series analysis. In this case the choice of linear time series models based Auto Regression (AR) and Moving Average (MA) models was preferred for its computational simplicity which translates to less time consumption and less memory requirement.

3.3 Autoregressive Integrated Moving Average (ARIMA) Model

The ARIMA model is a combination of Auto-Regressive (AR) and Moving Average (MA) that is can be used for univariate times series analysis and modelling. The approach is based on Box Jenkins technique where the present value of a time series data is characterised by previous values over consistent time range and some noise term. The AR term which is denoted by an order ‘ p ’ can be denoted as AR(p) and represented by the equation;

$$X_t = \sum_{j=1}^p \phi_j X_{t-j} + \varepsilon_t \quad (3-01)$$

where; $\varphi = (\varphi_1, \varphi_2, \varphi_3, \dots, \varphi_p)$ is the vector of AR model coefficients of past values having zero means and a constant variance, ε_t is the forecast error.

A Moving Average (MA) model on the other hand uses the lagged values of the forecasting errors (in a regression-like pattern) to improve the current values. It is denoted by MA(q) having an order 'q' and can be expressed as;

$$X_t = \varepsilon_t - \sum_{j=1}^q \theta_j \varepsilon_{t-j} \quad (3-02)$$

where; $\theta = (\theta_1, \theta_2, \theta_3, \dots, \theta_p)$ is the vector of MA coefficients of past values, $\varepsilon \sim N(0, \sigma^2)$ which is a normally distributed random white noise having zero means and a constant variance σ [88].

The combination of AR and MA gives ARMA models which is described as a model of the order p and q denoted using ARMA (p, q) and is expressed as;

$$X_t = \sum_{j=1}^p \varphi_j X_{t-j} + \varepsilon_t - \sum_{j=1}^q \theta_j \varepsilon_{t-j} \quad (3-03)$$

It is important to note that X_t represents the obtained present value of a time series data which is correlated to its past values. For stationary time series data, the ARMA model can be used for forecasting and analysis [88,89]. However, if data is non-stationary (i.e. the mean and variance of the data is not constant over time), the ARMA model need to be differenced (denoted as 'd') till it becomes stationary and before it is analysed [90]. In this case, the model is described as Autoregressive Integrated Moving Average (ARIMA) where the integrated (I), represents the number of times the data is differenced. The ARIMA model is represented by ARIMA(p,d,q) with p being the AR order, d being the degree of differencing of the stationary data and q being the MA order. For prediction and forecasting, the ARIMA model can be finally represented as [77,91];

$$X_t = \mu + \varphi_1 X_{t-1} + \varphi_2 X_{t-2} + \dots + \varphi_p X_{t-p} + \varepsilon_t + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \dots + \theta_q \varepsilon_{t-q} \quad (3-04)$$

where; μ is a constant term obtained from successive means of the coefficients of AR and MA

3.4 Renewable Energy Data from Nigeria

Nigeria is a country with abundant renewable and sustainable energy resources [29] which is why there is a lot of potentials for adoption of RE generation systems. An estimated solar irradiance of 3.5-7.0kWh/m²/day are available for energy generation in Nigeria with an approximate annual wind capability of 150,000J per annum at a normal speed of 2-7m/s is [5,29]. Katsina state (with long. 12.985°N, lat. 7.617°E) was used as a case study. The choice of Katsina was based on the fact that this reuse hybrid solar-pico-hydro solution is targeted at remote areas where there is little or no infrastructure for electricity. In addition, the proximity to a small river and distance from the commercial big city was also considered for the choice of location. However, this choice does not in any way hinder or limit the accuracy of the analysis as it can be applicable to any desired location.

In this case, the historical data of solar irradiance pattern is required before hand so as to see the shape or behaviour of solar insolation in the specific area [92]. Several techniques and equipment can be used to measure and record solar irradiance data, depending on the desired outcome. Irrespective of the measuring and data collection device and/or technique, Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) are the most widely available solar radiation data used in solar systems design, sizing, and decision making with respect to amount of solar flux [93]. Since the GHI is the sum of direct normal irradiance, diffuse horizontal irradiance and ground-reflected radiation, most application of solar radiation employ the use of GHI data for solar systems related purposes. In order to successfully perform time series analysis on a specific kind of data, there is need to identify certain specific features of the dataset.

3.4.1 Historical Data

Historical solar irradiance was obtained from NASA archives for the selected location in Nigeria. The solar irradiance data is readily available on the NASA website and can be easily assessed for any desired purpose. One-year historical data was initially collected and sorted to remove outliers and missing values as the case maybe. After pre-processing and analysing the data, it was plotted as a time series graph which is shown in Annex A1. However, due to the large number of data points, it is quite almost impossible to observe the pattern and behaviour of the time series data from visual perspective which is pertinent for time series analysis. Thus, one-week data was randomly extracted from the entire bulk for easier illustration and observation of the behaviour of the data to processing and analyses. A high resolution dataset may be required for instant “step-ahead” control and decision making which is why high resolution data at 15mins interval is considered for forecasting. One-year historical solar irradiance data at 15minutes interval (i.e. 35,040 steps) is used for all analyses but for easier visualisation one-week data is displayed to clearly see the properties of the data interval (i.e. 672 steps) as shown in Figure 3.01(a) and (b) respectively.

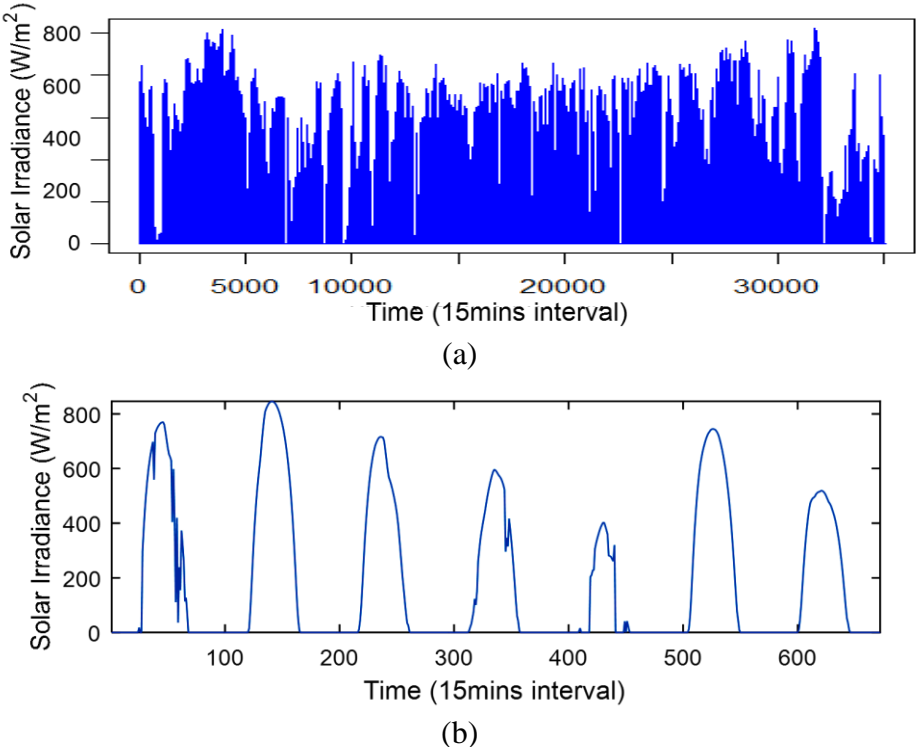


Figure 3.01: Solar irradiance data for one week

A visual observation of the solar irradiance data in Figure 3.01 shows presence of trend and seasonality which is due to the daily pattern of sunshine and sunset. During the night, the solar irradiance value remains zero and as such makes it quite unconventional. In addition, days with a lot of cloud cover or rainfall also disrupt the pattern of the data and as such, solar irradiance data need to be specially filtered by removing trends and seasonality before being used for time series forecasting. This process is termed as “Integration” of the data in ARMA thus making the process become a seasonal ARIMA model forecasting.

3.4.2 Solar Irradiance Data Pre-processing

It has already been established in previous literatures that solar irradiance data which are stochastic in nature [94], can be broadly classified as a type of time series data. Based on these components, the data can be used for statistical characterization to extract specific features and descriptive information that can be used to perform numerous analyses using the information deduced from the data points [80]. As a general rule of thumb and for the avoidance of all doubts, normality test was performed on the data to ensure that, even if contaminated with a few outliers and missing data, the solar irradiance data still obeys a normally distributed population. Due to the fact that the solar irradiance sample data being considered for a duration of one year at 15-minutes time interval is more than 2000 data points, the Jarque-Bera test was used to check the solar irradiance data for normality. For the solar irradiance data under consideration, the bell-shaped pattern of every statistical data that conforms to normality is shown in Figure 3.02. This is a confirmation that despite being highly stochastic in natures, solar irradiance data over a long period of time possesses a normally distributed population and consequentially, can be treated as a time series model in extension.

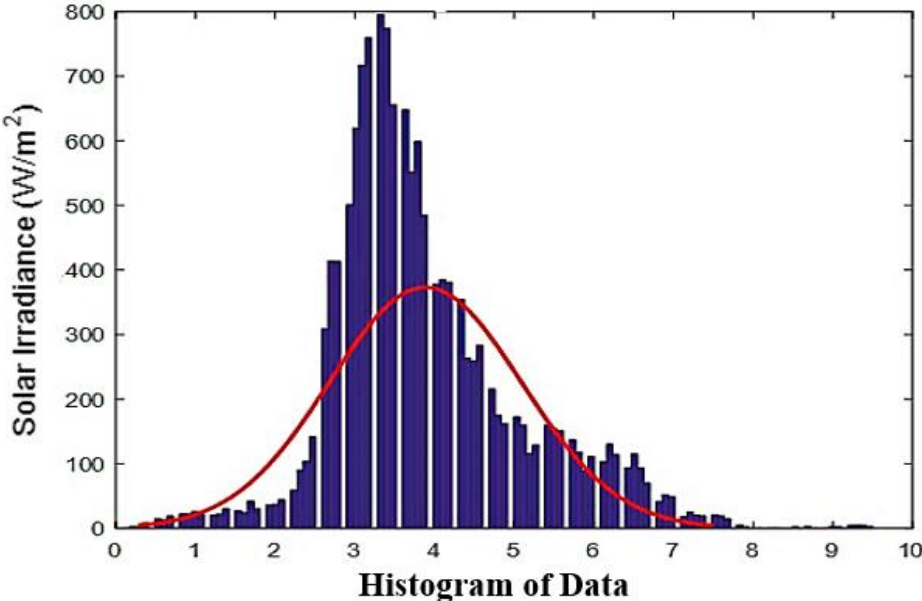


Figure 3.02: Result from normality test

From Figure 3.02 it can be observed that there is a little skewness to the left for the Q-Q (Quantile-Quantile) plot of the histogram. This is one of the characteristics of real world datasets which indicates that it may be necessary to pre-process or transform the data before use (an indication of seasonality). However, this does not pose any serious threat as the orientation of the bell-shape indicates normality since it possesses a single peak. After confirming the normality of the data, the next step is removal of trends and seasonality before performing ARIMA modelling

3.4.3 Removal of Trends and Seasonality

In order to perform time series analysis on the data presented in Figure 3.01, R-software was used. R-software is a free open source software which can be used for statistical computing and graphics [95]. For the solar irradiance data, Figure 3.03 shows the decomposition of the data based on presence of trend and seasonality as outputted by R. This is because in order to predict with this time series data, differencing is required by removing trend and seasonal effects from the data. Thus only the random/residual aspect of the data should be used to develop the ARIMA model.

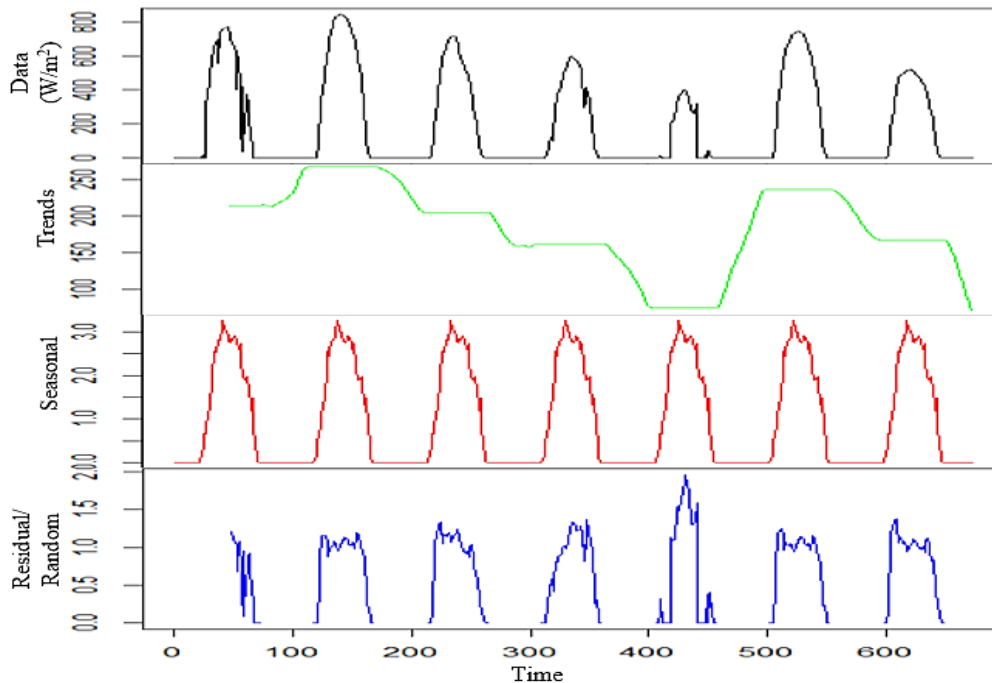


Figure 3.03: Solar irradiance data showing trends and seasonality components

Normally, the “*auto.arima*” command in R software can be used to automatically analyse and select the best ARIMA model for forecasting any set of input data. This uses the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) to select the best model. The Auto Correlation Function (ACF) and Partial Auto Correlation Function (PACF) are also used to determine the values of p and q in ARIMA based on the lags.

The ACF is used to investigate or visualise patterns and correlations/relationships between the data points of a time series model and its lagged version. This simply means that the self-similarity if the model is measured over different delay times. On the other hand, PACF complements the ACF by filtering any intervening lags (previous lags effect) when considering the self-similarity between a model and its lagged version over time. Generally, the ACF and PACF are manually used to select the order of the p and q order of ARIMA models but, further observations in previous works have shown that it is easier and more accurate to select these values based on the lowest values AIC and BIC [96]. This is already adopted by the “*auto.arima*” command in the R-software thus making it very simple for times series forecasting. With this command, forecasting was initiated for one whole day for the solar irradiance data. The results showed that the most suitable model for the solar irradiance data is ARIMA (1,1,5) summarised in Table 3.02.

Table 3.02: ARIMA (1,1,5) model values

	AR1	MA1	MA2	MA3	MA4	MA5
	0.838239	-0.740549	0.02376	-0.006226	0.008786	0.00566
Std. Error	0.078334	0.0137037	0.00244923	0.00251079	0.00229131	0.0028360

The variance of the model is estimated to be 2426.86 with a standard error of 4.762 and the constant value, c is -0.000233481. Since the model has been differenced one time, the generic equation shown in (3-04) has to be differenced to obtain:

$$X_t = \mu + X_{t-1} + \phi_1 X_{t-1} - \phi_1 X_{t-2} + \varepsilon_t + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \theta_3 \varepsilon_{t-3} + \theta_4 \varepsilon_{t-4} + \theta_5 \varepsilon_{t-5} \quad (3-05)$$

Since we already know that this ARIMA model is only suitable for short term forecasting, a real-time updating technique is developed to forecast to a maximum of 3-steps ahead and update the data before performing another forecast as shown in Figure 3.04. This flowchart shown in Figure 3.04 will be a continuous process which continuously updates its data after each forecasting step(s). The essence of this proposed technique is solely for decision making and control purposes whereby short-term forecasted values can be used to decide ahead of time. The standard ARIMA process is followed using historical data to forecast the next step(s), Y_f , where $f = 1, 2, 3, \dots$ depending on the number of steps to be forecasted.

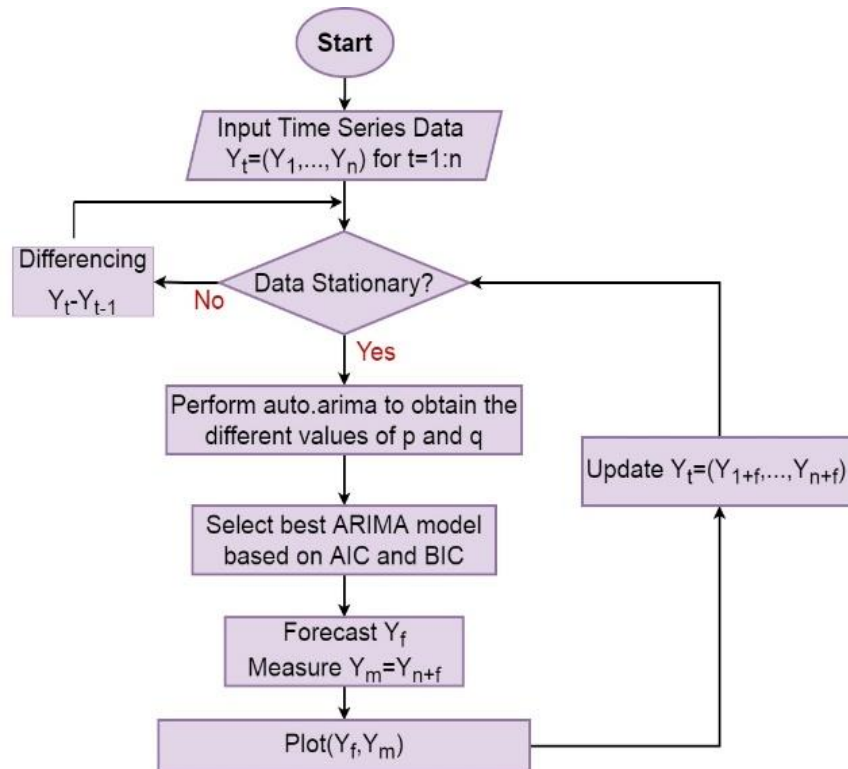


Figure 3.04: Flow chart for implementing real-time ARIMA forecasting

Using the procedure highlighted in Figure 3.04, forecasting was done based on three different scenarios for solar irradiance data; which are 1-step ahead (i.e. $f=1$), 2-steps ahead (i.e. $f=2$) and 3-steps ahead (i.e. $f=3$). As predicted, the RMSE reduced as the number of forecasted steps ahead reduced and this was a way of improving accuracy in the forecasting of solar irradiance while maintaining the use of ARIMA time series model. A summary of the root mean square

error (RMSE) values of the results is shown in Table 3.03, while Figure 3.05 shows the predicted values against the actual values of solar irradiance for the three scenario. This technique can be easily deployed in control and decision making processes whereby forecasted values can be used to make decisions ahead of time.

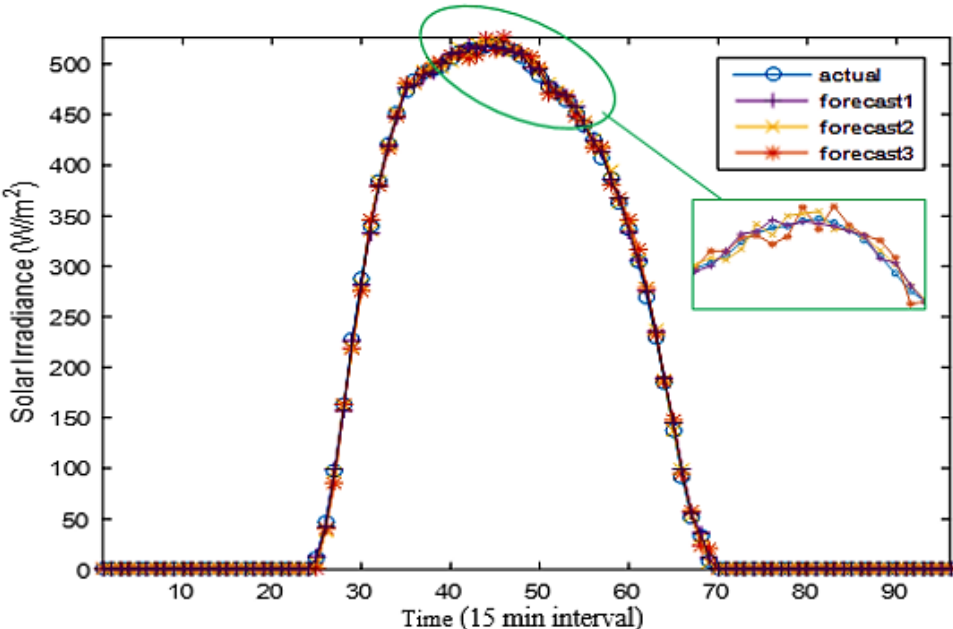


Figure 3.05: Real-time ARIMA forecasting for solar irradiance in 3 different scenario

Table 3.03: Comparison of RMSE values

S/N	Prediction steps	RMSE
1	1 steps ahead (Forecast1)	3.52
2	2 steps ahead (Forecast2)	3.85
3	3 steps ahead (Forecast3)	6.50

In conclusion, the development of the real-time ARIMA technique was necessitated due to the need to reduce the forecasting error of solar irradiance prediction and while maintaining the fundamental of the combination auto regression and moving average technique. The real-time forecasting algorithm has proven to be an adoptable method which can be reliable when deployed for planning purpose. The forecasting algorithm can be used to plan a load scheduling technique to ensure that the system never encounters a complete shutdown during low insolation or rainy days.

3.5 Battery Energy Management

After considering the possibility of using the simple, economical and noncomplex forecasting technique for prediction of solar irradiance, it is possible to use the predicted values of irradiance to plan the battery charging schedule. This is to ensure the system does not have a complete shut down since there could be uncertainties in the behaviour of solar generation power due to hindrances such as temporary shading, due to rain, dust or obstructions that could reduce energy generation over long or short period of time. As described in subsection 2.5, the reuse hybrid solar-pico-hydro generator can be used to serve a rural household based on the sizing results achieved displayed in Table 2.08. Recall that in the load model details shown in Table 2.01, only essential load was used to design the system due to consideration of cost which is one of the major constraints in rural areas of developing countries like Nigeria.

To portray the possibility of energy scheduling and management based on the adoption of the reuse system, it is assumed that the essential load constitutes only (40%) of the total load that can be served in a household thus the load duration curve can be modified to as shown in Figure 3.06 with the daily peak load being 859W as compare to 343W for essential loads. It is important to remember that the essential load details of a rural consumer were assumed based on the basic important equipment that most of the rural households would have. With this in mind, non-essential loads are additional devices which may not necessary be needed on day to day usage and are considered as optional loads.

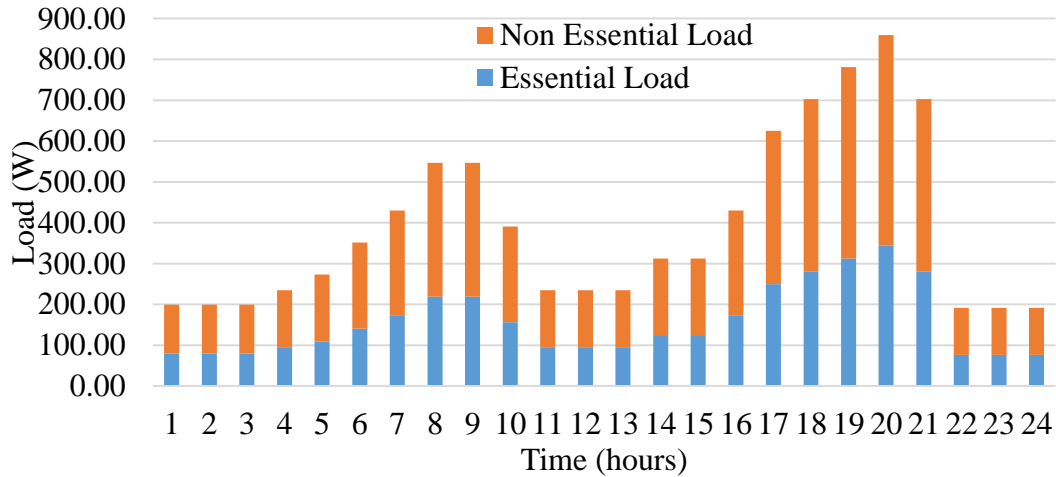


Figure 3.06: Load duration curve for total loads in a rural home

Based on the load details in Figure 3.06, a load management algorithm can be deduced to monitor the state of charge of the batteries and the evolution of the system during the essential loading conditions. Before this was done the hourly load demand was extrapolated to obtain 15mins interval as the solar irradiance data and this data is shown in Annex C. Thus, to achieve this aim, the system sizing results shown in Table 2.08 for three reuse pico-hydro turbines was adopted. This specified that the best combination was three pico-hydro turbines of 55W peak, with 1.67kW peak of solar panel and five units of 52Ah lead acid batteries will be sufficient for the essential load to be served all year round with minimal disruptions.

The main factor which was considered most important for managing the interaction of load is the SoC of the battery packs which can be obtained as [97]:

$$SOC_t = SOC_{t-1} \left[\frac{P_{load_t}}{\eta_{inv}} - (P_{PVt} + P_{HYDROt}) \right] \eta_{BC} \quad (3-06)$$

where; SOC_t and SOC_{t-1} are the current and previous state of charge of the battery,

P_{load_t} is the load demand (W),

η_{inv} is the inverter efficiency (adopted to be 95%),

P_{PVt} is the Power generated from the solar panel,

P_{HYDROt} is the power generated from the reuse pico-hydro turbine

Since the peak capacity of the photovoltaic and pico-hydro generators are known already, it is less cumbersome to handle any constraint which would determine the working conditions of

the battery system. To ensure that the battery safety is guaranteed, the SoC constraint is defined as follows:

$$SOC_{\min} \leq SOC_t \leq SOC_{\max} \quad (3-07)$$

where; SOC_{\min} is the minimum state of charge of the battery selected to be 20%,

SOC_{\max} is the maximum battery state of charge at full charge of 100%?

Thus, from this constraint, whenever the battery state of charge is less than 20%, the system shuts down. This decision will protect the batteries and ensure that they are not completely drained while in operation.

It is somewhat difficult to develop a desired energy management algorithm for a system that depends on the stochastic behaviour of weather data, but it is not impossible as long as certain constraints are fulfilled. Recall that it was explained in section 2.2 that the rural household load demand was established for only essential loads and thus the sizing results was intentionally designed for only essential loads. This is based on the assumption that critical loads are small load that can be easily powered for smooth day-to-day activity while other loads are set aside for luxury purposes. Thus the total load which is a sum of essential and non-essential loads shown in Figure 3.06 can be obtained as:

$$Pload_{Ess} = 0.4 * Pload_{Total} \quad (3-08)$$

where; $Pload_{Ess}$ is the essential load demand and

$Pload_{Total}$ is the total load demand which is the sum of essential and non-essential load

In order to achieve an energy management scheme for the reuse pico-hydro system, the battery state of charge is observed at every 15minutes for a daily period. Since annual average sunshine hours in a day is approximately six hours [98], a typical day will have some solar energy production between 08h00 and 17h00 irrespective of the time of the year. In view of this, a typical day is used to simulate the battery SoC to see the daily pattern of the battery banks under normal conditions. It is important to know that the solar generation is more of importance in this combination since the energy from the pico-hydro system is constant all year round (because river flowrate is sufficient for the reuse pico-hydro turbines as shown in subsection 2.5.2).

Since the battery SoC is the main driver of the energy management algorithm, some constraints are defined to achieve the main objective of ensuring that the battery state of charge is never zero. This aim is definitely dependent on energy generation from both the solar panels and the pico-hydro generator such that if there is no generation for too long, the battery will become too low thus resulting in a shutdown of the system. Besides from the state of charge constraint earlier defined in equation 3-06, the powerflow equation guiding the exchange of energy between the generators and the battery bank is constrained as:

$$Pload_t \leq Pgen_t + Pbatt_t \quad (3-09)$$

where; P_{load_t} is the load demand at any point in time

P_{batt_t} is the battery power input or output at any point in time, and

$$P_{gen_t} = P_{PV_t} + P_{HYDRO_t} \quad (3-10)$$

Thus, using a typical day having average number of sunshine hours as a case study, the battery initial state of charge is varied between minimum value 20% and full charge of 100% to see the final state of charge at the end of the day such that;

$$SOC_{final} \approx SOC_{initial} \quad (3-11)$$

where; $SOC_{initial}$ is the state of charge at the beginning of the day (t=1) and,

SOC_{final} is the state of charge at the end of the day (t=96).

Given the value where the final SoC at the end of the day is equal to the initial SoC at the beginning of the day, it is assured that the system can successfully serve the essential load within which it was designed at any point in time for the period of 24h without shutdown. Thus, the constraint described in equation (3-10) helps to select the best initial value of SoC for testing and setting and achieving energy management under different energy generation or load demand conditions.

3.5.1 Battery Energy Management Under Essential Load Conditions

In order to see the robustness of the system, and based on the conditions described in equations (3-05) to (3-10), several iterations were made varying the initial value of the battery state of charge at the beginning of the day. This is to see the behaviour of the system under varying daily conditions while assuming that the load is kept constant and energy generation is also similar. One of the advantage of the system is the possibility that the pico-hydro generator is available all year round due to the constant river flow rate as shown in Table A1.3 [66]. With this advantage, the based load can be taken care of all day since the energy from the hydro supply is available all day. The energy management investigation was performed for one day at 15minutes interval and the results are shown in Figure 3.07. The parameters used to initialise the simulation are shown in Table 3.04.

Table 3.04: Parameters for energy management

S/N	Parameter	Value
1.	Minimum Battery SoC	20%
2.	Maximum Battery SoC	100%
3.	Total battery Capacity	3120Wh
4.	Initial Battery SOC	20%:10:100%
5.	Inverter Efficiency	95%
6.	Charging/Discharging Efficiency	90%

Based on these input parameters, nine different sets of plots showing the values of the battery state of charge of charge against time as obtained is shown in Figure 3.07.

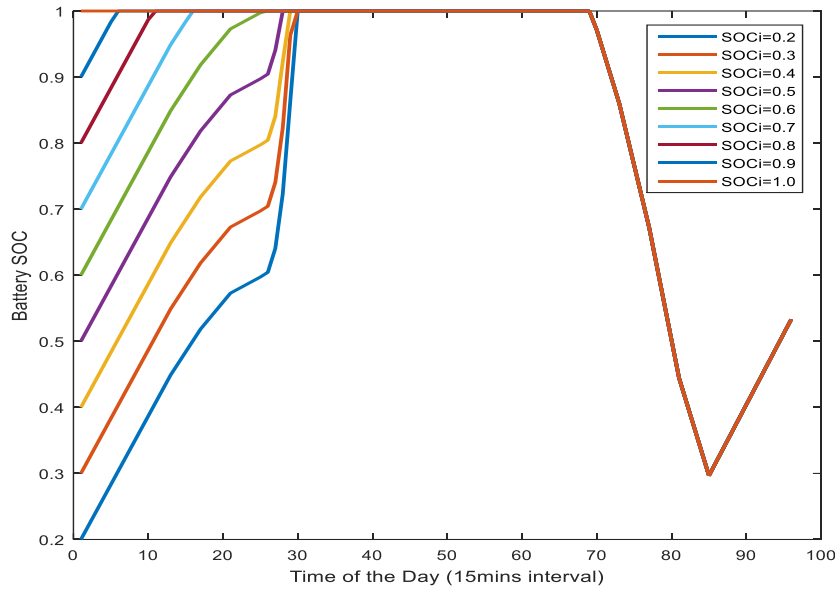


Figure 3.07: Battery State of Charge for essential loads only

Results in Figure 3.07 have established the fact that the system can satisfactorily supply the essential loads irrespective of initial SoC value at the beginning of the day and there is guarantee of zero downtime so long as there are sufficient sunshine hours. As long as the load demand does not vary, the results shown in Figure 3.07 has assisted in visualising the constraint stated in equation (3-10) whereby the final state of charge at the end of the day (i.e. at $t=96$) is 0.56. Thus, moving forward, this value will be used as the initial value of battery state of charge at the beginning of each day (i.e. $t=1$). The meaning of the criteria and SoC selection is to help display the behavioural pattern of the battery under a normal sunny day and the value can be used to test the system and battery SoC response under worst case scenario (i.e. a day with minimal or no sunshine due to rain or any other condition).

Since the behaviour of the system has been observed under normal/generic solar irradiance condition, a typical cloudy day with limited sunshine period is examined to see the system behaviour. However, further evaluations will be done with the initial SoC value (i.e. 0.56) assumed to be 0.56 which indicates the battery at the beginning of the day is 56%. The solar irradiance data for a predicted rainy day with little sunshine period is shown in Annex A3 and the SOC plot based on the current system size is shown in Figure 3.08.

