UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

ENVIRONMENTAL IMPACTS OF SOLAR PV INTEGRATION INTO EXISTING DIESEL MINI-GRID.

By

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Science in Environmental and Bio-Systems Engineering in the Department of Environmental and Bio-systems Engineering of The University of Nairobi.

MAY 2020

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This thesis is dedicated to my late Dad.

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ABBREVIATIONS

CC:	Cycle Charging
CIDP:	County Integrated Development Plan
COE:	Cost of Energy
D:	Diesel
D-PV:	Diesel Solar Photovoltaic Hybrid
EE:	Ecosystem Effects
EOHS:	Emissions Optimization by HOMER Software
ERB:	Electricity Regulatory Board
ERC:	Energy Regulatory Commission
GDC:	Geothermal Development Authority
GDP:	Gross Domestic Product
GoK:	Government of Kenya
GWP:	Global Warming Potential
GHG:	Green House Gas
HE:	Human Effects
HH:	Human Health
HOMER:	Hybrid Optimization Model for Electric Renewables
ICT:	Information and Communication Technology
IEA:	International Energy Agency
IRENA:	International Renewable Energy Agency
KENGEN:	Kenya Electricity Generating Company Ltd
KETRACO:	Kenya Electricity Transmission Company Ltd
KPLC:	Kenya Power & Lighting Company
KPHC:	Kenya Population and Housing Census
LCA:	Life Cycle Assessment
LCC:	Life Cycle Cost
LCIA:	Life Cycle Impact Assessment
LCOE:	Leveled Cost of Energy
LF:	Load following
NPC:	Net Present Cost
NREL:	National Renewable Energy Laboratory

PM:	Particulate Matter
PPA:	Power Purchase Agreement
PV:	Photo Voltaic
PVGIS :	Photovoltaic Geographical Information System
RE:	Renewable Energy
REREC:	Rural Electrification and Renewable Energy Corporation
REP:	Rural Electrification Programme
RES:	Renewable Energy Sources
RET:	Renewable Energy Technologies
SE4All:	Sustainable Energy for All
SEA:	Sustainable Energy
SHS:	Solar Home System
UEC:	Unified Electricity Cost
UECE:	Unified Electricity cost with Environmental cost
UHC:	Unburnt Hydro Carbons
UNEP:	United Nations Environment Programme
WEO:	World Energy Outlook

NOMENCLATURE

AC:	Alternating Current
CO:	Carbon Monoxides
CO_2:	Carbon Dioxides
CH_4	Methane
DC:	Direct Current
D_{pv}:	Derating factor of PV array (77%)
G_{Tstc}:	Solar radiation at STC (1kW/m^2)
G_T:	Solar radiation at the tilted surface
$G_{Tn:}$	solar radiation at NOCT (0.8 kW/m^2)
KM^2	Square Kilometer
KWh:	Kilo Watt Hour
KW:	Kilo Watt
MW:	Mega Watt
NO:	Nitrogen Oxide
NO_2:	Nitrogen dioxide
SO_2:	Sulphur dioxide
Twh:	Terawatt hour
Wh:	Watt hour
$M^{2:}$	Square meter

ABSTRACT

Judith Nduku Kimeu

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Environmental Impacts of Solar PV Integration into Existing Diesel Mini-grid

Renewable Energy (RE) is traditionally considered to be clean and free. However, in these last decades, RE related issues are becoming more and more significant and involves the rational use of RE resource and the related environmental impact due to the emission of pollutants. Therefore, there is pressing need for developing RE Technologies (RET), especially solar photovoltaic (PV) to cope with the challenges of energy shortage and environmental degradation. Integration of solar PV into existing Diesel (D) mini grid has both positive and negative environmental effects. The claim that RE is clean need to be verified during utilization, and thus, the net environmental impacts need to be quantified.

In this thesis, environmental effects of D-PV hybrid deployment were reviewed and then the emissions evaluated using HOMER software. Health and Ecosystems effects were further analyzed using Modified Recipe Model of the Life Cycle Impact Assessment (LCIA). A case study of Lodwar Town in Turkana County Kenya was used.

Simulated results reveal that deployment of hybrid Diesel-PV (D-PV) enables 77% decrease in net emission levels at 60% PV penetration which is the optimal scenario. Use of pure PV reduces net health effects (H) by 32% while D-PV when applied optimally results in 88% decrease. When a pure PV system was simulated, the average ecosystem effects became 73% while for the hybrid system, such effect are 88%.

Thus, the hybrid D-PV system is preferred in reducing environmental effects.

Keywords: D-PV mini-grid, Environmental Impacts, HOMER, Modified Recipe Mode

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

World statistics currently indicate that over 1.5 billion people mainly in the rural areas and informal settlement of developing countries have no accessibility to electricity. Governments mostly in the developing countries must accelerate the universal access to electricity by investing heavily on the energy sector. As such, adoption of Renewable Energy (RE) is inevitable were through centralized mini grids at local level using village distribution network. Solar, wind and geothermal are the most common Renewable Energy Sources (RES). Hybrid systems whereby one or more renewable sources, a battery system or a diesel generator are integrated together to increase access to uninterrupted electricity that is environmental and economic friendly (Solar Power Awards, 2018) are a good way of electrifying isolated rural communities.

Grid extension is costly in isolated rural communities and may not be feasible in implementation. However, RES can be integrated together to come up with an affordable hybrid system that can impact the end users. Even though the nature of rural economies pushes for low cost energy programs, quality affects the system's lifespan and thus the superiority of the system components can guarantee a long-lasting program with lowest generation costs. Appropriate sizing of the system increases the efficiency gains and cost savings, thus energy efficiency. The load and the power generated by a system is influenced by the energy efficiency and raises the cost of the project. As a result, energy policies in developing countries should be constituted by supply and demand side management. In designing household and community energy systems many designer's advice on the consumers on how to reduce short term investment costs, thus the need for creating awareness on energy-efficient appliances (Alliance for Rural Electrification, 2017).

In sub-Saharan Africa, energy sources such as diesel are used to distribute energy in arid and semi-arid communities. However, a system that is fully served by diesel gensets is more expensive than hybrid ones. Hybrid mini-grids on the other hand exploit several local renewable resources combined with the diesel gensets to complement one another (ARE n.d.).

Turkana County is one of the counties that is powered by off grid mini grids powered by diesel generators and with the highest poverty index in Kenya. According to Turkana County Government (n.d.), nearly 92% of the population lives below the poverty line, earning less than two US dollars per day (Turkana County Integrated Development, 2013-2017). Being a solar energy potential zone, with an average potential of around 4-6 kWh/m^2, when installed solar PV modules can be used to convert the solar radiation into electricity.

Solar PV system is a form of clean energy that can be a great substitute of diesel gen set or a fuel saver for a hybrid (Solar-Diesel) system mini grid. Hybrid power systems have recently attained a lot of attention worldwide owing to their ability to combine several renewable energy sources and also include a backup generator as well as reducing emissions from the petroleum energy sources (WIT Press n.d.).

This thesis presents a hybrid power system of a solar PV and diesel generator system on which the environmental impacts of Solar PV integrated into a diesel mini-grid in Turkana County are investigated.

1.2 Problem Statement

Many areas in third world countries are not connected to the grid. Principal alternatives for connecting the communities include grid extension and off-grid generation (Muthamia, 2016). Turkana County is one of the regions powered by off-grid connection (diesel mini-grids) located in four town centres namely Lodwar, Lokichoggio, Lokori and Lokitaung with two more (Kakuma and Lokiriama) under construction. The total installed capacity is 3MW. However, these mini-grids have many problems such as high cost of electricity production, pollution from diesel Gen sets, problems related to partial load operation of diesel gen sets, logistical challenges, fuel shortage which can lead to power interruptions and may result in social unrest in the region (World Bank, 2017). This research therefore, sought to establish the environmental impacts of Solar PV integration into already installed diesel mini-grid with Turkana County as the case study.

1.3 Objectives

1.3.1 General Objective

The general objective is to investigate the environmental impacts of solar PV integration into existing diesel mini-grid.

1.3.2 Specific Objective

The specific objectives of this research are as follows:

i) To review the economic and environmental impacts of Diesel(D), Solar PV (PV) and D-PV mini-grids

ii) To test and evaluate the various pollutants in hybrid PV-Diesel Model using HOMER Software

iii) To analyse the environmental impact of injecting Solar PV into the existing mini grids using Modified Recipe Model

iv) To analyse the economic aspects of environmental effects

1.4 Research Questions

i) What are the environmental impacts of Solar, Diesel and Hybrid mini grids?

ii) How can the environmental impacts of PV-Diesel be practically modelled?

iii) How can the PV-Diesel Model be evaluated and tested using HOMER software?

iv) Will it be cost effective to hybridize or completely solarize the existing diesel Mini Grids?

1.5 Justification for the Study

The recent push for Kenya's energy access is part of the government's goal to achieve universal energy access by 2020. Kenya is committed to achieve the UN Sustainable Energy for All (SE4All) Initiative, which calls for universal access to modern energy services, doubling the global rate of improvement in energy efficiency, and the share of RE by 2030 (IRENA n.d.). Kenya is among the countries that have opportune potential for RES like solar, hydro, wind, biomass and geothermal resources. Consequently, the government seeks extensive exploration of RE generation to electrify rural areas (RECP, n.d.).

With high insolation rates, of an average of 5-7 peak sunshine hours and an average daily insolation of 4-6kWh/m^2, Kenya has a total estimated photovoltaic installations potential of 23,046 TWh/year.

The greatest challenge for Kenya's transition to a green economy will be the political and economic interest attached to a brown economy pathway against social economic and environmental gains associated with the RE. This thesis seeks to moderate the claim that RE is "clean"

1.6 Beneficiaries of the Research Output

The output of the research is useful to the following:

i) Government Institutions like Kenya Power and Lighting Company (KPLC), Kenya Electricity Generating Company Ltd (KENGEN), Kenya Electricity Transmission Company Ltd (KETRACO), Rural Electrification and Renewable Energy Corporation (REREC) and Non-governmental organizations. The findings of this study are relevant and provide valuable data that can be used to revamp the RE sector by integrating it with the existing power grid. The research information could also be used to develop policies that can boost RE development and access in line with Kenya's Vision 2030.

ii) The residents of Turkana County: The information on the Diesel PV hybrid system will help the county advance the accessibility to clean, reliable and affordable energy. This will enable the local community to save energy and therefore money on their energy bills. Thus the County may also reinvest part of the profits to the community projects in the area.

iii) Manufacturers and dealers of RE products in order to align their business activities and products with the demand from the RE sector and the hybrid power systems. The study will be used to further increase the engagement of RE sector market players and potential consumers for economic empowerment.

iv) Scholars and researchers interested in studying the hybrid power systems can use the research findings of this thesis to appreciate that integration of several RES has both positive and negative environmental significance. This study therefore acts as an entry point to many researches as it could considerably enrich and broaden the present literature materials on RE.

1.7 Scope of Work

The scope of this thesis is limited to the environmental impacts of D-PV mini grids. HOMER software was used in the simulation to analyse the trends and enable the sizing of solar PV system integrated to the diesel power generation. Modified Recipe Model is then applied to analyse the health and ecosystems effects. Socio effects are not considered.

The thesis simulated different power supply systems for Diesel PV Hybrid systems with the aim of determining if it is viable to have a full Solar Mini-grid or a hybrid mini-grid. Within the confines of the study, a workable D-PV system was developed with Turkana County in Kenya as the case study.

1.8 Thesis Organization

The rest of the thesis is organized as follows: Chapter 2 contains review of environmental effects of Solar, Diesel and the Hybrid System. Chapter 3 is the methodology which include HOMER, Modified Recipe Model and the Case Study of Turkana County; Kenya. Chapter 4 includes the environmental effects analysis while Chapter 5 is the economic analysis of environmental effects. Finally, Chapter 6 is conclusions and recommendations for further work.

CHAPTER TWO

ENVIRONMENTAL EFFECTS OF DIESEL SOLAR PV MINIGRIDS

Optimizing the use of inadequate resources is one of the major challenges facing any decision maker. There is increased recognition that the environmental impacts often need to be valued in economic terms in order to receive adequate consideration by the decision maker. The main aim of the economic impact analysis is to capture the hidden cost and benefits as well as the synergies and economies of scale that can be achieved from the identified environmental impacts of D-PV hybrid system.

Economic Analysis is employed in this thesis to determine if the overall economic benefit of the system exceeds its overall cost. It also seeks to evaluate the identified environmental impacts in qualitative terms and quantify them. In the past, environmental impacts were not converted into monetary terms.

2.1 Impact of Solar PV Mini-grid System

Solar photovoltaic (PV) generators convert the energy from the sun into electrical energy through their solar cells, which are manufactured from semiconductor-based materials. These solar cells are connected together in series or parallel to form a solar panel. Each solar panel can have a peak generation capacity from 80-200W, depending on size and technologies in materials used in production of the panel's. Panels can be installed together series or parallel in order to achieve the desired output capacity. The amount of solar radiation received at a specific location is called insolation, and this factor is used in determining the output of the PV generator. Seasons and climatic conditions have an influence on PV generation. During the warmer months the insolation is higher than in cold months. Similarly, insolation is higher during dry season than during the rainy season. In this scenario, the lower production of PV during the rainy season can be offset with a hybriding the system with another electricity generation plant like small hydro system which will operate at optimum levels due to higher availability of water resource in rainy and in cold months.

Secondly, the time of day also influences the production profile, with peak production at noon time when the sun is perpendicular to the Earth's surface, and no production during the nights. PV generators generate DC power and therefore extra components are necessary to adapt the voltage to the required applications. If the system includes batteries, normally the PV generator will be connected to the batteries through a charge controller. If instead the PV generator is connected to an AC bus bar feeder, it will need an inverter to adapt the voltage.

2.1.1 Environmental Impact

2.1.1.1 Positive Environmental Impact

Green Technology: Solar PV mini-grid is considered a green technology because it offers no pollution to the environment, the air is remains fresh. It replaces the tradition and conventional energy sources such as coal fired power plants that increase the content of Sulphur in the environment thus causing acid rain, and thermal power plants that use petrochemicals such as gasoline, where carbon (I1) oxide and other toxic substance are released into the environment causing public health concerns.

Reduction in Green House Effect: Global warming is an international concern to different governments around the world. There have been summits of various world leaders to make the earth habitable, and hence global warming is a threat to humanity. To salvage the remains of the earth, solar energy is a promising technology that offer no emission of greenhouse gases and carbon dioxide (Akyuz, *et al.*,2018).

2.1.1.2 Negative Environmental Impact

Solar PV Mini-Grid plants have the potency to cause environmental degradation and the loss of habitat. The degree of loss depends on the scalability of the technology, the land topography and the resources available for construction of the site. The materials to be used are proportional to the type of technology, like photovoltaic (PV) solar cells. For PV it requires about 3.5 to 10 acres per MW.

Another factor to be considered is that it is unlikely for solar system to share land with agricultural uses like crop production and animal husbandry.

The materials in which the solar systems are built require maintenance and cleaning. Cleaning of these surfaces makes use of chemicals which are relatively toxic to humans. They are similar to the chemicals used in semiconductor industry they include, hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1 1 1-tri-chloroethane and acetone. The amount of these substances used depends on the type of solar system as reiterated.

There are health complications when the storage units used to store heat energy are not ideal. Consequently, this may provide ideal environment for the growth of molds and fungi that causes different allergic reaction. It is also worth noting that **t**he need for renewable energy is inexhaustible, but comes with its own challenges. This might cause a shift in the ecological balance, owing to the facts that the surfaces of these panels reflect light because they are made with silicon-based materials. When birds and insect fly around this region they may die, hence affecting ecological patterns in the environment.

2.1.2 Economic Impacts of Solar

2.1.2.1Positive Economic Impacts

Cost effectiveness: Solar PV mini grid system has been seen to be very cost-effective, compared with the traditional/conventional electricity. The savings of an average household depending on the location can significantly cut down energy savings from as much as $60,000 to about $20, 000 in about two years of energy consumption (States & States, 2011). This can directly affect the cost of living of individuals in households towards a better and improved standard of living. Industrially and commercially the use of solar PV mini grid system in industrial heating has gained attention. This is in contrast with using other means of energy such as hydroelectric power. The rate of electrical energy consumed during such process will be very high, compared to the solar PV grid systems.

This will inherently affect the products in the market, where increase in industrial utility will correspond to an increase in the state of commodities in the market while a decrease in the use of industrial utility significantly causes a decrease in market commodities (States & States, 2011).

Growth and development of micro-enterprise in developing countries and their economies begins with small and private enterprises. The role of power in the management and optimization of these industrial processes is eminent; hence, the need for an efficient energy is required. Developing countries in Africa are faced with challenges of stable electricity supply, owing to the fact that the demand for the state is obviously more than the supply. Therefore, this has caused a lag in her economies, as compared with developed countries. Hydro power plants are failing due to the fact that constant supply of energy depends on the availability of water as the main substrate used. The phenomenon has spurred the interest in the diversification of other sources of the energy like solar, wind, and biomass. The use of solar PV mini grid system to power small scale businesses will cause a corresponding increase in the socio-economic aspect in a nation. Consequently, this will lessen the need on dependence from other nations; improve the gross and net GDP of developing countries such as Africa and parts of Asia. Regardless of the seemingly challenges and energy loopholes in these developing countries, microenterprises still manage to strive. Therefore, the utilization of solar PV mini grid system will significantly improve the growth and development of micro-enterprises (Oisamoje & Eguono, 2013).

Employment Opportunities: Renewable energy resources offer employment opportunities in design and fabrication, installation, repairs and maintenance has gained measurable employment for individuals. This niche has grown so fast in the recent years. UNEP estimated in 2009 that about 3 million people worldwide got employed in the RE sector (UNEP, 2011). The largest fraction of this employment rate was found in China, where about 1.12 million workers were estimated to have found jobs in the renewable energy industry, having over

100,000 job growth per year (Oisamoje & Eguono, 2013). International Renewable Energy Agency (IRENA) reported that in 2013 about 6.5 million people directly or indirectly worked in the renewable energy sector based on different reviews and the collection of annual data from sources that are different (IRENA, 2014). According of IRENA, China, Brazil, USA, India and Germany are among the top largest employers for RE, where solar PV mini-grid and wind power are the two most dynamic renewable sector (Oisamoje & Eguono, 2013).

Conservation of a Nation's Foreign Exchange: Developing countries are faced with fluctuations in the value of their currencies. The volatility is partly due to their economic instability and the income for export which is spent on the importation of parts for gasoline engine spare part, turbine engines, and likes which would have been saved in the nation's foreign exchange or diversified to other economic needs if solar power utilization is enhanced.

2.1.2.2 Negative Economic Impact

The evaluation of complex power which includes actual power, reactive power and apparent power, using the PV-grid system as a reference found out that only at high radiation from the PV system array that actual power is available. The conversation of low radiation energy to actual power relies on the process of drawing reactive power from the distribution transformer which is fed into the inverter and loads. The method has not been devised to capture this low energy and convert it into actual power form, meaning that there is still dependence on distribution transformer (Thongpron and Kirtikara, 2006).

2.2 Impact of Diesel Mini-Grid Systems

Diesel as a fuel is any liquid that is used in diesel engines, it is gotten from the distillation of crude-oil (Properties, n.d.). This has been the primary energy source for many nations, such as diesel and gasoline. (Rehman, 2015). This accounts for about 80% of the world's energy consumption rate (World Resource Institute, 2013).

There has been a steady decline of fossil fuel reserve globally, due to their limiting nature in water pollution, air pollution, coastal pollution, deforestation and global climate change. The current consumption rate and reserve of coal, oil and natural gas is estimated at 122 years, 42 years and 60 years world sustainability respectively (Lior, 2008) .

About 2.4 billion people depend on traditional energy sources, and about 1.6 billion people have no access to electric power supply as reported by World Bank. The estimated population of the world's growth rate which is about 2.8%, the need and consumption of electricity is supposed to double in 2020, this will push the electricity demand in developing countries to about 4.6% annually (Ã, 2008).

2.2.1 Environmental Impact of Diesel Mini Grid

2.2.1.1 Positive Environmental Impact of Diesel Mini grid

The environmental impacts of diesel mini grid are quite serious. So far there are no direct positive environmental impacts of diesel engines. However, the emission of CO_2 has adverse effects on the environment as well as in the maintenance of life on earth. Ideally, human civilization should prevent carbon dioxide from trending down to ranks that impend the survival living things that depend on it.

It is acknowledged that all life in the universe is carbon dependent and that the major source of this carbon is CO_2, which sequences through the global atmosphere. According to Greenie Watch. (n.d.) and Moore (2016), "as a minor gas at 0.04%, CO_2 infiltrates the entire atmosphere and becomes absorbed by the oceans and other water bodies (the hydrosphere), from where it provides the food for photosynthetic species. If there were no CO_2 or an insufficient level of CO_2 in the atmosphere and hydrosphere, there would be no life as we know it on our planet"

2.2.1.2 Negative Environmental Impact of Diesel Mini grid

Diesel is made up of carbon elements and thus discharges a mass of harmful materials together with direct emissions as Universiti Tenaga Nasional. (n.d.) posits that diesel contains "organic and elemental carbon (soot), toxic metals, nitrogen oxides that form ozone and nitrate particulate matter, volatile organic compounds, carbon monoxide (CO), carbon dioxide (CO_2), and a variety of toxic metals and gases such as formaldehyde, acrolein and polycyclic aromatic hydrocarbons" (Universiti Tenaga Nasional. (n.d.); Anayochukwu and Nnene, 2013).

Inhalation of these toxic elements can cause cancers, respiratory diseases cardiovascular diseases and others. These substances include carbon (II) oxide, and other toxic gasses. Diesel combustion discharges fine particles and toxic gases that can be inhaled thus finding their way into the most profound parts of the lungs where it can enter the body circulation system. It additionally can accumulate in lungs over time, hindering oxygen exchange to the blood and causing numerous health problems. Such as bronchitis asthma, acute and chronic respiratory symptoms such as painful breathing and shortness of breath, cancer, and premature deaths (NJDEP - stopthesoot.org. n.d.).

One major effect of these gases is the ability to cause greenhouse effect, and global warming, which in turn leads to deforestation, and degradation of agricultural lands, coupled with air and water pollution, the accumulation of solid waste, formation of smog and finally the extinction of some flora and fauna of various water bodies (Oisamoje & Eguono, 2013).

Diesel machines produce so much noise that can irritate the ears, and cause noise pollution, a recurrent exposure of sound of certain frequency can increase the chances of losing hearing.

2.2.2 Economic Impact of Diesel Mini Grid

2.2.2.1 Positive Economic Impact of Diesel Mini-grid

The simplicity of diesel minigrid systems increases the economic value at an industrial scale, such that it is easy to use and operate. It also offers a substantial level of dependence, such that industrial activities move smoothly. The engineering simplicity has made diesel mini-grid system of economic importance to small and medium scale companies (Blizard, n.d.)

In Africa, one prominent and efficient means to get energy is the use of machines that mechanically run on gasoline and diesel to generate electricity; this has been a major and steady substitute for the other forms of energy. This is largely due to the cost efficiency of diesel mini-grid system which is used in developing countries. The diesel mini-grid energy cost of 0.037 \$/kWh with a fuel cost of 0.067 \$/1kWh (Rehman, 2015). Today almost all homes in Africa and some other parts of the world rely on diesel mini-grid to power homes. The large industries also find solace in the use of diesel-mini-grid as an alternative for hydropower stations to drive their businesses and operate efficiently.

2.2.2.2 Negative Economic Impact of Diesel Mini-grid

Machines that make use of diesel as a source of energy often require a high cost to maintain, particularly because of the residues that are formed during operation. These residues include sooth, carbon (IV) oxide (CO_2), and other wastes that require adequate servicing of the combustion engines. In case of frequent breakdown of the engines, there may result over- expenditure which hamper the development of the grass root sectors in different economy (Schemes, n.d.).

Diesel mini-grid systems experience high cost in procuring lubricating parts of the plants. This can be potentially demanding on investors, because the cost of maintaining the plant might be greater or same with maximizing profit (Schemes, n.d.).

Most of the diesel plants seldom works well when the system is overloaded, coupled with the fact that diesel power plants are known not to work adequately for a very long time. This has serious effect in the economy of a nation that solely depends on diesel (Schemes, n.d.).

2.3 Hybrid Mini-Grid System (Solar Integrated With Diesel)

Hybrid mini-grid system integrating solar PV is an effective means of connecting the arid and semi-arid areas that are far from grid. Most of these areas have high peak sun hours annually that thus making solar power an effective source of energy. To improve the operation ability of renewable energy in these areas diesel generator can be used as standby source. According to Pak Insight (n.d.) and Ismail1, Moghavvemi, and Mahlia, (n.d) "a completely feasible design of a hybrid system consists of photovoltaic (PV) panels, a diesel generator as a backup power source. The type of the hybrid system and its configuration depend mainly on the availability of the renewable source in the location selected for installing this hybrid system" (Pak Insight. (n.d.); Ismail1, Moghavvemi, & Mahlia, n.d.).

A photovoltaic mini-grid hybrid system is a smart management integrated unit that makes sure that the quantity of solar energy fed into the system is commensurate to the need per time. It is also more feasible compared to diesel generator system or standalone PV system (Pak Insight. n.d)).

2.3.1 Environmental Impact of a Hybrid Power System

2.3.1.1 Positive Environmental Impacts

The hybrid system is optimized with intelligent system that auto regulates itself depending on the energy demand per time. This optimization helps in the reduction of emissions from carbon, and toxic waste, hence a reduction greenhouse effect and global warming gearing towards a smart environmental friendly system.

With the development of a hybrid system it compensate for the noise produced by diesel generators, hence controlling noise pollution, while achieving the same purpose of energy satisfaction (Othman, 2005).

2.3.1.2 Negative Environmental Impact

One basic negative environmental effect of a hybrid power system is that it's not emission free. There are still some quantities of toxic substances that are emitted to the environment, though they are minimized. These toxic substances can still bio-accumulate in the human system and cause public health issues. The emission of greenhouse gases still accompanies hybrid systems, hence the earth is still not entirely free from the dangers it brings (Usman, *et al.*, 2017).

2.3.2 Economic Impact of Hybrid Power System

2.3.2.1 Positive Economic Impact of Hybrid Power System

Low cost of fuel: Industrially, the use of hybrid system helps in maximizing profits, improve efficiency and increase proposed output industrially. The power system will directly or indirectly boost the economy of a nation, and since the supply chain is influenced by different factors of production. Hybrid mini-grid systems are the most cost-efficient means towards electricity generation, with respect to saving on the consumption and lower cost of maintenance. The fuel and transportation system for diesel into rural areas is very high, as well as the services and spare parts cost (Othman, 2005).

Increased rate of Employment Opportunity: According to Renewable Energy and Environmental Sustainability. (n.d.), the clean energy has potential for employment opportunities and countries with high unemployment rate should prioritize whether long-term or the immediate consequence of the economic recession (Malamatenios, 2016). The advent of hybrid power system tends to improve the employment opportunity in developing nations, coupled with the increased synergy between diesel and solar energies. This directly improves the net GDP of a nation's economy, because some of their domestic products can be exported to neighboring countries. The hybrid systems periodically needs maintenance, repair, and installation, these processes require human capital, which translate also into employment opportunities especially in developing countries.

2.3.2.2 Negative Economic Impact of Hybrid Power System

The hybrid power system is relatively expensive, judging by the different component that makes up a hybrid system, hence small scale business that rely on power may find it difficult to get, therefore slowing down productivity (Dricus, 2015).

The hybrid power system may require a high cost of maintenance, since the system built by the integration of various machine parts, and microprocessors. This cost may incur more expenditure for small-scale businesses and industries that may lead to liquidation pendent systems extra maintenance charges. Expenses such as replacement of the oil filter, fuel filter, spark plugs, etc., increases the costs of the diesel alone system (Hrayshat, 2009).

High Specificity: The hybrid mini-grid system is highly specific because it can't be utilized. Where there is no electricity/ electric grid, its utility is dependent on the main power supply called grid. Therefore, the deployment of these systems in rural areas or villages may incur more cost for private investors or the government (Dricus, 2015).

2.4 Chapter Conclusion

This chapter highlights the various economic and environmental impacts of PV power systems, diesel power systems and hybrid systems, and the quest for energy sustainability which is at the heart of every nation. This is geared toward sustainability and economic stability, especially in developing countries.

Industrialization is one key component in building an economically self-dependent economy hence the need for adequate energy is expedient in driving this agenda. Two key factors that determine the choice of technology to adopt with respect to energy generation are environmental and economic effect, especially in the present digital age.

From the foregoing literature review, it is evident that many research studies have been done concerning design, sizing and generation methods of Solar PV power systems worldwide. It is worth noting that due to advancement of technology, new design and sizing methods are emerging to improve on the subsequent results. Being an alternative source of power to conventional hydro, coal, diesel, wind and geothermal; solar PV is gaining popularity. Solar power integrated with a diesel off-grid power system has also been developed. However, despite all these developments, very little has been done concerning the economic and environmental impacts of solar PV integrated with diesel mini-grids. Thus, this thesis aims at quantifying the environmental impacts of solar PV integrated with diesel mini-grid.

CHAPTER THREE

METHODOLOGY

This chapter covers Hybrid Optimization Model for Electrical Renewables (HOMER) as the modeling software for the emissions and the Modified ReCiPe model for modelling the Environmental impacts in terms of Human health, Ecosystems and Net Resources Cost. The case study area is also discussed here.

3.1 HOMER Software

Renewable Energy Sources have complexities as pointed out by unescochair.bntu.by. (n.d.) that their power output may be seasonal, intermittent, and their availability may also be uncertain. A hybrid power system can be developed using different sources of renewable energy, with varying confidence level that the design meet the power requirements. Design of hybrid systems can diverge from pencil and paper designs to complex computer-generated energy system (Jacobus et al. 2010). Therefore, power engineers need to utilize the optimization and system modeling programs in order to minimize cost of power systems requiring renewable energy. In this thesis, HOMER was used as optimization and modelling software for the hybrid system and the Modified Recipe model was used in the modelling of the environmental impacts.

Hybrid Optimization Model for Electrical Renewables (HOMER) was developed to help designers explore the three principal tasks optimization, simulation and sensitivity analysis of a system (Farret and Godoy, 2006). According to Lamnadi, Trihi and Boulezhar, (2016) "HOMER allows simulation of both grid-connected and off-grid systems which generate electricity from combinations of various energy sources like solar PV modules, micro-turbines, wind turbines, batteries ,biomass based power generators, fuel cells, hydrogen storage and auxiliary generators with numerous fuels options and different load types" (Gupta et. al 2015). According to IntechOpen - Open Science Open Minds IntechOpen. (n.d.), "HOMER software, National Renewable Energy Laboratory's (NREL) micro power simulation and optimization model, has the capability to assess a range of equipment options over varying constraints to optimize small power systems" (Energy Innovations: Science & Technology at NREL, fall 2009).

According to Givler and Lilienthal (2005), HOMER software afford the best opportunity for governments and organizations to model and design large rural electrification projects. The program scans stimulation of all potential conformations of system configurations at a high speed of processing thus allowing for the assessment of thousands of combinations (Energy Innovations: Science and Technology at NREL, fall 2009). In carrying out the simulations, HOMER categorizes the feasible combinations in order of increasing net present cost. Accorging to Givler and Lilienthal (2005), "the cost is the present value of the initial, component replacement, operation, maintenance, and fuel costs. HOMER lists the optimal system configuration, defined as the one with the least net present cost, for each system type. HOMER's sensitivity analysis then repeats this optimization as user-defined factors, such as fuel price, load size, reliability requirement, and resource quality are varied".

". Figure 3.1 shows a basic architecture of HOMER software.

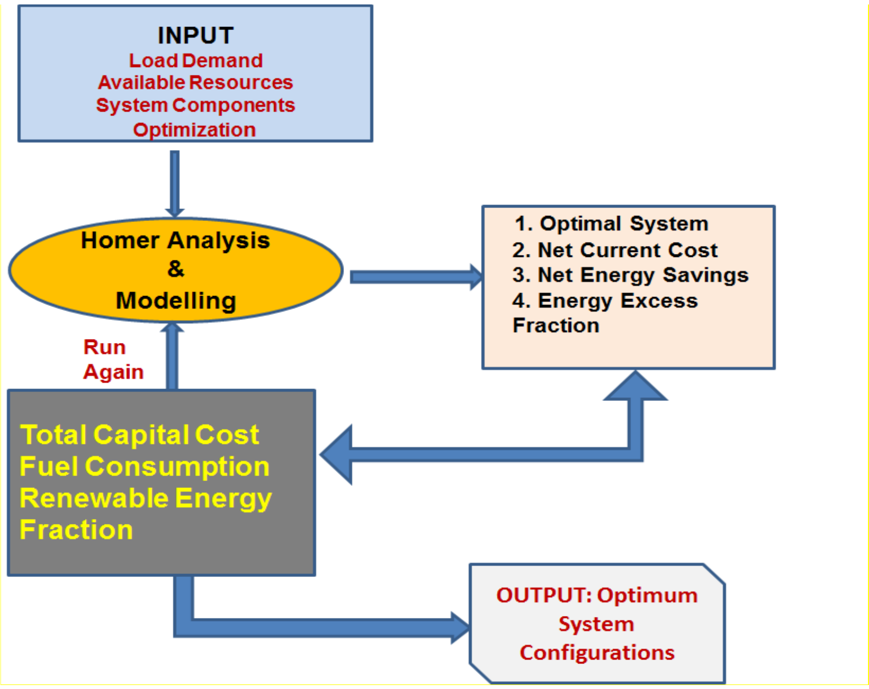

Figure 3.1: HOMER software Architecture (Source: Belu et al., 2014)

Figure 3.1 reveals the design result of the quantity of cases of various RES under weather conditions, load demands, capacity ranges, fuel expenses, and carbon emission constraints to choose the optimum system. According to Asee Peer Document Repository (n.d.) as cited by *Belu et al., (2014)*, "this software package can be used to design and analyze hybrid power systems for both stand-alone and grid-connected applications. Input information to be provided to HOMER includes: electrical loads (one year of load data), renewable resources, component technical details and costs, constraints, controls, type of dispatch strategy, etc. it designs an optimal power system to serve the desired loads, performing several simulations to ensure best possible matching between supply and demand in order to design the optimum system" (Asee Peer Document Repository (n.d.)).