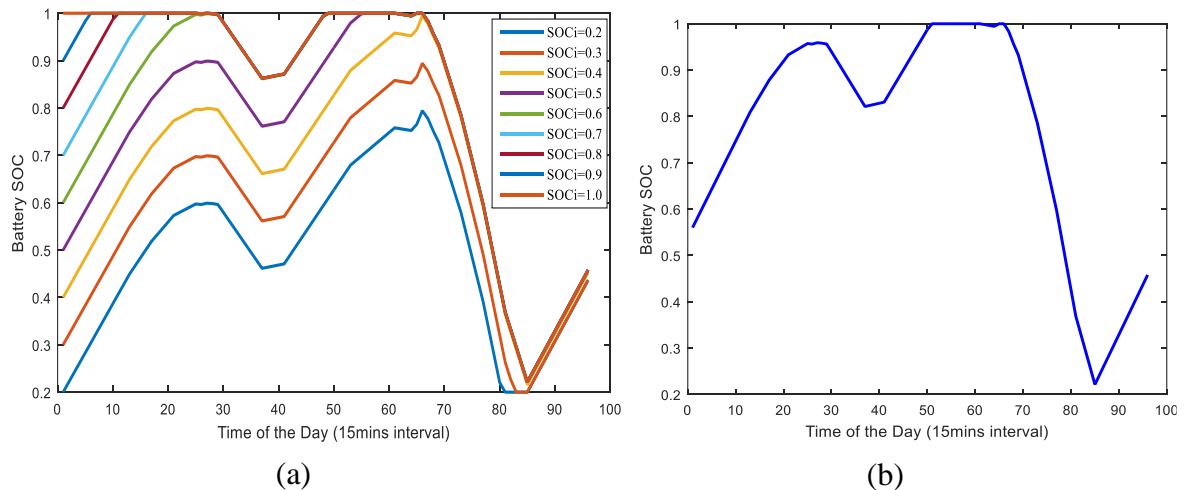


Figure 3.08: Battery SoC for essential loads only on a rainy day with low sunshine hours

It is evident that the system is able to sustain itself even during extremely poor weather conditions and avoid any downtime as long as the battery is above 40% at the beginning of the day as shown in Figure 3.08(a). Since the results shown in Figure 3.07 have indicated that on a normal day with a minimum of 5 hours of sunshine, the final SoC at the end of the day is approximately 56%, then the initial SoC was selected as 0.56 as shown in Figure 2.10(b). Thus it is easy to conclude that at the end of any average day with more than 5 hours of sunshine, and under the same loading conditions, the system will have zero downtime or loss of power supply if the next day happens to be a rainy day. This also justifies that for a bad insolation day which can occur randomly (especially in rainy season), the system can endure the whole day as long as there is 1-2 hours of sunshine. Therefore, it is clearly established that for the essential load, the reuse hybrid solar-pico-hydro system can withstand the one-day autonomy period if there is very little or insignificant sunshine hours. The next step is to observe how the system performs under total load conditions.

3.5.2 Battery Energy Management Under Total Load Conditions

As explained earlier, the essential load data was assumed to be forty percent of the total load that can be possibly connected in the household. Thus, the same procedure for the battery energy management was applied to the total load based in the parameter listed in Table 3.04 and the results are shown in Figure 3.09.

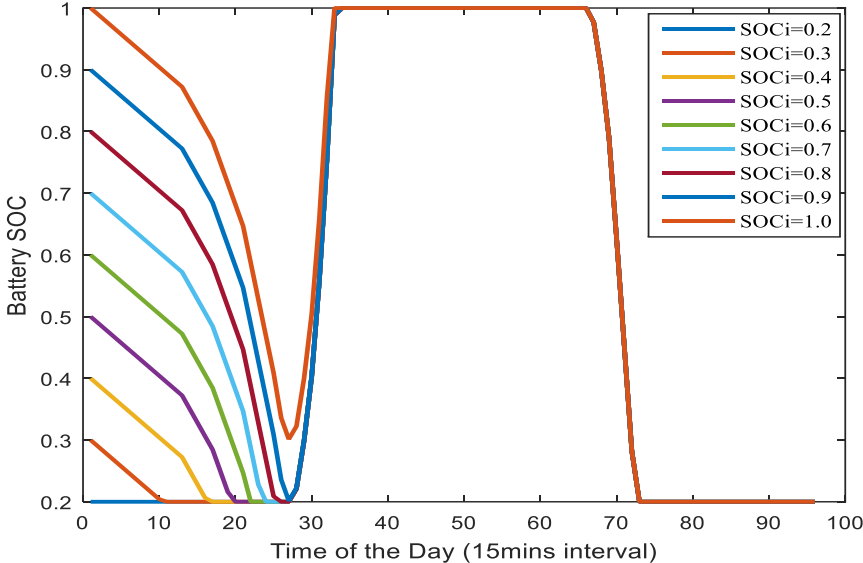


Figure 3.09: Battery State of Charge for total loads

It can be observed that depending on the initial battery state of charge, the system has several hours of shutdown (when $SoC \leq 20\%$) in the morning for Figure 3.09 and constantly after between 18h00 and 19h00 for all, irrespective of the initial SoC. This is indicative that the system only goes to full charge during peak sunshine hours and whenever there is no solar irradiance, the battery and the pico-hydro turbine do not supply enough energy to keep the system running. This is obviously due to the fact that the component sizing was done based on essential loading conditions only, thus this is not surprising. In order to mitigate this effect, load shifting can be applied to shift non-essential loads to another time whenever the solar irradiance forecast show the there is insufficient energy to keep the battery above a specific threshold. This can be the peak sunshine hours during which the battery is full and there is saturation for some hours as observed in Figure 3.07. Thus, the implementation of load shifting based on solar irradiance forecasting is investigated to see the energy management performance.

3.5.3 Battery Energy Management Based on Load Shifting of Non-Essential Loads

It has been clearly established that based on the sizing and battery SoC investigation, the system can successfully take care of all essential loads under normal conditions as expected. However, the investigation also indicated that the system will experience a lot of downtimes if non-essential loads are added on it as shown in Figure 3.09. Thus, in order to maximise the benefits of the abundant solar insolation during the daytime, two solutions are proposed. First is implementation of load shifting methodology to ensure that essential loads are served during peak sunshine hours only. Secondly is the inclusion of a load curtailing constraint which allows for more loads to be served based on the battery state of charge.

— Load Shifting

Load shifting basically involves shifting some amount from one-time period to another. This means that some amount of which are not served at a specific time of the day are moved to another time when the conditions are more favourable [99]. In this case, load shifting is introduced to shift nonessential loads to periods of sunshine hours only. As such, instead of shutting down solar energy production during periods when the battery is fully saturated, non-essential load can be served during this period while maintaining the battery SoC at maximum. The load duration curve for the shifted load is shown in Figure 3.10.

$$P_L = \begin{cases} \text{fort} = 1:28, & P_L = P_{Ess} \\ \text{fort} = 29:67 & P_L = P_{Shifted} \\ \text{fort} = 68:96 & P_L = P_{Ess} \end{cases} \quad (3-12)$$

where; $P_{Shifted}$ is the sum of non-essential loads outside sunshine hours (i.e. at $t=1:28$ and $t=68:96$).

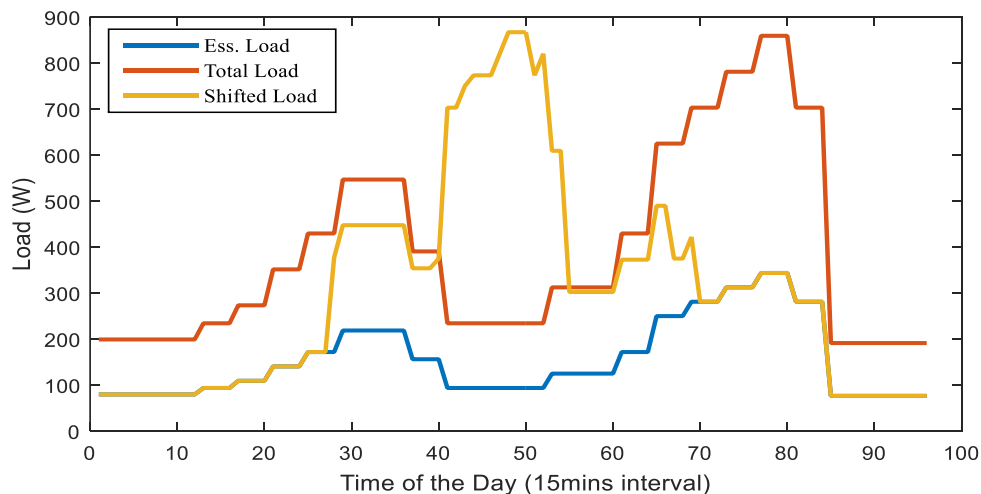


Figure 3.10: Load duration curve showing shifted load

The load shifting described in (3-12) is depicted in Figure 3.10 will be applied on a normal day with very good sunshine hours as done for the previous essential loads and total loads ins 3.5.1 and 3.5.2 respectively.

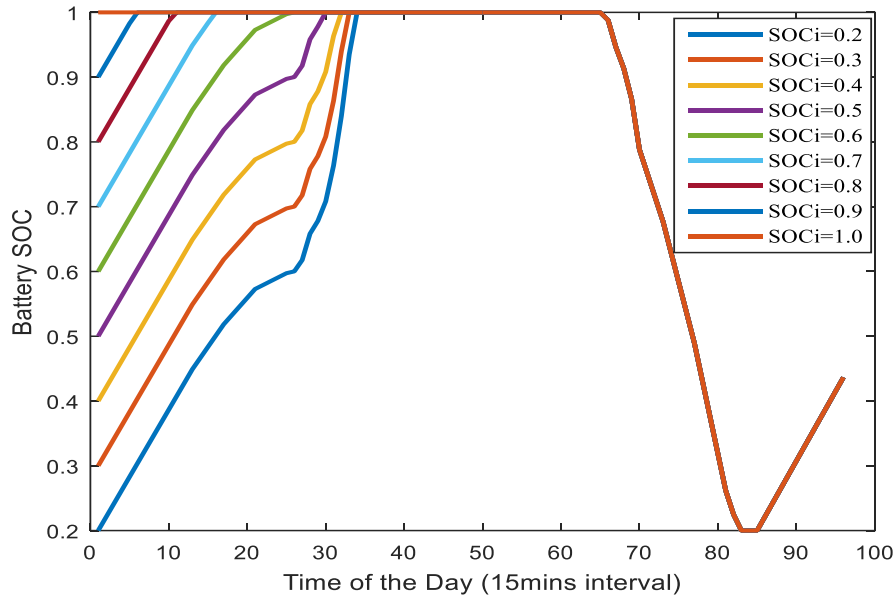


Figure 3.11: Battery SoC under shifted load

With the results shown in Figure 3.11, the load shifting is sufficient during the peak sunshine hours. However, there is a downtime of 1 hour which can be observed (between $t=82$ and $t=84$) for this day. Running the same shifted load on a typical rainy day with minimum sunshine will entirely show a different pattern for the battery SoC as the system will have multiple hours of downtime as shown in Figure 3.12.

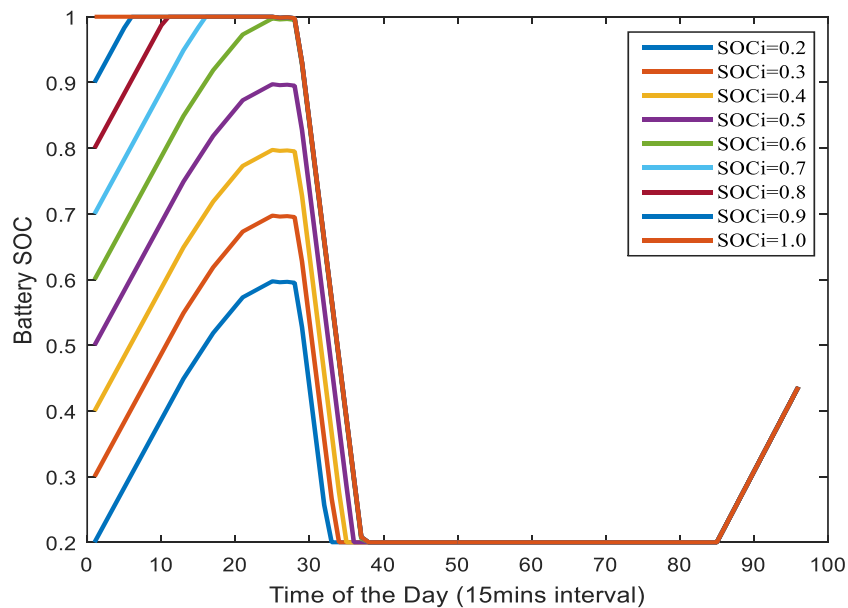


Figure 3.12: Load duration curve showing shifted load on a rainy day

From Figure 3.12, it is quite obvious that the system is unable to sustain the shifted load on a typical rainy day, irrespective of the initial battery SoC and thus there will be downtime during the day since there is limited sunshine. This is obviously expected since the system sizing was done for only essential load and the shifted load is only taking advantage of battery saturation during the peak sunshine hours. In order to ensure the system runs even under limited solar irradiance condition, a load curtailing constraint is introduced under the shifted load condition.

— Load Curtailment

Curtailing is the process of reducing load demand during some specific periods of time due to constraints such as insufficient generation, emergencies or congestion [100]. It is an energy management process that is adopted when supply is insufficient. For the shifted load scenario, shown in Figures 3.11 and 3.12, load curtailment is proposed to avoid system shutdown irrespective of the amount of sunshine hours in a day. In order to achieve this, a constraint is introduced such that whenever the battery is below 50%, only essential loads are served:

$$\text{if } SOC_t < 0.5, Pload_{t+1} = 0.4Pload_t \quad (3-13)$$

Equation (3-12) will ensure that irrespective of the solar irradiance during the day, the current battery state of charge will determine the amount of load that can be served and the system will not shutdown abruptly if there's a day with inadequate amount of sunshine as seen in Figure 3.12. Based on equation (3-13), the result of the battery SoC under this constraint for total load and is investigated as shown in Figure 3.13. It is important to note that the battery initial SoC is set at 56% since it is assumed that after a normal sunny day, the final SoC is approximately 56% as indicated in subsection 3.5.1.

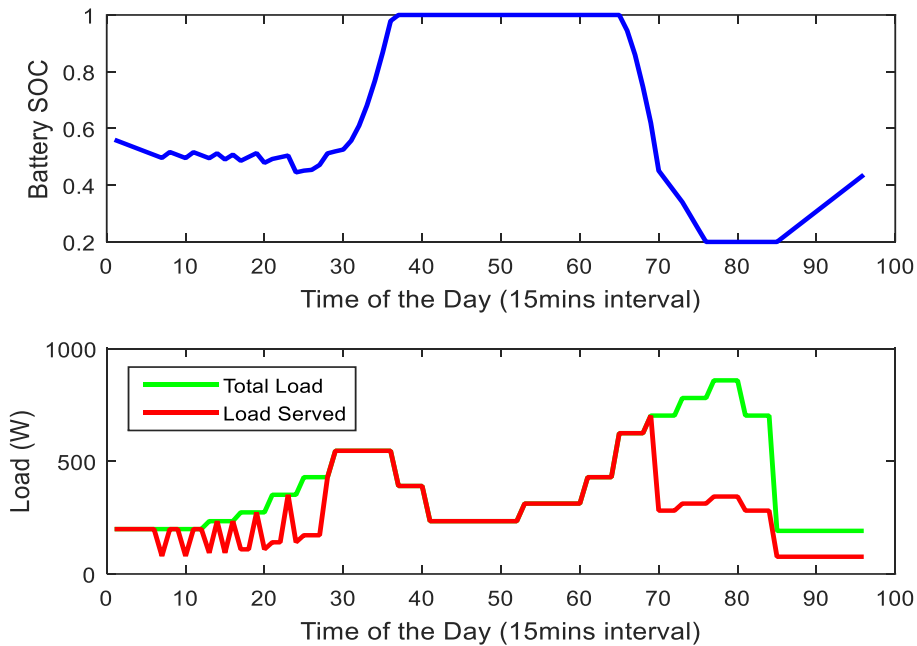


Figure 3.13: Battery SoC under load curtailment for total load

Since the aim is to reduce system downtime as much as possible, a combination of the load shifting and load curtailment conditions are used to develop an energy management algorithm which would be used to manage the reuse hybrid system under whichever loading conditions (total load, essential load, or shifted load) as the case may be.

3.5.4 Battery Energy Management Algorithm

The combination of load shifting and load curtailment technique under certain constraints defined by the battery state of charge can be used to design an energy management algorithm. The algorithm is intended to ensure the system derives maximum benefit from the available power from both the generators and the battery at every point in time. In addition, the maximum load

possible must be served at all times while adequately protecting the battery from potential damage or complete discharge. The flowchart that describes the proposed energy management algorithm for this system is shown in Figure 3.14. For decision making implementation, the energy management algorithm can be linked with the real-time ARIMA forecasting algorithm described in subsection 3.3 to ensure prompt decision making

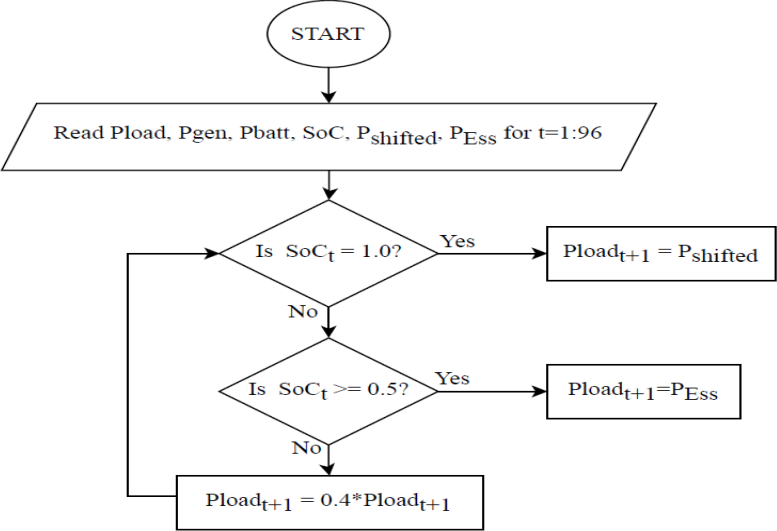


Figure 3.14: Flowchart for battery energy management algorithm

From the flowchart shown in Figure 3.14, this is an indication that the shifted load profile is given priority which means all non-essential loads are only served during the sunshine hours or whenever the battery is fully charged. Furthermore, whenever the battery is below 50%, curtailment is introduced to ensure there is no system outage. Figure 3.15 highlights a combination of load shifting and curtailment which has successfully eliminated any system downtime that was observed in Figure 3.13 while serving majority of the load. This indicates that so long as the constraint is being respected under normal solar irradiance condition, the system is guaranteed zero downtime. On the contrary, for a typical rainy day with poor amount of solar irradiance, the battery SoC is presented in Figure 3.16 for total load and shifted load profiles respectively.

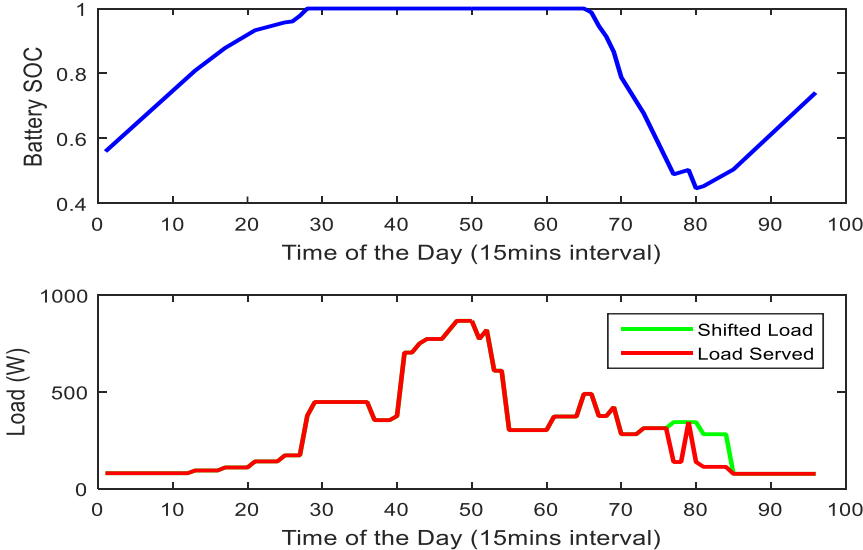


Figure 3.15: Battery SoC under prioritised energy management for shifted load

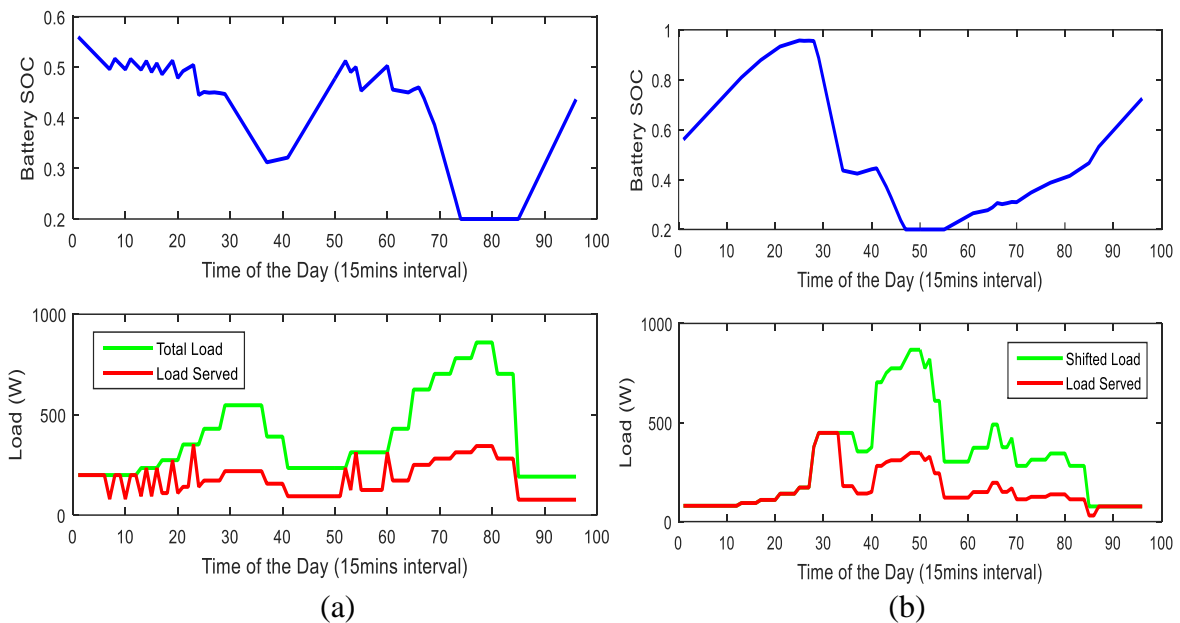


Figure 3.16: Battery SoC under prioritised energy management during a rainy day

Figure 3.16(a) shows the battery SoC under total load conditions for a rainy day while Figure 3.16(b) shows the SoC for shifted load for the same rainy day. Obviously from both plots, not all loads can be served since the amount of sunshine on this specific day is very low but the downtime is also reduced to ensure some loads can be served all through the day. Thus, non-essential loads such as refrigeration, ironing, or even air conditioning and other deferrable loads will be unusable during days like this. In addition, due to the constraints guiding the battery energy management algorithm, the period of downtime has significantly reduced when compared to the SoC results shown in Figure 3.12 where the system downtime was almost half of the whole day.

3.6 Conclusion

The modelling and forecasting of times series data based on a real-time ARIMA model has been presented and the effectiveness of the forecasting technique was tested on solar irradiance data. Furthermore, the forecasted solar irradiance data was used to develop an energy management plan for the reuse hybrid solar-pico-hydro system to ensure that the battery state of charge is effectively optimised to serve the loads in a household. The SoC results ensured that, not only were there was no blackouts/downtime during the use of essential loads, but also there is a possibility of including additional loads as long as solar irradiance is averagely available (for 4-6 hours) daily. This is achievable without compromising on size/cost of the system or management of worst case scenario but consequently results in a minimal downtime of 1 hour. To improve on this drawback, load shifting was introduced to ensure that all additional or non-essential loads are served during the sunshine hours of the day since it was observed that there was battery saturation at this time. The energy management scheme was then modified to include load shifting and load curtailment and the results proved to be excellent during a normal sunny day as there was no downtime. However, for a typical rainy day, the system downtime was observed to be approximately 2 hours in a day when compared to 11 hours for the system without the energy management scheme. These results have proven the possibility of deriving maximum benefits from reuse solar-pico-hydro system if installed in a rural household. The final step is to investigate the effect of deploying this solution on the

environment by performing a life cycle assessment focused on environmental impact assessment.

CHAPTER FOUR

LIFE CYCLE ASSESSMENT OF REUSE HYBRID SOLAR-PICO HYDRO GENERATION SYSTEM

4.1 Introduction

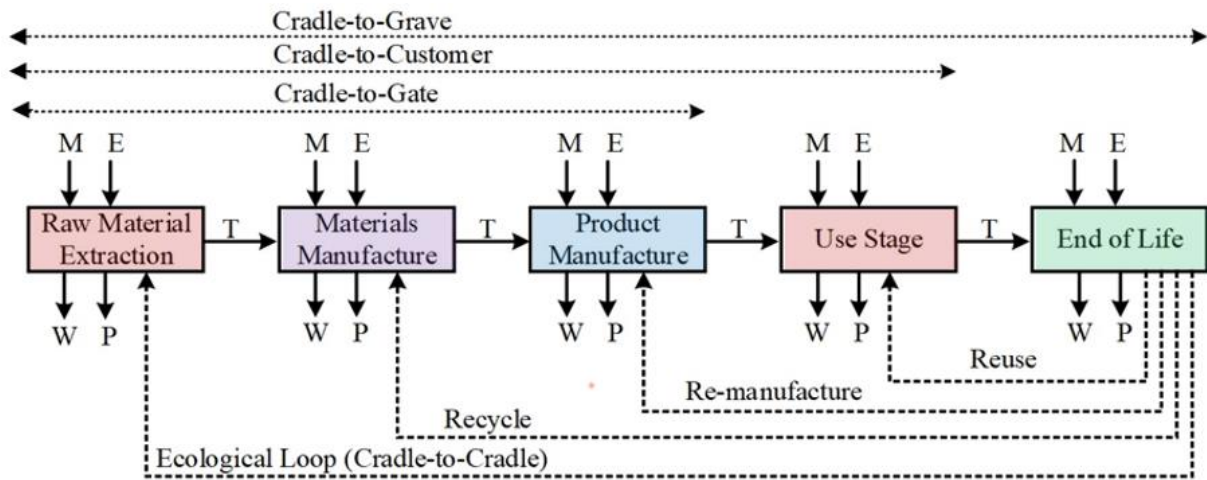
In this chapter, a comprehensive Life Cycle Assessment (LCA) and environmental impact analysis is conducted for the hybrid solar-pico hydro system designed based on reuse components, with a focus on its application for energy generation in a typical household. Since the components of the reuse system have been designed and a systemic approach to ensure the reuse system can satisfy the energy needs of a small household was also achieved, the final step involves applying LCA to evaluate its environmental impact throughout its lifecycle. Utilizing the ISO 14040/44 standards, each component within the reuse system is identified and assessed. The Simapro software is employed for modelling, utilizing the IMPACT 2002+ method to conduct an environmental impact assessment. This enables us to highlight the contribution of each component to the overall environmental impact.

Furthermore, a comparative analysis is undertaken between the reuse system and a new conventional system. This comparative evaluation aims to underscore the advantages offered by the reuse system, shedding light on its superior environmental performance.

4.2 General overview of LCA

By definition, life cycle assessment is a comprehensive and systemic approach used in analysing and calculating the environmental impacts of a product, process or service throughout its entire lifetime [101]. This process involves the exploration of all the contributory effects of every component (from manufacture stage to the end-of-life/disposal phase) that make up a specific product, while evaluating the cumulative effects over their lifetime [102]. This includes raw material extraction, manufacturing processes, transportation, and the use phase. All contributing effects, such as the machinery used in each phase, maintenance, and other associated factors, are also taken into account in the life cycle assessment.

The main aim of LCA is to identify the environmental burdens caused by a product (as well as its processes and activities) by exploring opportunities for reducing the impacts of this product or item over its lifetime. To do this, the environmental impact needs to be studied before possible review or decisions can be taken to reduce the environmental burden of the product. From a global perspective, life cycle assessment was conceptualized since the 1990s when there was a debate on the most effective standard for comparison between two or more products having the same objective(s) [103]. When environmental concerns, such as resource depletion, energy efficiency, and pollution, gained prominence, companies started using indexes such as energy efficiency, pollution control and solid waste management to justify better products. But, there was no standard procedure or uniform methodology, limiting the acceptability of these claims. In the 1990s, an organisation called Society of Environmental Toxicology and Chemistry (SETAC) developed a standardized code of practice for a uniform guide in performing life cycle assessment. This development triggered the publication of journals, workshops, and forums in the field of LCA. Subsequently, the International Organization for Standardization (ISO) created two standard frameworks for LCA: ISO 14040 and ISO 14044. Life cycle assessment is generally divided into several subcomponents: raw material extraction, manufacturing, packaging, distribution, use phase, and disposal phase. Each of these phases has its associated impacts at every stage, and the overall combination is what makes the total impact contribution of a product or service to the Earth, as shown in Figure 4.01. Depending on the approach and desired goals, life cycle assessment could be cradle to gate, cradle to customer, cradle to grave or cradle to cradle [104].



M= Materials, E= Energy, W= Waste, P= Pollution, T=Transport

Figure 4.01: Phases of life cycle assessment [104]

The ISO 14040 describes the principles and framework for performing life cycle assessment while the ISO 14044 describes the specific requirements and guidelines for life cycle assessment analysis. The ISO-14040 standard is the backbone of LCA of today which defines the LCA process in four phases: the goal and scope definition, inventory analysis, impact assessment and interpretation [105].

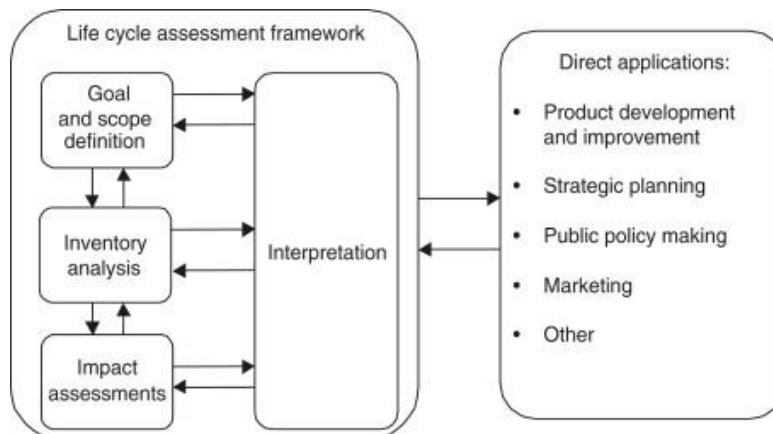


Figure 4.02: LCA framework [106]

— Goal and Scope Definition

The first step is a descriptive phase, whereby the focus of the problem is defined and explained. The definition of the purpose of the assessment, its boundaries, and the identification of the product or service that will be evaluated is clearly stated. According to ISO 14040 guidelines, this phase requires a detailed and unambiguous explanation of the intended application, the rationale for conducting the LCA study, the target audience, and whether the results will be publicly disclosed for comparative assertions [105].

After defining the goal of the study, it is also important to concisely define the scope of the study. When defining the scope, two pivotal factors are the functional unit and system boundaries, both instrumental in elucidating the study's limitations. The functional unit serves as a quantified measure of a product or service which can be used to describe the performance of the product or service and can serve as a means of comparison. The functional unit needs to be quantitative and precise, broadly defined and be specific to performance requirements. In addition, system boundaries define the limits of the study. This explains the set of criteria that

determines the processes to be considered, the corresponding inputs and outputs as well as the associated impacts during life cycle assessment [102,103,107]. These boundaries can also be defined in terms of life cycle stages of a product and the geographical scope of product use or service implementation as the case may be.

— **Life Cycle Inventory Analysis**

Life cycle inventory is a comprehensive list of all the inputs and outputs associated with each stage of the entire life of a product or service under study. The life cycle inventory analysis is the most tedious, cumbersome and time-consuming aspect of life cycle assessment. This phase provides a detailed understanding of the resource consumption, emissions, and environmental burdens of each process associated with the different stages of the product or service’s life cycle [101]. Life cycle inventory analysis first involves collecting data for all processes, activities, and raw materials relevant to the study (extraction, manufacturing, transportation, usage, maintenance, and end-of-life disposal or recycling or reuse, as the case may be). The next step is to compile this data into input and output inventories. Examples of input inventory include materials used, energy consumed, water usage, etc., while the output inventory encompasses products, emissions, and waste. Thirdly, the defined functional unit is used to correspondingly scale each inventory sub-data to define the performance of the product or service before transforming the information into impact categories, which will be explained in the next subsection. Figure 4.03 is an illustration of life cycle inventory analysis.

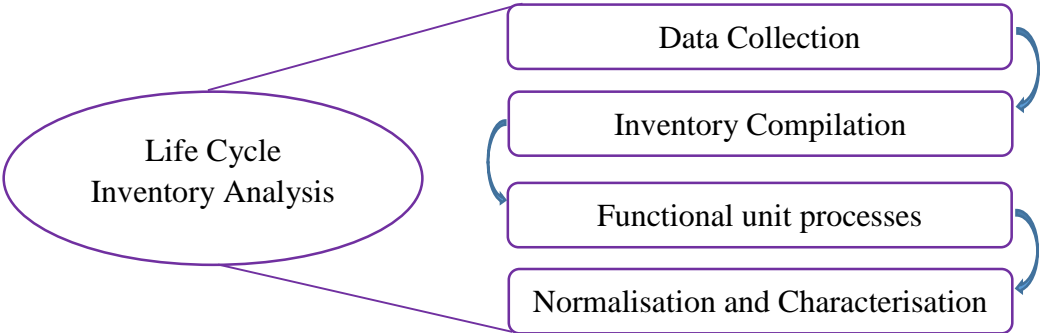


Figure 4.03: Life cycle inventory analysis

— **Life Cycle Impact Assessment**

The impact assessment phase provides an insight into the environmental impacts based on the life cycle inventory flows. This is the stage where each of the inventory results is assigned to a specific impact category by focusing on, and classifying indicators from the inventory data into their categories [103,108]. Impact assessment phase completes the LCA process and the outcome can be classified into: Characterization, Normalization, Weighting, and Aggregation [107,109,110].