3.1.3 Hybrid System Design

Modern hybrid and energy storage systems have many specifications to consider before selecting and sizing a complete hybrid system. A wide variety of tools ranging from simple rules of them to software packages exist. Hybrid systems design consider time correlation between the intermittent sources and the dispatch strategy. This require in depth sizing and optimization of the systems. For sizing and optimization, software packages have been developed that offer user interface for quicker and more accurate results. Optimizing each component of the hybrid system need much time in computing and thus a complex computer programme is needed. HOMER was used to model the power system physical behaviour in analysing the environmental effects of the hybrid system as it allows for flexible renewable energy hybrid energy design.

3.2 Modified ReCiPe Model

3.2.1 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment (LCIA) is usually used as a technique to compare and analyze the energy using environmental impacts associated with the development of the energy source over their life-cycle. The framework of LCA methodology is shown in Figure 3.2. LCA stages includes definition of goal and scope, life cycle inventory analysis, impact assessment and interpretation of results. The goal and scope definition describes the fundamental question (objective), the system, its restrictions and the definition of a functional unit. The flows of materials pollutants, resources are recorded in inventory analysis. These elementary flows (emissions, resource consumption, etc.) are characterize and aggregated for different environmental problems in impact assessment and finally deductions and conclusions are drawn in interpretation stage. For Solar PV, we adopt the *Modified ReCiPe Model* which is a Life Cycle Impact Assessment (LCIA) for Renewable Energy Systems.

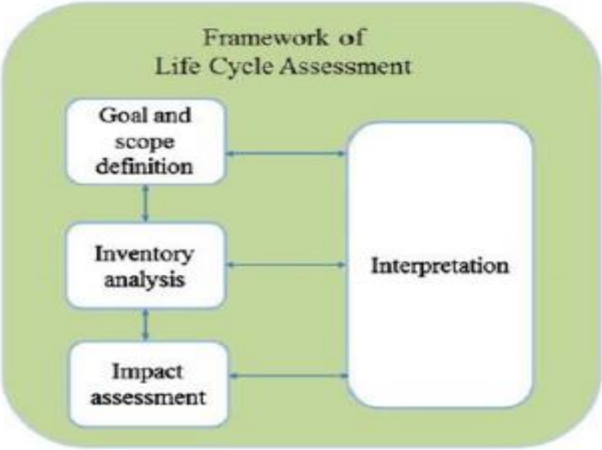

Figure 3.2: Life Cycle Assessment (LCA)

3.2.2 Modified Recipe Model

$ReCiPe$ is a Life Cycle Impact Assessment (LCIA) method for RE released by Heijungs et al (2008). In this thesis, $ReCiPe\ Version$ 1.3 $Model$ is adopted, which has input, midpoint and endpoint indicators. The inputs considered in this model include the raw materials , land use, the optimized emissions by using RE (NO_X , SO_2 and CO_2) , VOS, P,CFC, Cd, PAH, DDT etc. The output is the end point categories which include Human health, Ecosystems, Social and Net Resources Cost.

The midpoint indicators for each end point stated above include the following:

i) *Human Health:* Human Toxicity , Radiation, Ozone depletion, particulate formation ,Photochemical Oxidant formation, and climatic change

ii) *Ecosystem:* Terrestrial acidification Climate change, terrestrial ecotoxicity marine ecotoxicity, agricultural land occupation, natural land transformation, marine eutrophication and fresh water ecotoxicity.

iii) *Net Resources Cost:* Fossil fuel consumption, mineral consumption and water consumption.

This thesis considers health, ecosystem and net cost effects, social effects are recommended for future work. There are eighteen midpoint impact categories and three endpoint impact categories in the $ReCiPe$ method. Characterization factors are used to convert emissions to the units of the midpoint impact categories, and from midpoint to endpoint.

The goal of $ReCiPe$ is to synchronize midpoint and endpoint impact categories in a single framework. This method builds on the previously existing Centrum Milieukunde Leiden (CML 2002) and Eco-indicator 99 methods, the latter of which methodology uses the endpoint approach, and the former, midpoint.

There are both advantages and disadvantages of using midpoints and endpoints impact categories. Midpoints are fairly accurate, but the units, usually in terms of a reference compound, such as CO2 for climate change, can render it difficult for the analyst or a policy maker to understand the overall impact. In the other hand, endpoints are much easier to conceptualize since they are expressed in terms of tangible effects using a point system, dollar amounts, number of species affected, or number of human life years lost (DALY), to which it is easier to relate. However, the method of translating the midpoint impacts to endpoint units incorporates much uncertainty. This uncertainty stems from poor understanding of the mechanisms through which pollutants affect ecosystems and human life and the dependence these mechanisms may have on geographical factors. Thus, the tradeoff between result accuracy and result interpretation becomes quite evident.

3.3 Case Study : Turkana County

The research study focused on Turkana County, one of the regions powered by off-grid connection (diesel mini-grids). "Turkana County is situated in North Western Kenya. It borders West Pokot and Baringo Counties to the South, Samburu County to the South East, and Marsabit County to the East. Internationally it borders South Sudan to the North, Uganda to the West and Ethiopia to the Northeast. The County shares Lake Turkana with Marsabit

County. The total area of the county is 77,000 KM^2 and lies between Longitudes 34^0 30' and 36^0 40' East and between Latitudes 1^0 30' and 5^0 30' North. According to the Kenya Population and Housing Census (KPHC) results, the County population stood at 855, 399. It is projected to have a population of 1,036, 586 in 2012 and 1,427,797 in 2017. These projections are based on a population growth rate of 6.4% assuming constant mortality and fertility rates (Turkana County Government CIDP, 2013)".

Specifically, the research study focused on lodwar in Turkana County. Lodwar is one of the towns in Turkana County powered by off-grid connection (diesel mini-grids). Other town centres are Lokichoggio, Lokori, Lokitaung, Kakuma and Lokiriama with the latter two being the most recent. The Population densities in these towns are low with a population of 146,275 people, and the lifestyle is predominantly pastoral. Turkana County is a solar energy potential zone, with average annual radiation of around 4-6 kWh/m^2 (JRC, 2012).

3.3.1 Load Assessment and Meteorological Data

3.3.1.1 Load Assessment

In assessing the load demand, energy demand was estimated from the customer energy consumption from commercial and industrial entities, public services such as hospitals and schools and households in Lodwar. The installed capacity for the town is 1440 kW with peak energy demand of 650 kW, the four locations has installed capacity of 3000kW (3MW) from the diesel gen set. Therefore, in this study the researcher designed a 1440kW hybrid system for Lodwar town. The loading scenarios for are as shown on Figure 3.3 and 3.4.

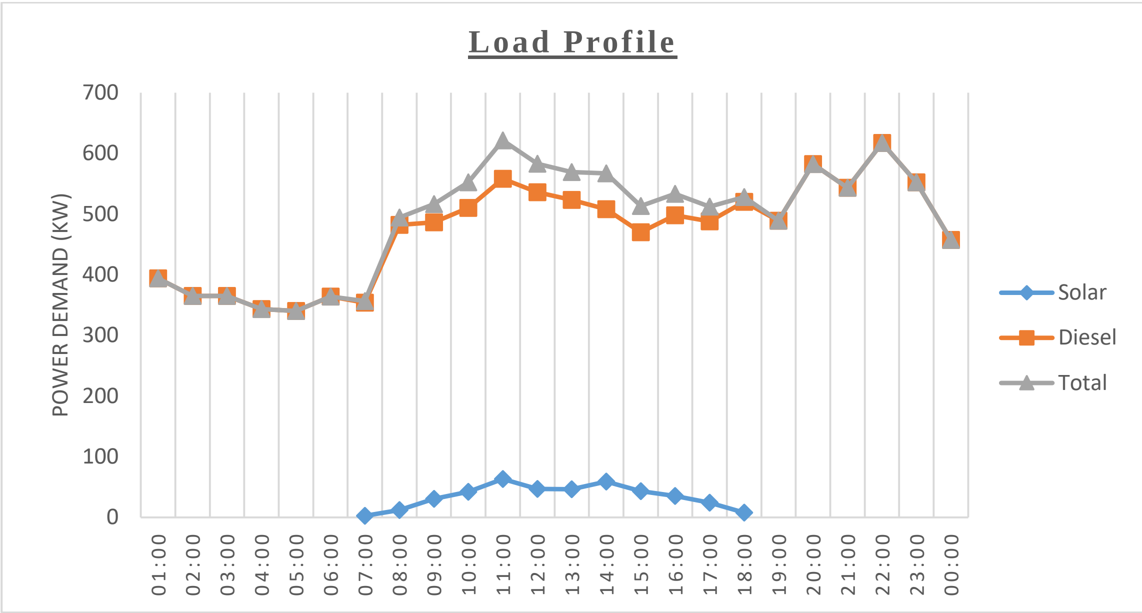

Figure 3.3 Typical load demand profile for Lodwar. Source: (Ministry of Energy, 2013)

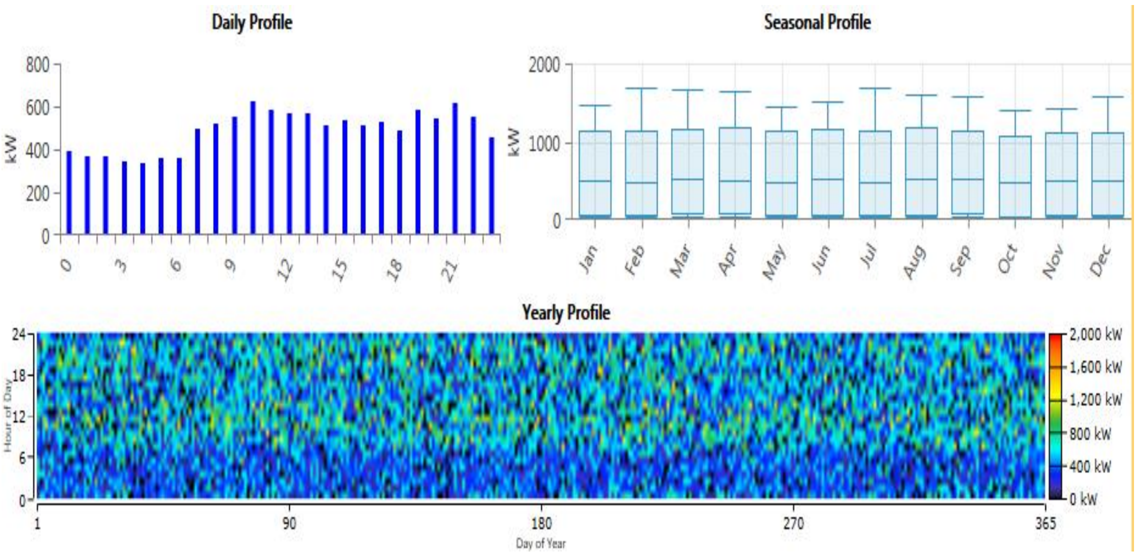

Figure 3.4 Profile Load for Lodwar

3.3.1.2 Meteorological Data

The solar radiation data was obtained by geographical coordinates of Lodwar on the geographical location of the county on the Photovoltaic Geographical Information System (PVGIS). This is shown in Table 3.1 and Figure 3.5.

Table 3.1: PVGIS estimates of solar electricity generation

Month	**Clearness Index**	**Daily Radiation KWh/m^2**
January	0.409	4.300
February	0.480	5.120
March	0.591	6.220
April	0.640	6.370
May	0.763	7.030
June	0.829	7.280
July	0.792	7.090
August	0.720	6.910
September	0.631	6.470
October	0.514	5.420
November	0.412	4.330
December	0.402	4.180

Source: Solar radiation database: PVGIS-CMSAF (JRC, 2012)

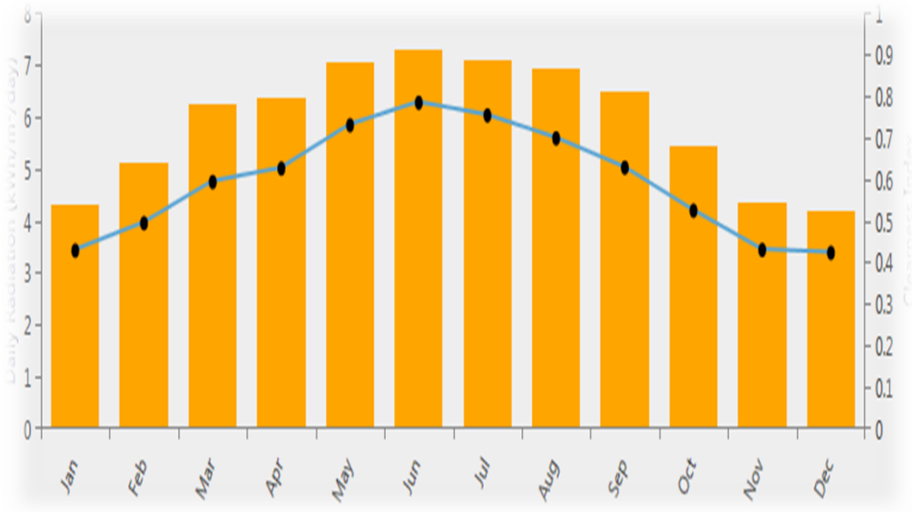

Figure 3.5: Solar Radiation data (Source: HOMER Pro Software)

3.3.2.1 Schematic Diagram

Figure 3.6 shows the complete model of hybrid system consisting of solar PV and diesel generator. The output result from the HOMER software indicate the peak scaled demand of primary load as 1013.72 kW and total average consumption is 11,756 kWh/day.

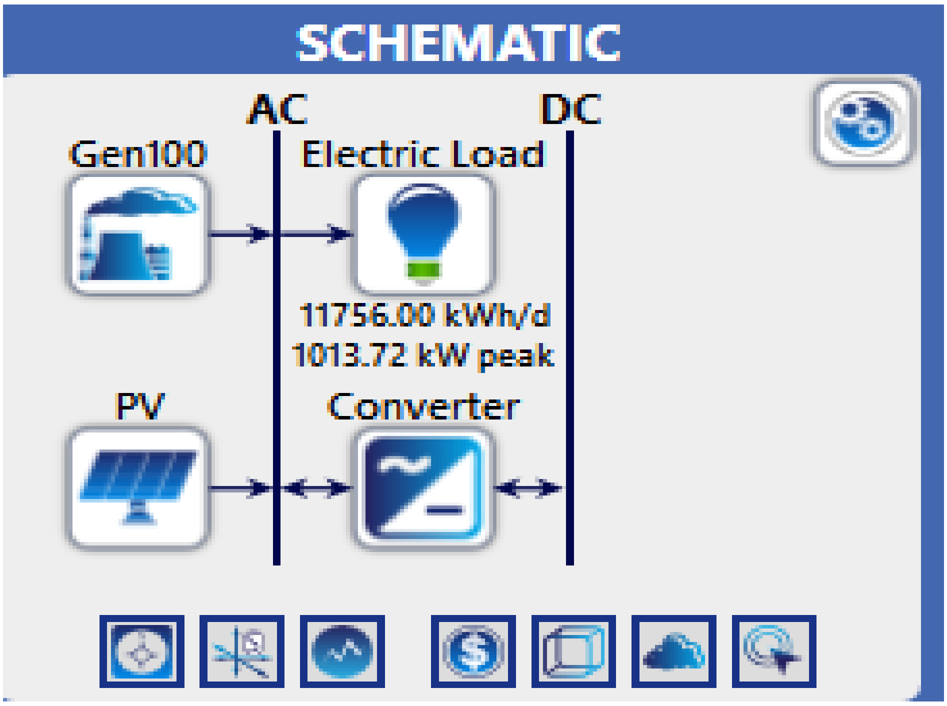

Figure 3.6: Schematic of Diesel Solar Hybrid System

Diesel generators are alernating in nature, therefore, they are tied to the AC bus-bar while Solar PV is tied to DC bus-bar because the output from the solar panel is DC. The converter is connected between AC and DC bus-bar since they convert the DC outputs of the PV system and the battery into AC.