There are numerous impact categories that can be considered during the life cycle impact assessment phase. There are a lot of specific categories and variations which are dependent mostly on the scope of the study but the most commonly used impact categories in LCA applications are: Global Warming Potential (GWP), Acidification, Eutrophication, Ozone depletion, Human toxicity, Ecotoxicity (Freshwater, Marine, Terrestrial), Depletion of Abiotic Resources, Land use, Water use, Resource depletion, Human health, Biodiversity, Land transformation, Ionizing radiation [111]. These impact categories have been continuously updated and adopted for uniformity and standard comparison based on different impact characterization and interpretation.

Generally, in life cycle impact assessment, impact categories are classified into two: midpoint and endpoint categories. This makes it possible to have a general structure for the environmental impact assessment of products or services and give foresight for easy characterization and interpretation.

1. **The Midpoint Category:** These are categories which belong to, or are associated with factors that contribute directly to environmental impacts. They represent the intermediate steps in the impact assessment process that are highly detailed, scientifically quantifiable representation of their potential impact contributions.
2. **The Endpoint Category:** The endpoint category has a larger and more holistic combination of indicators that concentrates more on human wellbeing and environmental quality. A more generic perspective is given by this category and it makes it quite easier for communication and decision-making purposes with non-specialists in the field of LCA. The endpoint category is a combination of midpoint category indicators but focuses more on the final consequences on the environment.

Table 4.01: Comparison between endpoint and midpoint impact categories

Endpoint Impact categories	Midpoint Impact Categories
They focus on ultimate environmental impacts	They focus on specific environmental impacts
They simplify complex cause and effect relationship between emission and environmental impacts	They provide more detailed and more specific information about each environmental contribution to overall impact
Easier for non-experts to understand	They require some expertise to understand
They may oversimplify complex interactions leading to misinterpretation	They may be less intuitive for non-experts
They directly relate to generally recognisable impacts	They allow for the assessment of trade-offs between different environmental impacts

Table 4.01 shows the similarities and differences between endpoint and midpoint categories. In as much as the life cycle interpretation phase requires a broad multidisciplinary knowledge and effective communication, endpoint category is often for decision makers and stakeholders who only want to see the overall environmental impact of a product or service to guide in sustainable decision-making and choices. Midpoint category, on the contrary, gives deeper insights for specific and more detailed interpretation and can guide in merging practical applicability of the product or service choices with actions that can provide a more sustainable design. The midpoint category can be summarised into four encompassing categories represented as damage category as shown in Figure 4.04. This presentation of the impact contribution can easily be interpreted as it gives a general view of LCA results.

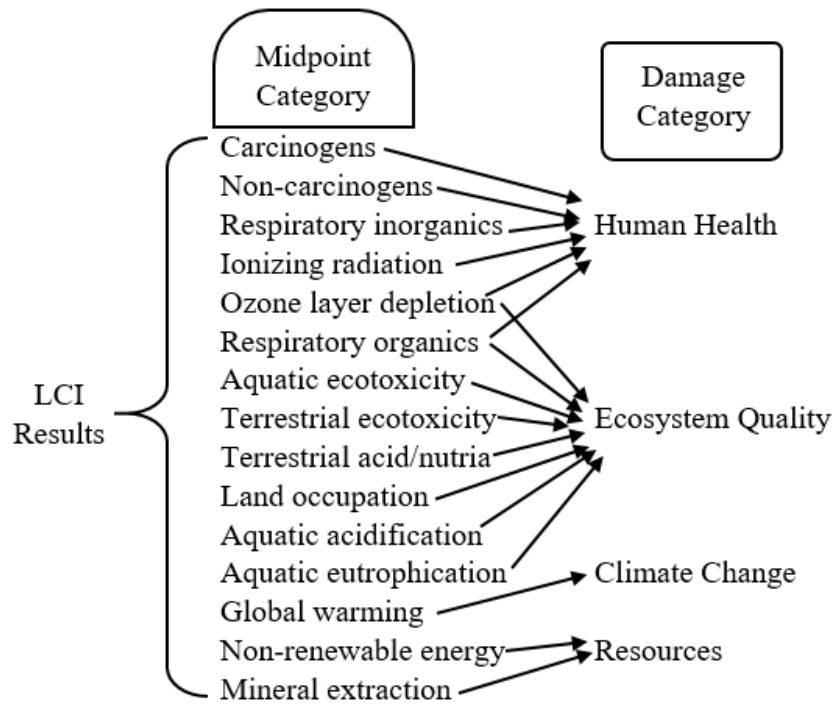


Figure 4.04: Overview of life cycle impact category

— Life Cycle Interpretation

The results of the impact categories need to be interpreted to fully understand the essence of the life cycle assessment study. The life cycle interpretation is the final phase of life cycle assessment which can guide for comparison, product or system redesign, decision-making and many more. The interpretation encompasses the procedures to completely analyse and conclude on the outcome of the study. It can be used to compare different scenario, perform comparative and sensitivity analysis, and identify improvement opportunities that can also involve life cycle management [107,110]. The materials and energy flows compiled in the inventory phase are classified based on their potential impacts on the environment.

1. **Characterization:** the process that involves quantifying and classifying each particular impact category based on a common unit, thus translating the collected inventory data into impact scores for specific impact categories. This is done by multiplying each category contribution as followed in the flow process by their characterization factor to obtain the specific indicator result for that category [112]. Characterization factors are numerical values that aggregates the quantity of a specific input or output with its potential impact on the environment [111]. The indicator results based on characterization can be expressed as:

$$Indicator\ result_{cat} = \sum_i m_i \times Characterization\ factor_{cat,i} \quad (4-01)$$

Where; i is the type of intervention (substance or resource extraction) and m_i is the mass of the substance i in kg.

2. **Normalization:** Just like characterization, normalization is another result presentation technique whereby the impact assessment results are compared with a reference value or benchmark. It provides a relative overview of the magnitude of respective impacts by expressing them in relation to a common or easily understood parameter. This reference parameter could relate to a given person, community, or system over a specific period of time. It can also be an indicator for checking consistency and communicating

information based on relative significance of the result or vice versa [111,112]. The normalized indicators results can be expressed as:

$$\text{Normalised indicator result}_{cat} = \frac{\text{Indicator result}_{cat}}{\text{reference}_{cat}} \quad (4-02)$$

Normalisation is a crucial step in communicating LCA results as it can be used to contextualise the severity of each impact category and can be used to make sustainable decisions in redesigning or re-orienting the system, product or service being assessed.

3. **Weighting:** This is an optional aspect in LCA result presentation. It involves assigning weights (indicating relative importance) to specific impact categories based on stakeholder decisions or specific societal demands. Additionally, weighting aggregates the normalised impact results into a single score, providing a generic overview of the overall environmental performance and can be expressed as [111,112]:

$$\text{Weighting impacted score} = \sum_i \text{impact score}_i \times m_i \quad (4-03)$$

Weighting can vary for each method, as the exact weighting formula and factors may differ based on individual user decisions. Therefore, it is optional and not commonly utilized, except in situations where specific interests are explicitly declared.

4. **Aggregation:** as the name implies, this step involves adding or summation of all impact scores of the different impact categories to obtain an overall perspective of the impact contribution of the product or service. The aggregated results only present the life cycle assessment in the simplest possible form by showing a combined presentation of all impact categories in a singular form [101,110,111]. It is expressed as:

$$\text{Total aggregate score} = \sum_i \text{impact score for each category} \quad (4-04)$$

Most LCA studies present results based on characterization or normalization, as this is generally comparable in relation to the functional unit. To complete the explanation of life cycle interpretation, it is important to discuss the presentation of impacts results and their significance or meaning/representation. Figure 4.04 shows the impact categories that comprise the midpoint and endpoint categories. These categories indicate different environmental impact damage, as shown in Table 4.02 [108,113].

These impacts categories are interpreted holistically to provide a comprehensive life cycle assessment report for a product or service. However, this does not mean that there are no limitations in LCA studies, and these limitations may impact the accuracy of the study. The results of LCA studies are highly dependent on the availability of data, such that, the more data you have, the more cumbersome it becomes. Additionally, LCA studies are time-consuming and can be quite expensive due to the numerous expertise required. To address some of these challenges, specialized software programs have been developed and adopted for LCA analysis.

Table 4.02: Impact categories and their interpretations

S/N	Impact Category	Inference	Unit
1.	Carcinogens	Potential to cause cancer	kg C ₂ H ₂ Cl equivalent
2.	Non-carcinogens	Potential to cause adverse health effect but not related to cancer	kg C ₂ H ₂ Cl equivalent
3.	Respiratory inorganics	Potential to cause respiratory diseases	kg PM _{2.5} equivalent
4.	Ionizing radiation	Potential to cause adverse health due to exposure to radiation (*Bq means Becquerel; a unit for measuring radioactivity)	Bq c-14 equivalent
5.	Ozone layer depletion	Potential to release ozone layer depleting substances (CFC, HCFC, etc.)	kg CFC-11 equivalent
6.	Respiratory organics	Potential to cause respiratory diseases specifically from organic compounds that have Carbon-Hydrogen (C-H) bonds	kg C ₂ H ₄ equivalent
7.	Aquatic ecotoxicity	Potential to have adverse effect on aquatic ecosystems and inhabitants	kg TEG water
8.	Terrestrial ecotoxicity	Potential to have adverse effect on terrestrial ecosystems and inhabitants	kg TEG soil
9.	Terrestrial acidification/nutrication	Potential to cause changes in soil acidity and nutrient imbalance	kg SO ₂ equivalent
10.	Land occupation	Potential to cause distortion in land use, ecosystem, biodiversity and land related factors	m ² org. arable
11.	Aquatic acidification	Potential to cause imbalance in the acidic content and pH of water bodies	kg SO ₂ equivalent
12.	Aquatic eutrophication	Potential to disrupt aquatic ecosystem by disorienting growth of algae and aquatic plants	kg PO ₄ P-limitation
13.	Global warming potential	Potential to distort greenhouse gases and cause global warming	kg CO ₂ equivalent
14.	Non-renewable energy	Potential of causing depletion in available non-renewable energy sources such as fossil fuels	MJ primary
15.	Mineral extraction	Potential of causing depletion in earth crust minerals as a result of activities such as mining, quarrying etc.	MJ surplus

Several software packages are commercially available for use in performing LCA studies, with each one having its unique merit and demerit based on users' preference. However, all these software products follow the same guideline and pattern based on the ISO 14040-44 standards for conducting life cycle assessment. A list of commercially available software for life cycle assessment are shown in Table 4.03. Simapro software is selected for the study in this scenario as it is the most preferred software and has the highest ratings from most LCA specialists.

Table 4.03: LCA software

S/N	Software	Availability
1.	Ecochain	Cloud based (ecochain.com)
2.	GaBi	Downloadable (gabi-software.com)
3.	Oneclicklca	Cloud based (oneclicklca.com)
4.	Brightway	Cloud based (github.com/LCA-ActivityBrowser)
5.	OpenLCA	Downloadable (openlca.org)
6.	SimaPro	Downloadable (Simapro.com)

— Simapro Software

The Simapro software is a licensed software used for conducting life cycle assessment and other sustainability-related studies. Developed by PRé consultants, this software provides a platform to model, replicate, and analyze the life cycle of a product along with its associated flows, from raw material extraction to disposal after use. All events associated with these life cycle flows are integrated into the inventory of the software, allowing for systematic processing of impacts at each stage. Users can define and model the life cycle of any product or system by defining the inputs, outputs, and processes involved at each stage. Users can easily quantify and see the impact assessments methods and categories as well as outcomes of all the impacts categories for interpretation and further analyses. Finally, results can be visualized, compared and customized as desired. Thus, the Simapro software is generally adopted for its numerous advantages. It is also noteworthy that Simapro is constantly updated, thus reflecting the latest advancements in LCA data and methodologies [114].

The hybrid solar pico-hydro system which was described in subsection 2.3 will be subjected to a life cycle assessment study. The components sizes are the key parameters required to commence the LCA study since the ISO 14044 standard procedure involves the use of weights of all components that make up the product. Thus, emphases will be placed on how the weights of each component was obtained [14]. In order to model the system on Simapro, all subcomponents are disassembled, identified and weighed accordingly and this information is used to choose the inventory details on Simapro. The reuse hybrid solar-pico-hydro system was divided into five parts for easier modelling. The parts comprising the subcomponents are: the induction machine (which serves as the electric generator), The reuse turbine system (mechanical drive unit), the solar panel and its components, lead acid battery and the power supply unit with inverters. Each component is individually explained in the subsequent subsections describing the life cycle inventory. Each subcomponent was modelled in Simapro as primary data and EcoInvent 3.9.1 database was used for secondary data inputs. The entire system comprising all the components and data was analysed using IMPACT 2002+ method and the corresponding results discussed accordingly. All the standard steps of performing LCA are followed and discussed subsequently.

4.3 Life Cycle Assessment of a reuse Hybrid Solar Pico-Hydro System

The hybrid solar-pico hydro system which was described in subsection 2.3 will be subjected to a life cycle assessment study. The components sizes are the key parameters required to initiate the LCA study. In order to model the system on Simapro, all subcomponents are disassembled, identified and taken into account, and this information is used to choose the inventory details from EcoInvent 3.9.1 database. The reuse hybrid solar-pico hydro system was divided into five parts. The parts comprising the subcomponents are: the induction machine (which serves as the electric generator), the reuse turbine system (mechanical drive unit), the solar panel and its components, lead acid battery and the power supply unit with inverters. Each component is

individually explained in the subsequent subsections describing the life cycle inventory. Each subcomponent was modelled in Simapro as primary data and EcoInvent database was used for secondary data inputs. The entire system comprising all the components and data was analysed using IMPACT 2002+ method and the corresponding results discussed accordingly. All the standard steps of performing life cycle assessment are followed and discussed subsequently.

The exploration of life cycle assessment for reused components in energy generation applications is a developing area of research. However, since the emergence of renewable energy, several authors have delved into the life cycle impacts of both new and recycled options for renewable energy generation systems. This research has contributed significantly to elucidating the consequences of choices in deploying renewable energy systems for energy generation purposes. For example, [115] investigated the impacts of nine power-generating alternatives in a stand-alone mobile house, concluding that wind energy generation with backup supply from a diesel-powered generator is the most environmentally friendly means of energy generation for a mobile household. This insight underscores the need for adoption of LCA studies in all areas even to gain a comprehensive understanding of the impact contributions of different systems. Other investigations such as [116] highlighting the significance of LCA and life cycle cost in new methods of energy storage in small compressed air energy storage system for photovoltaic systems have been able to stress the dynamic nature of life cycle assessment.

Furthermore, the positive effect of reusing components and second-life applications have been highlighted as advantageous, as shown in [117]. In this study, an investigation into the LCA of a solar PV system based on reused components revealed a reduced environmental impact compared to a new system. Numerous other advantages of LCA have been extensively discussed, while various reviews have underscored its major limitations, including a lack of comprehensive publications in some specific areas, the complexity of inventory allocation, and the absence of validation assurance that models perfectly represent real-life scenario [111,118,119]. Additional limitations include the scarcity of inventory data which, as experienced in the course of this study and reliability of data as mentioned in [1].

Despite the limited availability of publications in the realm of LCA studies for reused components in the context of energy generation through renewable energy systems, this study investigates the LCA of a reuse hybrid solar-pico hydro generation system. The implementation of the LCA will be done such that the impact contributions of the reuse components will be a fraction of their total impacts during their lifetime as annotated in Figure 4.05. Subsequent details of the processes are explained in the succeeding subsections. The findings are then compared with those of a new system serving the same purpose. Assumptions based on available inventory data are presented, and to ensure a fair comparison of results, the systems are modeled under similar conditions and disposal scenarios.

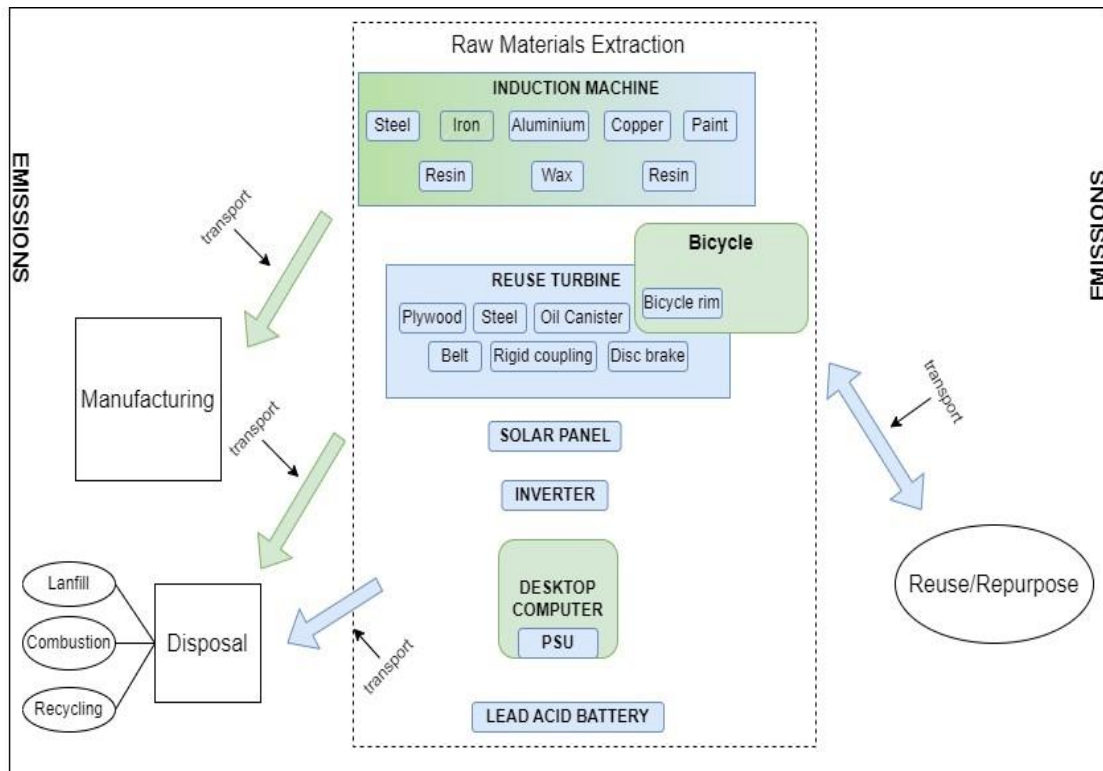


Figure 4.05: Life cycle of the reuse hybrid generation system

4.3.1 Goal and Scope Definition

The goal of this life cycle assessment is to study and evaluate the environmental impacts of a frugal innovation hydro generation system based on reuse materials. This will be accomplished by first investigating the impacts of the reuse system on its own. Subsequently, the study will explore the impact of the pico-hydro generator when hybridized with solar systems, also utilizing reused materials. Finally, the environmental performance of the reuse hybrid system will be compared with that of a new conventional technology hybrid system serving the same purpose. The evaluation spans from cradle to customer, encompassing all aspects of both systems, with modeling conducted from the extraction phase to the disposal phase.

— Functional Unit

The functional unit is to satisfy the daily load demand of a rural household in Nigeria for a period of five years using hybrid solar-hydro reuse technology for energy generation. Furthermore, it aims at analysing the environmental impact assessment of reuse generation system (Solar-Hydro) for delivering an annual energy demand of 3068 Wh. Thus, the reuse system sizing design must ensure that the load is met for the next five years. This means that it is necessary to incorporate the total number of components that make up the system (as well as replacements where applicable). Based on this functional unit, a new system which is based on the latest technology in the Nigerian market is compared with the reuse system.

— System boundary

Defining system boundaries is crucial as reused components only contribute to their second-life impacts. These components have already been used during a first lifetime, and thus, their impacts during this initial period should be excluded from our study. This represents a significant advantage of the reuse solution, since these components have not undergone

complex recycling procedures; instead, they are simply repurposed for a second life to generate electricity.

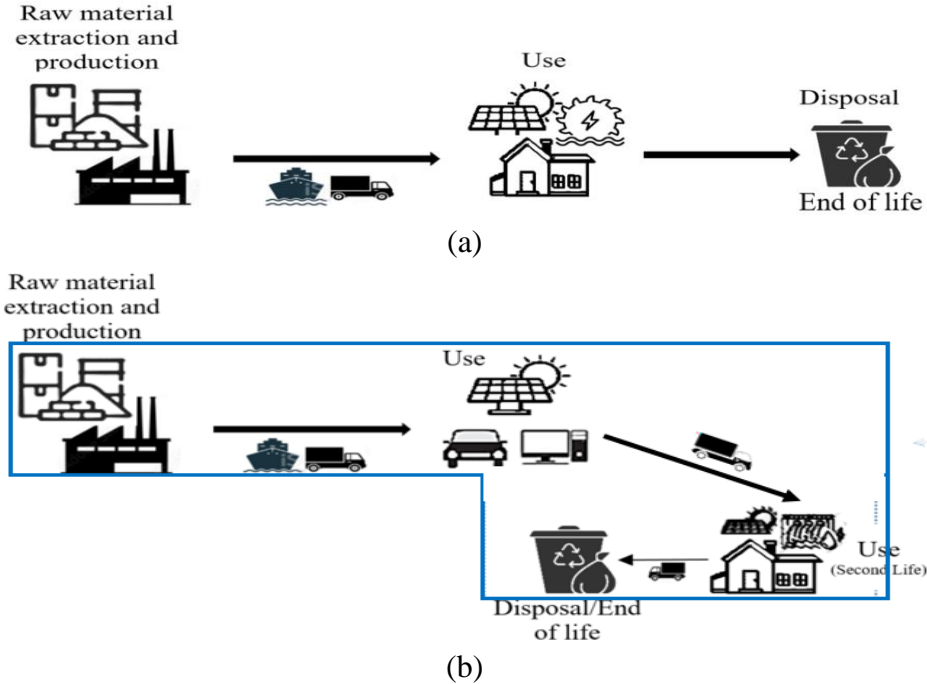


Figure 4.06: (a) LCA boundary for conventional system [117] (b) LCA boundary for reuse system

The system boundary for the conventional solution follows the pattern shown in Figure 4.06 (a) while Figure 4.06 (b) delineates the boundary of the reuse solution. Since all the reuse components already have undergone an initial usage lifetime, it is important to clearly specify that a second life scenario is being considered based on a meticulous examination of the behaviour of these components after their first lifetime. Amongst other assumptions, to be highlighted as needed, three particularly crucial assumptions collectively establish the boundaries for this study of the reuse phase.

1. The number of years each component served for its primary purpose in the first life and the subsequent number of years it can be reused before replacement. The second lifetime is expressed as a ratio of the first life.
2. The efficiency of the component during the reuse lifetime (which is lower for some components). This efficiency directly influences the performance of the components, exemplified by the typical case of aging in batteries, where it reduces the reuse lifetime.
3. The study explicitly excludes the impact of the components' first lifetime. Consequently, the impacts during the reuse lifetime represent only a fraction of the total impacts incurred by components throughout their entire lifespan, encompassing both the first use phase and the subsequent reuse phase.

Table 4.04 shows the list of assumptions based on the assumed lifetime of the reuse components with respect to their total lifetime. These assumptions are generally derived from recommendations by popular manufacturers regarding the total lifetime of the devices or components.

As an example, an induction machine has an average usage lifetime of fifteen years before potential breakage [120]. However, in certain situations, especially in developing countries, it can be repaired and continue serving for an additional lifetime of five years. For the reuse turbine system, there are several components but considering the fact that the plywood will constantly be in water, it is used as a benchmark for estimating the overall lifetime of the turbine. An initial lifetime of ten years was set as a general standard. Given that the reuse turbine system requires manual re-assembling before reuse, the expected reuse lifetime was assumed to be half of the initial lifetime, i.e. five years. This assumption takes into account possible repairs and maintenance during the re-assembly process.

Table 4.04: Components of reuse turbine

S/N	Components/Parts	Total lifetime (years)	Reuse lifetime (years)	Percentage of impact during reuse period (%)
1.	Induction Machine (400W)	15	5	33.33
2.	Reuse turbine	10	5	50
3.	Power Supply Unit	5	1	20
4.	Solar Panel	30	5	16.67
5.	Inverter	5	2	40
6.	Lead Acid Battery	4	1	25

The reuse lifetime of power supply units was capped at one year since most electronic devices have a lifetime ranging between 1.5-16 years depending on the components and usage conditions [121]. Consequently, we assumed a total lifetime for the PSU of five years, which corresponds to the average life of a desktop computer.

For solar panels, with an average lifetime of thirty years, the assumed reuse lifetime was set at five years. In contrast, the inverter, also an electronic device with a total lifetime of five years, was assumed to have a reuse lifetime of two years. Lastly, the lead acid battery was estimated to have a reuse lifetime of one year, while its total lifetime was assumed to be four years. These assumptions are grounded in practical considerations and industry standards to provide a comprehensive perspective on the reuse phase of these components.

4.3.2 Life Cycle Inventory

The inventory of the system will be divided into several subsections for easier comprehension. The procedural guideline for inventory collection based on the ISO 14040 standard is observed for the reuse components. With the exception of the electric machine, which was not decoupled, all other components were disassembled, identified and measured accordingly. Each component was then selected in EcoInvent based on the available data and in instances where exact desired information is not available, the closest alternative is chosen. The rationale for such choices is systematically explained. The hybrid reuse system is divided into five subcomponent parts for easier analysis and understanding. These subcomponents include the induction machine, the reuse hydro turbine, the power supply unit, the solar panel (along with its associated components), and the reuse lead acid battery.

4.3.2.1 The induction machine

For the purpose of life cycle assessment, the induction machine is generally referred to as the electric generator that converts the mechanical energy from the reuse hydro turbine into electricity. A 0.4kW electric machine is selected for the reuse hydro system based on the

analysis presented in [58] and the system sizing procedure explained in subsection 2.2. However, inventory data for this machine size was unavailable in the literature, thus making it quite complex to perfectly represent the desired machine. Data for three different sizes of induction machines (which are 0.37kW, 1.1kW and 11kW) were obtained from [122,123]. The materials that make up an induction machine at manufacturing phase are listed in Table 4.05. For each of the material, the required weight for a 0.4kW machine is extrapolated using the models obtained respectively. Each material is treated uniquely, with the model equation for each graph used to determine the corresponding weight based on the data for machines ranging from 0.37kW to 11kW. The choice of these three machines was driven by the scarcity of materials inventory details and information regarding the manufacturing of electric machine. Furthermore, it was assumed that the materials that comprise induction machines are the same for both motors and generators from which the masses of each component was derived. Table 4.05 provides a comprehensive list of all the components constituting the induction machine, along with their respective masses.

Table 4.05: Component of the induction machine

S/N	Materials	0.37kW	1.1kW	11kW
1.	Electrical Steel (kg)	3.885	5.94	39.6
2.	Other steel (kg)	0.777	1.65	10.45
3.	Cast iron (kg)	1.11	2.75	14.3
4.	Aluminium (kg)	1.332	1.87	9.9
5.	Copper (kg)	0.703	1.364	7.04
6.	Insulation material (kg)	0.0222	0.055	0.22
7.	Packing material (kg)	0.74	1.1	9.9
8.	Impregnation resin (kg)	0.148	0.33	1.1
9	Paint (kg)	0.0444	0.11	0.55

— Electrical steel and other steel

Electrical steel is a low magnetic loss, high permeability steel specially designed for electrical equipment that require efficient magnetic flux conversion. Usually used in the manufacturing of equipment that requires effective conversion of magnetic flux, it serves as a low-alloyed steel which contributes to the overall efficiency of the machine. While other types of steel, such as stainless steel or alloy steel, may be present in the machine, they are typically used for different aspects of production, such as braising or casing. Thus, low-alloyed steel is selected as electrical steel, while unalloyed steel was considered for other applications This decision is based on the types of steel available in EcoInvent and the fact that most steel types share a similar manufacturing process with only slight variations. For the weight of steel required for 0.4kW machine, the model equations obtained for each graph are expressed in (4-05) and (4-06) for electrical steel and other steel respectively (see Figure 4.07):

$$y = 0.055x^2 + 2.7342x + 2.8658 \quad (4-05)$$

$$y = -0.0289x^2 + 1.2382x + 0.3228 \quad (4-06)$$

where; y is the weight of electrical steel for figure 4.07 (a), the weight of other steel for figure 4.07 (b) and x is the power rating of the electric machine in kilowatts in both cases.

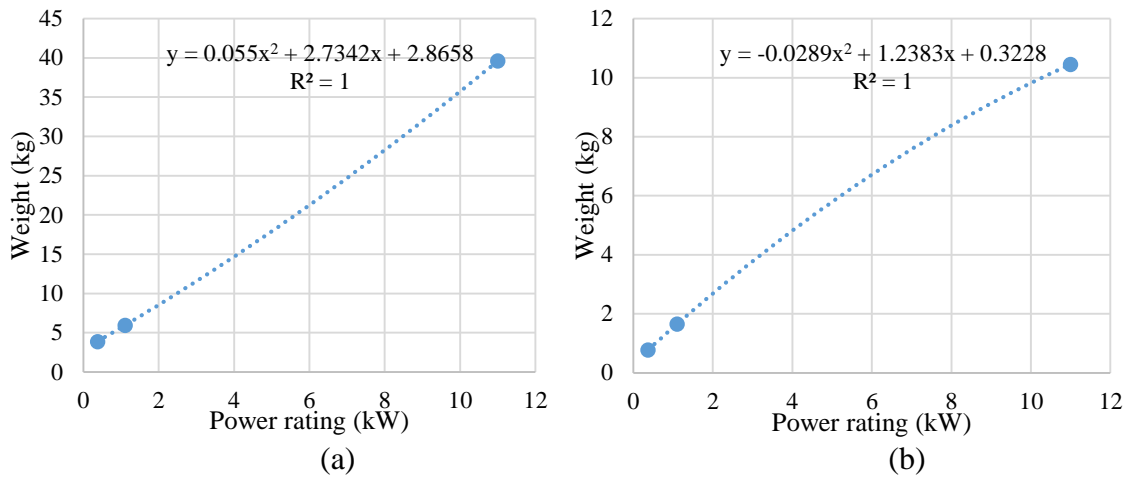


Figure 4.07: Model of weight against power rating of electric machines for (a) Electrical steel and (b) Other steel- R-squared is referred to as the coefficient of determination in regression analysis.

— Cast Iron

Cast iron, in contrast to steel, is primarily utilized for mechanical strength or support in electrical machines and may be employed in housing frames or specialized rotors. To maintain clarity and consistency in the investigation, a generic cast iron is selected from the EcoInvent database, eliminating ambiguities associated with this material. Similar to the approach taken for steel, the models that represent cast iron and aluminium are shown in Figure 4.08. The generic equations for these models are as follows:

$$y = -0.1016x^2 + 2.3959x + 0.2374 \quad (4-07)$$

$$y = 0.8082x + 1.0079 \quad (4-08)$$

where; y is the weight of cast iron for figure 4.08 (a), weight of aluminium for figure 4.08 (b) and x is the power rating of the electric machine in kilowatts for both (a) and (b).

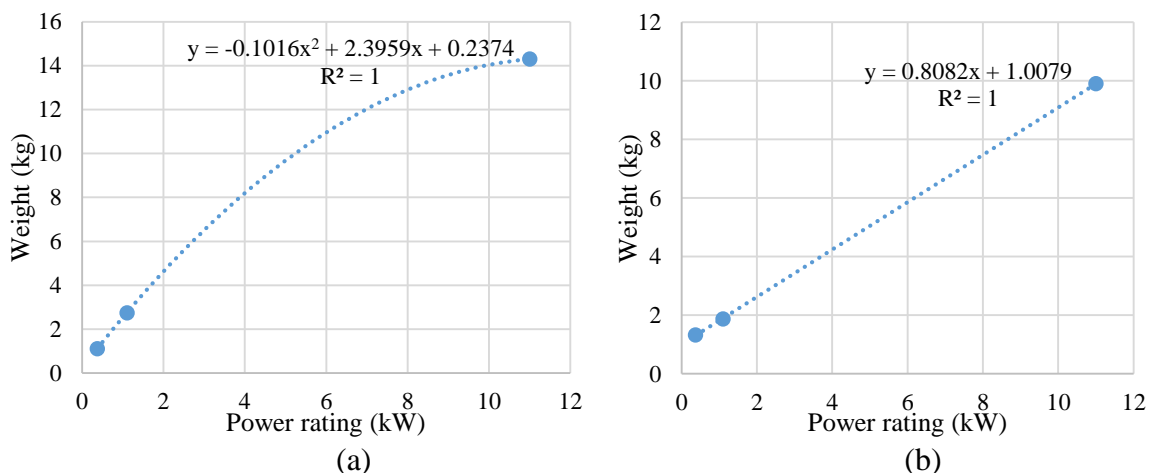


Figure 4.08: Model of weight against power rating of electric machines for (a) Cast iron and (b) Aluminium- R-squared is referred to as the coefficient of determination in regression analysis.

— Aluminium

Aluminum is extensively employed in the manufacturing of electric machines due to its lightweight nature, making it suitable for various purposes and different subcomponents. It finds application in heat sinks, enclosures, and other components, as per the manufacturer's specifications.