3.3.2.2 Simulations

HOMER was used to optimize the system by testing the best alternative PV-diesel hybrid combinations. This section highlights several scenarios corresponding to different hybrid power system conformations (Diesel generator set and PV+ Diesel generator set). The software optimizes the operation for each scenario, their drawbacks and benefits to come up with the best configurations.

3.3.2.2.1 Scenario 1: Standalone Diesel Generator Set

In this scenario a standalone diesel generator powering a micro-grid is utilized. This is actually the most frequent configuration that you are likely to meet in areas which are powered by micro-grid. Therefore, a diesel generator is used to supply all the power required by the micro-grid and even may need to dump some power production to avoid running at very low load (<30%).

3.3.2.2.2 Scenario 2: PV+ Generator Set

The hybrid system design is made of a diesel generator and a solar power plant without storage system. The solar power plant supplies power during the day but the Genset must still be idling as a spinning reserve: this allows it to kick in very fast to meet the load in case the PV power drops. The Genset remains the grid former, regulating voltage and frequency**.**

3.3.3 Operating Strategies

In the design of Hybrid Renewable Energy Systems, there are two operating strategies considered; these are Load following (LF) and Cycle Charging (CC) dispatch strategies. In LF criteria the diesel generators are designed to supply the loads only when the PV power output is unavailable, with the PV arrays supplying the load and charging the batteries in case of excess power. On the contrary, CC employs diesel generators to meet the loads demand and charge the batteries at the same time (Laith, Saad, Lanre, & James, 2017). In this thesis, LF was considered as the optimal strategy since its design reduces excess energy and the total net present cost (NPC), hence it was used for the analysis. The strategy requires an "overall energy management system to control the flow of energy where the system operates in different modes according to the surrounding atmospheric conditions. At normal operating conditions, where the sun is available, the control system gives the PV arrays the highest priority to supply the loads. When there is insufficient energy supply from the PV, the conventional diesel generators will supply the loads" (Laith, Saad, Lanre, & James, 2017).

3.3.4 Solar PV and Diesel Modelling

3.3.4.1 Solar PV Array Modeling

In this study, design of the PV system parameters was declared as optimally inclined south-oriented solar PV modules for maximum conversion of solar radiation into electrical energy. The components for the simulation of solar photovoltaic system in Hybrid Optimization Model for Electric Renewables (HOMER) software were; solar modules and inverter for converting DC into AC (Pavlovic *et al*., 2013).

Solar cells are setup in combined series/parallel combinations to form an array represented by a simplified circuit model as shown in Figure 3.7

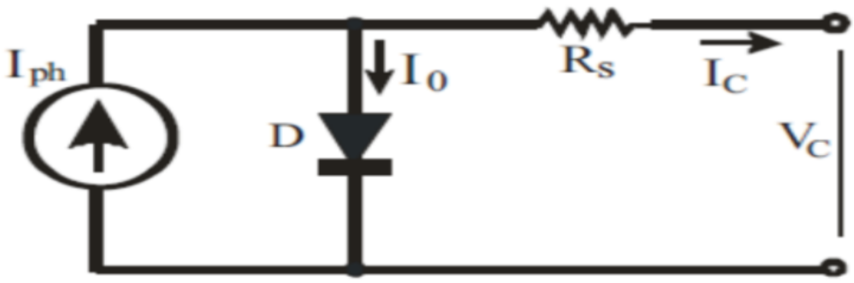

Figure 3.7 Simplified Equivalent circuit of Photovoltaic cell (Source: Kalambe, 2017)

The power generation by the PV array was simulated by HOMER using the equation 3.1. This modelling equation also considers the solar cell temperature (T_c) effect on the PV power production (Chandel and Rahul, 2013) as given in equation 3. 2.

$$P_{pv} = P_{rpv} D_{pv} [\frac{\bar{G}_T}{\bar{G}_{Tstc}}]\{1 + \alpha_p (T_c - T_{stc}\} \quad (3.1)$$

Where;

$$T_C = \frac{T_a + (T_{cn} - T_{an})\left[\frac{G_T}{G_{Tn}}\right]\left\{1 - \frac{\eta_{mp}(1 - \alpha_p T_{stc})}{\tau\alpha}\right\}}{1 + (T_{cn} - T_{an})\left[\frac{G_T}{G_{Tn}}\right]\left\{\frac{\eta_{mp}\alpha_p}{\tau\alpha}\right\}} \quad (3.2)$$

Where: P_{pv} is the Output of PV array; P_{rpv} the rated capacity of PV array, D_{pv} the derating factor of PV array (77%), G_{Tstc} is the Solar radiation at STC ($1kW/m^2$),G_T Solar radiation at the tilted surface, α_p is the temperature coefficient of power (-0.48%°C), T_{an} is the Nominal ambient temperature (20°C), T_{cn} is the Nominal operating cell temperature (47°C), G_{Tn} is the solar radiation at NOCT (0.8 kW/m^2), η_{mp} is the maximum power point efficiency under STC (13%), T_{stc} is the cell temperature under STC (25°C), $\tau\alpha$ is the product of solar transmittance and absorptance (0.9) (Ogunjuyigbe and Ayodele, 2016).

3.3.4.2 Diesel Generator Modelling

The diesel generator supply power equivalent to the total load demand which is normally given by the manufacturer of the diesel generator, according to (Kalambe, 2017), the fuel consumption (FC) vs. the supplied load (SL) curve should be established as follows

$$FC = a \times SL + b \quad (3.3)$$

a and b are coefficients that can be calculated using the least square method for a number of experimental measurements as follows (Krivošík, 2017).

$$a = \frac{N\sum(SLi \times FCi) - \sum SLi \sum FCi}{N\sum SL^2 i - (\sum SLi)2} \quad (3.4)$$

$$b = \frac{\sum FCi - a\sum SLi}{N} \quad (3.5)$$

Where; I -the examined measurement (I.e. 1, 2…N).

SLi - the load being supplied and

FCi - the fuel being consumed by the diesel generator when it supplies load SLi.

The above mentioned curve is of significant importance for the economic assessment of every power system for possible use (Krivošík, 2017; (Kalambe, 2017)Similarly, the efficiency of the diesel generator is strongly dependent on the load it supplies and is given as;

$$nn_{DG} = \frac{P_{out}}{P_{in}} = \frac{SL}{MCV \times FC} \quad (3.6)$$

Substituting *FC* with equation 4.3

$$nn_{DG} = \frac{P_{out}}{P_{in}} = \frac{SL}{MCV\ (a \times SL + b)} \quad (3.7)$$

If the load to be supplied is less than 30% of the diesel generator rating capacity, the diesel generator operation should be prevented not only due to its low performance, but mainly due to the damage the machine may suffer, which limits its useful life (Krivošík, 2017).

3.3.4.3 Inverter

The design of the hybrid system require a grid-tied inverter to connect the PV DC to the AC grid. HOMER software technology allowed the selection of the inverter size and cost to simulate and optimize an inverter size to meet the PV area and load demand. Since the PV system has a number of array strings, a number of string inverters are desirable. According to Alayan (2016) "the advantages of string inverters are reduction of combiner boxes and easier system troubleshooting and monitoring"

The inverter characteristics for this design are shown in Table 3.2. According to Alayan (2016), "the model SMA TriPower 15000TL has a large V_{mpp} range of 360-800V, which gives some flexibility in using different modules voltage characteristics and design with different string lengths. The maximum voltageis 1000V and the efficiency is 98.1%. this high efficiency makes the SMA TriPower 15000TL the best selection for the design.

Table 3.2 Inverter Specifications

Inverter Type	Sunny TriPower STP 15000TL-10
Inverter Efficiency	98.1%
Max voltage	1000V
M_{pp} voltage range	360V-800V
String inverter size	500kW
Lifetime	15 years
Electronic MPPT	Yes

3.4 Chapter Conclusion

HOMER software was used in this thesis for the Modelling of Diesel PV hybrid and the preliminary analysis of the results. Modified Recipe Model version of LCIA was applied in the in depth analysis of the environmental impacts of Solar PV for the case of Lewder Town in Turkana County.

Chapter 4 and Chapter 5 contains the analysis of environmental impacts and economic analysis of such impacts respectively.

CHAPTER FOUR

ENVIRONMENTAL IMPACTS ANALYSIS

This chapter covers introduction to emissions due to burning fossil fuels, emission analysis, Environmental effects analysis and chapter conclusion.

4.1 Fuel Combustion Emissions

With the rising adoption of "clean" energy and energy mixing globally, there is need for serious research to find out whether Renewable Energy Technology (RET) sources are as clean and harmless as they are believed to be (Musau, Odero, & Wekesa, 2017)

Combustion of fuel in a diesel generator emits a number of gases like Sulphur dioxide (SO_2), Nitrogen Oxides (NOx), Carbon dioxide (CO_2) and also Methane (CH_4). Carbon dioxide (CO_2) has the largest percentage of these emissions. Consequently, this research considered Sulphur dioxide (SO_2), Nitrogen Oxides (NOx), Carbon dioxide (CO_2), Methane (CH_4) and Particulate Matter (PM), Unburned Hydrocarbon (UHC) in the determination of the emission costs of the system. The major ones are discussed in the next subsections.

4.1.1 SO_2Emissions

The Sulphur content of the fuel determines the Sulphur oxides (SOx) emissions which varies some 0.3 to 3.0 %. The following equation determines specified SO_2 emission factors.

$$EF_{\mathrm{i}} = 2C_S(1-\alpha_S)\frac{1}{H_u}10^6\left(1-ɳ_{sec\beta}\right) \tag{4.1}$$

The value of SO_2 content in flue gas (C_{SO2}) is:

$$C_{\mathrm{SO2}} = EF_{\mathrm{SO2}}\ \frac{1}{V_{fg}}E_{fuel}\left[\frac{g}{m^3}\right] \tag{4.2}$$

$$E_{fuel} = (FCH_u)10^{-3} \tag{4.3}$$

Where EF_i represents specified emission factor for pollutant i (SO_2, NOx, CO_2, CH_4, N_2O) [g/Gj], Cs $_{fuel}$ is fuel Sulphur content in fuel [kg/kg], αs is Sulphur retention in ash [%], H_u is the lower heating value of fuel (fuel oil or natural gas)[MJ/kg], ɳ_$sec\beta$ is reduction efficiency of secondary measures [%], β is availability of secondary measures, E_{fuel} is Energy from fuel [GJ], FC is Fuel consumption (1 kg oil or 1 NM^3 dry natural gas) and V_{fg} is Specific flue gas volume.

4.1.2 NOx Emissions

NOx is composed of two important oxides formed after combustion of fossil fuels. These are nitric oxide (NO) and nitrogen dioxide (NO_2). NO is the main component contributing over 90% of the total NOx. During the combustion of solid and liquid fuels, fuel-NO and thermal-NO are formed. The determination of NOx emission factors takes into account formation of fuel-NO and thermal-NO (Musau, Odero, & Wekesa, 2017). The maximum attainable amount of fuel nitrogen oxide ($C_{NO\ fuel\ max}$) is obtained by the relation.

$$C_{NO\ fuel\ max} = C_{N\ fuel} \frac{30}{14} \frac{1}{V_{fg}} \left[\frac{kg}{m^3}\right] \tag{4.4}$$

The content of NOx in the flue gas (C_{NOx}) is given by:

$$C_{\mathrm{NOx}} = EF_{\mathrm{NO2}} \frac{1}{V_{fg}} E_{fuel} \left[\frac{g}{m^3}\right] \tag{4.5}$$

Where; $C_{N\ fuel}$ is the nitrogen content in fuel (in mass nitrogen/mass fuel) [kg/kg] and E_{fuel} is the energy from fuel [GJ]. It is worth noting that the amount of NOx emissions is strongly influenced by content of oxygen in the flue gas.

4.1.3 $CO_{2equivalent}$ Emissions

Combustion of fossil fuels emits many gases where Carbon dioxide (CO_2) is the main product as it is directly related to the carbon content of fuels. The equation (4.6) below determines specified CO_2 emission factors.

$$EF_{\mathrm{CO2}} = \frac{44}{12} C_{C\ fuel} \varepsilon_C \frac{1}{H_u} 10^6 \left[\frac{g}{GJ}\right] \tag{4.6}$$

The carbon dioxide content in the flue gas (C_{co_2}) is given by;

$$C_{\text{CO2}} = EF_{\text{CO2}} \frac{1}{V_{fg}} E_{fuel} \left[\frac{g}{m^3}\right] \quad (4.7)$$

Where $C_{C\ fuel}$ is carbon content of fuel (in mass Carbon/mass fuel) [kg/kg] and ε_C is the fraction of carbon oxidised (defined as the main part of carbon which is oxidised to CO_2).

In addition to CO_2, methane (CH_4) and nitrous oxide (N_2O) are among the most notorious greenhouse gases from fossil fuels combustion. Each of these gases has active radioactive or heat-trapping properties and can be converted to CO_2 equivalent using the emission factors shown in Table 4.1. Thus their Global Warming Potential (GWP) can be determined.

Table 4.1: GWP for Choice Gases

Gas	100-Year GWP
CH_4	25
N_2O	298

4.1.4 Other GHG Emissions

Others Green House Gas (GHG) emissions include Carbon Monoxide (CO), Unburnt Hydro Carbons (UHC) and Particulate Matter (PM).

4.2 Emissions Analysis

4.2.1 Emissions Optimization by HOMER Software (EOHS)

The specified emissions for various cases and PV penetration are tabulated in Table 4.2 where the emission factors involved are obtained in the HOMER Software. With the hybrid system, there is reduced emissions as compared to the pure sources. This is because the power exchange in the mini grid result in reduced emissions. HOMER credits the power system with these reductions. The system can even achieve negative emissions of more or more pollutants if it sells allot of low-emission power to the mini grid.

Table 4.2: Emissions for Various Power Systems at Different Levels of PV Penetration

Parameter	Units	Diesel (D)	Solar (PV)	Diesel-PV(D-PV)					
				25%	40%	50%	**60%**	70%	80%
CO_2	Kg	160,579	98,800	131,039	75,490	195,747	**60,704**	98,100	89,897
CO	Kg	25	244	21	109	234	**72.3**	88	101
UHC	Tons	345	27	98.5	22	25.9	**8.01**	56	67
PM	Tons	36	21	31.6	18.8	17.6	**5.45**	18	34
SO_2	Kg	696	428	568	327	628	**195**	207.4	345.6
NO_X	Kg	2,208	2,576	1278	1160	902	**712**	1780	2145

The least emission levels were observed at 60% penetration for selected pollutants as shown in Table 4.2 above. We take the Diesel generation as the base.

Table 4.3: Emissions at Optimal PV Penetration

Parameter	Units	Diesel (D)	Hybrid (D-PV)	Δ%
CO_2	Kg/yr.	99	13.4	**+86.5**
CO	Kg/yr.	141	85.4	**+39.4**
UHC	Tons /yr.	220	35.2	**+84.0**
PM	Tons /yr.	1.9	0.2	**+89.5**
SO_2	Kg /yr.	288	46.7	**+83.8**
NO_X	Kg /yr	340	72.9	**+78.6**
Average				**+76.97**

From the Table 4.3, it is apparent that with optimal penetration, hybrid system result in 77% decrease in emission levels.

4.2.1 Cost Equivalent for Optimized Emissions

HOMER takes the emission penalties into account when comparing the costs of different generation sources, which is Diesel (D) and Solar (PV) in this thesis. The following equation is used to determine the penalty for the emissions C_e:

$$C_e = \frac{C_{CO_2} M_{CO_2} + C_{CO} M_{CO} + C_{UHC} M_{UHC} + C_{PM} M_{PM} + C_{SO_2} M_{SO_2} + C_{NO_X} M_{NO_X}}{1000} \quad (4.8)$$

Where C denotes the penalty for the corresponding emission, PM or UHC in $\$/t$ while M is the annual emissions for the particular substance in kg/yr.

The various results for the total emissions and the cost equivalent without and with cost constraints are as shown in Tables 4.4a and 4.4b. These are taken at the optimal PV penetration of 60%. Without the cost constraints reduces the emissions levels by 0.46% but results to increase in resources cost by 0.3%. With cost constraints, the emissions decrease by 4.6% and the cost equivalent increases by 38.7%. Thus, a more accurate determination of optimal emissions is including the resources cost equivalent as a condition. Such a tradeoff between emissions levels and optimal cost is paramount due to the increased environmental concerns.