Generally, Aluminium Metal Matrix Composite (AMMC) is used in the production of electric machines due to its high strength, stiffness, low density and corrosion resistance. AMMC consists of highly pure Aluminium which can be reinforced by Alumina (Al_2O_3), Silicon Carbide (SiC) or Titanium Carbide (TiC) depending on the specific requirements [124]. A significant advantage of AMMC lies on its utilization of reused aluminium from scrap which saves about 90% of the impacts instead of using Aluminium manufactured from scratch [125].

— Copper

The use of copper in electric machines can never be overemphasized, due to its numerous and excellent combination of electrical and thermal properties. However, due to its relatively higher cost, manufacturers limit its use to critical components and explore substitutes where applicable. Copper is commonly employed in windings, but it can also find application in other crucial areas, including interconnections, rotor and stator cores, terminals, and more. For the purpose of this investigation, copper is selected from EcoInvent, which specifically represents concentrated copper, also known as Electrolytic-Tough Pitch (ETP), which is characterized by its 99% purity level.

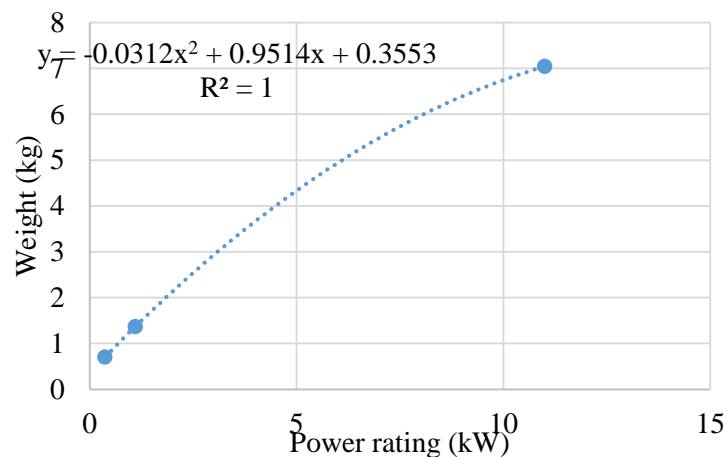


Figure 4.09: Model of weight against power rating of electric machines for copper - R-squared is referred to as the coefficient of determination in regression analysis.

Figure 4.09 represents the model of the weight of copper against the power rating of the electric machine. The model equation describing this relationship is shown in equation (4-09):

$$y = -0.0312x^2 + 0.9514x + 0.3553 \quad (4-09)$$

where; y is the weight of weight of copper in kilograms and x is the power rating of the electric machine in kilowatts.

— Insulation and Packing Materials

Paraffin wax is chosen as the insulation material in this scenario due to its widespread use and availability. While insulation materials are not explicitly defined, the selection of paraffin wax

in EcoInvent is justified by its popularity and the assumption that the same insulation material is used for all insulation aspects of the electric machine manufacturing procedure. In addition, flexible foam and paper packaging are chosen in EcoInvent, representing generally obtainable packaging materials.

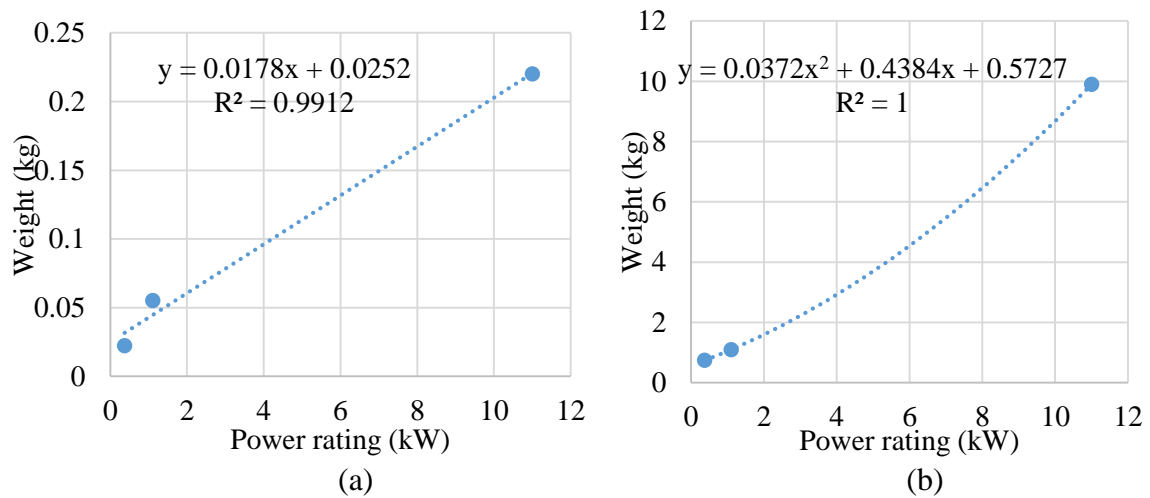


Figure 4.10: model of weight against power rating of electric machines for (a) Insulation material and (b) Packaging material- R-squared is referred to as the coefficient of determination in regression analysis.

The models representing insulation material and packaging material are shown in Figure 4.10 while the generic equations for these models are as follows:

$$y = 0.0178x + 0.0252 \quad (4-10)$$

$$y = 0.0372x^2 + 0.4384x + 0.5727 \quad (4-11)$$

where; y is the weight of insulation material for Figure 4.10 (a), weight of packaging material for Figure 4.10 (b) and x is the power rating of the electric machine in kilowatts for both (a) and (b).

— Impregnation resin and paint

Resins are mostly used for filling voids and gaps, primarily serving purposes such as protection and dampening. Typically composed of polyester, they are selected as "Polyester resins" in EcoInvent to represent their use in the electric machine manufacturing process. Resins contribute to enhancing protection and minimizing vibrations within the components.

In addition, paint serves as a finishing product, providing surface shining and enhancing aesthetics. It is selected in EcoInvent without ambiguity, representing its role in the final stages of the electric machine manufacturing process.

Finally, for impregnating resin and paint, the models are shown in Figure 4.11. The generic model equation can be given as:

$$y = -0.0845x + 0.1748 \quad (4-12)$$

$$y = 0.0462x + 0.0427 \quad (4-13)$$

where; y is the weight of impregnating resin for Figure 4.11 (a), weight of paint for Figure 4.11 (b) and x is the power rating of the electric machine in kilowatts for both (a) and (b).

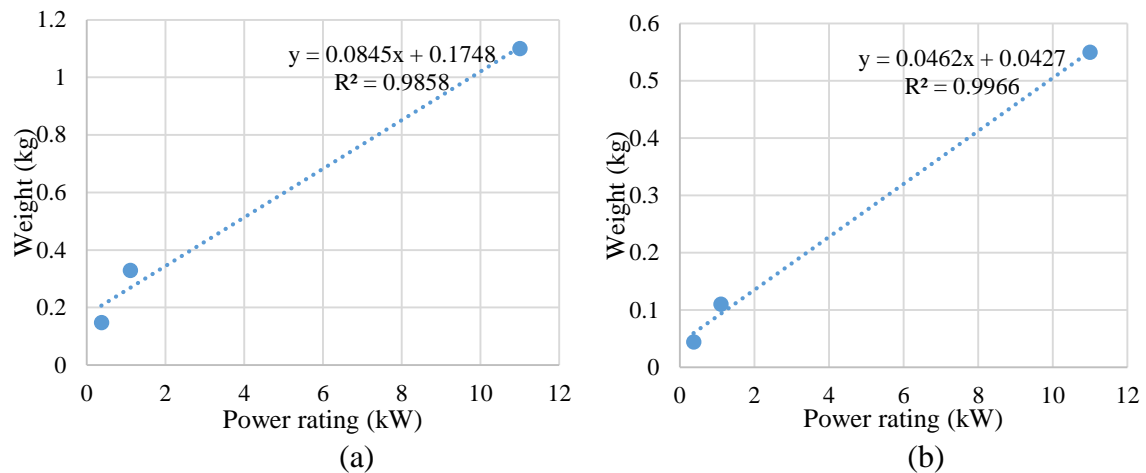


Figure 4.11: Model of weight against power rating of electric machines for (a) Impregnation resin and (b) Paint- R-squared is referred to as the coefficient of determination in regression analysis.

For each of the material used in the electric machine, each model described from equation (4-05) to (4-13) were used to obtain the values of the corresponding weights of the materials required for 0.4 kW electric machine and the results are summarised in Table 4.06.

Table 4.06: Weights of materials/components for electric machine

S/N	Materials	Weight (kg)	Input in EcoInvent database
1.	Electrical Steel	3.96828	Steel, low-alloyed {GLO}
2.	Other steel	0.77188	Steel, unalloyed {GLO}
3.	Cast iron	1.17950	Cast iron {GLO}
4.	Aluminium	1.35400	Aluminium alloy, metal matrix composite {GLO}
5.	Copper	0.73087	Copper {GLO}
6.	Insulation material	0.02359	Wax, lost-wax casting {GLO}
7.	Packing material	0.75401	Waste packaging paper {GLO}
8.	Impregnation resin	0.15582	Polyester resin, unsaturated {GLO}
9	Paint	0.04715	Electrostatic paint {GLO}
*GLO: Global			

For each of the materials listed in Table 4.06, the corresponding weights were inputted into EcoInvent, thus creating a model that accurately represents the composition of the electric machine.

4.3.2.2 The reuse turbine

The reuse turbine is the mechanical aspect of the hydro turbine which is used for transferring energy from the moving water to the induction machine which in turn generates electricity. This turbine is a concept of frugal innovation which was explained in subsection 2.3 and thus all the components were dismantled, identified and weighed individually for the purpose of the LCA study.

Table 4.07: Weight of materials/components of reuse turbine

S/N	Component		Material	Weight (kg)	Input in Simapro database
1.	Oil storage canister		Steel	4.65	Steel unalloyed {GLO}
2.	Marine plywood		Tropical hard wood	11.5	Plywood {ROW}
3.	steel frame		Steel	0.6	Reinforcing steel {GLO}
4.	26-inch bicycle rim	Ring	Reinforced Aluminium	0.385	Aluminium scrap, post consumer {GLO}
		Spokes	Steel	0.504	Steel, low-alloyed {GLO}
5.	Disc brake		Cast iron	0.300	Cast iron {GLO}
6.	Link belt		Polyurethane Leather	0.8	Polyurethane adhesive {GLO}
7.	Belt bearing		Elastoproxy rubber	0.35	Synthetic rubber {GLO}
8.	Rigid Coupling		Reinforced Aluminium	0.8	Aluminium alloy, ALi {GLO}

From the list of materials provided in Table 4.07, a bicycle rim is fundamentally made up of two different materials which are reinforced aluminium and steel whereby the ring is aluminium and the spokes are made of steel.

4.3.2.3 Solar panel and its components

The solar panel generally considered is available on Simapro in terms of the required surface area. This is easily relatable since the amount of energy generated by solar panels is dependent on the solar irradiance, surface area and panel efficiency. According to data from majority of PV panels manufacturers, the density of a solar panel having approximately 15% efficiency has been estimated to be around 12kg/m² [1]. Thus, the area of PV can be calculated using:

$$A_{PV} = \frac{P_{PV}}{\mathfrak{S}_{PV}} \quad (4-09)$$

where; P_{PV} is the size of the PV module required and \mathfrak{S}_{PV} is the efficiency of the PV module.

Based on equation (4-09), for each of the sizing the corresponding area of PV module required as input in Simapro is highlighted in Table 4.08.

Table 4.08: Solar panel required for input in Simapro

No. of Hydro Generators	Solar Module		Lead Acid Batteries (52Ah)	
	Peak Power (kW)	Area required (m ²)	Number of Batteries	Weight (kg)
1	3.1	20.67	9	135
2	2.31	15.4	7	107
3	1.7	11.13	5	75
Input in Simapro database	Photovoltaic panel, single-Si wafer {RER}		Battery, lead acid, rechargeable, stationary {RoW}	
*ROW: Rest of the world; RER: Europe				

4.3.2.4 Lead acid battery

Similar to the solar panel case, the design of the battery must also be considered in life cycle modeling. Therefore, it is essential to convert the sizing results for batteries into the respective weights of their components. In the economic analysis detailed in the second chapter, it was observed that the weight of batteries varied among manufacturers, regardless of the Ah-rating. Consequently, an average weight of 15 kg was selected based on a general observation of the weight of 52Ah lead acid car batteries, which was taken into account during the sizing process.

Since the lead acid battery is directly available in EcoInvent database, there is only the need to specify the weight desired based on the lifetime of the study period. The weights and the corresponding input in Simapro are highlighted in Table 4.08 alongside the solar panels results for each corresponding load estimation technique.

4.3.2.5 Power Supply Unit and Inverter

The operation and functionality of the PSU have been explained in subsection 2.3, along with the rationale for determining the necessary quantity of PSUs. This determination is grounded in the power and voltage balance constraint between the solar module and the combined PSU configuration. As the PSU is readily accessible in the EcoInvent database, the only requisite action is to specify the number of PSUs in the system, which, in this instance, is four. The inverter, similar to the battery and PSU, is also directly available in EcoInvent. The Simapro input for both the PSU and inverter is displayed in Table 4.09.

Table 4.09: PSU and Inverter input in Simapro

	Power Supply Unit	Inverter (0.5 kW)
Amount	4	1
Input in Simapro database	Power supply unit, for desktop computer {RoW}	Inverter, 0.5kW {RoW}

4.3.2.6 Transportation

The distance travelled by each of the components from production till its end of life is described under transportation. In this study, since the location considered is a rural area in Nigeria, some assumptions are made to create the transportation scenario of the final product. The assumptions are as follows:

1. The solar panels and their components, battery, inverter etc.) are imported from China via sea and they have to be moved using freight lorries from the ports to the rural area.
2. The reuse components are obtained and disposed within ten percent (10%) radius of the distance between sea port to location of consumption.
3. The reuse products have a total of three different transportation scenario (from China to Nigeria via sea, for the port to rural area via road, 10% of distance from port to rural area for reuse purpose). This means that reuse components are sourced close to the rural areas where the system will be used.
4. The distance after use to disposal is negligible.
5. The distance to local retailers is not considered.

Based on the assumptions listed, the transportation data and the corresponding Simapro inputs are highlighted in Table 4.10

Table 4.10: Transportation details and input in Simapro

S/N	Location	Distance (km)	Input in Simapro database
1.	China to Nigeria (sea freight)	19,576	Transport, freight, sea, container ship {GLO}
2.	Within Nigeria (seaport to first use consumer)	1,006	Transport, freight, lorry > 32 metric ton, EURO6, {GLO}
3.	Within Nigeria (from first use to reuse consumer)	100	Transport, freight, lorry > 32 metric ton, EURO6, {GLO}

From Table 4.10, in addition to the assumptions listed earlier, it is important to highlight that the end user of the reuse system is located in a rural settlement in Katsina state, Nigeria (lat.12.98°N & long. 7.62°E). The distances for sea travel were sourced from “fluentcargo.com” while road distances were obtained from “maps.google.com”. These distances are estimations and may not be 100% accurate, as they can vary based on the specific starting and ending points. These transportation values will also be utilized in sensitivity analysis to evaluate the impact of changes in distance on the results of the impact assessment.

4.3.3 Impact Assessment Results

The impact assessment results are divided into two segments: initially, focusing on the exclusive outcomes from reusing the pico-hydro turbine, and subsequently, examining the results arising from the hybrid solar-hydro reuse system. The results of the reuse hybrid system are then compared with those of a conventional hybrid system which serves the same purpose based on the same functional unit. The conventional system incorporates state-of-the-art technology prevalent in Nigeria's renewable energy market, with all components being newly manufactured.

To achieve the lifetime specified in the functional unit, the components in the inventory database were aggregated to allocate the total mass of components which will satisfy the defined lifetime, referred to as the component service time, and detailed in Table 4.11. The components listed in Table 4.11 represent the base case scenario for the design of the reuse solution. These values are dependent on the sizing results discussed in Chapter 2 and can be modified accordingly.

Table 4.11: Components lifetime and replacement

S/N	Components/Parts	Component Lifetime	Number of components	Number of replacement	Total number of Component for 5 years
1.	Induction Machine (400W)	5 years	1	-	1
2.	Reuse turbine	5 years	1	-	1
3.	Power Supply Unit	1 year	4	16	20
4.	Solar Panel	10 years	1 set	-	1 set
5.	Inverter	2 years	1	1.5	2.5
6.	Lead Acid Battery	1 year	1 set	4 sets	5 sets

4.3.3.1 Impact assessment results of reuse hydro system

The reuse pico-hydro system consists of two key components, as discussed in subsections 4.3.4: the induction machine and the mechanical turbine. Utilizing the inventory data presented in

Tables 4.05 and 4.06, the system was modelled in Simapro, and the IMPACT 2002+ method was employed for analysis. The results from the analysis will be presented in three formats; the midpoint impact categories (characterisation), the normalised impact categories (based on global normalisation), and the damage assessment. Additionally, a Sankey diagram illustrating the contribution magnitude of each component is included.

For each of these results, the contribution of each component that constitutes the reuse hydro turbine to the overall total impact is illustrated. Based on the midpoint impact assessment, fifteen impact categories are presented for the three different results. Figure 4.12 shows the characterised midpoint impacts and it can be observed that plywood, aluminium, steel and copper are the major contributors to the environmental impacts. This is not surprising given the rigorous exploration processes these components undergo, from mining to raw materials processing. Likewise, in Figure 4.13, the legend corresponds to the one presented at the top of Figure 4.12 and the results in Figure 4.13 follows the same trend. In contrast, the damage assessment indicates zero values for aquatic acidification and eutrophication. This suggests that the reuse turbine system does not have any potential to cause damages to aquatic life or affect the balance in pH of water bodies.

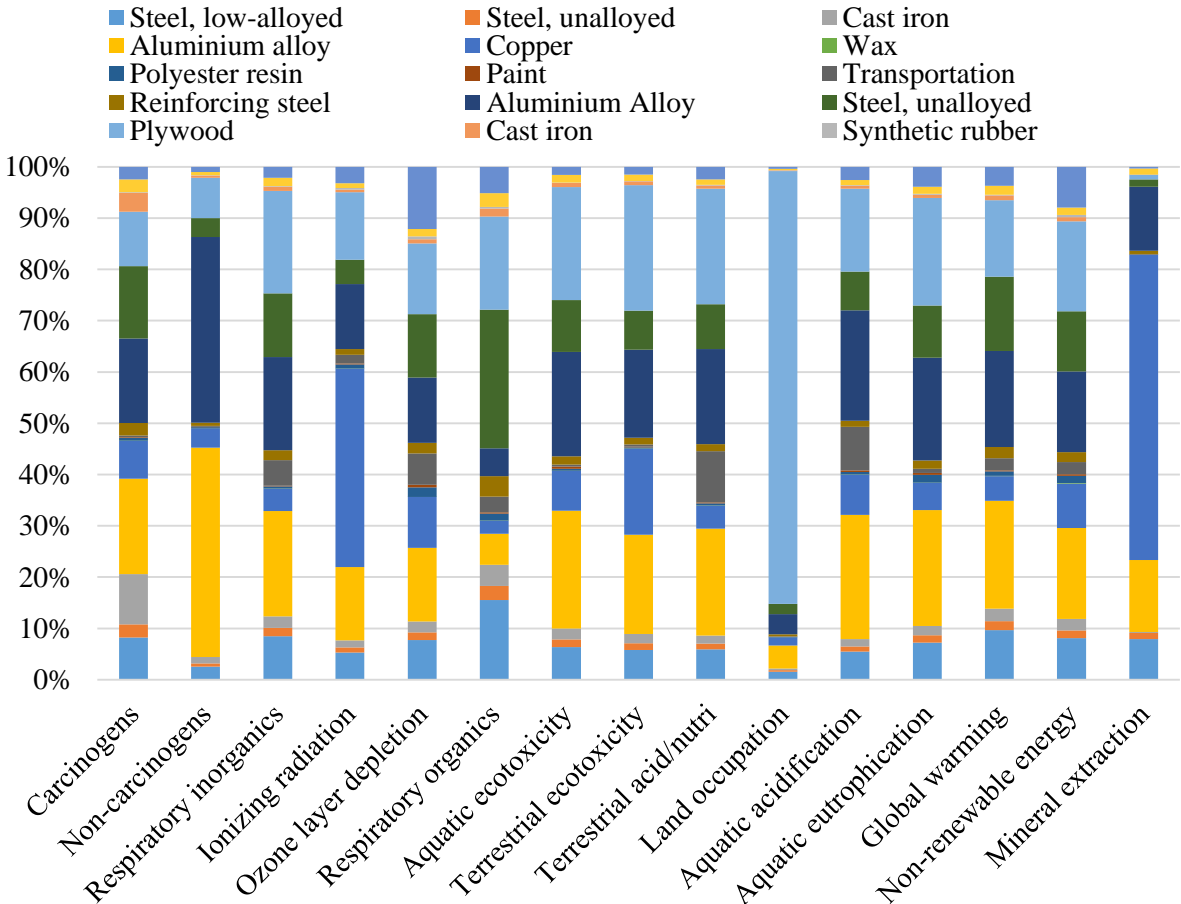
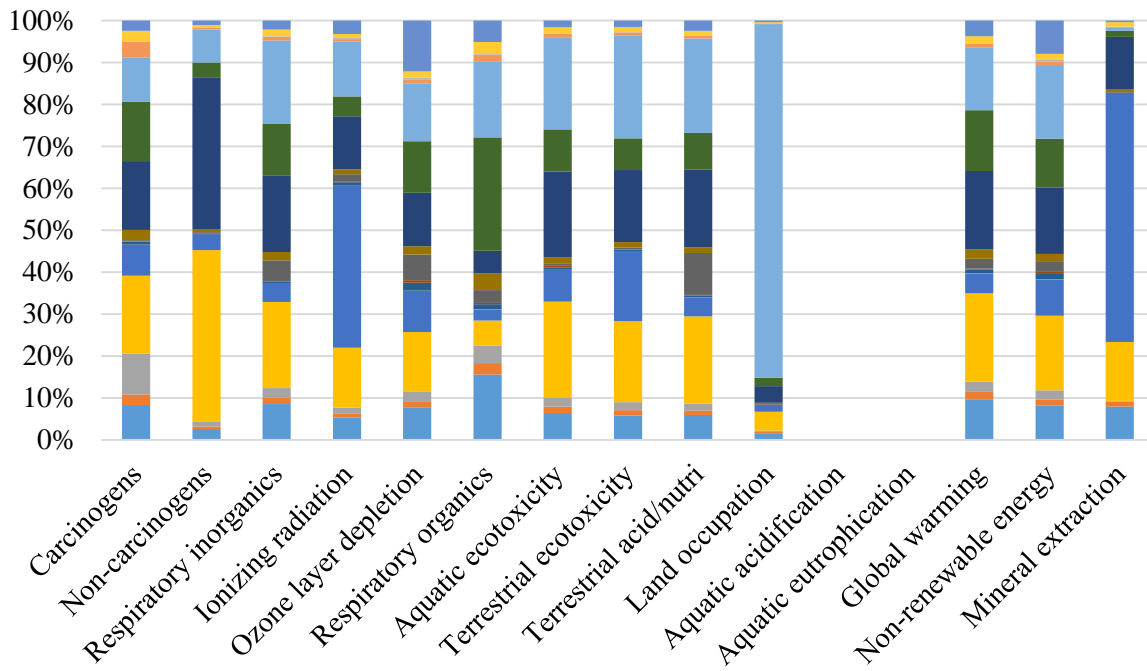
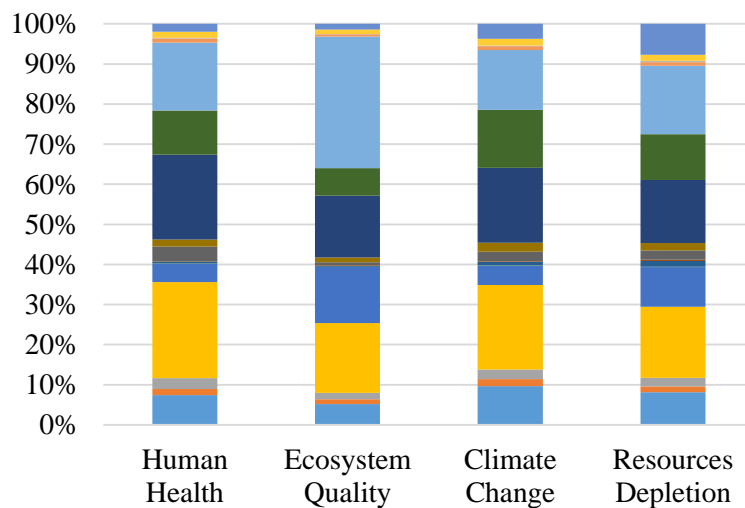


Figure 4.12: Midpoint impact results of reuse pico-hydro generator (Characterisation)



(a)



(b)

Figure 4.13: Midpoint impact results of reuse pico-hydro generator (Damage Assessment)

Finally, for the reuse hydro turbine, the normalised midpoint impact scores are shown in Figure 4.14. There is clear indication that the impact contribution of the reuse system is not very significant when normalised according to the European standard for annual emissions per inhabitant. The most significant impact in this result is respiratory inorganics, followed by global warming potential and non-renewable energy effects. Nine out of the fifteen impacts categories are insignificant, with values below 0.0005, and can be easily disregarded. As expected, these results exhibit a consistent trend, focusing attention on only six categories, while the others are negligible

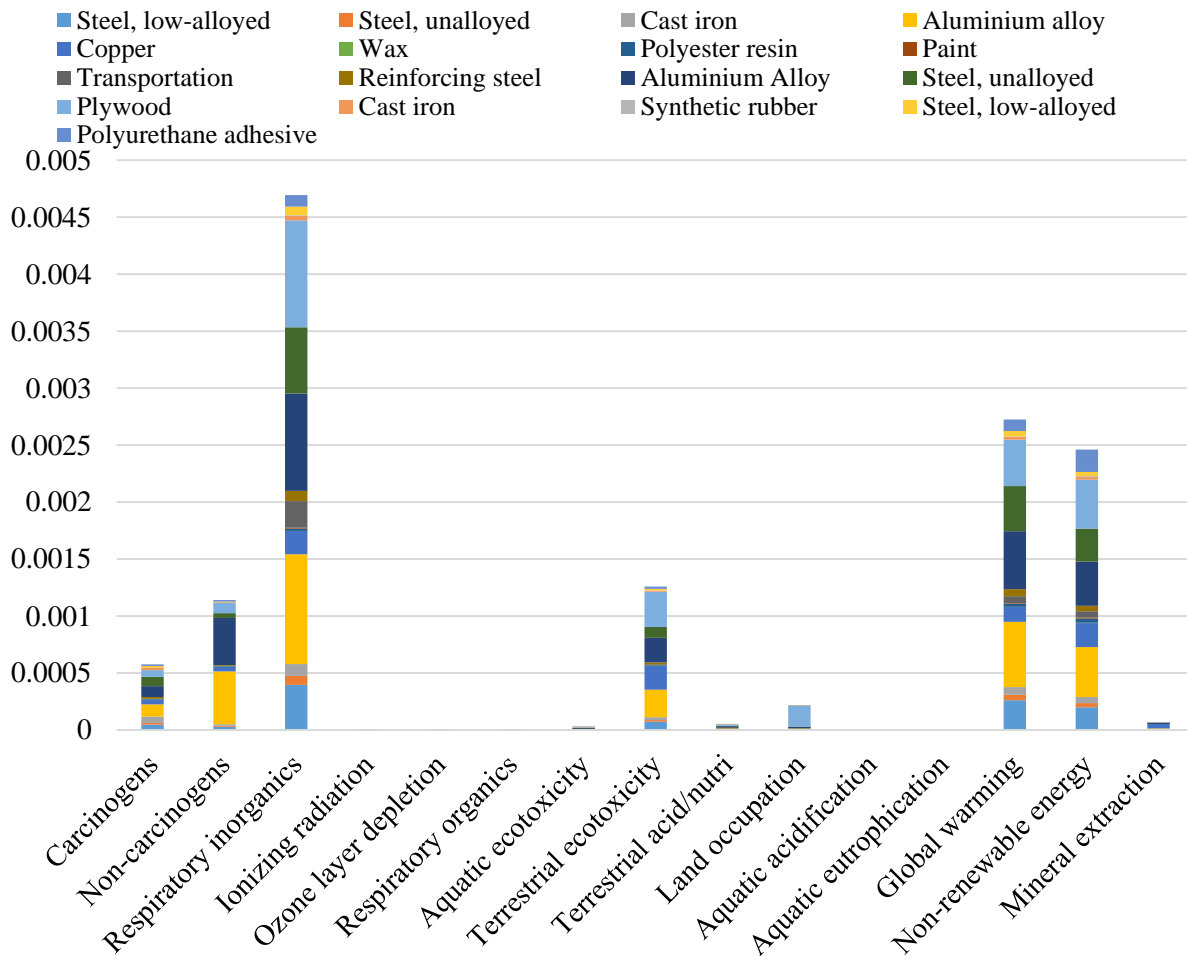


Figure 4.14: Normalised midpoint impact scores of reuse pico-hydro generator

4.3.3.2 Impact assessment results of reuse hybrid solar-pico-hydro system

Having examined the impacts of the reuse pico hydro turbine in isolation, the subsequent phase involved modelling the hybrid system. This comprehensive system incorporates the solar panel module along with its components, the batteries, power supply units and other relevant elements, all based on the defined functional unit and a lifespan of five years. The aggregated weights of each of the components as shown in Table 4.11 and while respecting the required number of units, were utilised.

Three distinct scenarios were explored, contingent upon sizing solution derived from the number of reuse turbines. These scenarios encompass the hybrid solution featuring one reuse turbine, the hybrid solution with two reuse turbines, and finally, the same configuration with three reuse turbines. For each scenario, mirroring the approach used for the hydro turbine exclusively, the characterised midpoint impact score, damage assessment, and the normalised impact scores are presented.

— Results of hybrid solution with one reuse hydro generator

The sizing information outlined in Table 4.11 reveals variations in the number of components required for each scenario. This discrepancy arises from the inverse relationship between the size of the hydro generator and the corresponding reduction in the size of solar panel components. Consequently, in each scenario, the updated sizing information is presented prior to the impact contribution results. In the first scenario where the number of hydro generators is

one, the component sizes are detailed in Table 4.12. The impact assessment results are displayed in Figures 4.15 to 4.18. From Figure 4.15 which shows the characterised midpoint impact contribution, it is observed that the major contributor is the lead acid battery. This is obviously expected as lead acid batteries are characterised by very high environmental footprints. The solar panel is the second biggest contributor overall and other significant contributions are from the transportation and the PSU. For the solar panel, emissions from production of glass and silicon are the major reasons for the noticeable impacts while the emission from fuel consumption is definitely the reason for the significant impacts from transportation. The Damage assessment which is easier to interpret is presented in Figure 4.15.