Table 4.4a): Emissions Optimization without Cost Constraints

Parameter/Source	D	PV	Δ% **(D to PV)**	D-PV	Δ% **(D to D-PV)**
Emissions, E(kg/h)	9.8778	9.8247	**+0.54**	9.8327	**+0.46**
Cost Equivalent, C($/h)	1.5048	1.6477	**-9.50**	1.9766	**-0.30**

Table 4.4b: Emissions Optimization with Cost Constraints

Parameter/Source	D	PV	Δ% (D to PV)	D-PV	Δ% (D to D-PV)
Emissions, E(kg/h)	15.9215	15.9625	**-0.26**	15.1886	**+4.60**
Cost Equivalent, C($/h)	1.1879	1.3519	**-13.81**	1.6475	**-38.69**

The optimal emissions levels can then be applied to evaluate the Health and Ecosystems effects for they are responsible for the various indicators. These are discussed in Sections 4.4 and 4.5.

4.3 Environmental Effects

4.3.1Health Effects (HE)

The mid-point indicators for Human Health (HH) considered in this thesis include the following:

H_1: Ozone depletion (Kg CFC-11-eq)

H_2:Human Toxicity

H_3: Ionizing Radiation

H_4: Particulate Matter [PM] Formation

H_5:Photochemical Oxidation Formation [PCOF](KtNMVOC)

H_6/E_1:Climate Change / Global Warming Potential [GWP] (MtCO_2-eq)

The simulated results are as shown in Table 4.5 below. Use of D-PV hybrid reduces H_2(Human Toxicity) by 92% and 68% is for pure PV deployment. It is worth observing that use of hybrid system reduces H_3(Ionising Radiation) by 80% while PV technology increases the same by 39%. Use of pure Solar (PV) increases H_1 by 119% while the hybrid reduces the same by 69% . H_1 (Ozone Depletion) is closely related to the NO_X emissions and with Diesel, this increases due to the combustion of fossil fuels. Solar adds four (4) times more of H_4(Particulate Matter [PM]) relative to the hybrid. This is due to two reasons; the PV manufacturing process where there is incomplete combustion of fossil fuels and the wafer-sawing process which creates fine silicon dust particles.

Table 4.5: Health Effects

Source /Parameter	Diesel (D)	Solar (PV)	Δ% **(D to PV)**	Diesel-Solar (D-PV)	Δ% **(D to D-PV)**
H_1	1,954.90	4,285.08	**-119.20**	608.85	**+68.86**
H_2	92.50	29.85	**+67.73**	7.55	**+91.84**
H_3	4,905.23	6,806.98	**-38.77**	1,005.34	**+79.50**
H_4	163.78	39.56	**+78.85**	10.58	**+90.77**
H_5	730.00	82.23	**+88.74**	26.22	**+96.41**
H_6/E_1	305.34	25.16	**+91.76**	9.89	**+96.76**
Average(H)			**+31.54**		**+88.80**

PV deployment in the minigrid reduces photochemical oxidation formation [PCOF] significantly, that is by almost 97%. Solar contributes highly to the 92% H_6/E_1(Ozone Depletion) reduction while for D-PV hybrid is the even more that is 97%. This is due to the energy-intensive silicon purification process where more fossil fuels (with carbon) are combusted. It is worth to note that the midpoint impact category of "climate change" contributes to both the damage to "human health" and damage to "ecosystems" endpoint categories.

By average, deployment of pure PV technology reduces net health effects (H) by 32% while the actual hybrid system when applied optimally results in 88% decrease in the same. Thus, the D-PV system is preferred.

4.3.2 Ecosystems Effects (EE)

The mid-point indicators for Ecosystems effects (E) include the following:

H_6/E_1:Climate change / Global Warming Potential [GWP] ($MtCO_2$-eq)

E_2: Terrestrial acidification (Kt SO_2-eq)

E_3: Terrestrial Eco-toxicity (Kt1, 4-DCB-eq)

E_4: Marine Eco-toxicity (Kt1, 4-DCB-eq)

E_5: Marine eutrophication and fresh water Eco-toxicity (Mt-N-eq)

E_6:Land Occupation [LO] $(km^2.a)$

E_7:Land Transformation [LT] (km^2)

The results for the Diesel (D), Solar (PV) and Diesel-Solar (D-PV) Hybrid system are as shown in Table 4.5. With the Diesel base, the hybrid technology reduces E_1 by 97%, E_2 by 96%, E_3 by 57%, E_4 by 90%, E_5 by 97%,E_6 by 91% and finally E_7 by 85%. When a pure PV system was simulated, the average effects became 73% while for the hybrid system, the net ecosystem effect is 88%. Thus, the hybrid system is preferred in reducing the Ecosystems effects.

Table 4.6: Ecosystems Effects

Source /Parameter	Diesel (D)	Solar (PV)	Δ% **(D to PV)**	Diesel-Solar (D-PV	Δ% **(D to D-PV)**
H_6/E_1	305.23	25.67	**+91.59**	9.56	**+96.87**
E_2	1300.45	115.01	**+91.16**	52.33	**+95.98**
E_3	4.53	4.34	**+4.20**	1.95	**+56.95**
E_4	2010.45	460.25	**+77.11**	210.13	**+89.55**
E_5	356.27	28.44	**+92.02**	10.76	**+96.97**
E_6	8512.30	950.78	**+88.83**	740.56	**+91.30**
E_7	17.31	5.74	**+66.84**	2.61	**+84.92**
Average (E)			**+73.11**		**+87.51**

4.4 Chapter Conclusion

From the simulated results, it is apparent that the deployment of hybrid system reduces environmental effects. That is, D-PV enables 77% decrease in net emission levels at the 60% PV penetration which is the optimal scenario.

The standard practice involves including emissions cost in place. Thus the practical way in D-PV cost analysis is including the cost constraints in place. This results in 5% increase in emissions computed and 39% increase in cost equivalent.

Environmental effects are determined from the optimal case of PV penetration. Use of pure PV technology reduces net health effects (H) by 32% while the actual hybrid system when applied optimally results in 88% decrease in the same. When a pure PV system was simulated, the average effects became 73% while for the hybrid system, the net ecosystem effect is 88%. Thus, the hybrid system is preferred in reducing both the Health and Ecosystems effects.

CHAPTER FIVE

ECONOMIC ANALYSIS OF ENVIROMENTAL EFFECTS

In this chapter, economic analysis results of the D-PV hybrid system for different configurations is presented and discussed. The focus of this thesis is on existing standalone generators, and a hybrid PV/Diesel system. HOMER software was used in the simulations of different scenarios. According to Laith et al. (2017), this procedure entailed establishing a reference case as the first step, followed by the determination of operational behaviours of existing and hypothetical sysytems based on economical, technical, and environmental contraints.

5.1 Diesel Only System

The diesel gen set considered for the hybrid system has a nominal capacity of 1014 kW with a mean electrical output of 492 kW, electrical production of 4,309,695 kWh/yr and 8760 hours of operation per year. The system's marginal generation cost of this configuration is 0.291 $/kWh. The results for the diesel generator are presented in the Table 5.1.

Table 5.1: Diesel Gen-Set Simulation Results

Quantity	**Value**	**Units**
Hours of operation	8,760	Hrs/yr
Number of starts	1	Starts/yr
Operational life	1.70	Yr
Capacity factor	44.7	%
Fixed generation cost	255	$/yr
Marginal generation cost	0.291	$/kWh
Electricity production	4,309,695	kWh/yr
Mean electricity output	492	kW
Min electricity output	275	kW

Max electricity output	1014	kW

The HOMER modelling design considered 1100 kW diesel generator system with an initial cost of $440,000 and Net Present Cost (NPC) of $45,100,000. Operation and maintenance costs for the system was $1,927,200 per year

5.2 D-PV Hybrid System

After simulating the hybrid system as designed by HOMER by placing the necessary input resource parameters, the electrical results in Table 5.2 were obtained.

Table 5.2: Electrical Output of the System

Production	kWh/yr	%
PV array	2,542,379	62
Generator	1,501,560	38
Total	**4,043,939**	**100**

From the table of electrical results shown, it can be seen that PV array accounts for a total of 62% of the hybrid production whereas Diesel generator accounts for 38% total electrical energy. Therefore, Solar PV scheme is taken as the base load of the hybrid system since it is more than the diesel system.

Figure 5.1 represents the monthly average electric production of hybrid system comprising of solar PV and Diesel generator which were obtained as a result of the simulation. The simulated parameters areas tabulated in Table 5.3.

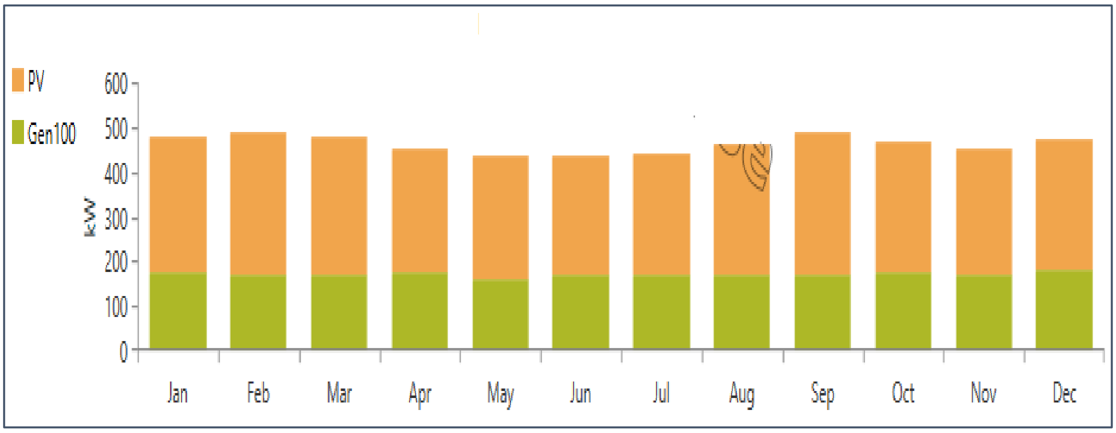

Figure 5.1: Monthly Electric Production of the Hybrid System

The system's electrical energy consumption by AC primary load is 4,226,826 kWh/yr which is equivalent to 100% of the total electrical energy generated by the hybrid system. The excess electricity produced by the system is about 620,215 kWh/yr that accounts for 12.8%, while the unmet load is 64,114kWh/yr with a capacity shortage of 4.74%.

Table 5.3: Hybrid System Simulation Parameters

Quantity	**Value**	**Units**
Rated Capacity	1,100	Kw
Mean output	215	kW
Mean energy output	5,156	kWh/d
Capacity factor	19.5	%
Total production	1,881,779	kWh/yr
Minimum output	0	kWh/yr
Maximum output	1,061	Kw
PV Penetration	43.9	%
Hours of operation	4,378	Hrs/yr
Levellised cost	0.0744	$/kWh

In this case, the simulation was performed for the PV system and the diesel generator. HOMER configuration input for diesel generator optimized two systems within same simulation. The first row result shown in Table 5.4 present a hybrid system with capacity shortage of 4.8%. the simulation here was done with the diesel generator as the backup. the system yielded a Net Present Cost (NPC) of $28,700,000 and Cost of Energy (COE) is 0.530 $/kWh.

Table 5.4 HOMER'S Optimization Results

Export... Export All... **Sensitivity Cases** Left Click on a sensitivity case to see its Optimization Results. Compare Economics Column Choices...

Architecture					Cost				System		Gen100							
		PV (kW)	Gen100 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)	Capital Cost ($)	Production (kWh/yr)
		1,100	600	LF	$28.7M	$0.530	$2.09M	$1.89M	29.8	897,379	8,760	2,965,262	897,379	1,051,200	1,031,986	1,650,000	1,881,779
			1,100	LF	$45.1M	$0.822	$3.49M	$440,000	0	1,360,161	8,760	4,309,694	1,360,161	1,927,200	1,564,185		

In the second row the system show results for a diesel generator alone to supply a maximum of 1100kW with diesel fuel consumption of 897,379$ltr/year$. The net present cost is $45,100,000 while the cost of energy (COE) is 0.822$/kWh. The renewable fraction is 30%.

A similar study carried out by Achraf, (2014b) as cited by Alayan (2016) on a "PV-diesel hybrid energy generation system for IUT academic building in bangladesh. HOMER was used to perform the techno-economic evaluation of both configurations. Comparisons between models show that the proposed PV-diesel hybrid model could reduce to 10BDT/kWh compared to the conventional model (1 Dollar=78 BDT)"

5.3 Economic Analysis

5.3.1 Basic Costs

This section is a basic analysis on the current system used to supply power in Lodwar. The cost summary of the hybrid system in terms of the Net Present cost by component size and cost type obtained after simulation is given in the Table 5.5 as compared to diesel only system.

Table 5.5 Cost Summaries

Parameter	**Diesel (D)**	**D-PV System**	Δ%
Net Present Cost (NPC) ($)	45,100,000	28,700,000	**+36.36**
COE ($)	0.822	0.530	**+17.72**
Operating Cost ($/yr)	3,490,000	2,090,000	**+40.92**
Initial Capital ($)	440,000	1,890,000	**-329.55**
Total fuel (L/yr)	1,360,161	897,379	**+34.03**
Total Fuel cost ($/yr)	1,564,185	1,031,986	**+34.03**
O&M ($/yr)	1,927,200	1,051,000	**+45.47**
Average			**-17.29**

Table 5.5 shows the economic result for the diesel system and the hybrid system. Net present cost and the cost of energy are higher for the diesel system than the hybrid configuration. The diesel consumption was higher for the diesel system than the modified hybrid system as shown in the table. The cost difference shows significant contribution of the PV generator to the energy mix as opposed to the diesel only system. The overall increase is 17% which is due to the high initial cost of solar PV at 330%.

In financial analysis of this simulation model, the results of hybrid system configurations yield a simple payback time (SPBT) of 1.04 years. Therefore, the PV-Diesel system is compared to the diesel only system. Economics plays an integral role in both simulation process as it operates the system so as to minimize the total Life Cycle Cost (LCC), and in its optimization process, wherein it searches for system configuration with the lowest total life cycle cost. The life cycle cost calculation includes the initial cost of construction, component replacement, maintenance and fuel cost. In this study, the LCC was taken for the system that satisfied reliability in terms of costs and power demand.

5.3.2 Life Cycle Cost (LCC)

For high integrated hybrid system (HIHS), the externalities values of energy production for diesel and PV are $4.286 cent\ \$/kwh$ and $0.142 cent\ \$/kwh$ respectively. A Summary of the plant costs for various cases are as shown in Table 5.6. From the table, the installation cost remain the same while the hardware cost decrease by 12%. Operation and maintenance cost rises by 502% and the total cost decreases by 4%.

Table 5.6: Integrated Plant Costs

	Plant Costs ($)			
Plant	Installation	Hardware	O&M	Total
Diesel (D)	1,465,580.00	9,357,360.00	292,100.00	11,115,040.00
D-PV	1,465,580.00	8,286,750.00	1,758,950.00	11,511,280.00
Δ%	**0**	**+11.44**	**-502.17**	**-3.57**

The UEC cost for the power plants includes the O&M, fuel costs, environmental costs (economic value due to the pollutant emitted to the atmosphere), cost of money, overall hardware and installation cost and the substitute costs of every part at the end of the operative life. UEC with gross environmental costs is denoted by UECE in this thesis.

These are summarised in Table 5.7, from which, it can be seen that when environmental effects are accounted for, the overall cost rises by 5.6%. Pure PV system reduces UEC by 46% and UECE by 64%. D-PV hybrid system reduces UEC by 72% and UECE by 72% hence complete solarisation of the system is not economically viable. The hybrid is thus the preferred one.

Table 5.7: UEC for Different Plants ($\$/kWh$)

Plant	UEC	UECE	Δ%
Diesel (D)	1.98F4	1.989	**-0.25**
PV	1.078	0.719	**+33.30**
Δ%	**+45.67**	**+63.85**	
D-PV	0.559	0.590	**-5.5**
Δ%	**+71.82**	**+71.80**	

5.4 Chapter Conclusion

D-PV cost more than the pure Diesel (D) by 17.3%. The LCC for D-PV increase by 4% with Diesel mini-grid as the base. With the environmental effects accounted for, D-PV is 72% cheaper in terms of UECE. D-PV with net environmental impacts in 5.6% more costly. Economic analysis of Diesel and diesel PV mini-grid presented that hybrid has more initial cost due to inclusion of PV. However, the hybrid is cheaper in operation and maintenance leading to COE. Thus, there must be a trade-off between accounting for environmental effects in D-PV and cost.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

6.1 Conclusion

In this thesis, environmental effects of integrating solar into existing diesel mini grid were quantified using HOMER software and Modified Recipe Model; with Lodwar Town in Turkana County being used as the Case Study. The following conclusions can be drawn:

- Deployment of hybrid Diesel-PV (D-PV) system reduces environmental effects. That is, D-PV enables 77% decrease in net emission levels at the 60% PV penetration which is the optimal scenario.
- Use of pure PV technology reduces net health effects (H) by 32% while the actual hybrid system when applied optimally results in 88% decrease in the same. When a pure PV system was simulated, the average effects became 73% while for the hybrid system, the net ecosystem effect is 88%. Thus, the hybrid system is preferred in reducing both the Health and Ecosystems effects.
- Economic analysis of Diesel and D- PV mini-grid presented that hybrid has more initial cost due to inclusion of PV. However, the hybrid is cheaper in operation and maintenance leading to high cost of energy.

6.2 Further Work

Areas of further research and development that needs to be further considered include the following:

- Optimization for environmental effects for the Diesel-PV Hybrid can be done using deterministic, heuristic and hybrid methods.
- Include Social effects in the environmental effects analysis. This is in addition to the health effects, ecosystems effects and net cost considered in this thesis.

- Consider hybrid systems with other Renewable Energy Sources (RES) like wind, Biomass, Hydro and Geothermal.
- Consider phased installation of battery storage to replace the Genset in order to maximize the environmental benefits and quantify the further reduction in the environmental impacts.

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APPENDIX A: TURN IT IN REPORT

F56/69128/2011 MSC (EBE) Judith Nduku Kimeu

ORIGINALITY REPORT

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4	Laith M. Halabi, Saad Mekhilef, Lanre Olatomiwa, James Hazelton. "Performance analysis of hybrid PV/diesel/battery system using HOMER: A case study Sabah, Malaysia", Energy Conversion and Management, 2017 Publication	1%
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21 M.H. Ashourian, S.M. Cherati, A.A. Mohd Zin, N. Niknam, A.S. Mokhtar, M. Anwari. "Optimal green energy management for island resorts in Malaysia", Renewable Energy, 2013 <1%
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64	Baghdadi, Fazia, Kamal Mohammedi, Said Diaf, and Omar Behar. "Feasibility study and energy conversion analysis of stand-alone hybrid renewable energy system", Energy Conversion and Management, 2015. Publication	<1%
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73	Nopporn Patcharaprakiti, Krissanapong Kirtikara, Khanchai Tunlasakun, Juttrit Thongpron et al. "Chapter 3 Modeling of Photovoltaic Grid Connected Inverters Based on Nonlinear System Identification for Power Quality Analysis", IntechOpen, 2011 Publication	<1%
74	Zelalem Girma. "Techno-economic analysis of photovoltaic pumping system for rural water supply in Ethiopia", International Journal of Sustainable Energy, 2015 Publication	<1%

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77	Shekhar K. Pawar, Yogesh V. Aaher, Ajit C. Chaudhari, Yogesh B. Jadhav. "Modeling and simulation of hybrid solar-wind-grid power generation system for electrification", 2014 International Conference on Advances in Engineering and Technology (ICAET), 2014 Publication	<1%
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79	Akikur, R.K., R. Saidur, H.W. Ping, and K.R. Ullah. "Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid	<1%

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rural electrification: A review", Renewable and Sustainable Energy Reviews, 2013.
Publication

80	Fehmi Görkem Üçtuğ, Adisa Azapagic. "Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries", Science of The Total Environment, 2018 Publication	<1%
81	Mohammad Mohammadi, Roghayeh Ghasempour, Fatemeh Razi Astaraei, Esmail Ahmadi, Armin Aligholian, Ashkan Toopshekan. "Optimal planning of renewable energy resource for a residential house considering economic and reliability criteria", International Journal of Electrical Power & Energy Systems, 2018 Publication	<1%
82	Syed Shah, Gordhan Valasai, Asif Memon, Abdul Laghari, Nabi Jalbani, Jody Strait. "Techno-Economic Analysis of Solar PV Electricity Supply to Rural Areas of Balochistan, Pakistan", Energies, 2018 Publication	<1%
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appraisal", Energy Policy, 2020
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International Journal of Scientific and Research Publications

International Journal of Scientific and Research Publications, Volume 9, Issue 6, June 2019 247
ISSN 2250-3153

Environmental Effects of Solar PV, Diesel and the Corresponding Hybrids in Kenya: Case Study of Turkana County

Judith Nduku Kimeu[1], D. O Mbuge[2],

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http://dx.doi.org/10.29322/IJSRP.9.06.2019.p9042

Abstract: **Renewable Energy (RE) is perceived to play an increasingly important role in fast-tracking accessibility to affordable electricity as an alternative to the nonconventional sources. The role of such REs in mitigating negative environmental effects has been given much emphasis. Developing isolated mini-grids has been one of the potential projects in scaling up RE to achieve rural electrification in line with Kenya's energy solar PV-Diesel Hybrid minigrids systems are discussed. Further, the proposed Simulation Software policies. In this paper, the environmental effects of solar PV Minigrid, Diesel minigrid and the corresponding (Homer) and the Case Study (Turkana County) are discussed.**

Key Words: Environmental Effects, Renewable Energy, Solar, Diesel, Hybrid and Homer

I: INTRODUCTION

World statistics currently indicate that over 1.5 billion people mainly in the rural areas and informal settlement of - lack access to electricity in most developing countries. Governments mostly in the developing countries must accelerate the universal access to electricity by investing heavily in the energy sector. As such, adoption of renewable energy is inevitable where through centralized mini-grids at the local level using village distribution network. Solar, wind and geothermal are the most common renewable energy sources. Hybrid systems where one or more renewable sources, a battery system or a diesel generator are integrated together to increase access to uninterrupted electricity that is environmentally friendly (Solar Power Awards, 2018).

Designing grid extension is costly in isolated rural communities and may not be feasible in implementation. However, renewable energy generation sources can be integrated together to come up with an affordable hybrid system that can impact the end users. Even though the nature of rural economies pushes for low-cost energy programs, quality has affected the system's lifespan, and thus the superiority of the system components can guarantee a long-lasting program with lowest generation costs. Appropriate sizing of the system increases the efficiency gains and cost savings, thus energy efficiency. The load and the power generated by a system is affected by the energy efficiency and raises the cost of the project. As a result, energy policies in developing Countries should be established by supply and demand-side management. In designing household and community energy systems many designers advice on the consumers on how to reduce short-term investment costs, thus the need for creating awareness on energy-efficient appliances (Alliance for Rural Electrification, 2017).

In sub-Saharan Africa, energy sources such as diesel are used to distribute energy in arid and semi-arid communities. However, a system that is served entirely by diesel gen sets is more expensive than hybrid ones. Hybrid mini-grids, on the other hand, exploit several local renewable resources combined with the gen-sets to complement one another (ARE n.d.).
Turkana County is one of the counties that is powered by off-grid mini-grids powered by diesel generators and with the highest poverty index in Kenya. According to Turkana County Government (n.d.), nearly 92 percent of the population -earns less than two US dollars per day (Turkana County Integrated Development, 2013-2017). Being a solar energy potential zone, with an average potential of around 4-6 kWh/m2, solar PV modules can be used to convert the solar radiation into electricity (RECP, 2018). Solar PV system is a form of

clean energy that can be a great substitute of diesel gen set or a fuel saver for a hybrid (Solar-Diesel) system mini-grid. Hybrid power systems have recently attained a lot of attention worldwide owing to their ability to combine several renewable energy sources and also include a backup generator as well as reducing emissions from the petroleum energy sources (WIT Press n.d.).

II: ENVIROMENTAL EFFECTS

A: Solar PV Mini-grid

Ideally, solar PV energy adoption is viewed to have environmental benefits over the conventional diesel mini-grid (Boateng, 2016; Tsoutsos et al., 2005). These benefits link the low carbon/greenhouse gas emissions of solar PV generation and utilization. Olatomiwa, Mikhilef, Huda, & Sanusi (2015) in their study stated that adoption of the conventional DG hybrided with renewable enery - would not only reduce diesel consuption and operating cost ,it would also signifiantly decrease the operating hours of the DG leading to reduction in greenhouse gas emissons. .

A study carried out by Anayochukwu & Nnene (2013) on measuring the environmental impact of power generation at GSM Base station sites, concluded that "it is important to quantify the environmental impact of using DG in GSM base stations. l Greenhouse gases (GHG) pollute the environmentand adversely affect the life of human beings.Indirect impacts generated by GHGs affect the quality of health.. Jade (2011) carried out a study comparing the environmental impacts of DG with hybrid diesel-wind electricity for off-grid communities in Ontario incorporating a Life Cycle Approach. The study evaluation determined that "although designers cannot entirely avoid diesel generated energy, hybrid diesel-wind does have the potential to provide reductions in environmental impacts between 12-46% when comparing it to the diesel generator system. The LCA indicated that the seven First Nations off-grid communities analyzed have the potential to reduce their environmental impacts caused by diesel generated electricity production through the implementation of hybrid-diesel wind" (Jade, 2011). The reduction was determined to be dependent on the renewable energy sources penetration level.

a) Positive Environmental Impact

Green Technology: Solar PV mini-grid is considered a green technology because it offers no pollution to the environment, the air remains fresh. It replaces the tradition and conventional energy sources from coal power plants that increase the content of Sulphur in the atmosphere thus causing acid rain, and petrochemicals such as gasoline, where carbon (I1) oxide is released, and other toxic substance of public health concerns.

Reduction in Green House Effect: Global warming is an international concern to different governments around the world. There have been summits of various world leaders to make the earth habitable, and hence global warming is a threat to humanity. Solar energy is a promising technology that offers no emission of greenhouse gases and carbon dioxide (Akyuz *et al.,*2018).

b) Negative Environmental Impact

Solar PV Mini-Grid plants have the potency to cause environmental degradation and the loss of habitat. The degree of damage depends on the scalability of the technology, the land topography and the resources available for construction of the site. The materials to be used are proportional to the type of technology, like photovoltaic (PV) solar cells. For PV it requires about 3.5 to 10 acres per megawatt. Another factor to be considered is that it is unlikely for the solar system to share the land with agricultural uses (scientist, 2013).

Solar systems design materials require maintenance and cleaning. Cleaning of these surfaces makes use of chemicals which are relatively toxic to humans. These chemicals include , hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, 1, 1, 1-trichloroethane and acetone which are similar to chemicals used in the semiconductor industry. The amount of these substances used depends on the type of solar system as iterated.

There were health complications when the storage units used to store heat energy is not ideal. Consequently, this may provide the perfect environment for the growth of molds and fungi that causes a different allergic reaction. It is also worth noting that the need for renewable energy is inexhaustible, but comes with its challenges. Thus, it might cause a shift in the ecological balance, owing to the facts that the surfaces of these panels reflect light because of silicon-based materials in their structure. When birds and insect fly around this region, they may die, hence affecting ecological patterns in the environment.

B: Diesel Mini-Grid

a) Positive Environmental Impact

The environmental impacts of diesel mini-grids are quite severe. So far there are no direct positive environmental impacts of diesel engines. However, the emission of CO2 has adverse effects on the environment as well as in the maintenance of life on earth. Ideally, human civilization should prevent carbon dioxide from trending down to ranks that impend the survival of living things that depend on it.

All life in the universe is carbon based and that the source of this carbon is CO2, which sequences through the global atmosphere by either natural or human processes. According to GREENIE WATCH. (n.d.) and Moore (2016), "as a minor gas at 0.04%, CO2 infiltrates the entire atmosphere and has been absorbed by the oceans and other water bodies (the hydrosphere), where it provides the food for photosynthetic species. If there were no CO2 or an insufficient level of CO2 in the atmosphere and hydrosphere, there would be no life as we know it on our planet" (GREENIE WATCH. (n.d.)).

b) Negative Environmental

Diesel is made up of carbon elements and thus discharges a mass of harmful materials together with direct emissions as Universiti Tenaga Nasional. (n.d.) posits that diesel contains "organic and elemental carbon (soot), toxic metals, nitrogen oxides that form ozone and nitrate particulate matter, volatile organic compounds, carbon monoxide (CO), carbon dioxide (CO2), and a variety of toxic metals and gases such as formaldehyde, acrolein and polycyclic aromatic hydrocarbons" (Universiti Tenaga Nasional. (n.d.); Anayochukwu and Nnene, 2013).

Inhalation of these toxic substances can cause cancers, cardiovascular diseases, respiratory diseases, and others. These substances include carbon (II) oxide and other toxic gasses. Diesel combustion discharges fine particles and toxic gases that can enter the body circulation system through the lungs once inhaled. It additionally can accumulate in lungs over time, hindering oxygen exchange to the blood and causing numerous health problems. Such as chronic respiratory symptoms such as shortness of breath and painful breathing; asthma; bronchitis; cancer; and premature deaths (NJDEP - StopTheSoot.org. (n.d.)).

One significant effect of these gases is the ability to cause greenhouse effect, and global warming, which in turn leads to deforestation, and degradation of agricultural lands, coupled with air and water pollution, the accumulation of solid waste, formation of smog and finally the extinction of some flora and fauna of various water bodies (Oisamoje & Eguono, 2013). Diesel machines produce so much noise that can irritate the ears, and cause noise pollution, repeated exposure of sound of a specific frequency can increase the chances of losing hearing.

C Solar PV Diesel- Hybrid Mini-Grid

a) Positive Environmental Impacts

An intelligent system optimizes the hybrid system that autoregulates itself depending on the energy demand per time. This optimization helps in the reduction of emissions from carbon, and toxic waste, hence a modification of the greenhouse effect and global warming gearing towards a smart environmental friendly system.With the development of a hybrid system, it compensates for the noise produced by diesel generators, hence controlling noise pollution while achieving the same purpose of energy satisfaction (Othman, 2005).

b) ***Negative Environmental Impact***

One primary adverse environmental effect of a hybrid power system is that it's not emission free. There are still some quantities of toxic substances that are emitted to the environment, though minimal. These toxic substances can still bio-accumulate in the human system and cause public health issues. The emission of greenhouse gases always accompanies hybrid systems. Hence the earth is still not entirely free from the dangers it brings (Usman et al., 2017).

III: HOMER SOFTWARE

HOMER means Hybrid optimization Model for Electric Renewable. It is a software that is used for the designing, modelling and analysis of renewable energy systems. Renewable Energy Laboratory of the US developed it with an aim of coming up with more efficient renewable energy micro grid and has over time evolved to be a tool to design smart, more environmentally friendly energy micro grids.

The Homer software utilizes inputs as load demand and the available energy resources as well as the components of the power system in its calculations to design an optimal system. It reviews all available energy sources in all possible combinations. The design and analysis process is at times tasking due to uncertainties such as cost of fuel and power as well as future load size. To determine the hybrid system size using the software, an optimum system statement is formulated that minimizes the construction and operation costs with the maximum possible allowed risk determined. To do this, parameters such as wind speed, solar irradiation and load profile are determined.

System optimization is done after considering several combinations of hybrid renewable energy solutions based on the total net present cost (TNPC). The optimal system is the one with the lowest TNPC. The content and the weakness for the software is as shown in Table 1.

Table 1: HOMER SOFTWARE

Content	Deficiency/Weakness
• Designing, modelling and analysis of renewable energy systems by considering wind speed, solar irradiation and load profile. • Optimization of renewable energy system based on the lowest TNPC	• Only considers CO_2 emissions in its analysis of RE systems • Does not consider social impacts directly • Does not consider health impacts directly

IV: PROPOSED CASE STUDY

This research seeks to establish the economic and environmental impacts of solar PV integration into the existing diesel mini-grid in Turkana County. According to Turkana County Government (2013), “Turkana County is situated in North Western Kenya. It borders West Pokot and Baringo Counties to the South, Samburu County to the South East, and Marsabit County to the East. Internationally it borders South Sudan to the North, Uganda to the West and Ethiopia to the Northeast. The County shares Lake Turkana with Marsabit County. The total area of the county is 77,000 KM2 and lies between Longitudes 340 30’ and 360 40’ East and between Latitudes 10 30’ and 50 30’ North”. The map of the county plus the daily solar irradiance is shown n Figure 1.

The County population stood at 855, 399 according to the Kenya Population and Housing Census (KPHC) results. The population is projected to be 1,036, 586 in 2012 and 1,427,797 in 2017 based on a population growth rate of 6.4 percent assuming constant mortality and fertility rates (Turkana County Government CIDP. (2013)”.

The research study is focusing on Turkana County, one of the regions powered by off-grid connection (diesel mini-grids) located in 4 town centers namely Lodwar, Lokichoggio, Lokori and Lokitaung with two more (Kakuma and Lokiriama) under construction. The Population densities in these towns are low with a population of 146,275 people, and the lifestyle is predominantly pastoral. These towns are deficient regarding access to electricity supply.