Table 4.12: Components lifetime and replacement for Scenario 1

S/N	Components/Parts	Number of components	Number of replacement	Total number of Components for 5 years
1.	Induction Machine (400W)	1	-	1
2.	Reuse turbine	1	-	1
3.	Power Supply Unit	8	32	40
4.	Solar Panel	9	-	9
5.	Inverter	1	1.5	2.5
6.	Lead Acid Battery	9	36	45

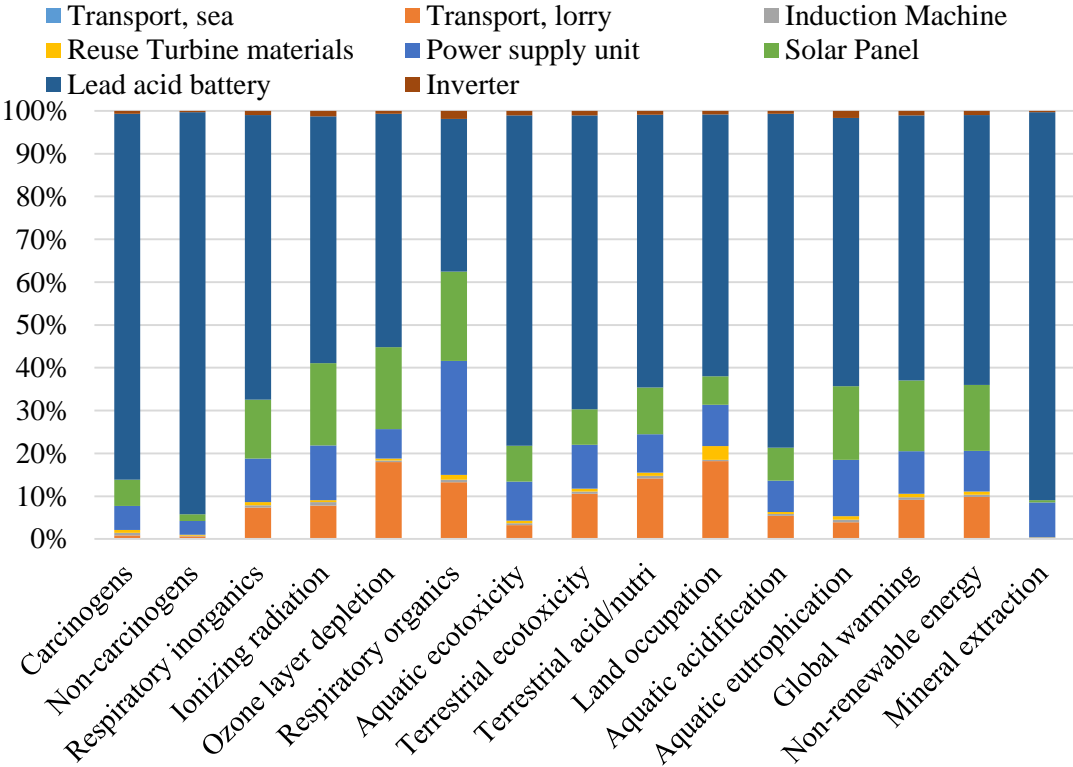
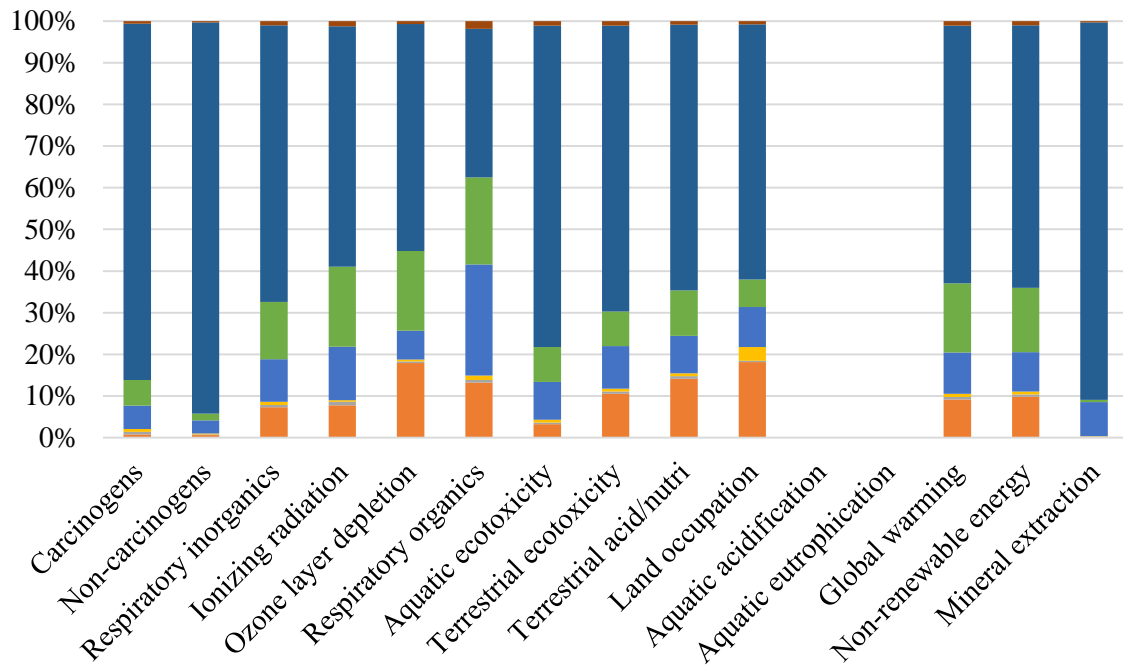
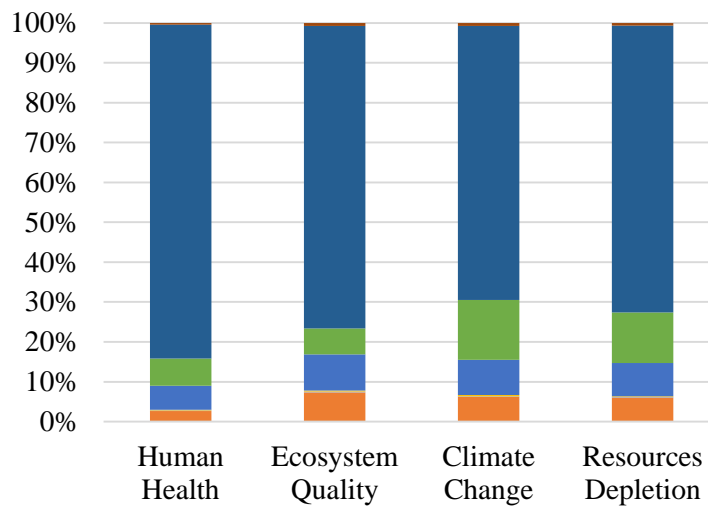


Figure 4.15: Midpoint impact results of reuse hybrid solution with 1 hydro turbine (Characterisation)



(a)



(b)

Figure 4.16: Midpoint impact results of reuse hybrid solution with 1 hydro turbine (Damage Assessment)

It is important to note that there is insignificant aquatic damage which is why there is no value for aquatic acidification and eutrophication in Figure 4.16 (a). However, the contribution of each component to the general damage assessment is displayed in Figure 4.16 (b). The observation from the results is further corroborated by the Sankey diagram depicting the contribution of each process to the normalised impact for reuse solution with 1 hydro turbine in Figure 4.17 where the battery alone contributed 78% to the impact score of the entire system. This dominance can be attributed to the lead-acid batteries' well-documented high environmental footprint [117] and its short lifespan of one year in the reuse solution. In addition, the annual replacement of the battery banks is also a big contributory factor to the overall impact since the greater number of components, the higher the impact contribution.

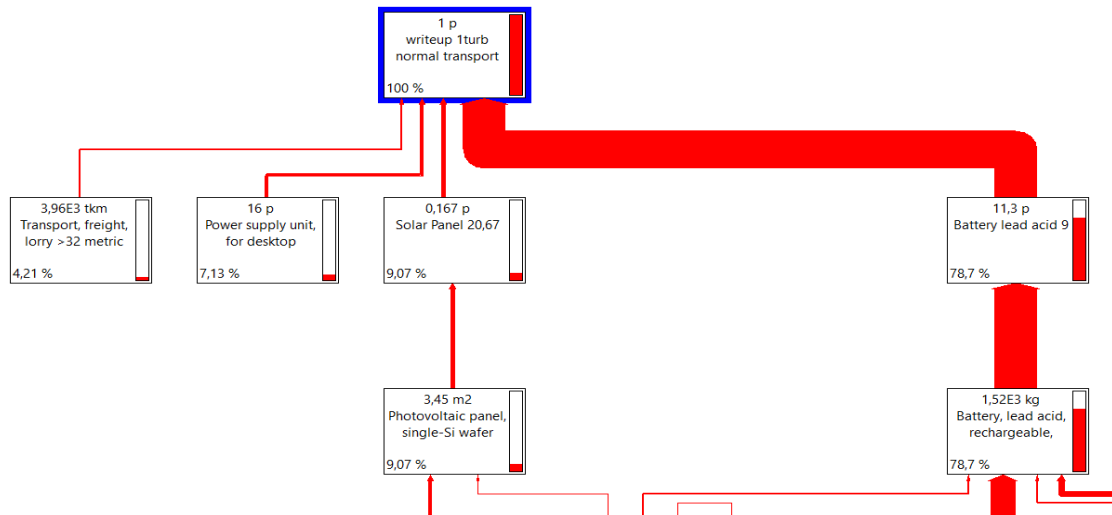


Figure 4.17: Sankey diagram depicting the contribution of each process to the normalised impact for reuse solution with 1 hydro turbine

The normalised impact for the first scenario of the hybrid reuse solution is shown in Figure 4.18. From the results, only 7 impacts scores are significant with respiratory inorganics as the highest impact. The impact values for aquatic acidification and aquatic eutrophication are also zero, meaning that the effect of this system on aquatic life and quality is so low that it can be considered as natural variation

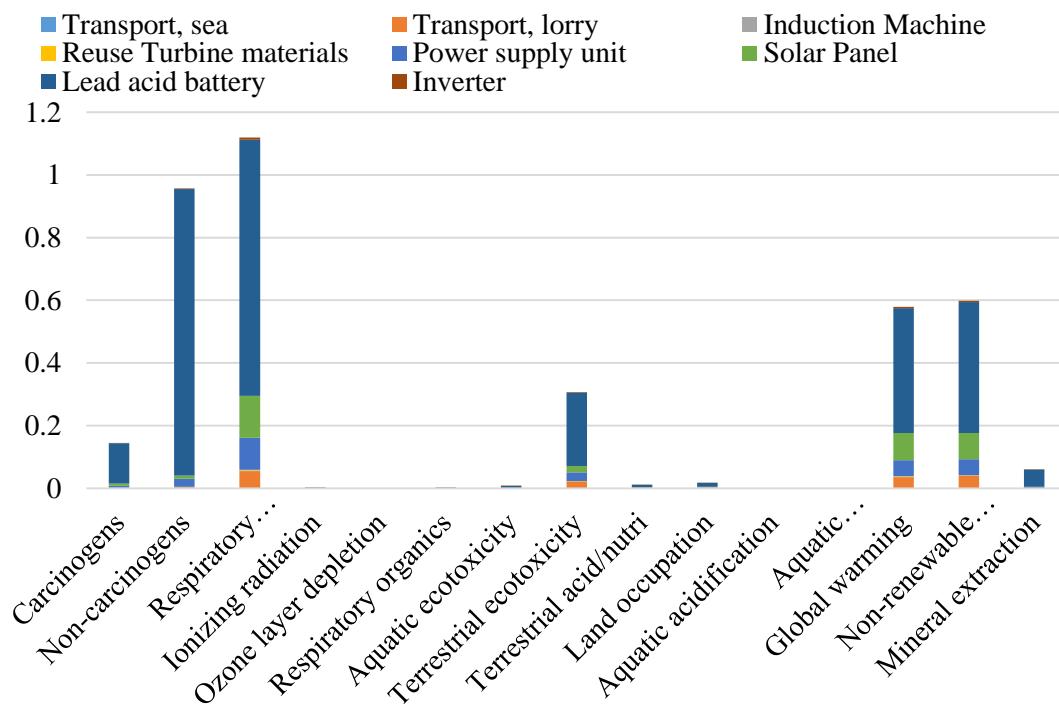


Figure 4.18: Normalised midpoint impact p scores of reuse hybrid solution with 1 hydro turbine

— *Results of hybrid solution with two reuse hydro generators*

The second scenario involves two hydro turbines in the hybrid reuse system. The updated sizes of the components are shown in Table 4.13. These values are used to model the system and the results are presented as follow.

Table 4.13: Components lifetime and replacement for Scenario 2

S/N	Components/Parts	Number of components	Number of replacement	Total number of Component for 5 years
1.	Induction Machine (400W)	2	-	2
2.	Reuse turbine	2	-	2
3.	Power Supply Unit	6	24	30
4.	Solar Panel	7	-	7
5.	Inverter	1	1.5	2.5
6.	Lead Acid Battery	7	28	35

The results depicted in Figures 4.19 and 4.20 are consistent with the findings in scenario 1. Similarly, the primary contributor is the lead acid battery, which, despite a decrease in quantity, still has a significant impact, accounting for approximately 73% of the total impacts, as illustrated in Figure 4.21. Nevertheless, the implementation of two hydro turbines in this solution has led to an overall reduction in impacts, as indicated by the normalized impact in Figure 4.22.

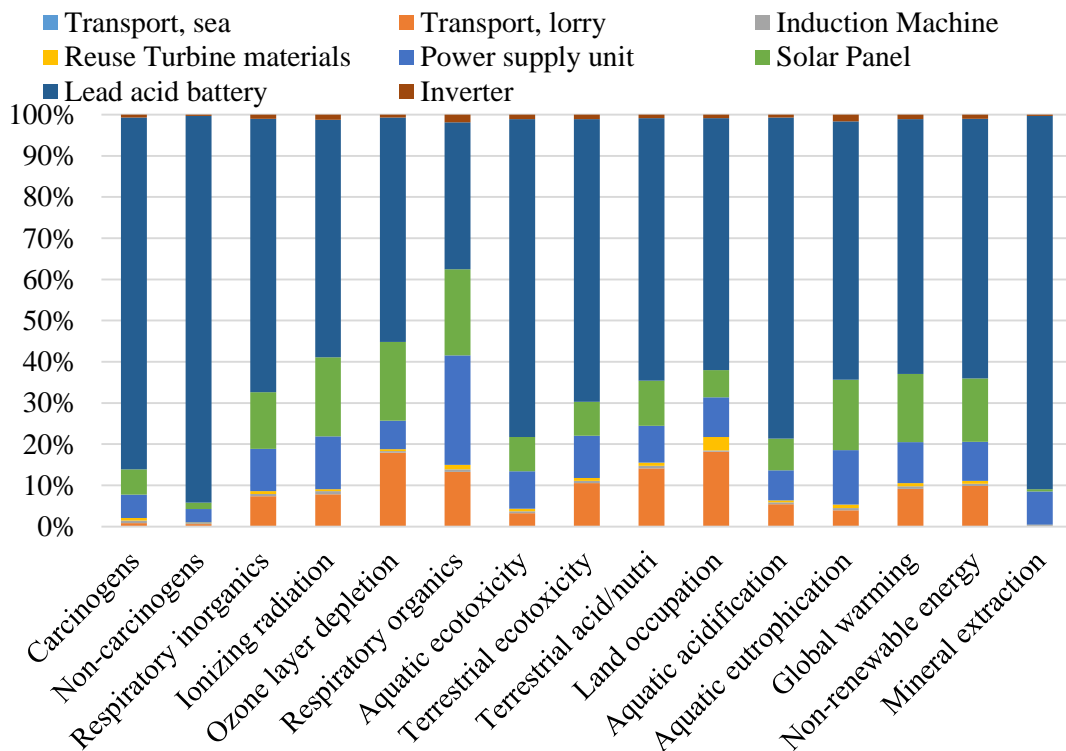
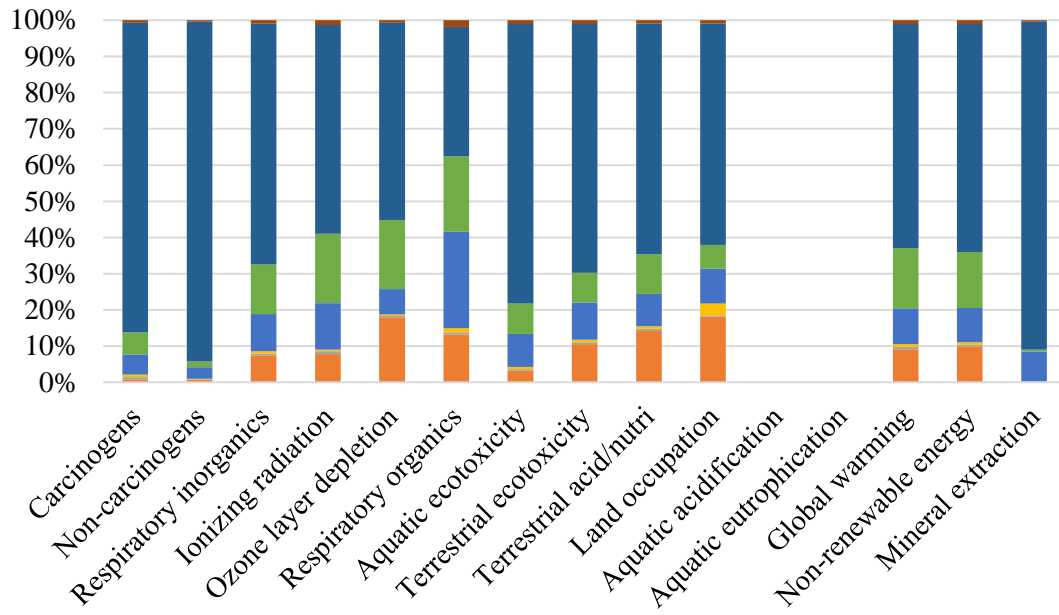
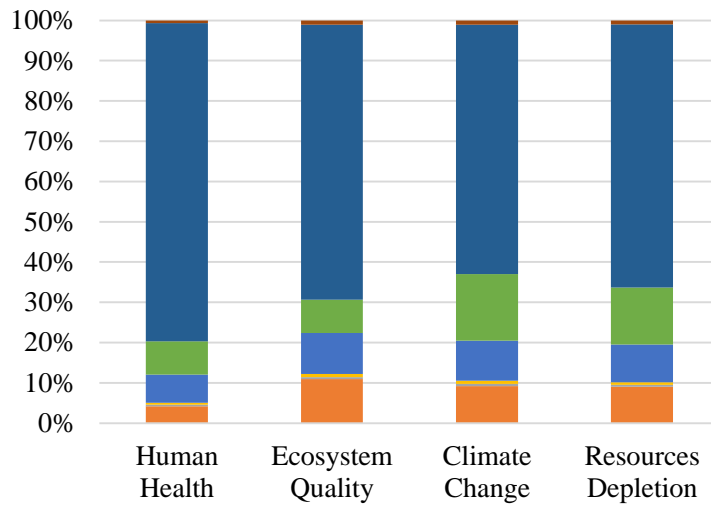


Figure 4.19: Midpoint Impact results of reuse hybrid solution with 2 hydro turbines (Characterisation)

To further corroborate the results shown in Figure 4.18 and 4.19, the network flow of impacts is presented in Figure 4.02 while the normalised impact assessment scores are shown in Figure 4.22.



(a)



(b)

Figure 4.20: Midpoint impact results of reuse hybrid solution with 2 hydro turbines (Damage Assessment)

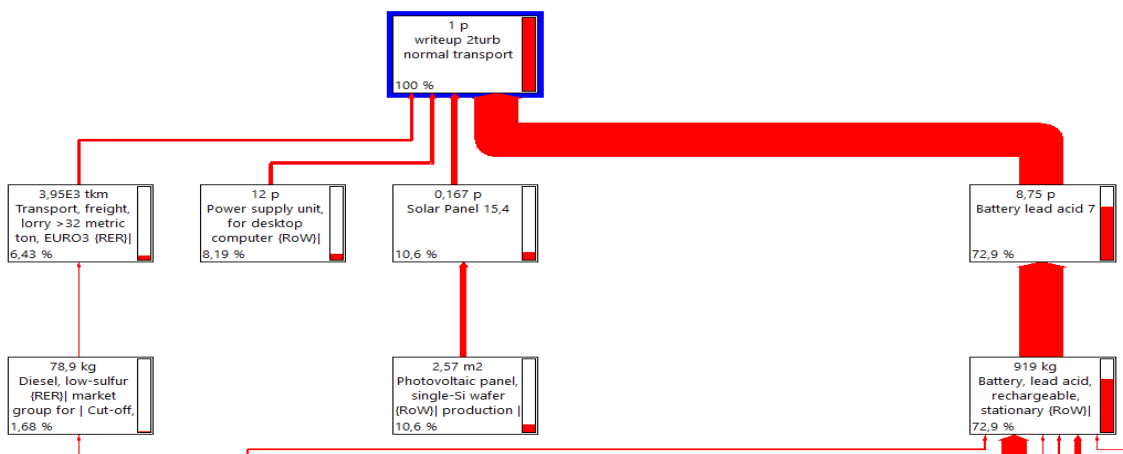


Figure 4.21: Network flow of characterised impact contribution for reuse solution with 2 hydro turbines

As expected and highlighted in Figure 4.22, the normalised impacts for scenario 2 have significantly reduced. The highest impact, respiratory inorganics is now less than 1.0, with only seven of the impacts scores visible, and the remaining eight are less than 0.01. This reduction is justifiable because the impact contribution of adding one reuse hydro turbine is low compared to the impact contribution of the batteries and solar panel that were replaced by the hydro-turbine. Another contributing factor is the reduction in the total number of replacements for lead acid batteries that will be used over the entire life time of the system.

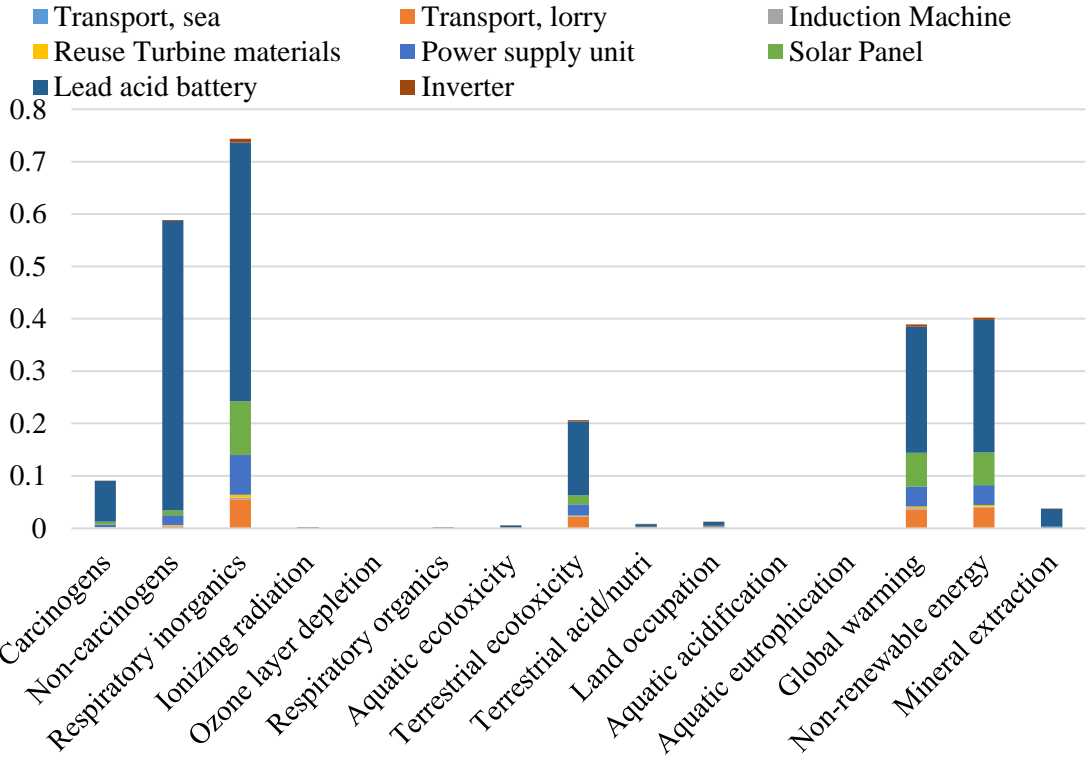


Figure 4.22: Normalised midpoint impact scores of reuse hybrid solution with 2 hydro turbine

— *Results of hybrid solution with three reuse hydro generators*

The third and final scenario involves three reuse hydro turbines with sizes of solar panels and lead acid batteries decreasing as shown in Table 4.14. Similar to the previous two scenarios, the updated sizes were utilised to model the environmental impacts on Simapro and the results presented accordingly in Figures 4.23 to 4.24.

Table 4.14: Components lifetime and replacement for Scenario 3

S/N	Components/Parts	Number of components	Number of replacement	Total number of Component for 5 years
1.	Induction Machine (400W)	3	-	3
2.	Reuse turbine	3	-	3
3.	Power Supply Unit	4	16	20
4.	Solar Panel	5	-	5
5.	Inverter	1	1.5	2.5
6.	Lead Acid Battery	5	20	25

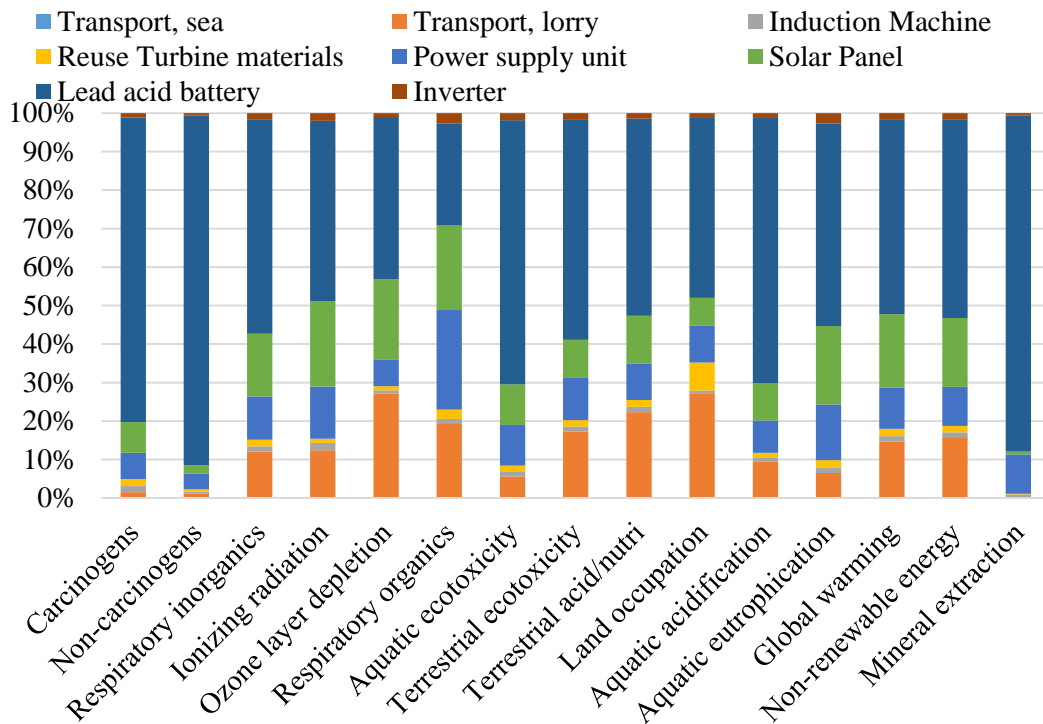
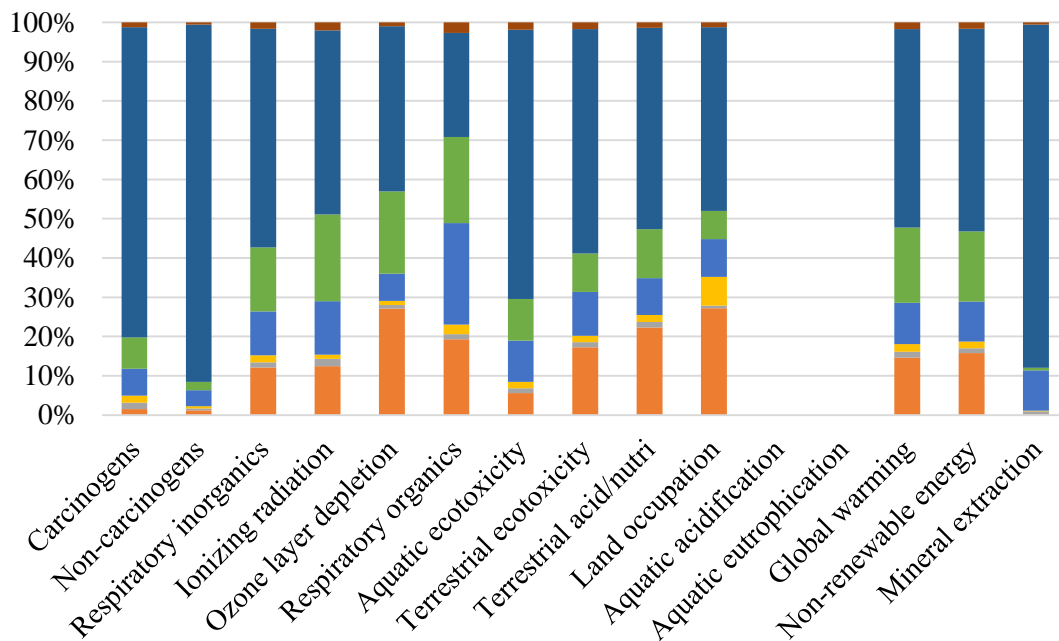
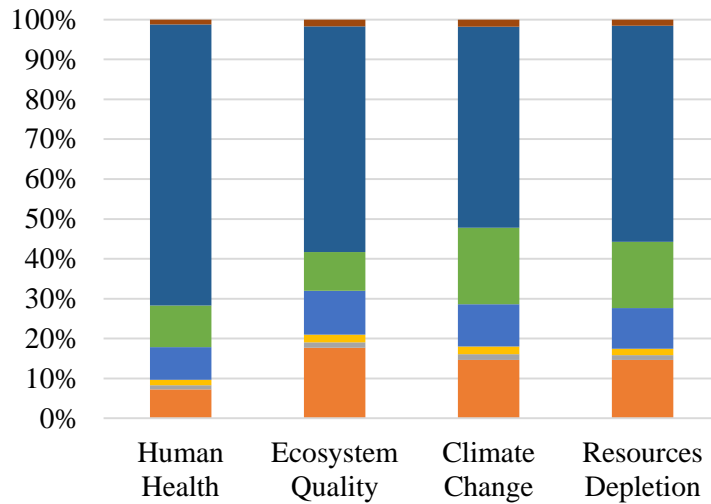


Figure 4.23: Midpoint impact results of reuse hybrid solution with 3 hydro turbines (Characterisation)

An additional decrease is observed in the overall impact scores of the reused hybrid system due to the introduction of three hydro generators, leading to a reduction in the sizes of the most significant impact contributors in the system (the lead acid battery and solar panel). The lead acid battery continues to be the most substantial contributor, as depicted in the trend from Figures 4.23 and 4.24. Despite the presence of three reused hydro turbines, the impact contribution remains significantly low and is not visible in the network diagram of average impact contributors presented in Figure 4.24. In contrast, the battery has contributed approximately 63% of the impacts in this scenario.



(a)



(b)

Figure 4.24: Midpoint impact results of reuse hybrid solution with 3 hydro turbines (Damage Assessment)

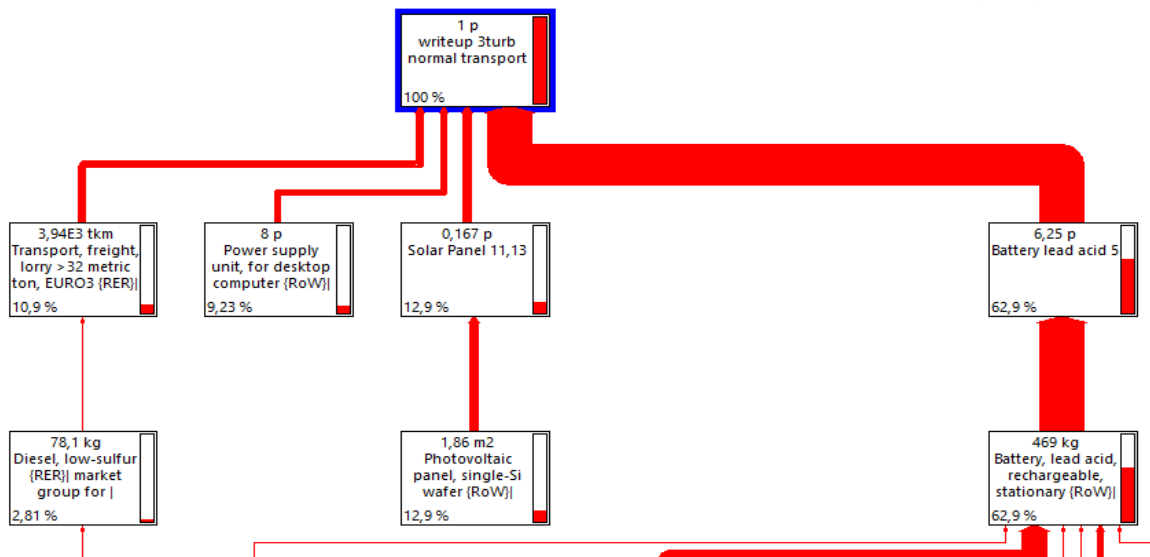


Figure 4.25: Network flow of characterised impact contribution for reuse solution with 3 hydro turbine

For the normalised midpoint impacts shown in Figure 4.26, respiratory inorganics remains the highest with a normalised value of approximately 0.46. This is acceptable for a system with an overall low impact contribution with only five indicators having normalised impact score between 0.05 and 0.3. The remaining indicators are negligibly low and can be overlooked when compared to respiratory inorganics. Clearly, the hybrid reuse system with three hydro turbines and five solar panels is the most environmentally friendly as shown by the set of results. It will be adopted for comparison with a hybrid system comprising new components.

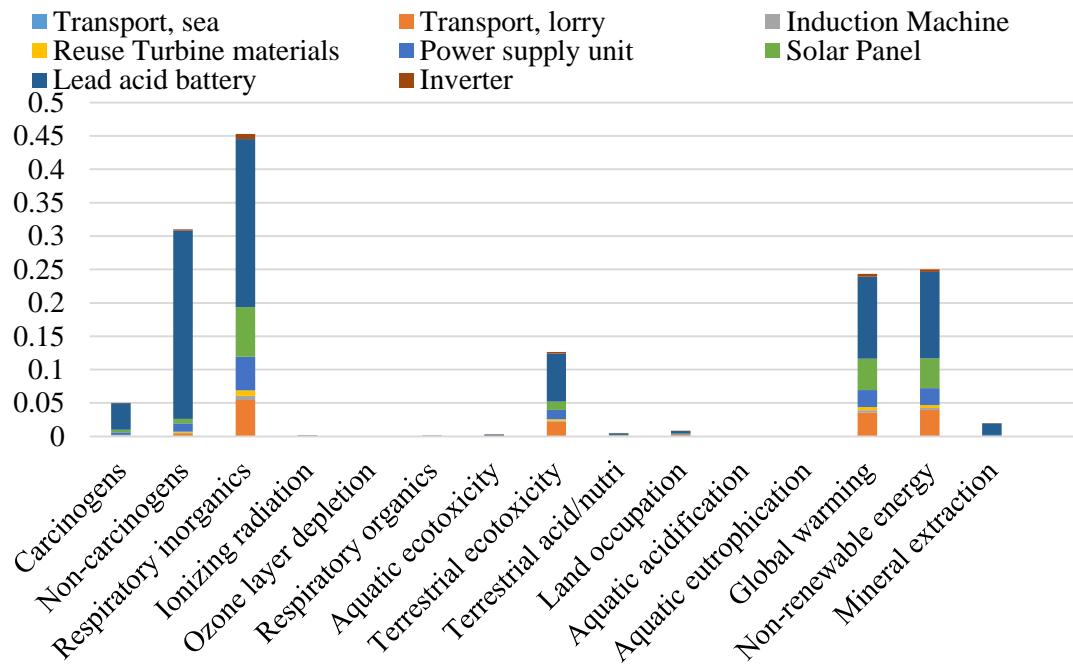


Figure 4.26: Normalised midpoint impact scores of reuse hybrid solution with 3 hydro turbine

4.3.3.3 Impact Assessment Results of Conventional Hybrid Solar-Pico Hydro System

The conventional system, as explained earlier, involves the utilisation of the latest and available technology in the renewable energy market in Nigeria. Regarding the components and inputs in Simapro, the conventional hydro turbine employs a permanent magnet synchronous machine in contrast to the induction machine used in the reuse system. The polycrystalline solar panels are used instead of monocrystalline ones in the reuse solution, and the lead acid batteries are replaced by lithium batteries. The generic data for hydropower turbine was obtained from [126] while data for the Permanent Magnet Synchronous Machine data was retrieved from [127,128]. These data which make up the conventional hybrid system are presented in Table 4.15.