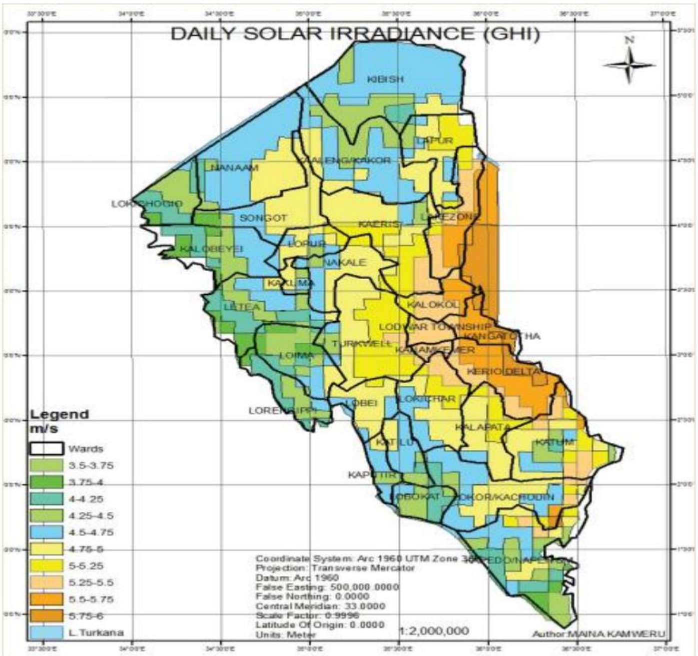

Figure 1: Daily solar Irradiance of Turkana County:
Source :*(Turkana County Resource Maps, 2016)*

V: CONCLUSION

In this paper, environmental impacts of solar, diesel and the corresponding hybrid system are presented. It is apparent that the Hybrid methods are more environmental friendly as compared to the individual sources. Further, the proposed simulation method; Homer is introduced and its capability to handle environmental issues illustrated. Lastly, Turkana County in Kenya, which is the Case Study; have been described. The proposed research study will present a hybrid power system of a standalone PV system and diesel generator and thus investigate the economic and environmental impacts of Solar PV integrated into a diesel mini-grid in Turkana County. Further work shall include the formulation of the Hybrid System and the environmental effects and analysis of the simulated results.

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APPENDIX C: CONFERENCE PAPER (Accepted for Presentation)

Gammarth, Tunisia
ENERGYCON 2020
IEEE International Energy Conference

6th IEEE International Energy Conference

28th Sept. - 1st Oct. 2020, Ramada Plaza Hotel, Gammarth, Tunisia

Analysis of Environmental Effects in Diesel-Solar Minigrid Using HOMER Software and Modified Recipe Model

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Abstract

Use of Energy Sources have both positive and negative environmental effects. Sustainability in the development of energy sources requires methods and tools to measure the environmental impacts of such deployment and this includes Renewable Energy Sources. This paper considers the environmental impacts of Solar PV in an existing Diesel-PV minigrid using Life Cycle Assessment (LCA). Modified ReCiPe Model is adapted for the analysis ecosystem and health effects. The emissions are determined using HOMER software. Simulated results reveal that hybrid Diesel (D)-Solar (PV) is preferred in reducing the environmental effects at an increased emission allowable cost.

Key Words: Diesel-PV Hybrid, Environmental Effects, HOMER, Modified ReCIPE Model

I: INTRODUCTION

In the 21st Century, energy-related problems have become more and more significant and they involve the rational use of the energy resources and the economic-environmental impacts due to the emission of pollutants [1]. Hence, there is urgent need to come up with Renewable Energy Technologies (RETs), especially photovoltaic (PV) to cope with the simultaneous challenges of energy shortage and environmental degradation [2].

Solar PVs, which directly generate electricity from solar energy; is free from fossil energy consumption and greenhouse gases (GHG) emission during its operations. Thus, it seems to be completely clean and have no environmental impacts. However, during it's life cycle, it takes in a large amount of energy and emits some greenhouse gases (GHG) during some crucial stages such as solar cells manufacture, solar PV assembly, balance of PV system (BOPVS), PV material transportation, PV system installation and retrofitting and PV system disposal or process recycling [3]. When sun waves hits PV materials, photons with a certain wavelength trigger electrons to flow through the materials to produce Direct Current (DC).

Commercial PV materials include multi-crystalline silicon, mono-crystalline silicon, amorphous silicon, and thin film technologies, such as Cadmium Telluride (CdTe) and Copper Indium Diselenide (CID). Their LCAs were well studied in [4] but no environmental study and analysis was carried out. A typical PV system consists of the PV module and the Balance of System (BOS) structures for mounting the PV modules and converting the generated electricity to Alternating Current (AC) of the proper magnitude for usage in the electric power grid [5]. Thus, there is need to study and analyze the life cycle of the PV with the view of quantifying their economic-environmental impacts before deployment. This is the objective of this paper.

Paper Organization: The rest of the paper is organized as follows: Section II gives the overview of the Diesel-Solar PV mini-grid while part III presents the HOMER software. Section IV introduces Life Cycle Assessment (LCA) and later presents the Modified Recipe Model. Section V presents the results and their analysis and Section VI is the Paper Conclusion. Finally Section VII includes the References.

II: DIESEL-PV MINIGRID

The research study focused on Turkana County, one of the regions powered by off-grid connection (diesel mini-grids). "Turkana County is situated in North Western Kenya. It borders West Pokot and Baringo Counties to the South, Samburu County to the South East, and Marsabit County to the East. Internationally it borders South Sudan to the North, Uganda to the West and Ethiopia to the Northeast. The County shares Lake Turkana with Marsabit County. The total area of the county is 77,000 KM^2 and lies between Longitudes 34⁰ 30' and 36⁰ 40' East and between Latitudes 1⁰ 30' and 5⁰ 30' North. According to the Kenya Population and Housing Census (KPHC) results, the County population stood at 855, 399. It is projected to have a population of 1,036, 586 in 2012 and 1,427,797 in 2017. These projections are based on a population growth rate of 6.4% assuming constant mortality and fertility rates [6].

Specifically, the research study focused on lodwar in Turkana County. Lodwar is one of the towns in Turkana County powered by off-grid connection (diesel mini-grids). Other town centres are Lokichoggio, Lokori, Lokitaung, Kakuma and Lokiriama with the latter two being the most recent. The Population densities in these towns are low with a population of 146,275 people, and the lifestyle is predominantly pastoral. Turkana County is a solar energy potential zone, with average annual radiation of around 4-6 kWh/m2 [7]

I Load Assessment and Meteorological Data

In assessing the load demand, energy demand was estimated from the customer energy consumption from commercial and industrial entities, public services such as hospitals and schools and households in Lodwar. The installed capacity for the town is 1440 kW with peak energy demand of 650 kW, the four locations has installed capacity of 3000kW (3MW) from the diesel gen set. Therefore, in this study the researcher designed a 1440kW hybrid system for Lodwar town. The loading scenarios for the are shown on Figure 1 and 2[7]

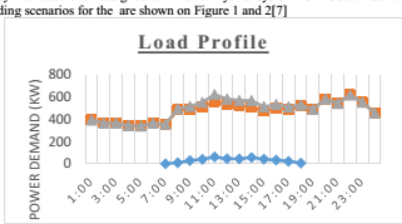

Figure 1: Typical load demand profile for Lodwar. Source: (Ministry of Energy, 2013)

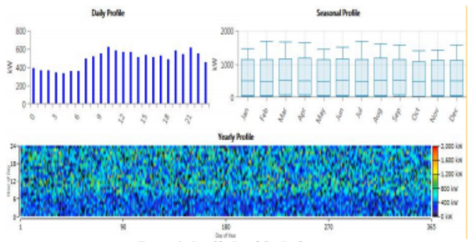

Figure 2: Profile Load for Lodwar

The solar radiation data was obtained by geographical coordinates of Lodwar on the geographical location of the county on the Photovoltaic Geographical Information System (PVGIS). This is shown in Table 1 and Figure 3.

Table 1: PVGIS estimates of solar electricity generation

Month	Clearness Index	Daily Radiation (kWh/m2/day)
January	0.409	4.300
February	0.480	5.120
March	0.591	6.220
April	0.640	6.370
May	0.763	7.030
June	0.829	7.280
July	0.792	7.090
August	0.720	6.910
September	0.631	6.470
October	0.514	5.420
November	0.412	4.330
December	0.402	4.180

Source: Solar radiation database: PVGIS-CMSAF (JRC, 2012)

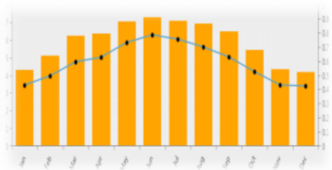

Figure 3: Solar Radiation data (Source: HOMER Pro Software)

Figure 4 shows the complete model of hybrid system consisting of solar PV and diesel generator. The output result from the HOMER software indicate the peak scaled demand of primary load as 1013.72 kW and total average consumption is 11,756 kWh/day.

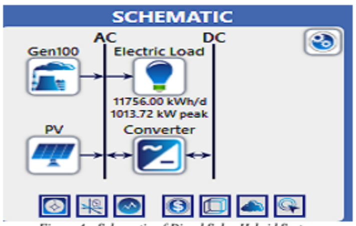

Figure 4:: Schematic of Diesel Solar Hybrid System

Diesel generators are alernating in nature, therefore, they are tied to the AC bus-bar while Solar PV is tied to DC bus-bar because the output from the solar panel is DC. The converter is connected between AC and DC bus-bar since they convert the DC outputs of the PV system and the battery into AC.

Operating Strategies

In the design of Hybrid Renewable Energy Systems, there are two operating strategies considered: Load following (LF) and Cycle Charging (CC) dispatch strategies. In LF criteria the diesel generators are designed to supply the loads only when the PV power output is unavailable, with the PV arrays supplying the load and charging the batteries in case of excess power. On the contrary, CC employs diesel generators to meet the loads demand and charge the batteries at the same time [8. In this paper, LF was considered as the optimal strategy since its design reduces excess energy and the total net present cost (NPC), hence it was used for the analysis. The strategy requires an "overall energy management system to control the flow of energy where the system operates in different modes according to the surrounding atmospheric conditions. At normal operating conditions, where the sun is available, the control system gives the PV arrays the highest priority to supply the loads. When there is insufficient energy supply from the PV, the conventional diesel generators will supply the loads"[8].

II Solar PV and Diesel Modelling

Solar PV Array Modeling

In this study, design of the PV system parameters was declared as optimally inclined south-oriented solar PV modules for maximum conversion of solar radiation into electrical energy. The components for the simulation of solar photovoltaic system in Hybrid Optimization Model for Electric Renewables (HOMER) software were; solar modules and inverter for converting DC into AC.
Solar cells are setup in combined series/parallel combinations to form an array represented by a simplified circuit model as shown in Figure 5.

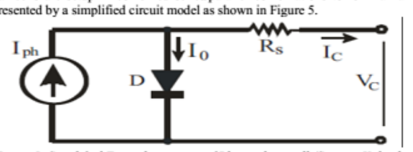

Figure 5: Simplified Equivalent circuit of Photovoltaic cell (Source: Kalambe, 2017)

The power generation by the PV array was simulated by HOMER using the equation 3.1. This modelling equation also considers the solar cell temperature (T_c) effect on the PV power production (Chandel and Rahul, 2013) as given in equation 3. 2.

$$P_{pv} = P_{rpv} D_{pv} [\frac{G_T}{G_{Tstc}}] \{1 + \alpha_p (T_c - T_{stc}\} \qquad (1)$$

Where;

$$T_C = \frac{T_a + (T_{cn} - T_{an}) \left[\frac{G_T}{G_{Tn}}\right] \left\{1 - \frac{\eta mp(1-\alpha_p T_{stc})}{\tau\alpha}\right\}}{1 + (T_{cn} - T_{an}) \left[\frac{G_T}{G_{Tn}}\right] \left\{\frac{\eta mp \alpha_p}{\tau\alpha}\right\}} \qquad (2)$$

Where: P_{pv} is the Output of PV array; P_{rpv} the rated capacity of PV array, D_{pv} the derating factor of PV array (77%), G_{Tstc} is the Solar radiation at STC (1kW/m^2),G_T Solar radiation at the tilted surface, α_p is the temperature coefficient of power (-0.48%/°C), T_{an} is the Nominal ambient temperature (20°C), T_{cn} is the Nominal operating cell temperature (47°C), G_{Tn} is the solar radiation at NOCT (0.8 kW/m^2), η_{mp} is the maximum power point efficiency under STC (13%), T_{stc} is the cell temperature under STC (25°C), τα is the product of solar transmittance and absorptance (0.9) [9]

Diesel Generator Modelling

The diesel generator supply power equivalent to the total load demand which is normally given by the manufacturer of the diesel generator. According to [10], the fuel consumption (FC) vs. the supplied load (SL) curve should be established as follows

$$FC = a \times SL + b \qquad (3)$$

a and b are coefficients that can be calculated using the least square method for a number of experimental measurements as follows (Krivošík, 2017).

$$a = \frac{N \sum(SLi \times FCi) - \sum SLi \sum FCi}{N \sum SL^2 i - (\sum SLi)2} \qquad (4)$$

$$b = \frac{\sum FCi - a \sum SLi}{N} \qquad (5)$$

Where; I -the examined measurement (I.e. 1, 2…N).
SLi - the load being supplied and
FCi - the fuel being consumed by the diesel generator when it supplies load SLi.
The above mentioned curve is of significant importance for the economic assessment of every power system for possible use [10]. Similarly, the efficiency of the diesel generator is strongly dependent on the load it supplies and is given as;

$$nn_{DG} = \frac{P_{out}}{P_{in}} = \frac{SL}{MCV \times FC}$$

(6)

Substituting *FC* with equation 4.3

$$nn_{DG} = \frac{P_{out}}{P_{in}} = \frac{SL}{MCV\ (a \times SL + b)}$$

(7)

If the load to be supplied is less than 30% of the diesel generator rating capacity, the diesel generator operation should be prevented not only due to its low performance, but mainly due to the damage the machine may suffer, which limits its useful life.

Inverter

The design of the hybrid system require a grid-tied inverter to connect the PV DC to the AC grid. HOMER software technology allowed the selection of the inverter size and cost to simulate and optimize an inverter size to meet the PV area and load demand. Since the PV system has a number of array strings, a number of string inverters are desirable. According to [11]"the advantages of string inverters are reduction of combiner boxes and easier system troubleshooting and monitoring" The inverter characteristics for this design are shown in Table 2. According to

Alayan [11], "the model SMA TriPower 15000TL has a large V_{mpp} range of 360-800V, which gives some flexibility in using different modules voltage characteristics and design with different string lengths. The maximum voltageis 1000V and the efficiency is 98.1%" This high efficiency makes the SMA TriPower 15000TL the best selection for the design.

Table 2 Inverter Specifications

Inverter Type	Sunny TriPower STP 15000TL-10
Inverter Efficiency	98.1%
Max voltage	1000V
M_{pp} voltage range	360V-800V
String inverter size	500Kw
Lifetime	15 years
Electronic MPPT	Yes

III: HOMER SOFTWARE

Hybrid Optimization Model for Electrical Renewables (HOMER) was developed to help designers explore the three principal tasks optimization and; simulation, sensitivity analysis of a system. According to [12] "HOMER allows simulation of both grid-connected and off-grid systems which generate electricity from \combinations of various energy sources like solar PV modules, micro-turbines, wind turbines, batteries ,biomass based power generators, fuel cells, , hydrogen storage and auxiliary generators with numerous fuels options and different load types" [13]. According to IntechOpen - Open Science Open Minds | IntechOpen. (n.d.), "HOMER software, National Renewable Energy Laboratory's (NREL) micro power simulation and optimization model, has the capability to assess a range of equipment options over varying constraints to optimize small power systems" (Energy Innovations: Science & Technology at NREL, fall 2009).

According to [14], HOMER software afford the best opportunity for governments and organizations to model and design large rural electrification projects. The program scans stimulation of all potential conformations of system configurations at a high speed of processing thus allowing for the assessment of thousands of combinations (Energy Innovations: Science & Technology at NREL, fall 2009). In carrying out the simulations, HOMER categorizes the feasible combinations in order of increasing net present cost. According to [14], "the cost is the present value of the initial, component replacement, operation, maintenance, and fuel costs. HOMER lists the optimal system configuration, defined as the one with the least net present cost, for each system type. HOMER's sensitivity analysis then repeats this optimization as user-defined factors, such as fuel price, load size, reliability requirement, and resource quality are varied".

Hybrid Optimization Model for Electrical Renewables (HOMER) was developed to help designers explore the three principal tasks; simulation, optimization and sensitivity analysis of a system. HOMER allows simulation of grid-connected and off-grid systems which generate electricity from various combinations of solar PV modules, wind turbines, biomass based power generators, micro-turbines, fuel cells, batteries, hydrogen storage and auxiliary generators with various fuels options and different load types[12-14]. According to IntechOpen - Open Science Open Minds | IntechOpen. (n.d.), "HOMER software, NREL's micro power optimization model, has the capability to assess a range of equipment options over varying constraints to optimize small power systems" (Energy Innovations: Science & Technology at NREL, Fall 2009). Figure 6 shows a basic architecture of HOMER software.