Table 4.15: Weights of materials/components for conventional hybrid solution

S/N	Materials	Weight (kg)	Input in Simapro database
1.	Permanent Magnet	0.0041	Permanent Magnet, for electric motor {GLO}
2.	Electrical Steel	0.0687	Steel, low-alloyed {GLO}
3.	Other steel	0.8956	Steel, unalloyed {GLO}
4.	Cast iron	0.0009	Cast iron {GLO}
5.	Aluminium	1.4520	Aluminium alloy, metal matrix composite {GLO}
6.	Copper	0.0563	Copper {CN}
7.	Insulation material	0.0006	Wax, lost-wax casting {GLO}
8.	Impregnation resin	0.0972	Polyester resin, unsaturated {GLO}
9.	Paint	0.0804	Electrostatic paint {GLO}
10.	Glass fibre	0.0050	Glass fibre {RoW}
11.	Wood	0.0002	Wood (16.9MJ/kg) as input
12.	Reinforcing steel	0.3140	Reinforcing steel {GLO}
13.	Cement	1.6080	Cement cast plaster {GLO}
14.	Solar Panel	module	Photovoltaic panel, multi-Si wafer {GLO}
15.	Inverter	Piecewise	Inverter, 0.5kW {GLO}
16.	Battery	75	Battery, Li-ion, rechargeable {GLO}

{GLO}:Global, {CN}:China, {RoW}:Rest of the World

From the results displayed in Figure 4.27, the highest contributors remain the solar panel and lithium battery, which is expected and unsurprising because of the rigorous manufacturing process involved for these two components. However, in the case of the synchronous machine, it can be observed that its contribution to the overall impacts is quite insignificant. This is due to the fact that synchronous machines are lightweight and, consequently, have fewer impacts per unit. Similarly, from Figure 4.28, the aquatic impacts are negligible, and this holds true the case of the reuse solution as well. This further confirms the advantages of renewable energy sources for generating electricity as the system does not emit significant acidic content that could change the pH balance of water bodies or affect aquatic life.

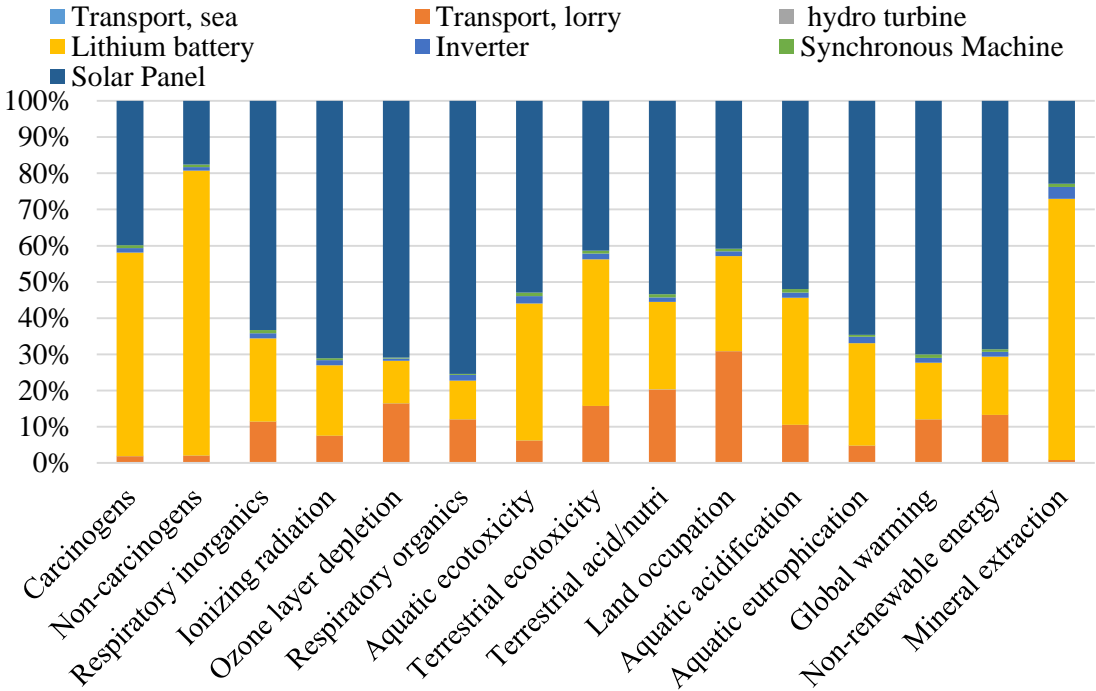
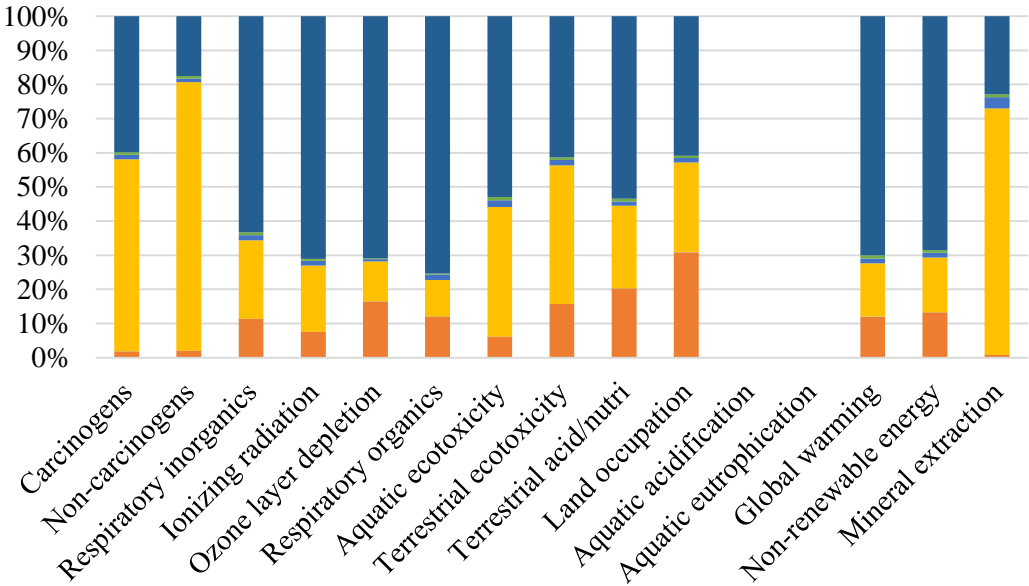
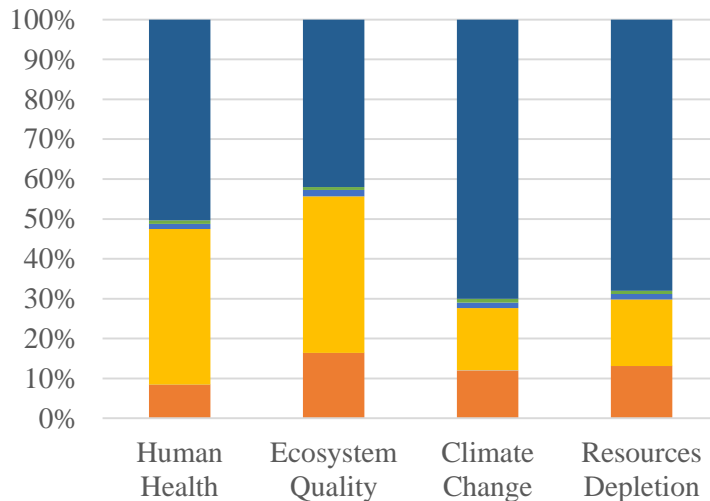


Figure 4.27: Midpoint impact results for new hybrid system (Characterisation)



(a)



(b)

Figure 4.28: Midpoint impact results for new hybrid system (Damage Assessment)

For the normalised impact results of the conventional system, the pattern remains consistent the reuse system, where respiratory inorganics have the highest impact out of the six impacts with obvious normalised scores. However, having a normalised impact value of approximately 0.5 is still subtle and falls within the acceptable range according to European standards for life cycle assessment. The results in Figure 4.29 were compared with the impact contributions of the reuse solutions.

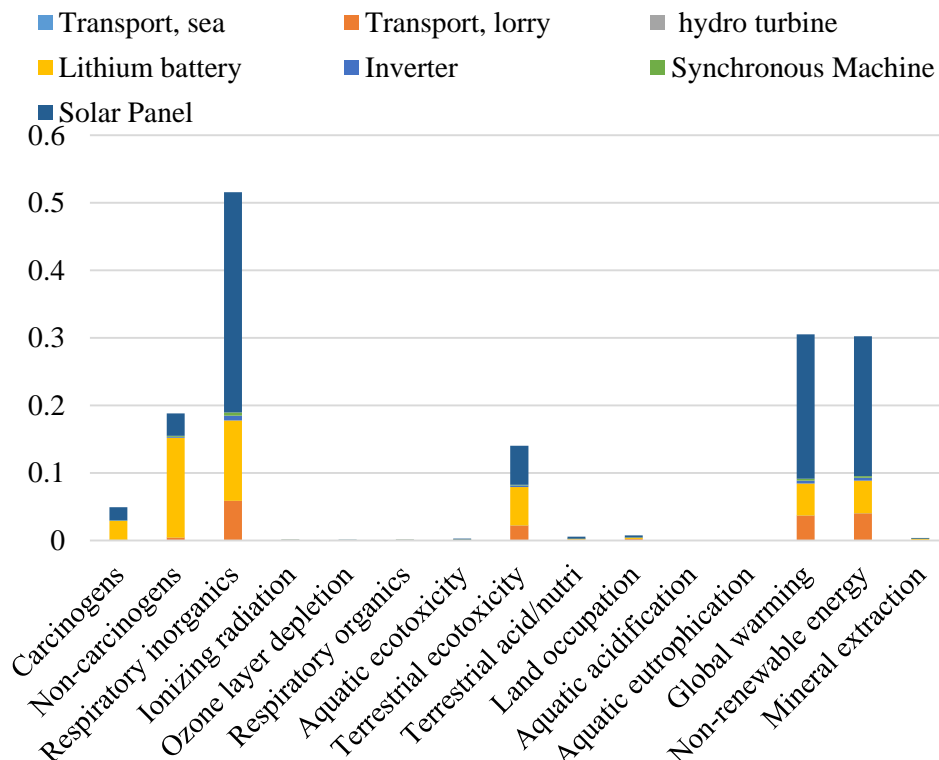


Figure 4.29: Normalised midpoint impact scores for new hybrid system

The normalised impact results are presented in Figure 4.30 are highlighted for comparison purposes and evaluation. The comparison shows that based on impact performance, the first and second scenarios of the reuse solution (i.e. 1 hydro turbine and 2 hydro turbines with solar

panels) have higher impact scores than the other solutions. However, there is considerable competition between scenario 3 of the reuse solution and the conventional solution

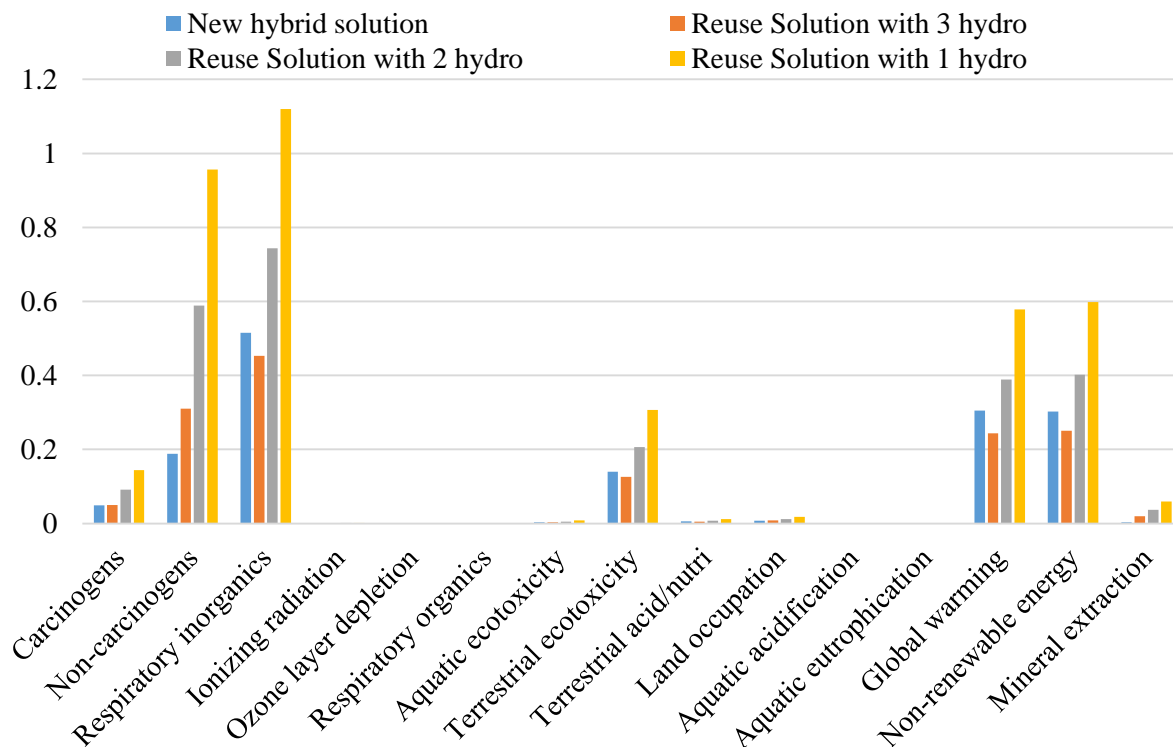


Figure 4.30: Comparison between normalised midpoint impact scores of new and reuse systems

It is noticeable in Figure 4.30 that the new solution has lower impacts in some categories. The new/conventional solution has a lower impact contribution than the reuse solution in seven categories (carcinogens, non-carcinogens, ozone layer depletion, respiratory organics, aquatic ecotoxicology, terrestrial acid/nutrition, and aquatic eutrophication). This is largely due to the presence of lead in the old lead acid batteries. Yet, on the contrary, the reuse solution has lower impact scores in eight categories (respiratory inorganics, ionizing radiation, terrestrial ecotoxicity, land occupation, aquatic acidification, global warming potential, non-renewable energy and mineral extraction). The conclusion as to which solution will be better with respect to these outcomes will be dependent on the purpose of the study. Considering the comprehensive focus of this research on employing frugal innovation and reuse technology for rural electrification reduction of emissions and CO₂, the reuse solution is preferable due to its lower impact on global warming. This choice is reinforced by the cost benefit and e-waste reduction associated with the reuse solution.

4.4 Presentation of the sensitivity analysis

The LCA study of the reuse hydro turbine system was presented, revealing the numerous benefits of reusing materials from e-waste or other disposed components. Besides the advantage of cost, the reuse turbine has proven to be highly ecological with the highest impact score, respiratory organics, being less than 0.005 (normalisation score). The adoption of this reuse hydro turbine in a hybrid reuse solar-hydro system further confirmed the positive environmental impact benefits of reusing systems.

However, the constraint of using a maximum of three hydro turbines has limited the potential for further reducing the impact contribution. Yet, the results from the three different scenarios

for the reuse hybrid system have reiterated one of the goals of LCA study which is to identify hotspots in products. In this case, the hotspot is the lead acid battery which has always contributed more than 50% of the impacts in all three scenarios despite a progressive reduction in size.

Finally, a comparison was made between the hybrid reuse system and a new/conventional hybrid generation system based on recent technology. The conclusion drawn from this comparison, in line with the theme of this study is that the reuse hybrid system is more environmentally friendly than the new system and has an overall reduced impact when compared with a new system. This conclusion is only applicable to the third scenario, which comprises 3 pico-hydro turbines. In addition, based on the presented results, there is a possibility of further investigating the changes in impact score when certain parameters are varied.

The aim of the sensitivity analysis is to observe the effect of changing some crucial parameters on the output results of life cycle assessment and to assess the extent of changes caused by alterations in the values of these parameters. Three different parameters are varied: the impact of transportation, the influence of battery lifetime and the influence of PSU (Power Supply Unit) lifetime.

For each system, the aim is to investigate and examine the effects of these three parameters on each of the impact category. Understanding the impact of varying these parameters is crucial for determining which ones can be adjusted or changed, especially given that certain factors are solely based on assumptions. The sensitivity analysis will be conducted based on the results of each of the scenario using the standard load model.

To provide more specificity in the sensitivity analysis, six impact categories were selected due to their visible significance in the impact assessment results. These categories include Carcinogens, Non-carcinogens, Respiratory inorganics, Terrestrial ecotoxicity, Global warming and Non-renewable energy. The figures showing the results of other impact categories concerning the variation in sensitive parameters are presented in Annex E.

4.5 Sensitivity Analysis for Reuse System with one Hydro turbine

The sizing results for the first scenario with one hydro turbine included eight solar panels, ten batteries and five PSUs and the impact assessment results have been discussed in subsection 4.3.3.2 for the midpoint impact categories. Subsequently, the effect of varying the values of transportation, battery life time and PSU lifetime within the range of 10% to 30% will be discussed. This means that for each of the parameters, an addition or subtraction of ten percent of its initial value is varied and the effect on the impact contribution is recorded. This variation was applied up to thirty percent addition and reduction from the main value and the corresponding changes in impact scores are noted.

4.5.1 Influence of transportation (reuse system with one hydro turbines)

The transportation details presented in Table 4.10 are adjusted accordingly for local distance considering our assumption that the reuse solution is sought within a 100 km radius of the consumer usage point. Therefore, varying the value of transport within the seaport and the final consumption point is imperative in this sensitivity analysis. This analysis is quite important for transportation since assumptions were made on the distance between the disposal point after the initial lifetime of the components and the second life or location of reuse. Thus seeing the

effect of varying transportation distance can help deduce the significance of such assumption on the impact assessment results.

Table 4.16: Influence of transportation on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	-0.16%	-0.10%	-0.05%	+0.05%	+0.10%	+0.16%
Non-carcinogens	-0.11%	-0.07%	-0.04%	+0.04%	+0.07%	+0.11%
Respiratory inorganics	-1.47%	-0.98%	-0.49%	+0.49%	+0.98%	+1.47%
Terrestrial ecotoxicity	-2.13%	-1.42%	-0.71%	+0.71%	+1.42%	+2.13%
Global warming	-1.85%	-1.23%	-0.62%	+0.62%	+1.23%	+1.85%
Non-renewable energy	-1.98%	-1.32%	-0.66%	+0.66%	+1.32%	+1.98%

Based on the results observed in Table 4.16 and Figure 4.31, it can be concluded that the influence of a change in the transportation distance does not have a highly significant effect on the output of the impact assessment results. It is thus reasonable to conclude that a slight increase in the transportation distance may not significantly dominate the impact assessment results.

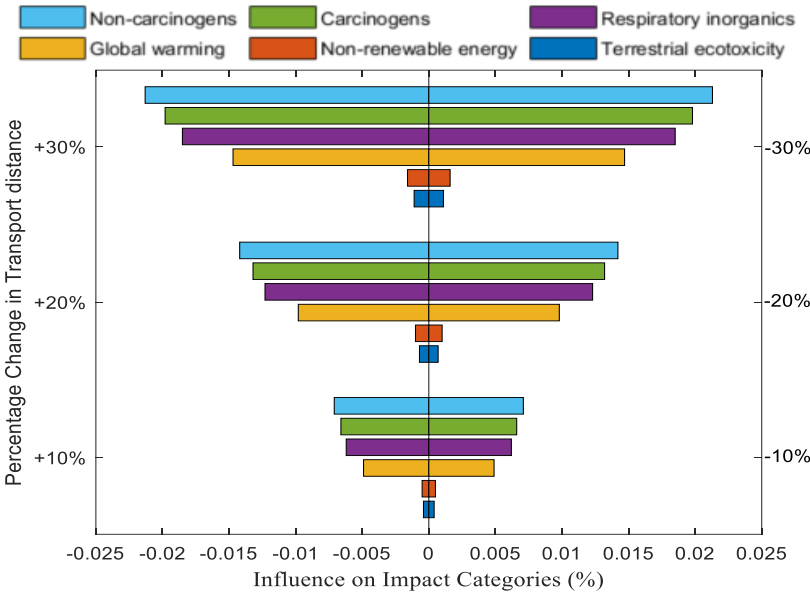


Figure 4.31: Influence of transportation on impact assessment results

4.5.2 Influence of battery lifetime (reuse system with one hydro turbines)

The influence of battery lifetime is very important in this system, given the challenge of obtaining the State of Health of old lead acid batteries to predict their lifetime. However, methods developed in [74] can be used for on field testing of old lead acid batteries to obtain their current state of health and, and subsequently, predict their lifetime. Furthermore, from the network flow of impact contribution in Figure 4.16, the battery is the major contributor (78.6%) to the overall impacts of the entire reuse system, making it a highly critical parameter. Increasing the battery lifetime means that a fewer number of batteries will be used throughout the duration of the reuse generation system (5 years) and vice versa. The results shown in Table 4.17 and Figure 4.32 confirm that there is an inverse proportionality between battery life time and impact scores.

Table 4.17: Influence of battery lifetime on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	92.77%	50.13%	20.91%	-15.47%	-27.23%	-36.38%
Non-carcinogens	99.44%	53.73%	22.41%	-16.58%	-29.19%	-38.99%
Respiratory inorganics	75.95%	41.04%	17.11%	-12.66%	-22.29%	-29.78%
Terrestrial ecotoxicity	79.34%	42.87%	17.88%	-13.23%	-23.29%	-31.11%
Global warming	71.60%	38.69%	16.14%	-11.94%	-21.02%	-28.08%
Non-renewable energy	72.80%	39.34%	16.41%	-12.14%	-21.37%	-28.55%

From the results displayed, it is also important to note that the percentage change in lifetime in the positive and negative direction is not symmetrical. Finally, the results strongly discourage the use of batteries with a lifetime of less than 1 year, as this would significantly increase the impact assessment scores.

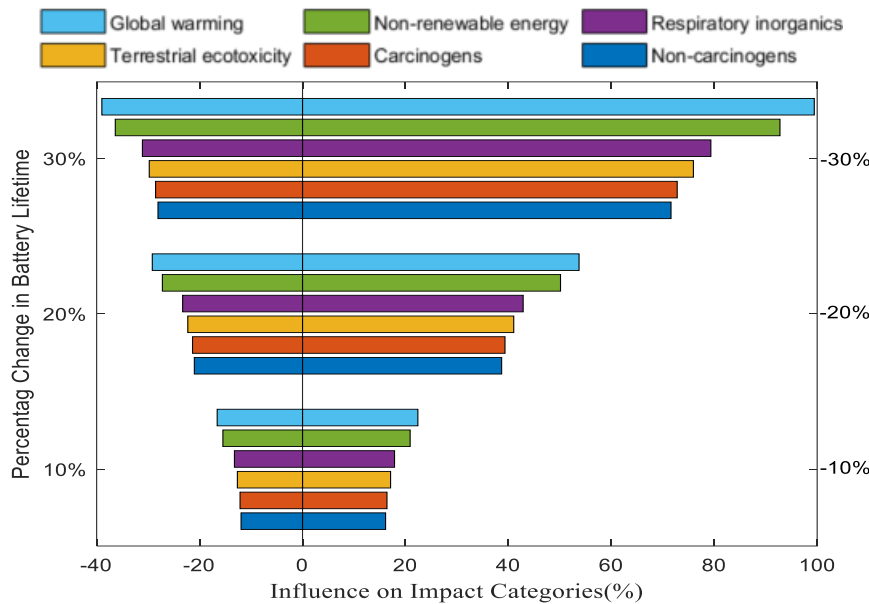


Figure 4.32: Influence of Battery Lifetime on Impact Assessment Results

4.5.3 Influence of PSU lifetime (reuse system with one hydro turbines)

The Power Supply Unit (PSU) has a lifetime of one year, but unlike the battery, there is a higher probability that it could last longer than this period before failure. Thus, increasing the lifetime implied a reduction in the total number of PSUs that will be replaced over the entire life of the reuse system. The results of this sensitivity analysis of PSU in the reuse hybrid system with one hydro generator are shown in Table 4.18.

Table 4.18: Influence of PSU lifetime on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	2.03%	1.18%	0.52%	-0.43%	-0.79%	-1.09%
Non-carcinogens	1.13%	0.66%	0.29%	-0.24%	-0.44%	-0.61%
Respiratory inorganics	3.88%	2.26%	0.99%	-0.82%	-1.51%	-2.09%
Terrestrial ecotoxicity	3.93%	2.30%	1.01%	-0.84%	-1.53%	-2.12%
Global warming	3.81%	2.22%	0.98%	-0.81%	-1.48%	-2.05%
Non-renewable energy	3.64%	2.12%	0.93%	-0.77%	-1.42%	-1.96%

The effects observed in Table 4.18 indicate that the sensitivity of the PSU has a relatively minor effect on the overall impact scores. For every 10% increase in the PSU lifetime, there is a

corresponding reduction of less than 1% on the impact score. In contrast, a reduction in lifetime of the PSU has a more pronounced effect on the impact scores, especially on terrestrial ecotoxicity. This observation emphasizes the importance of maximizing the PSU lifetime to minimize its impact on the overall environmental effects.

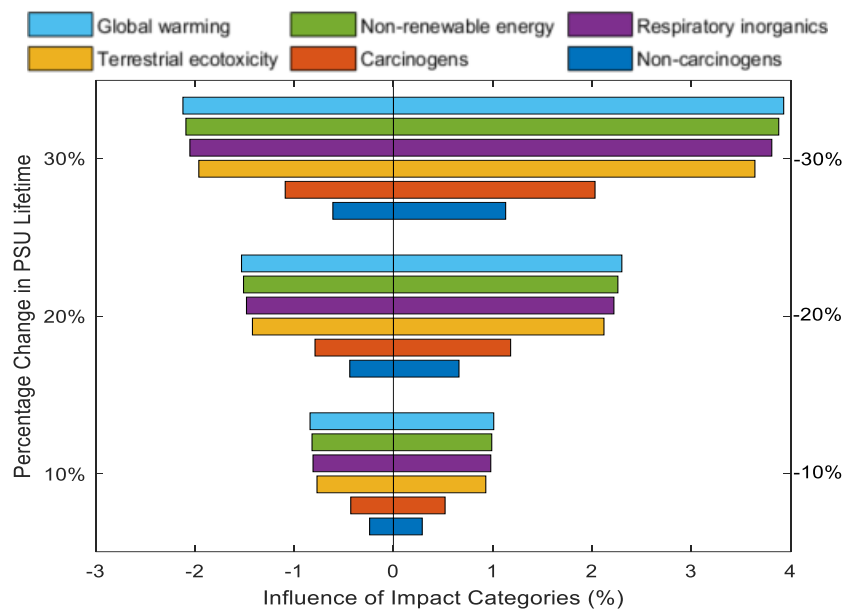


Figure 4.33: Influence of PSU lifetime on impact assessment results

4.6 Sensitivity Analysis for the Reuse System with two Hydro turbines

The second scenario, which combines two hydro generators, seven batteries, solar panels, and six PSUs, is also analysed, following the approach outlined in subsection 5.2. The results of the sensitivity analyses for the influences on transportation, battery lifetime, and PSU lifetime on the impact scores are presented respectively.

4.6.1 Influence of transportation (reuse system with two hydro turbines)

Similarly, as obtained in the first scenario with one hydro turbine, the influence of increasing or decreasing the transportation distance has a symmetrical effect and is directly proportional to the impact score values. Thus, the results of sensitivity of transportation distance on the reuse system with two hydro turbines is presented in Table 4.19 and Figure 4.34 respectively.

Table 4.19: Influence of transportation on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	-0.25%	-0.17%	-0.08%	0.08%	0.17%	0.25%
Non-carcinogens	-0.18%	-0.12%	-0.06%	0.06%	0.12%	0.18%
Respiratory inorganics	-2.21%	-1.47%	-0.74%	0.74%	1.47%	2.21%
Terrestrial ecotoxicity	-3.16%	-2.11%	-1.05%	1.05%	2.11%	3.16%
Global warming	-2.75%	-1.83%	-0.92%	0.92%	1.83%	2.75%
Non-renewable energy	-2.95%	-1.97%	-0.98%	0.98%	1.97%	2.95%

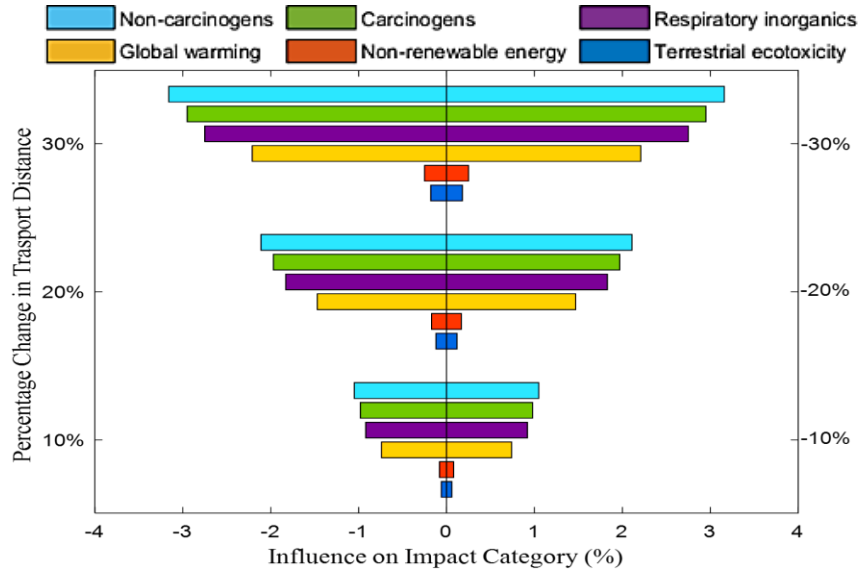


Figure 4.34: Influence of Transportation on Impact Assessment Results

4.6.2 Influence of battery lifetime (reuse system with two hydro turbines)

The influence of battery lifetime on the impact assessment results for the reuse system with two hydro generators is presented in Table 4.20 and Figure 4.35. In line with the explanation given in subsection 4.5.2, the influence of battery lifetime has a very significant effect on the total impact scores. The greater the number of replacements, the higher the impact score as well.

Table 4.20: Influence of battery lifetime on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	88.97%	48.08%	20.05%	-14.83%	-26.11%	-34.91%
Non-carcinogens	97.74%	52.82%	22.03%	-16.29%	-28.69%	-38.35%
Respiratory inorganics	69.14%	37.36%	15.58%	-11.53%	-20.29%	-27.12%
Terrestrial ecotoxicity	71.45%	38.61%	16.10%	-11.91%	-20.97%	-28.03%
Global warming	64.39%	34.80%	14.51%	-10.73%	-18.90%	-25.26%
Non-renewable energy	65.61%	35.46%	14.79%	-10.94%	-19.26%	-25.74%

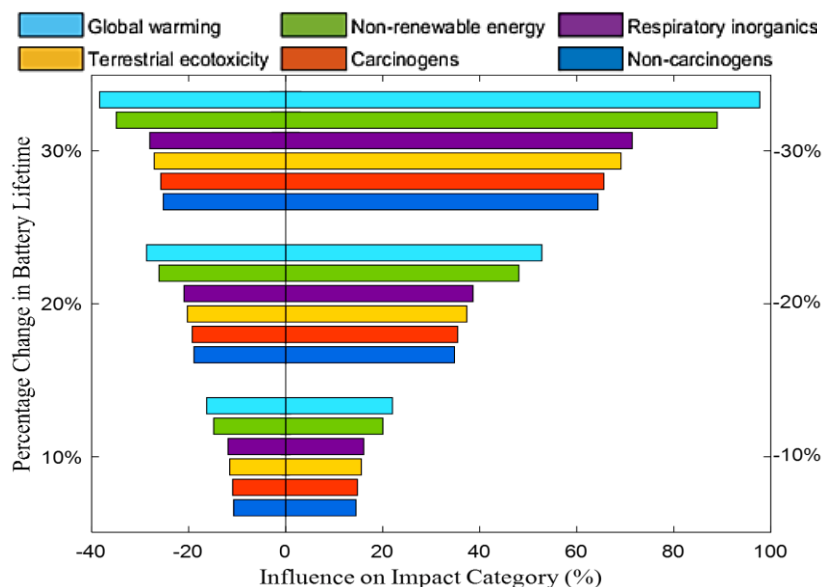


Figure 4.35: Influence of battery lifetime on impact assessment results

It is very important to note the extremely high effect the battery has on the impact contribution. Especially observing that a reduction of 30% in the battery lifetime could cause about 97% increase in non-carcinogen diseases. This further corroborates previous results where the battery was observed to be the major contributor to the impact scores.

4.6.3 Influence of PSU lifetime (reuse system with two hydro turbines)

Table 4.21 illustrates the influence of PSU lifetime on the impact assessment results of the reuse system with two hydro turbines. The effects are still tolerable and within the range of 5% maximum whenever the lifetime of the PSU reduces. However, as concluded in subsection 4.5.3, it is important to ensure that the PSU lifetime is maximised so as to prevent more frequent replacements and avoid spikes in the impact scores.

Table 4.21: Influence of PSU Lifetime on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	2.41%	1.41%	0.63%	-0.51%	-0.94%	-1.30%
Non-carcinogens	1.38%	0.80%	0.36%	-0.29%	-0.53%	-0.74%
Respiratory inorganics	4.38%	2.55%	1.13%	-0.93%	-1.70%	-2.35%
Terrestrial ecotoxicity	4.39%	2.56%	1.14%	-0.93%	-1.71%	-2.36%
Global warming	4.25%	2.48%	1.10%	-0.90%	-1.65%	-2.29%
Non-renewable energy	4.07%	2.37%	1.05%	-0.86%	-1.58%	-2.19%

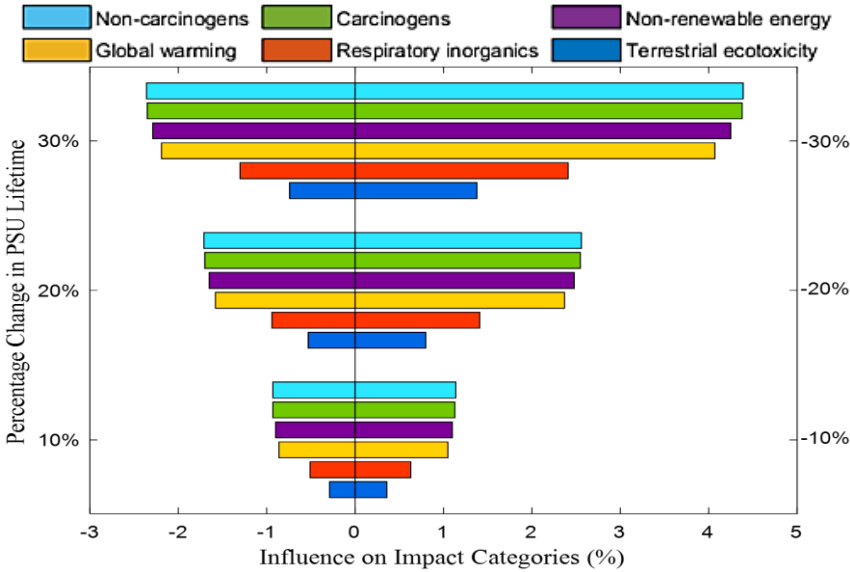


Figure 4.36: Influence of PSU lifetime on impact assessment results

4.7 Sensitivity Analysis for Reuse System with three Hydro turbine

Finally, the sensitivity analyses for the reuse hybrid system with three hydro generators, five solar panels, five batteries and seven PSUs are presented. This system is the preferred choice for the selected load model since it is more economical and has the least impact scores over its lifetime as compared to the other two scenarios. As previously done for other scenarios, the transportation, battery life and PSU lifetime influences are presented

4.7.1 Influence of transportation (reuse system with three hydro turbines)

The influence of transportation has always shown to be of little significance across board the impact categories except for terrestrial ecotoxicity which goes as high as 5% for 30% change in transportation distance. This is not surprising since it is as a result of direct emission and thus

it is only a sign that can be used to advise that all materials should be sourced as close to the consumer as possible to reduce the transportation distance. The results shown in Table 4.22 and Figure 4.37 are the influence of transportation on the impacts scores of reuses system with three hydro turbines and shows that for every 10% change in transport distance, there is equal and corresponding change in the impact scores.

Table 4.22: Influence of transportation on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	-0.45%	-0.30%	-0.15%	0.15%	0.30%	0.45%
Non-carcinogens	-0.34%	-0.23%	-0.11%	0.11%	0.23%	0.34%
Respiratory inorganics	-3.62%	-2.42%	-1.21%	1.21%	2.42%	3.62%
Terrestrial ecotoxicity	-5.16%	-3.44%	-1.72%	1.72%	3.44%	5.16%
Global warming	-4.40%	-2.93%	-1.47%	1.47%	2.93%	4.40%
Non-renewable energy	-4.74%	-3.16%	-1.58%	1.58%	3.16%	4.74%

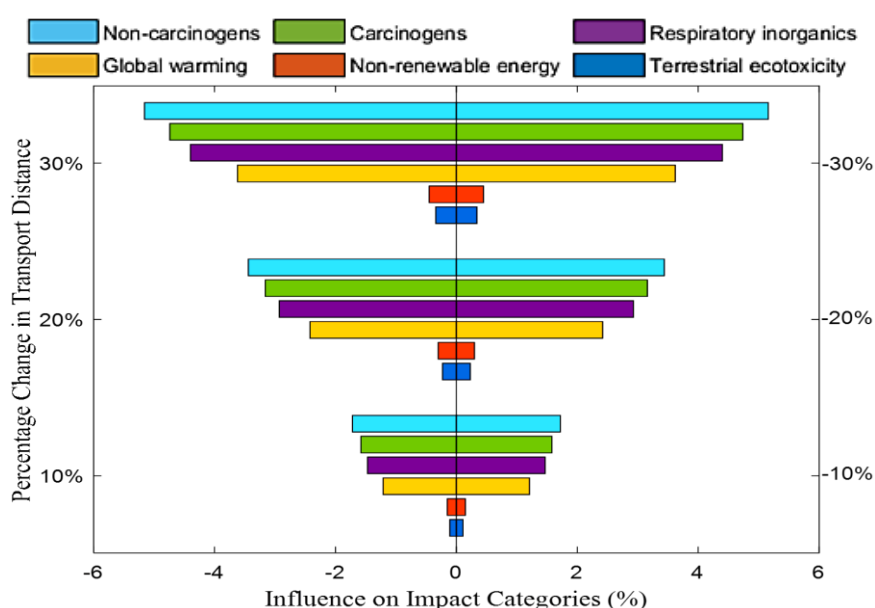


Figure 4.37: Influence of transportation on impact assessment results

4.7.2 Influence of battery lifetime (reuse system with three hydro turbines)

The battery lifetime sensitivity also follows the trend observed for the first two scenarios. From the results shown in Table 4.23 and Figure 4.38, the influence of battery on impact scores for the reuse system with three hydro turbines, confirms it is more sensitive to increasing the lifetime of the battery than reducing it. Therefore, the conclusion remains consistent: it is essential to ensure that the old lead acid battery has some appreciable state of health to achieve a longer lifetime in the system.

Table 4.23: Influence of battery lifetime on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	80.96%	44.45%	18.54%	-13.73%	-24.15%	-32.26%
Non-carcinogens	93.17%	51.15%	21.34%	-15.81%	-27.80%	-37.13%
Respiratory inorganics	57.04%	31.31%	13.06%	-9.68%	-17.02%	-22.73%
Terrestrial ecotoxicity	58.55%	32.15%	13.41%	-9.93%	-17.47%	-23.33%
Global warming	51.74%	28.41%	11.85%	-8.78%	-15.44%	-20.62%
Non-renewable energy	52.89%	29.04%	12.11%	-8.97%	-15.78%	-21.08%

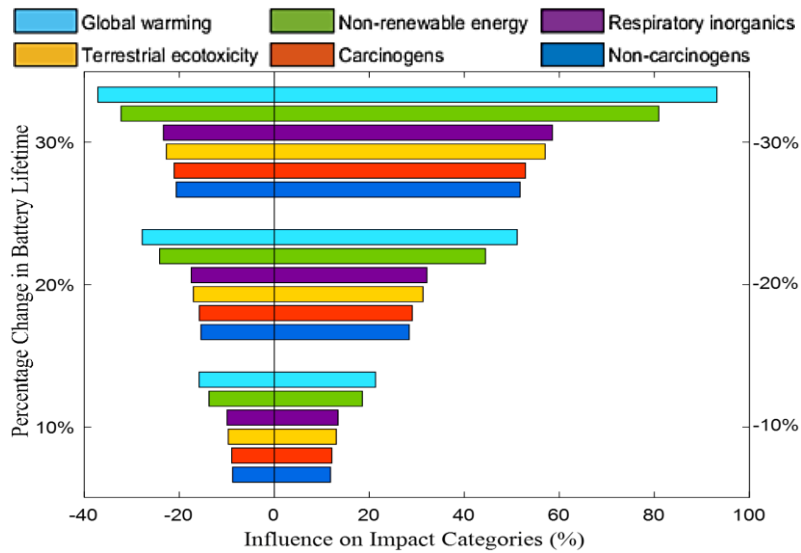


Figure 4.38: Influence of battery lifetime on impact assessment results

4.7.3 Influence of PSU lifetime (reuse system with three hydro turbines)

Finally, the influence of the PSU lifetime on the reuse system with three hydro turbines is presented in Table 4.24 and Figure 4.39. The results exhibit the same trend as with the first two scenarios, emphasizing the importance of increasing, even maximizing PSU lifetime. However, this is quite flexible since failure of electronic components can occur at any time but the results also show that future reducing the lifetime could become alarming and cause more significant contribution to the impact scores.

Table 4.24: Influence of PSU lifetime on impact assessment results

Impact Categories	-30%	-20%	-10%	+10%	+20%	+30%
Carcinogens	2.92%	1.70%	0.76%	-0.62%	-1.13%	-1.57%
Non-carcinogens	1.74%	1.02%	0.45%	-0.37%	-0.68%	-0.94%
Respiratory inorganics	4.79%	2.79%	1.24%	-1.02%	-1.86%	-2.58%
Terrestrial ecotoxicity	4.78%	2.79%	1.24%	-1.01%	-1.86%	-2.58%
Global warming	4.53%	2.64%	1.17%	-0.96%	-1.76%	-2.44%
Non-renewable energy	4.35%	2.54%	1.13%	-0.92%	-1.69%	-2.35%

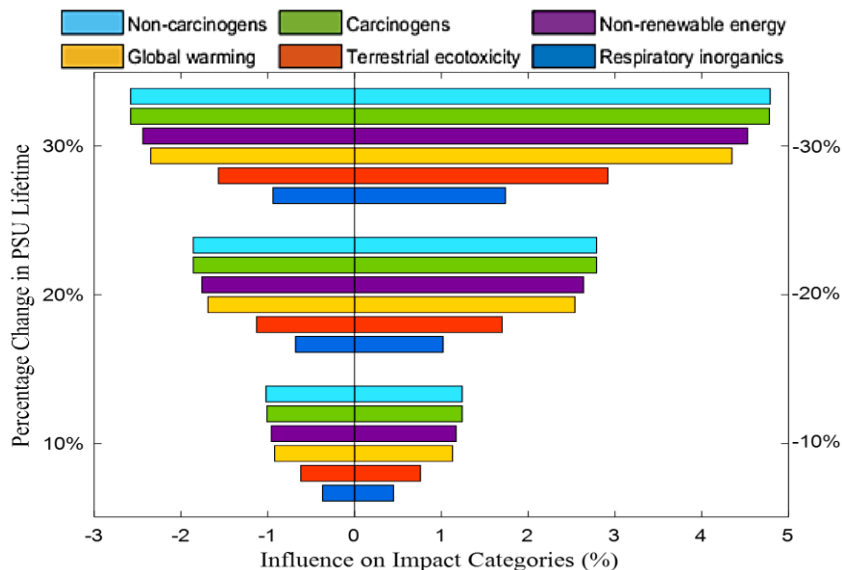


Figure 4.39: Influence of PSU lifetime on impact assessment results

4.8 Conclusions

The aim of performing sensitivity analysis is to observe the characteristics or behavioural changes in the impact assessment scores corresponding to changes specific fundamental parameters. The changes in the output can guide in decision-making, predict trends, and offer insights into the general behavior of the system. From the presented sensitivity analyses, three conclusions can be easily deduced based on the results.

The first inference is a confirmed fact indicated by the sensitivity analyses: Impact assessment scores are not linearly related to direct inputs from materials or resources. This can be seen in the influence of PSU and battery lifetime, whereby a 10% increase does not have the same effect on the impact score as a 10% decrease in lifetime. Secondly, it can also be concluded that the number of replacements during the lifetime of the system is key to the overall impact assessment results. Finally, adjusting the transportation distance within a reasonable range of values may not have a significant influence on the final impact assessment, making it permissible to source materials from regions farther from the consumers' location.

**GENERAL CONCLUSION AND
PERSPECTIVES FOR FUTURE
WORKS**

The lack of cheap, clean, reliable and affordable electricity continues to be a major concern worldwide, especially in developing countries characterized by low-income rural populations. These individuals often lack access to electricity due to the unavailability of infrastructure, poverty, and/or a lack of resources in their vicinity. This translates to an inability to engage in quality day-to-day activities and causes significant disruptions in their daily lives. To cope with the lack of electricity, people in these areas resort to unclean and unsafe methods such as wood burning and oil lanterns for day-to-day activities. Apart from contributing to environmental hazards, these practices also pose risks to health.

In tandem with the lack of energy access, there is an increasing generation of e-waste and used electrical and electronic equipment which are being shipped down to developing countries for second hand use or being disposed inadequately even when they still have some useful lifetime left. The confluence of these two challenges; lack of electricity on one hand and the problem of dumping e-waste on the other, has motivated the development of a reuse hybrid solar-pico-hydro system for electricity generation. This reuse hybrid system comprises old solar panels, used lead acid batteries, repurposed power supply units from old desktop computers, electric machines, old inverters, and finally, a frugal innovation based pico-hydro generation system. The combination of these components, amongst other peripherals, can be used to solve two issues: the reduction of e-waste and the enhancement of energy access in rural and remote communities.

This thesis has diagnosed the feasibility of adopting the reuse solution in a typical developing country. A rural location close to a small river was selected in Nigeria for the adoption of the reuse system to generate energy for a typical household. The thesis focused on four main aspects. The first is exploring the feasibility of adopting the reuse solution in Nigeria based on annual availability and generation of electronic waste and reuse material both within the country and imported components. Thus, the amount of e-waste and used electrical and electronic components available annually was explored and used to see the number of households and/or individuals that can have access to energy if the system is adopted thus showing the possibility of increasing the percentage of individual with electricity in Nigeria.

Secondly, a rural household load model was developed based for component sizing of the hybrid reuse system which was implemented using a commercially available software. This was done to see the adaptability of the reuse solution to an average software such as HOMER which is commercially available to most individuals and to obtain the number of components required for different combination of the hybrid generators. Generally, historical data of solar irradiance and river flow was used to size the components to be able to satisfy the load in worst case scenario. Economic analysis was then performed to the economic/financial advantage of the reuse system as compared to a new/conventional system serving the same load demand.

The next step involved performing time series forecasting for solar irradiance data in order to develop an energy management algorithm that will ensure that the system delivers adequate electricity to the load at all times. The algorithm also incorporated situations whereby additional loads can be added to the system during excess generation and on days with low generation, load rationing can be implemented based on battery state of charge.

Fourthly, a life cycle assessment and environment impact analysis were performed to evaluate the impact scores of the reuse hybrid solution using midpoint impact categories. The ISO standard 14040/44 was adopted in modelling the system and IMPACT 2002+ was used for analysis on Simapro software. The impact assessment result of the reuse hybrid system was compared with a new conventional system with similar characteristics over a lifetime of five years. Following this, a sensitivity analysis was performed on three key parameters of the reuse

system to examine the influence of changes in the values of these parameters on the output impact scores.

In general, the reuse hybrid solar-pico-hydro system has demonstrated adaptability to the Nigerian electricity market, providing a viable solution for energy generation and improving electricity access. First, the solution is cheaper and more affordable compared to a new system. The reuse system is as reliable as a conventional system and can even cater for additional loading conditions based on the energy management algorithm developed. It has proven to have lower environmental impacts as compared to a new/conventional system, contributing to Nigeria's efforts to achieve its intended nationally determined contributions towards global warming. Finally, the results affirm that the adoption of this system is feasible and applicable to a typical rural household, presenting an easily implementable solution.

However, certain downsides can be identified with the first one being the fact that this reuse can only be deployed to areas very close to a moving water body. The system was only tested as a standalone hybrid generation system feeding one household. Some assumptions were made during the feasibility studies and a significant change in the data can also change the results of the feasibility study. Finally, the life cycle assessment was done with some assumptions on the induction machine components due to the unavailability of data.

Future works

The analyses, results and algorithms provided in this thesis can form a basis for improving the reuse hybrid solar-pico-hydro generation system. Several areas can be explored for future works and could pave way for further development in this theme.

One very important aspect is to explore the possibility of designing a suitable control algorithm to efficiently manage the exchange of energy between the solar generator, the batteries and the pico-hydro generator(s). An optimal control will make it possible to fully exploit the advantages of each generator, both for energy supply, output voltage regulation, battery charging current regulation as well as predictive indication for shifting or limiting power demand respectively.

Asides the development of an optimal control scheme, the inclusion of on-line monitoring, load uncertainties for intrusive and/or non-intrusive load demand with interactions with load shifting or peak shaving can be considered. It would also be promising to explore the possibility of developing a wind generator using the same frugal technique derived from electronic wastes and reuse materials.

Another perspective to extending this thesis is to deploy multiple reuse generators to serve several households thereby forming a distribution grid and energy management can be implemented beyond just one house. Grid-connected or island system could be explored in terms of energy exchange to purchase or sell excess energy to the utility, as the case may be. This may offer several advantage in sizing cost and energy management since the load scenario will become entirely different

In conclusion, these areas of research offer considerable potential for extending the benefits of reuse materials, improving energy efficiency and paving way for a more sustainable and resilient future.

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ANNEX A

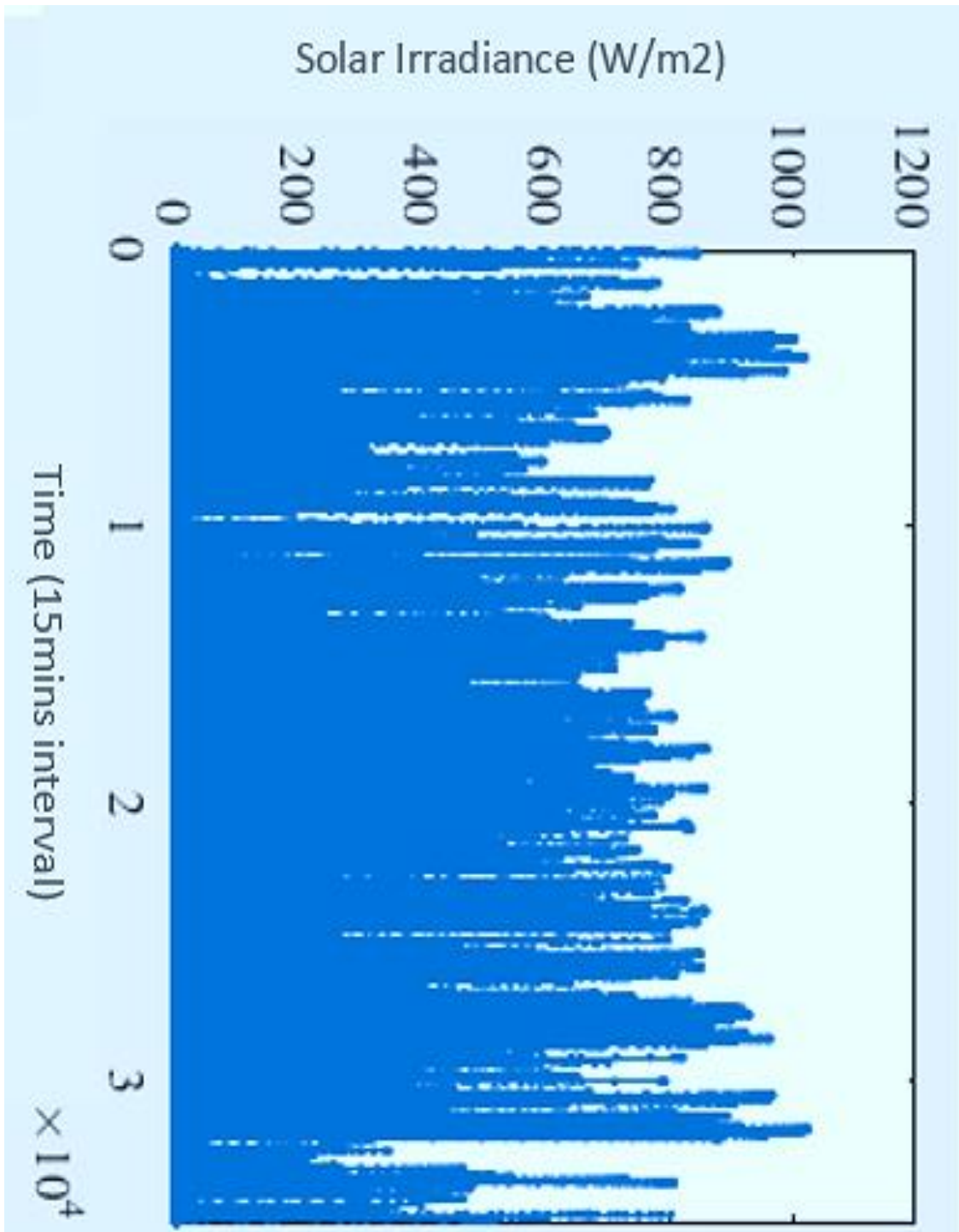


Figure A1: Solar irradiance time series data for one year

ANNEX B

Table B1.1: Analogue Technique Data for Consumer Load Usage of Rural Household

Time (hour)	TV (W)	Radio (W)	Lights (5)					Rechargeable (W)			Fan1 (W)	Fan2 (W)	Total (W)
1	0	0	26	26	0	0	0	0	0	0	40	0	92
2	0	0	26	26	0	0	0	0	0	0	40	0	92
3	0	0	26	26	0	0	0	0	0	0	40	0	92
4	0	0	26	26	0	0	0	0	0	0	40	0	92
5	0	0	26	26	0	0	0	0	0	0	40	0	92
6	0	0	26	26	0	0	0	0	0	0	40	0	92
7	0	5	26	26	0	0	0	0	0	0	40	0	97
8	0	5	26	26	0	0	0	0	0	0	40	0	97
9	0	5	26	26	0	0	0	0	0	0	0	0	57
10	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	120	120
16	0	0	0	0	0	0	0	0	0	0	40	120	160
17	0	5	0	0	0	0	0	0	0	0	40	120	165
18	0	5	0	0	26	26	26	5	0	0	40	120	248
19	65	5	26	26	26	26	26	5	5	0	0	120	330
20	65	5	26	26	26	26	26	5	5	5	0	120	335
21	65	0	26	26	26	26	26	5	5	5	0	120	330
22	65	0	26	26	26	26	26	0	5	5	40	0	245
23	65	0	26	26	26	26	26	0	0	5	40	0	240
24	0	0	26	26	0	0	0	0	0	0	40	0	92

Table B1.2: Standardised Technique Data for Consumer Load Usage of Rural Household [57]

Time	% of Load	Load Demand (W)	Time	% of Load	Load Demand (W)
1	0.02125	79.6875	13	0.025	93.75
2	0.02125	79.6875	14	0.033333	124.9988
3	0.02125	79.6875	15	0.033333	124.9988
4	0.025	93.75	16	0.045833	171.8738
5	0.029167	109.3763	17	0.066667	250.0013
6	0.0375	140.625	18	0.075	281.25
7	0.045833	171.8738	19	0.083333	312.4988
8	0.05833	218.7375	20	0.091667	343.7513
9	0.05833	218.7375	21	0.075	281.25
10	0.041667	156.2513	22	0.020417	76.56375
11	0.025	93.75	23	0.020417	76.56375
12	0.025	93.75	24	0.020417	76.56375

Table B1.3: Average Monthly River Flow Rate of Dutsinma River in Katsina, Nigeria [66]

S/N	Month	Flow rate (m ³ /s)
1.	January	3.6
2.	February	3.6
3.	March	3.6
4.	April	3.6
5.	May	3.6
6.	June	3.6
7.	July	8.8
8.	August	8.8
9.	September	8.8
10.	October	8.8
11.	November	3.6
12.	December	3.6

ANNEX C

Table C3.1: Extrapolated Essential Load Data at 15minutes Time Interval

S/N	Time	Load(W)
1	00:15	79.6875
2	00:30	79.6875
3	00:45	79.6875
4	01:00	79.6875
5	01:15	79.6875
6	01:30	79.6875
7	01:45	79.6875
8	02:00	79.6875
9	02:15	79.6875
10	02:30	79.6875
11	02:45	79.6875
12	03:00	79.6875
13	03:15	93.75
14	03:30	93.75
15	03:45	93.75
16	04:00	93.75
17	04:15	109.3763
18	04:30	109.3763
19	04:45	109.3763
20	05:00	109.3763
21	05:15	140.625
22	05:30	140.625
23	05:45	140.625
24	06:00	140.625
25	06:15	171.8738
26	06:30	171.8738
27	06:45	171.8738
28	07:00	171.8738
29	07:15	218.7375
30	07:30	218.7375
31	07:45	218.7375
32	08:00	218.7375
33	08:15	218.7375
34	08:30	218.7375
35	08:45	218.7375
36	09:00	218.7375
37	09:15	156.2513
38	09:30	156.2513
39	09:45	156.2513
40	10:00	156.2513
41	10:15	93.75
42	10:30	93.75
43	10:45	93.75
44	11:00	93.75
45	11:15	93.75
46	11:30	93.75
47	11:45	93.75
48	12:00	93.75
49	12:15	93.75
50	12:30	93.75
51	12:45	93.75
52	13:00	93.75
53	13:15	124.9988
54	13:30	124.9988
55	13:45	124.9988
56	14:00	124.9988
57	14:15	124.9988
58	14:30	124.9988
59	14:45	124.9988
60	15:00	124.9988
61	15:15	171.8738
62	15:30	171.8738
63	15:45	171.8738
64	16:00	171.8738
65	16:15	250.0013
66	16:30	250.0013
67	16:45	250.0013
68	17:00	250.0013
69	17:15	281.25
70	17:30	281.25
71	17:45	281.25
72	18:00	281.25
73	18:15	312.4988
74	18:30	312.4988
75	18:45	312.4988
76	19:00	312.4988
77	19:15	343.7513
78	19:30	343.7513
79	19:45	343.7513
80	20:00	343.7513
81	20:15	281.25
82	20:30	281.25
83	20:45	281.25
84	21:00	281.25
85	21:15	76.56375
86	21:30	76.56375
87	21:45	76.56375
88	22:00	76.56375
89	22:15	76.56375
90	22:30	76.56375
91	22:45	76.56375
92	23:00	76.56375
93	23:15	76.56375
94	23:30	76.56375
95	23:45	76.56375
96	00:00	76.56375

Table C3.2: Extrapolated Total (Essential + Non-Essential) Load Data at 15minutes Time Interval

S/N	Time	Load(W)
1	00:15	199.2188
2	00:30	199.2188
3	00:45	199.2188
4	01:00	199.2188
5	01:15	199.2188
6	01:30	199.2188
7	01:45	199.2188
8	02:00	199.2188
9	02:15	199.2188
10	02:30	199.2188
11	02:45	199.2188
12	03:00	234.375
13	03:15	234.375
14	03:30	234.375
15	03:45	234.375
16	04:00	273.4406
17	04:15	273.4406
18	04:30	273.4406
19	04:45	273.4406
20	05:00	351.5625
21	05:15	351.5625
22	05:30	351.5625
23	05:45	351.5625
24	06:00	429.6844
25	06:15	429.6844
26	06:30	429.6844
27	06:45	429.6844
28	07:00	546.8438
29	07:15	546.8438
30	07:30	546.8438
31	07:45	546.8438
32	08:00	546.8438
33	08:15	546.8438
34	08:30	546.8438
35	08:45	546.8438
36	09:00	390.6281
37	09:15	390.6281
38	09:30	390.6281
39	09:45	390.6281
40	10:00	234.375
41	10:15	234.375
42	10:30	234.375
43	10:45	234.375
44	11:00	234.375
45	11:15	234.375
46	11:30	234.375
47	11:45	234.375
48	12:00	234.375
49	12:15	234.375
50	12:30	234.375
51	12:45	234.375
52	13:00	312.4969
53	13:15	312.4969
54	13:30	312.4969
55	13:45	312.4969
56	14:00	312.4969
57	14:15	312.4969
58	14:30	312.4969
59	14:45	312.4969
60	15:00	429.6844
61	15:15	429.6844
62	15:30	429.6844
63	15:45	429.6844
64	16:00	625.0031
65	16:15	625.0031
66	16:30	625.0031
67	16:45	625.0031
68	17:00	703.125
69	17:15	703.125
70	17:30	703.125
71	17:45	703.125
72	18:00	781.2469
73	18:15	781.2469
74	18:30	781.2469
75	18:45	781.2469
76	19:00	859.3781
77	19:15	859.3781
78	19:30	859.3781
79	19:45	859.3781
80	20:00	703.125
81	20:15	703.125
82	20:30	703.125
83	20:45	703.125
84	21:00	191.4094
85	21:15	191.4094
86	21:30	191.4094
87	21:45	191.4094
88	22:00	191.4094
89	22:15	191.4094
90	22:30	191.4094
91	22:45	191.4094
92	23:00	191.4094
93	23:15	191.4094
94	23:30	191.4094
95	23:45	191.4094
96	00:00	199.2188

Table C3.3: Shifted Load Data at 15minutes Time Interval

S/N	Time	Load(W)						
1	00:15	79.6875	33	08:15	447.6375	66	16:30	489.8475
2	00:30	79.6875	34	08:30	447.6375	67	16:45	375.0019
3	00:45	79.6875	35	08:45	447.6375	68	17:00	375.0019
4	01:00	79.6875	36	09:00	447.6375	69	17:15	421.875
5	01:15	79.6875	37	09:15	353.9081	70	17:30	281.25
6	01:30	79.6875	38	09:30	353.9081	71	17:45	281.25
7	01:45	79.6875	39	09:45	353.9081	72	18:00	281.25
8	02:00	79.6875	40	10:00	375.0019	73	18:15	312.4988
9	02:15	79.6875	41	10:15	703.125	74	18:30	312.4988
10	02:30	79.6875	42	10:30	703.125	75	18:45	312.4988
11	02:45	79.6875	43	10:45	749.9981	76	19:00	312.4988
12	03:00	79.6875	44	11:00	773.4375	77	19:15	343.7513
13	03:15	93.75	45	11:15	773.4375	78	19:30	343.7513
14	03:30	93.75	46	11:30	773.4375	79	19:45	343.7513
15	03:45	93.75	47	11:45	820.3163	80	20:00	343.7513
16	04:00	93.75	48	12:00	867.1894	81	20:15	281.25
17	04:15	109.3763	49	12:15	867.1894	82	20:30	281.25
18	04:30	109.3763	50	12:30	867.1894	83	20:45	281.25
19	04:45	109.3763	51	12:45	773.4375	84	21:00	281.25
20	05:00	109.3763	52	13:00	820.3106	85	21:15	76.56375
21	05:15	140.625	53	13:15	609.3731	86	21:30	76.56375
22	05:30	140.625	54	13:30	609.3731	87	21:45	76.56375
23	05:45	140.625	55	13:45	302.3438	88	22:00	76.56375
24	06:00	140.625	56	14:00	302.3438	89	22:15	76.56375
25	06:15	171.8738	57	14:15	302.3438	90	22:30	76.56375
26	06:30	171.8738	58	14:30	302.3438	91	22:45	76.56375
27	06:45	171.8738	59	14:45	302.3438	92	23:00	76.56375
28	07:00	377.3419	60	15:00	302.3438	93	23:15	76.56375
29	07:15	447.6375	61	15:15	372.6563	94	23:30	76.56375
30	07:30	447.6375	62	15:30	372.6563	95	23:45	76.56375
31	07:45	447.6375	63	15:45	372.6563	96	00:00	76.56375
32	08:00	447.6375	64	16:00	372.6563			
			65	16:15	489.8475			

Table C3.4: Solar Irradiance Data on A Very Rainy Day

S/N	Time	Solar Irradiance (W/m ²)
1	00:15	0
2	00:30	0
3	00:45	0
4	01:00	0
5	01:15	0
6	01:30	0
7	01:45	0
8	02:00	0
9	02:15	0
10	02:30	0
11	02:45	0
12	03:00	0
13	03:15	0
14	03:30	0
15	03:45	0
16	04:00	0
17	04:15	0
18	04:30	0
19	04:45	0
20	05:00	0
21	05:15	0
22	05:30	0
23	05:45	0
24	06:00	0
25	06:15	8.8
26	06:30	63.5
27	06:45	110.7
28	07:00	0
29	07:15	3.28
30	07:30	0
31	07:45	0
32	08:00	0
33	08:15	0
34	08:30	0
35	08:45	0
36	09:00	0
37	09:15	0
38	09:30	0
39	09:45	0
40	10:00	0
41	10:15	0
42	10:30	0
43	10:45	0
44	11:00	0
45	11:15	0
46	11:30	0
47	11:45	0
48	12:00	0
49	12:15	0
50	12:30	0
51	12:45	0
52	13:00	0
53	13:15	0
54	13:30	0
55	13:45	0
56	14:00	0
57	14:15	0
58	14:30	0
59	14:45	0
60	15:00	0
61	15:15	60.7
62	15:30	32.84
63	15:45	108.56
64	16:00	520
65	16:15	742
66	16:30	119.5
67	16:45	67.8
68	17:00	33
69	17:15	26
70	17:30	18
71	17:45	4.3
72	18:00	5
73	18:15	0
74	18:30	1.4
75	18:45	0
76	19:00	0
77	19:15	0
78	19:30	0
79	19:45	0
80	20:00	0
81	20:15	0
82	20:30	0
83	20:45	0
84	21:00	0
85	21:15	0
86	21:30	0
87	21:45	0
88	22:00	0
89	22:15	0
90	22:30	0
91	22:45	0
92	23:00	0
93	23:15	0
94	23:30	0
95	23:45	0
96	00:00	0