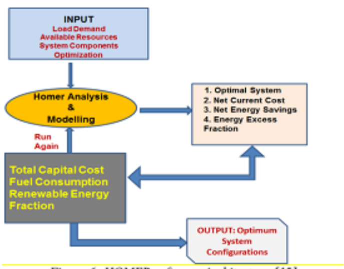

Figure 6: HOMER software Architecture [15]

Figure 3.1 reveals the design result of the quantity of cases of various RES under weather conditions, load demands, capacity ranges, fuel expenses, and carbon emission constraints to choose the optimum system. According to Asee Peer Document Repository (n.d.) as cited by *[15]* "this software package can be used to design and analyze hybrid power systems for both stand-alone and grid-connected applications. Input information to be provided to HOMER includes: electrical loads (one year of load data), renewable resources, component technical details and costs, constraints, controls, type of dispatch strategy, etc. it designs an optimal power system to serve the desired loads, performing several simulations to ensure best possible matching between supply and demand in order to design the optimum system"

I Hybrid System Design

II Simulations

HOMER was used to optimize the system by testing the best alternative PV-diesel hybrid combinations. This section highlights several scenarios corresponding to different hybrid power system conformations (Diesel generator set and PV+ Diesel generator set). The software optimizes the operation for each scenario, their drawbacks and benefits to come up with the best configurations.

Scenario 1: Standalone Diesel Generator Set

In this scenario a standalone diesel generator powering a micro-grid is utilized. This is actually the most frequent configuration that you are likely to meet in areas which are powered by micro-grid. Therefore, a diesel generator is used to supply all the power required by the micro-grid and even may need to dump some power production to avoid running at very low load (<30%).

Scenario 2: PV+ Generator Set

The hybrid system design is made of a diesel generator and a solar power plant without storage system. The solar power plant supply power during the day but the genset must still be idling as a spinning reserve: this allows it to kick in very fast to meet the load in case the PV power drops. The genset remains the grid former, regulating voltage and frequency.

IV: MODIFIED RECIPE MODEL

I: Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a technique used to compare and analyze the energy sources using the positive \and negative environmental impacts associated with the development of such over their entire life-cycle. The framework of LCA methodology is shown in Figure 7 [16]. LCA stages includes the following: Defining of the goal and scope of the study, analysis of the inventory, assessing of the impact and results interpretation. The goal and scope describes the objectives of the study, the energy system, it's boundaries and the definition of a functional unit. The flows of pollutants, materials, resources are recorded under the inventory analysis. These elementary flows are basically characterized and algebraically aggregated for various environmental impact problems in the impact assessment and finally conclusions are drawn in the interpretation stage. For Solar PV, we adopt the *Modified ReCiPe Model* which is a Life Cycle Impact Assessment (LCIA) for Renewable Energy Systems (RES).

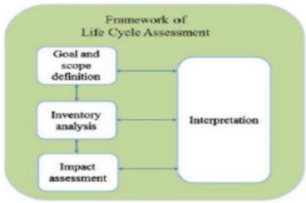

Figure 7: Life Cycle Assessment (LCA) [16]

II: Modified Recipe Model

ReCiPe is a Life Cycle Impact Assessment (LCIA) method for RE released by Heijungs et al [7]. In this paper, *ReCiPe Version* 1.3 *Model* is adopted, which has input, midpoint and endpoint indicators. The inputs considered in the model used in this paper include the raw materials for solar PV manufacture, land requirement and use and the total optimal emissions. The output is the end point categories which include Human Health (H), Ecosystems (E), Social(S) and Net Resources Cost(C). The midpoint indicators are as shown in Table 3 [8].

There are eighteen midpoint impact categories and three endpoint impact categories in the *ReCiPe* method. Characterization factors are used to convert emissions to the units of the midpoint impact categories, and from midpoint to endpoint. The goal of *ReCiPe* is to harmonize midpoint and endpoint impact categories in a single framework. This method builds on the previously existing Centrum Milieukunde Leiden (CML 2002) and Eco-indicator 99 methods, the latter of which methodology uses the endpoint approach, and the former, midpoint. There are both merits and demerits of using midpoints and endpoints. Midpoints are generally fairly accurate, but the units, usually in terms of a reference compound, such as CO2 for climate change, can render it difficult for the analyst or a policy maker to understand the overall impact. In the other hand, endpoints are much easier to conceptualize since they are expressed in terms of tangible effects using a point system, dollar amounts, number of species affected, or number of human life years lost (DALY), to which it is easier to relate. However, the method of translating the midpoint impacts to endpoint units incorporates much uncertainty. This uncertainty stems from poor understanding of the mechanisms through which pollutants affect ecosystems and human life and the dependence these mechanisms may have on geographical factors. Thus, the tradeoff between result accuracy and result interpretation becomes quite evident. The various emissions are determined using the HOMER Software [9] and the Health and Ecosystems effects analyses using the Modified Recipe Model.

Table 3:Mid-Point Indicators for Modified Recipe Model

Table 0: Mid-Point Indicators for Modified ReCiPe Model

End Point	Mid-Point Indicators
Human Health	Ozone depletion, Human Toxicity, Radiation, Photochemical Oxidant formation, particulate formation and climatic change
Ecosystem	Climate change, terrestrial ecotoxicity, terrestrial acidification, agricultural land occupation, natural land transformation, marine ecotoxicity, marine eutrophication and fresh water ecotoxicity
Social	Interrelation between resource cost and social effects of solar PV technology
Net Resources Cost	Fossil fuel consumption, mineral consumption and water consumption

V: RESULTS AND ANALYSIS

A: Emissions Optimization by HOMER Software (EOHS)

The specified emissions for various cases and PV penetration are tabulated in Table 4 where the emission factors involved are obtained in the HOMER Software. With the hybrid system, there is reduced emissions as compared to the pure sources. This is because the power exchange in the mini-grid result in reduced emissions. HOMER credits the power system with these reductions. The system can even achieve negative emissions of more or more pollutants if it sells allot of low-emission power to the mini-grid. The optimal emission levels (60% penetration) for selected pollutants are as shown in in Table 5. We take the Diesel generation as the base. From the table, it is apparent that with optimal penetration, hybrid system result in 77% decrease in emission levels.

Table 4: Emissions for Various Power Systems at Different Levels of PV Penetration

Parameter	Units	Diesel (D)	Solar (PV)	Diesel-PV(D-PV)					
				25%	40%	50%	**60%**	70	80
CO_2	Kg	160,579	98,800	131,039	75,490	195,747	**60,704**	98,100	89,897
CO	Kg	25	244	21	109	234	**72.3**	88	101
UHC	Tons	345	27	98.5	22	25.9	**8.01**	56	67
PM	Tons	36	21	31.6	18.8	17.6	**5.45**	18	34
SO_2	Kg	696	428	568	327	628	**195**	207.4	345.6
NO_x	Kg	2,208	2,576	1278	1160	902	**712**	1780	2145

Table 5: Emissions at Optimal PV penetration

Parameter	Units	Diesel (D)	Hybrid (D-PV)	Δ%
CO_2	Kg	99	13.4	**+86.5**
CO	Kg	141	85.4	**+39.4**
UHC	Tons	220	35.2	**+84.0**
PM	Tons	1.9	0.2	**+89.5**
SO_2	Kg	288	46.7	**+83.8**
NO_x	Kg	340	72.9	**+78.6**
Average				**+76.97**

B: Cost Equivalent for Optimized Emissions

HOMER takes the emission penalties into account when comparing the costs of different dispatchable generation sources. The following equation is used to determine the penalty for the emissions C_e:

$$C_e = \frac{\begin{pmatrix} C_{CO_2}M_{CO_2} + C_{CO}M_{CO} + C_{UHC}M_{UHC} \\ +C_{PM}M_{PM} + C_{SO_2}M_{SO_2} + C_{NO_x}M_{NO_x} \end{pmatrix}}{1000} \quad (8)$$

Where C denotes the penalty for the corresponding emission, PM or UHC in $\$/t$ while M is the annual emissions for the particular substance in kg/yr.

The various results for the total emissions and the cost equivalent without and with cost constraints are as shown in Tables 6 and 7. These are taken at the optimal PV penetration of 60%. Without the cost constraints reduces the emissions levels by 0.46% but results to an increase in resources cost by 0.3%. With cost constraints, the emissions decrease by 4.6% and the cost equivalent increases by 38.7%. Thus, a more accurate determination of optimal emissions is including the resources cost equivalent as a condition. Such a tradeoff between emissions and cost is paramount due to the increased environmental concerns.

The optimal emissions levels can then be applied to evaluate the Health, Ecosystems and Social effects for they are responsible for the various indicators. These are discussed in the next sections.

Table 6: Emissions Optimization without Cost Constraints

Parameter/ Source	D	PV	Δ% **(D to PV)**	D-PV	Δ% **(D to D-PV)**
Emissions, E(kg/h)	9.877	9.824	**+0.54**	9.83 27	**+0.46**
Cost Equiv, C($/h)	1.504	1.647	**-9.50**	1.97 66	**-0.30**

Table 7: Emissions Optimization with Cost Constraints

Parameter/ Source	D	PV	Δ% (D to PV)	D-PV	Δ% (D to D-PV)
Emissions, E(kg/h)	15.921	15.962	-0.26	15.18 8	+4.60
Cost Equiv, C($/h)	1.187	1.351	-13.81	1.647	-38.69

C: Health Effects (HE)

The mid-point indicators for Human Health (H) considered in this paper include the following:

H_1: Ozone Depletion (Kg CFC-11-eq)[OD]

H_2:Human Toxicity [HT]

H_3: Ionizing Radiation [IR]

H_4: Particulate Matter [PM] Formation

H_5:Photochemical Oxidation Formation [PCOF](KtNMVOC) [PMF]

H_6/E_1:Climate change / Global Warming Potential [GWP] ($MtCO_2$-eq)

The simulated results are as shown in Table 8. Use of D-PV hybrid reduces H_2(Human Toxicity) by 92% and 69.5% is for pure PV deployment. It is worth to observe that use of hybrid system reduces H_3(Ionising Radiation) by 80% while PV technology increases the same by 39%. Use of pure Solar (PV) increases H_1 by 119% while the hybrid reduces the same by 69% . H_1 (Ozone Depletion) is closely related to theNO_X emissions and with Diesel, this increases due to the combustion of fossil fuels. Solar adds four (4) times more of H_4(Particulate Matter [PM]) relative to the hybrid. This is due to two reasons; the PV manufacturing process where there is incomplete combustion of fossil fuels and the wafer-sawing process which creates fine silicon dust particles.

Table 8: Health Effects

Source /Parameter	Diesel (D)	Solar (PV)	Δ% **(D to PV)**	Diesel-Solar (D-PV)	Δ% **(D to D-PV)**
H_1	1,954.90	4,285.08	**-119.20**	608.85	**+68.86**
H_2	92.50	29.85	**+67.73**	7.55	**+91.84**
H_3	4,905.23	6,806.98	**-38.77**	1,005.34	**+79.50**
H_4	163.78	39.56	**+78.85**	10.58	**+90.77**
H_5	730.00	82.23	**+88.74**	26.22	**+96.41**
H_6/E_1	305.34	25.16	**+91.76**	9.89	**+96.76**
Average(H)			**+31.54**		**+88.80**

PV deployment in the existing Diesel (D) minigrid using the proposed approach reduces H_5(Photochemical Oxidation Formation) [PCOF] significantly, that is by almost 97%. Solar contributes highly to the 92% H_6/E_1(Ozone Depletion) reduction while for D-PV hybrid is the even more that is 97%. This is due to the energy-intensive silicon purification process where more fossil fuels (with carbon) are combusted. It is worth to note that the midpoint impact category of "climate change" contributes to both the damage to "human health" and damage to "ecosystems" endpoint categories. By average, deployment of pure PV technology reduces net health effects (H) by 32% while the actual hybrid system when applied optimally results in 88% decrease in the same. Thus, the D-PV system is preferred.

D: Ecosystems Effects (EE)

The mid-point indicators for Ecosystems effects (E) include the following:

H_6/E_1:Climate Change / Global Warming Potential [GWP] ($MtCO_2$-eq)

E_2: Terrestrial Acidification (Kt SO_2-eq) [TA]

E_3: Terrestrial Eco-Toxicity (Kt1, 4-DCB-eq) [TET]

E_4: Marine Eco-toxicity (Kt1, 4-DCB-eq)[MET]

E_5: Marine Eutrophication and Fresh Water Eco-Toxicity (Mt-N-eq)[MEFWET]

E_6:Land Occupation [LO] ($km^2.a$) [LO]

E_7:Land Transformation [LT] (km^2)

The results for the Diesel (D), Solar (PV) and Diesel-Solar (D-PV) Hybrid system are as shown in Table 9. With the Diesel base, the hybrid technology reduces E_1 by 97% , E_2 by 96%, E_3 by 57%, E_4 by 90% , E_5 by 97%,E_6 by 91% and finally E_7 by 85%. When a pure PV system was simulated, the average effects became 73% while for the hybrid system, the net ecosystem effect is 88%. Thus, the hybrid system is preferred in reducing the Ecosystems effects.

Table 9: Ecosystems Effects

Source /Parameter	Diesel (D)	Solar (PV)	Δ% **(D to PV)**	Diesel-Solar (D-PV	Δ% **(D to D-PV)**
E_1	305.23	25.67	**+91.59**	9.56	**+96.87**
E_2	1300.45	115.01	**+91.16**	52.33	**+95.98**
E_3	4.53	4.34	**+4.20**	1.95	**+56.95**
E_4	2010.45	460.25	**+77.11**	210.13	**+89.55**
E_5	356.27	28.44	**+92.02**	10.76	**+96.97**
E_6	8512.30	950.78	**+88.83**	740.56	**+91.30**
E_7	17.31	5.74	**+66.84**	2.61	**+84.92**
Average (E)			**+73.11**		**+87.51**

E: Economic Analysis of Environmental Effects

For high integrated hybrid system (HIHS), the externalities values of energy production for diesel and PV are $4.286 cent\ \$/kwh$ and $0.142 cent\ \$/kwh$ respectively. A Summary of the plant costs for various cases are as shown in Table 10. From the Table, the installation cost remain the same while the hardware cost decrease by 12%. Operation and maintenance cost rises by 502% and the total cost decreases by 4%.

Table 10: Integrated Plant Costs

	Plant Costs ($)			
Plant	Installation	Hardware	O&M	Total
Diesel (D)	1,465,580.00	9,357,360.00	292,100.00	11,115,040.00
D-PV	1,465,580.00	8,286,750.00	1,758,950.00	11,511,280.00
Δ%	**0**	**+11.44**	**-502.17**	**-3.57**

The UEC cost for the power plants includes the O&M, fuel costs, environmental costs (economic value due to the pollutant emitted to the atmosphere), cost of money, overall hardware and installation cost and the substitute costs of every part at the end of the operative life. UEC with environmental costs is denoted by UECE in this thesis. These are summarised in Table 11, from which, it can be seen that when environmental effects are accounted for, the overall cost rises by 5.6%.

Table 11: UEC for Different Plants ($\$/kWh$)

Plant	UEC	UECE	Δ%
Diesel (D)	1.984	1.989	**-0.25**
PV	1.078	0.719	**+33.30**
Δ%	**+45.67**	**+63.85**	
D-PV	0.559	0.590	**-5.5**
Δ%	**+71.82**	**+71.80**	

VI: CONCLUSION

From the simulated results, it is apparent that the deployment of hybrid system reduces environmental effects. That is, D-PV enables 77% decrease in net emission levels at the 60% PV penetration which is the optimal scenario. The standard practice involves including emissions cost in place. Thus the practical way in D-PV cost analysis is including the cost constraints in place. This results in 5% increase in emissions computed and 39% increase in cost equivalent. Environmental effects are determined from the optimal case of PV penetration. Use of pure PV technology reduces net health effects (H) by 32% while the actual hybrid system when applied optimally results in 88% decrease in the same. When a pure PV system was simulated, the average effects became 73% while for the hybrid system, the net ecosystem effect is 88%. Thus, the hybrid system is preferred in reducing both the Health and Ecosystems effects. D-PV cost more than the pure Diesel (D) by 17.3%. The LCC for D-PV increase by 4% with Diesel mini-grid as the base. With the environmental effects accounted for, D-PV is 72% cheaper in terms of UECE. D-PV with net environmental impacts in 5.6% more costly. Economic analysis of Diesel and diesel PV mini-grid presented that hybrid has more initial cost due to inclusion of PV. However the hybrid is cheaper in operation and maintenance leading to COE. Thus, there must be a trade-off between accounting for environmental effects in D-PV and cost. This paper recommendations the investigation of social effects of solar deployment in the future [19].

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