ANNEX D

Table D4.1: Comparison of Normalised Midpoint Impact Scores Between New and Reuse System

	New Solution	Reuse solution with 3 Hydro	Reuse solution with 2 Hydro	Reuse solution with 1 Hydro
Carcinogens	0.04916845	0.05030433	0.09114434	0.14450885
Non-carcinogens	0.18806509	0.31018691	0.58869879	0.95668129
Respiratory inorganics	0.51549514	0.45288027	0.74389303	1.11950622
Ionizing radiation	0.00095587	0.00068304	0.00108785	0.00161718
Ozone layer depletion	6.2705E-05	3.752E-05	5.6735E-05	8.174E-05
Respiratory organics	0.0007014	0.00041762	0.00060765	0.0008408
Aquatic ecotoxicity	0.00282829	0.00301661	0.00525611	0.00815001
Terrestrial ecotoxicity	0.14015881	0.12643036	0.20631016	0.30713863
Terrestrial acid/nutri	0.00538728	0.00490042	0.00772373	0.01139622
Land occupation	0.00736014	0.00814364	0.01219697	0.01751978
Aquatic acidification	0	0	0	0
Aquatic eutrophication	0	0	0	0
Global warming	0.30524445	0.24332913	0.38932542	0.57879879
Non-renewable energy	0.30216889	0.2503431	0.40181043	0.59864917
Mineral extraction	0.00353205	0.01953199	0.03689974	0.05973957

ANNEX E

E1: Sensitivity Analysis for Reuse System with One Hydro Turbine

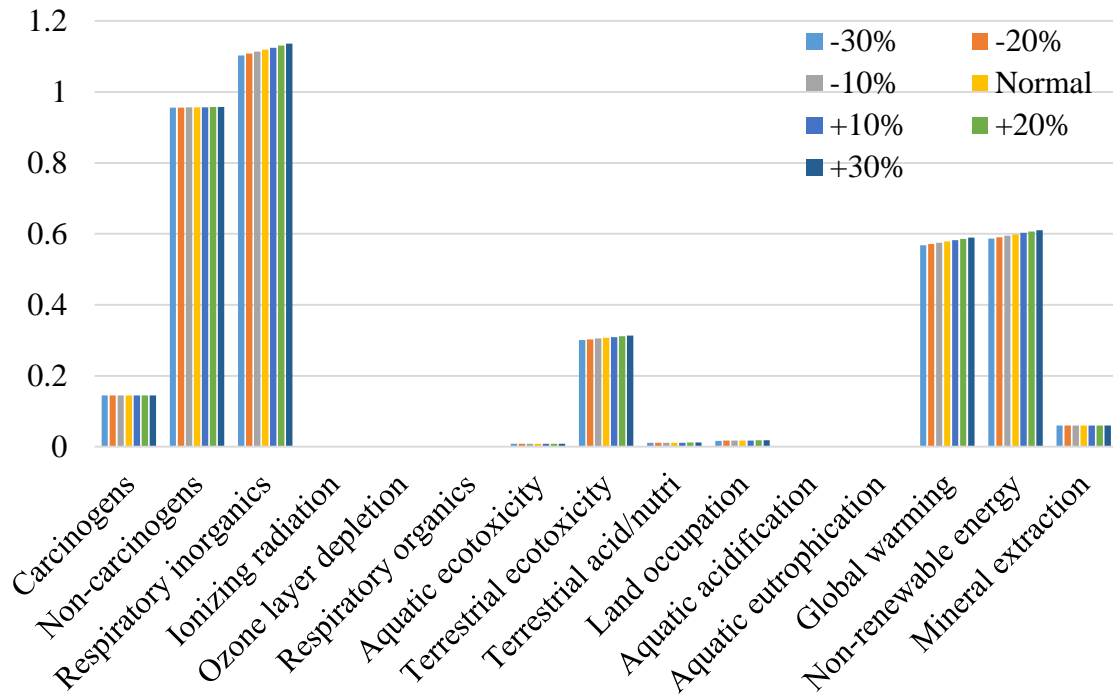


Figure 5.1a: Comparison of Influence of Transportation on Impact Results (Normalisation) for Reuse System with 1 Hydro Generator

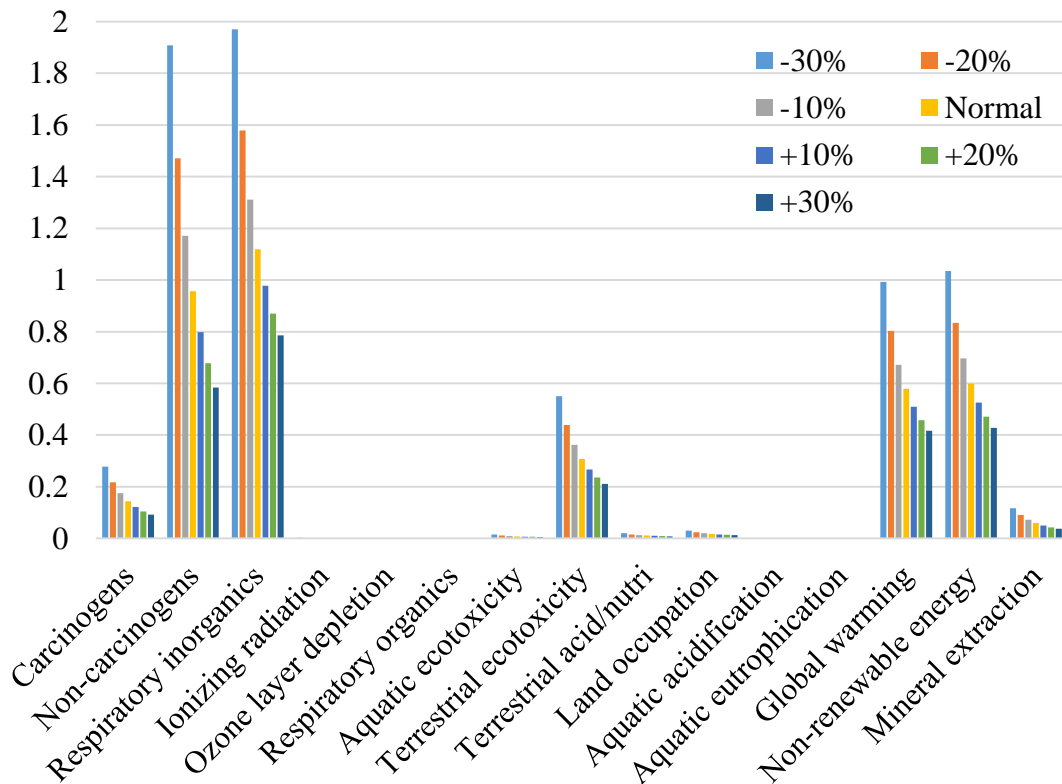


Figure 5.1b: Comparison of Influence of Battery Lifetime on Impact Results (Normalisation) for Reuse System with 1 Hydro Generator

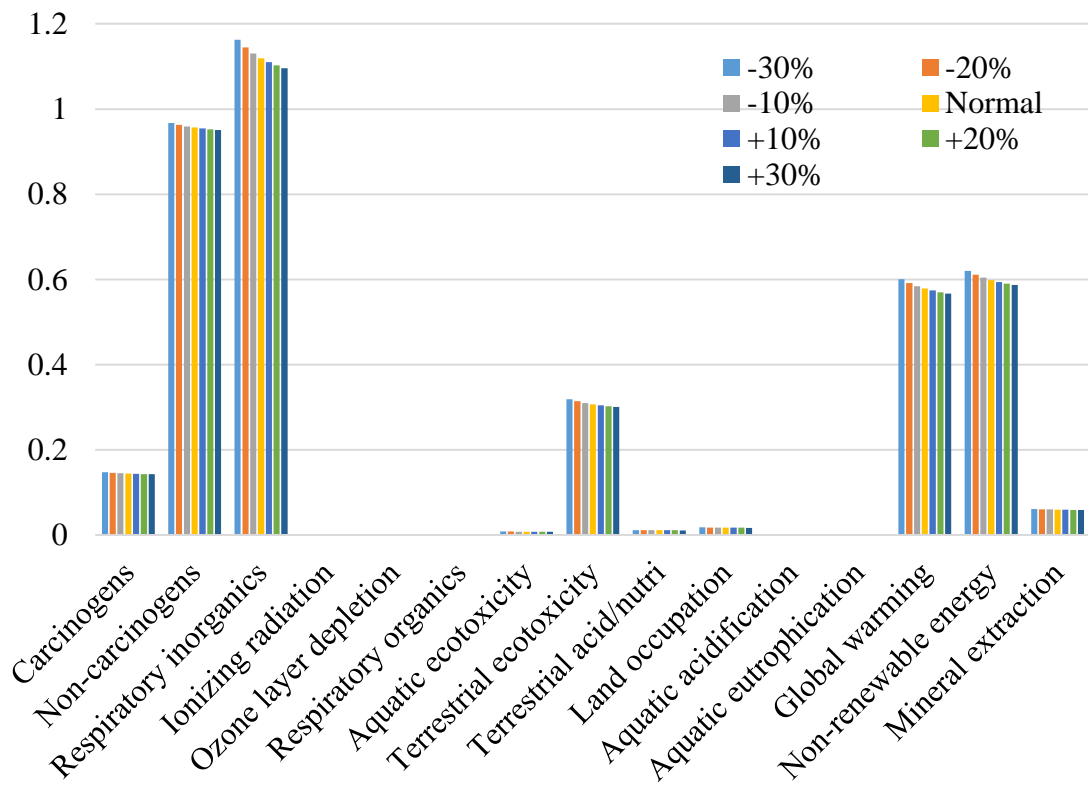


Figure 5.1c: Comparison of Influence of PSU Lifetime on Impact Results (Normalisation) for Reuse System with 1 Hydro Generator

E2: Sensitivity Analysis for Reuse System with Two Hydro Turbine

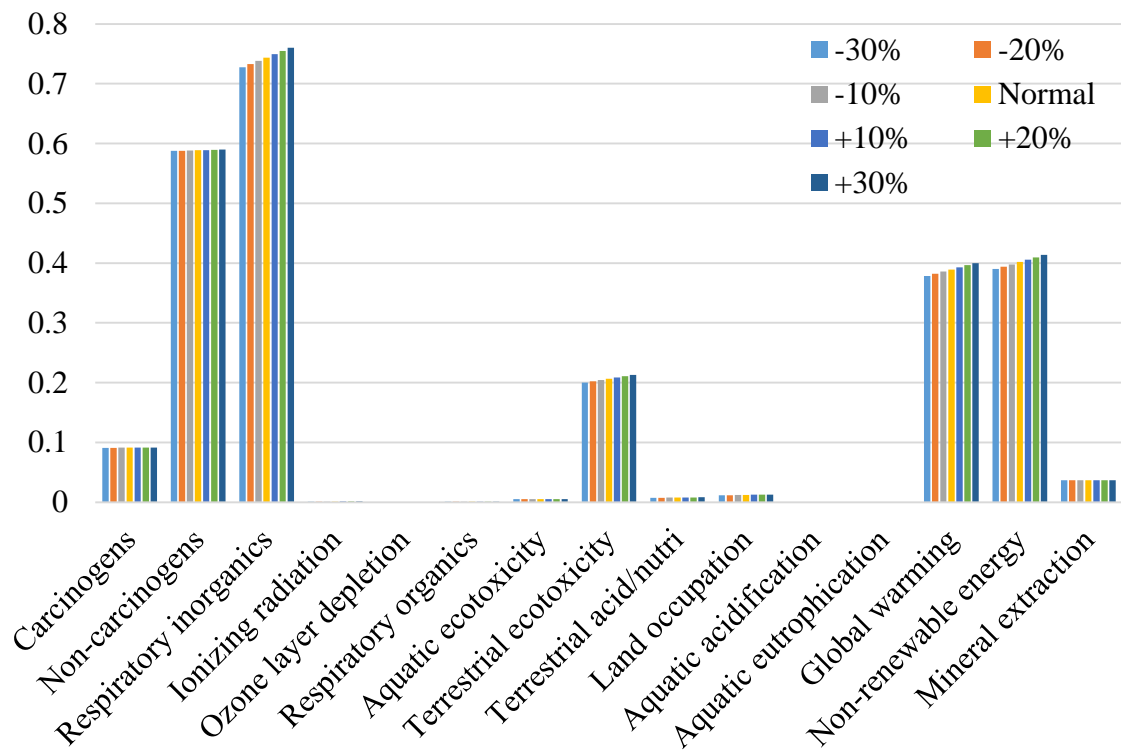


Figure 5.2a: Comparison of Influence of Transportation on Impact Results (Normalisation) for Reuse System with 2 Hydro Generators

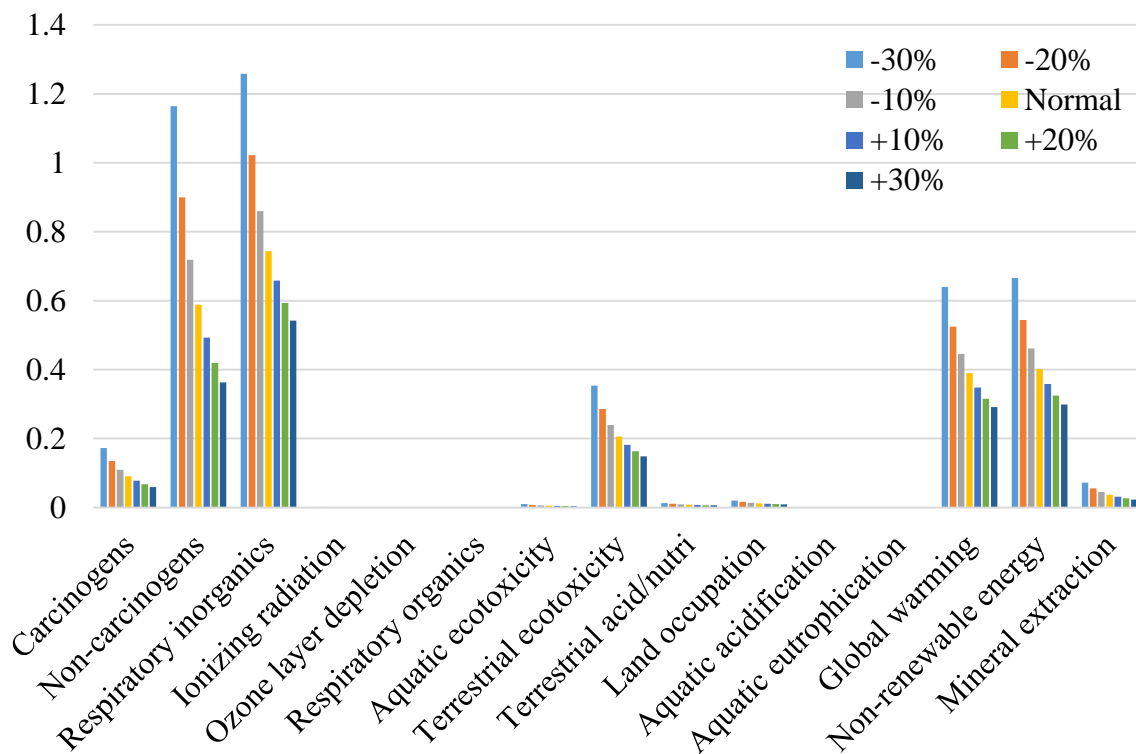


Figure 5.2b: Comparison of Influence of Battery Lifetime on Impact Results (Normalisation) for Reuse System with 2 Hydro Generators

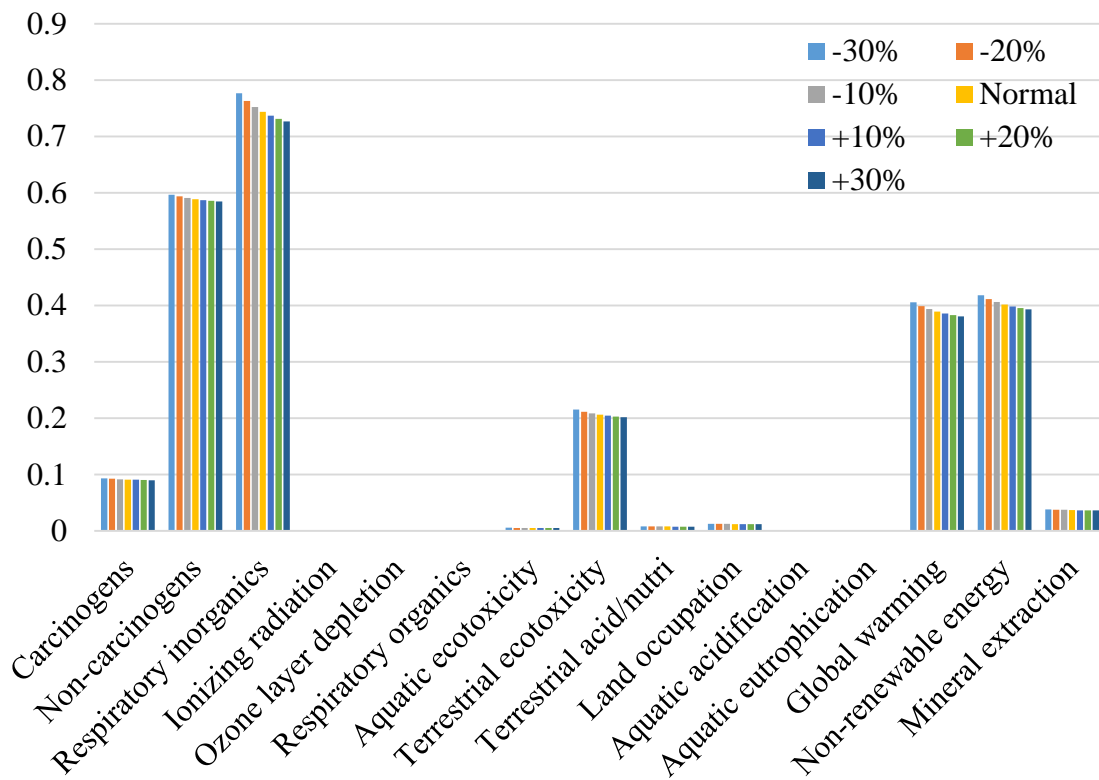


Figure 5.2c Comparison of Influence of PSU Lifetime on impact Results (Normalisation) for Reuse System with 2 Hydro Generators

E3: Sensitivity Analysis for Reuse System with Three Hydro Turbine

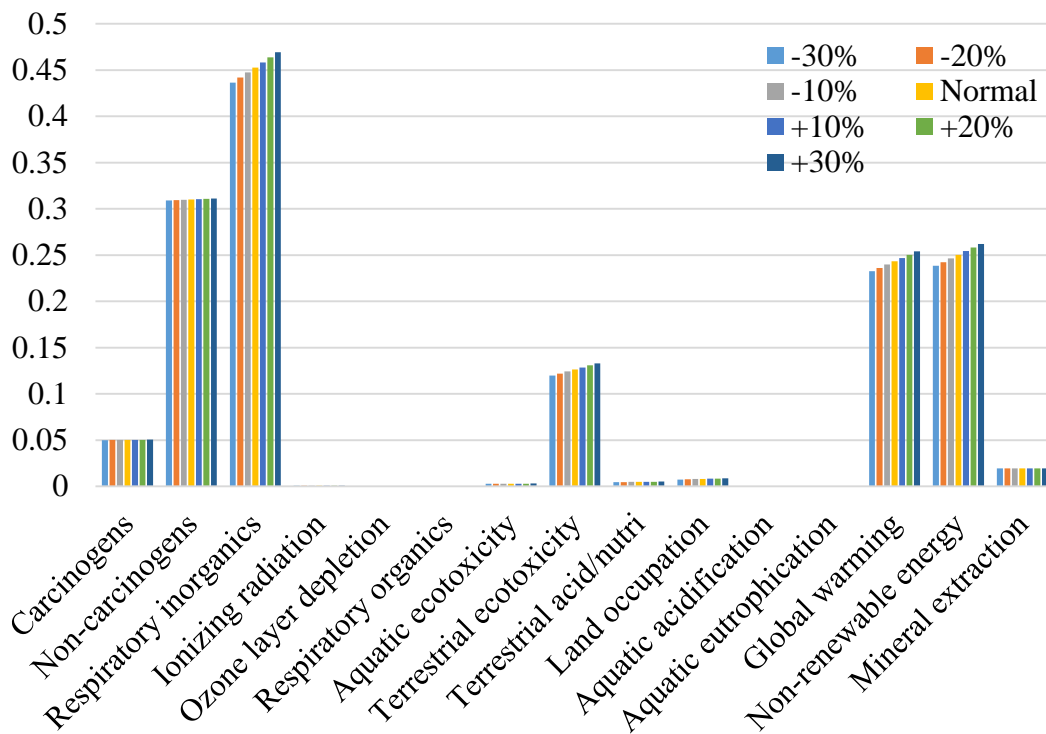


Figure 5.3a: Comparison of Influence of Transportation on Impact Results (Normalisation) for Reuse System with 3 Hydro Generators

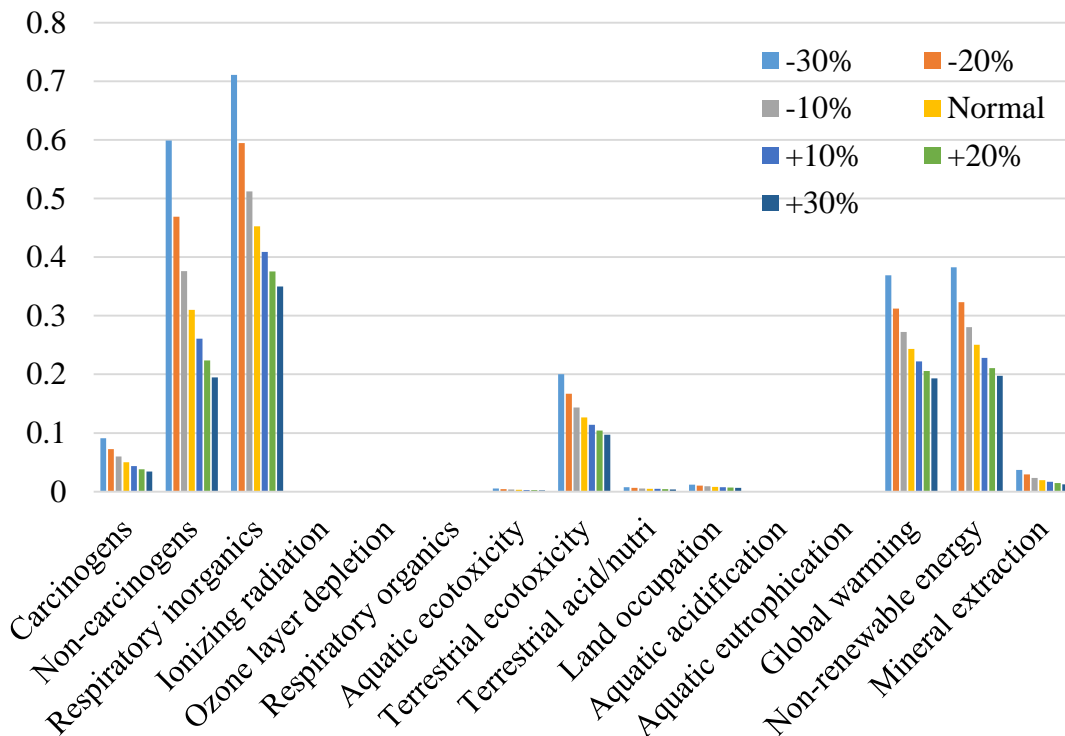


Figure 5.3b: Comparison of Influence of Battery Lifetime on Impact Results (Normalisation) for Reuse System with 3 Hydro Generators

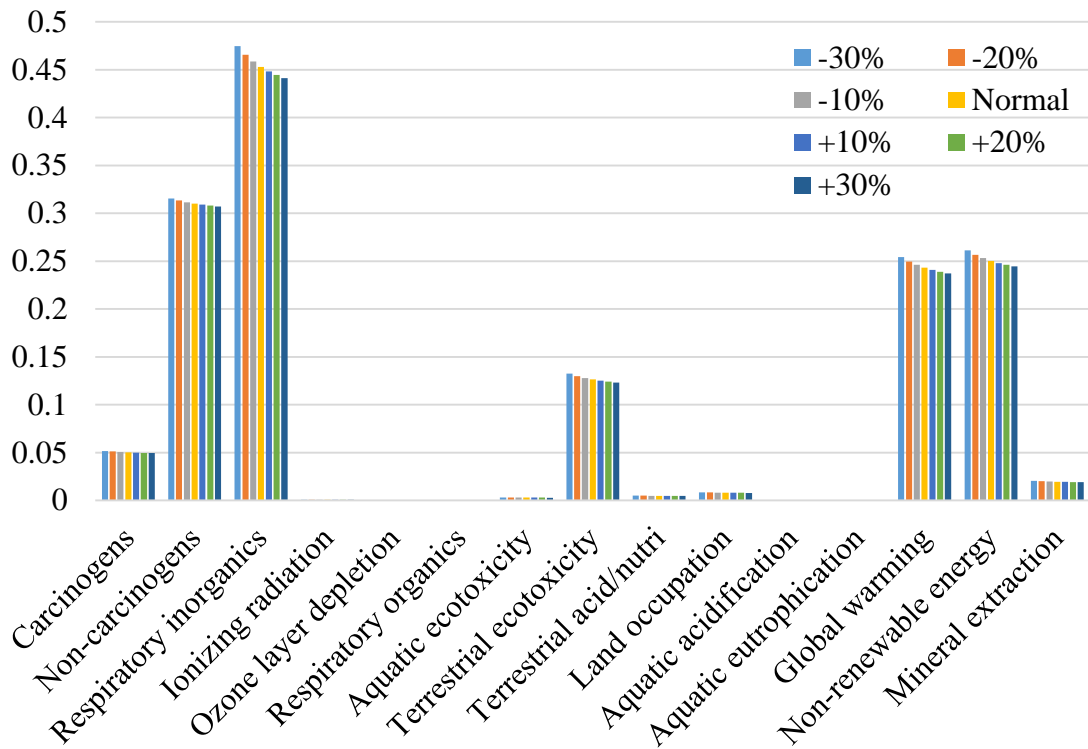


Figure 5.3c: Comparison of Influence of PSU Lifetime on Impact Results (Normalisation) for Reuse System with 3 Hydro Generators

Titre : Contribution à la production d'énergie électrique pour les zones rurales isolées utilisant composants de seconde vie et énergies renouvelables: faisabilité pratique et analyse du cycle de vie

Mots clés : Énergie renouvelable, Électrification rurale, Innovation frugale, Gestion de l'énergie, Analyses du cycle de Vie

Résumé : La demande croissante en électricité constitue depuis toujours un défi. Développer de nouvelles sources de production d'énergie durables devient une nécessité et un enjeu sociétal majeur afin de diminuer l'empreinte carbone du secteur. La principale motivation de cette thèse réside dans la possibilité d'adapter un système de production d'énergie solaire-pico hydraulique de deuxième vie, réutilisé à partir de composants électroniques. Ce système a été conçu en utilisant des matériaux réutilisés et des composants issus de déchets électroniques tels que des batteries au plomb, une source d'alimentation d'un ordinateur, une vieille machine à induction, etc. La thèse explore trois questions clés: est-il faisable d'appliquer et de mettre en œuvre le système de seconde vie en se basant sur des déchets électroniques? Le système de réutilisation est-il efficace et adaptable aux besoins énergétiques d'un ménage rural standard ? L'impact environnemental du système de réutilisation est-il inférieur à celui d'un nouveau système sur la même durée de vie ?

Les recherches ont débuté par l'étude de l'impact du déploiement du système de réutilisation sur l'accès à l'électricité. Un modèle de charge a été élaboré pour représenter un ménage rural typique au Nigeria, tandis que le dimensionnement optimal des composants a été réalisé en se basant sur ce même modèle pour le système de réutilisation ainsi que pour le nouveau système. Une analyse technico-économique a été conduite, révélant une réduction d'environ 65% du coût d'investissement initial et une diminution d'environ 15% du coût de l'énergie pour le système de réutilisation par rapport au système neuf.

Les résultats du dimensionnement ont généré trois scénarios combinant d'anciens panneaux solaires et une turbine hydroélectrique réutilisée, soumis à des analyses approfondies. Une étude de faisabilité basée sur la quantité annuelle de déchets électroniques au Nigeria a révélé qu'environ 127 000 foyers pourraient être électrifiés annuellement avec le système de production solaire-picohydraulique réutilisé.

Ensuite, deux algorithmes ont été développés. Un algorithme type « Autoregressive Integrated Moving Average » (ARIMA) a été élaboré pour anticiper l'irradiation solaire et un autre algorithme de gestion de l'énergie de la batterie, intégrant des stratégies de déplacement de la consommation et d'effacement a été élaboré aussi. L'application de cet algorithme a conduit à une réduction de 82 % de la probabilité d'un état de charge nul de la batterie au cours d'une journée de pluie typique. La phase finale consistait à évaluer l'impact environnemental du système par rapport à un système hybride neuf de configuration similaire. Enfin, une analyse du cycle de vie a été effectuée en utilisant le logiciel Simapro et la base de données Ecoinvent, en stricte conformité avec la norme ISO 14040/44. Les résultats ont montré que, pour le système de réutilisation, seules six des quinze catégories d'impact présentaient des scores significativement visibles. Le score d'impact normalisé pour l'ensemble des catégories était inférieur à 0,005 « Daily Adjust Life Years » (DALY), avec absence d'impact pour l'acidification aquatique et l'eutrophisation. De plus, une analyse de sensibilité a été réalisée et a mis en évidence que la durée de vie de la batterie constituait le paramètre le plus sensible, entraînant la modification la plus significative de la contribution à l'impact lorsqu'il était ajusté. En conclusion, cette thèse a réussi à démontrer la faisabilité de l'adoption d'un système de production solaire-picohydraulique réutilisé pour générer de l'énergie dans une zone rurale typique. Les avantages techniques, économiques et écologiques de l'adoption de ce système par rapport à un nouveau système ont été clairement établis, positionnant cette solution comme une réponse immédiate pour améliorer l'accès à l'électricité dans les zones rurales et isolées.

Title: Contribution to electric energy generation for isolated rural areas using second life components and renewable energies: Practical feasibility and life cycle analysis

Key words: Renewable Energy, Rural Electrification, Frugal Innovation, Energy management, Life Cycle Assessment

Abstract: The ever growing demand for electricity has always been a burden which has continued to inspire the need for development and evaluation of new sources for generating electricity. Besides the current challenge of high cost, the effect of ecological footprint and the global warming concerns have further made deployment of novel ideas a bit more difficult. The possibility of adapting a reuse solar-pico hydro energy generation system to a rural apartment for economic and ecological advantage was the key motivation for this thesis. This reuse system was made from old materials and e-waste components such as old lead acid batter, power supply unit from desktop computer an old induction machine and so on. This thesis thus answers three main research questions; is it feasible to apply and deploy the reuse system based on available e-waste components and second life materials? Is the reuse system efficient and adaptable to the energy needs of a typical rural household? Is the environmental impact contribution of the reuse system smaller than that of a new system over the same lifetime? The investigations commenced by exploring the effect of deploying the reuse system on electricity access. A load model was developed for a typical rural household taking a case study in Nigeria while optimal component sizing was done based on the developed load model for both the reuse and new systems. Techno-economic analysis was performed and a comparison between the new system and the reuse system indicated about 65% and 15% decrease in the initial capital cost and cost of energy respectively. From the sizing results, three different possible scenarios of combining old solar panels and the reuse hydro turbine were presented and further analyses were done based on these scenarios. Afterwards, a feasibility study of adopting the reuse system in Nigeria based on annually generated e-waste within the country was performed. The results showed that an average of about 127 thousand households can be electrified annually if the reuse solar-pico hydro generation system was adopted for energy generation in households. The second phase of the research was to develop a battery energy management algorithm to ensure maximum power supply to the loads irrespective of weather conditions and load demand. To achieve this, an Autoregressive Integrated Moving Average (ARIMA) algorithm was developed for forecasting solar irradiance vis-a-vis a battery energy management algorithm incorporating a combination of load shifting and load curtailment. The application of the energy management algorithm successfully reduced the possibility of having zero battery state of charge during a typical rainy day by 82%. After achieving a desirable energy management for the reuse system, the last step was to evaluate the environmental impact contribution of the system as compared to a new hybrid system of a similar configuration. To achieve this, life cycle assessment was performed with the aid of Simapro software and Ecoinvent database. The ISO 14040/44 standard was strictly adhered to and the result indicated that for the reuse system, only six out of the fifteen impact categories had significantly visible impact scores. The normalised impact score for all the impact categories were less than 0.005 Daily Adjust Life Years (DALY) with aquatic acidification and eutrophication having zero impacts score. Furthermore, sensitivity analysis was performed to see the influence of critical parameter on the environmental impact contribution. This revealed that battery lifetime was the most sensitive parameter which resulted in the highest change in impact contribution when varied. In conclusion, this thesis has proven the technical, economic, and ecological advantage of adopting the reuse solution for rural electrification.