DEVELOPING A TECHNO-ECONOMIC MODELLING TOOL FOR SMALL-SCALE UTILITY SOLAR PV TECHNOLOGY FOR QUANTIFYING ENVIRONMENTAL IMPACTS

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Developing A Techno-Economic Modelling Tool for Small-Scale Utility Solar PV Technology for Quantifying Environmental Impacts

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as University Supervisors

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DEDICATION

To my wife and children,

ACKNOWLEDGEMENT

I wish to acknowledge the efforts of my supervisors for guiding and encouraging me through this research. I would also like to thank the Postgraduate students of JKUAT for their insights geared towards the completion of this work.

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LIST OF ABBREVIATIONS

ARES	Autonomous Renewable Energy System
CF	Conversion factor
COE	Cost of Energy
DALY	Disability Adjusted Life Years
DC	Damage Costs
DCF	Discounted Cashflows
DEP	Depreciation
DR	Discount Rate
EC	Environmental Cost
EF	Emission factor
EIB	European Investment Bank
EU	European Union
EVSD	Ecosystem Service Value Database
GHG	Green House Gases
GIS	Geographical Information System
GWP	Global Warming Potential
HDF	Human Damage Factors
HOGA	Hybrid Optimization by Genetic Algorithms
HOMER	Hybrid Optimization of Multiple Energy Resources
HR	Hours per day
HTF	Human Toxicity Potentials

HYDROGEMS	Hydrogen Energy Models
IC	Initial Capital
INSEL	Integrated simulation Environment Language
INT	Interest rate
IPP	Power Independent Producers
IPSYS	Integrated Power System tool
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
LECOE	Levelized Externality Cost of Energy
LP	Loan Repayment
LTCOE	Levelized Total Cost of Energy
NMVOC	Non-Methane Volatile Organic Compounds
NREL	National Renewable Energy Laboratories
NRET	Non Renewable Energy Technology
O&M	Operations and Maintenance
PM	Particulate Matter
RAPSIM	Remote Area power Simulator
RC	Replacement Cost
RET	Renewable Energy Technology
ROI	Return on Investment
RV	Residual Value
SDR	System Degradation Rate

SOMES	Simulation and Optimization model for Renewable Energy Systems
SPECA tool	SolarPV based Power and Environmental Costing Assessment
TES	Thermal energy storage
USSE	Utility-Scale Solar Energy
WTA	Willingness To Accept
WTP	Willing To Pay
XC	External Cost
YLD	Years of Life Disabled
YLL	Years of Life Lost

ABSTRACT

Globally, attention has been focused on pollution and exhaustion of fossil fuels allied to conventional energy sources. In contrast, non-conventional energy/renewable energy sources have always been considered clean and environmentally friendly. The non-conventional (renewable) are being preferred because they are believed to be more environmentally friendly. Renewable Energy Technologies (RETs), especially Solar Photovoltaics, have seen many plants being constructed to supplement the grid or alternatives for those far from the grid. Solar Photovoltaics plants occupy large tracts of land, which would have been used for other economic activities for revenue generation such as agriculture, forestry, and tourism in archaeological sites. The negative impacts slow down the application of Solar PV. Still, a modeling tool that can quickly and quantitatively assess the effects in monetary form would accelerate the Solar PV application. This thesis presents a developed modeling tool that determines not only the techno-economic impacts but also the environmental impacts in monetary form for one to be able to assess the viability of a plant in a given region. Solar-PV based Power and Environmental Cost Assessment (SPECA) model was developed to help in the following ways: (i) understanding of Solar PV based power generation and its interactions with the resource inputs, the private costs, externalities, external costs, and hence the environmental and social-economic impacts over the lifespan of the plant (ii) aiding investors of Solar PV with a tool which has a clear graphical and user interface for detection of the main drivers of the Levelized Cost of Energy (LCOE) (iii) creating an enabling environment for decision-makers aided by a visual SPECA modeling tool which takes into account the financial viability and the environmental impacts of Solar PV. SPECA is a sizing tool for techno-economic analysis. It is mathematically based, capturing all the life cycle costs and their associated ecological burdens. The source codes of the SPECA model have been written in Visual Basic programming, while the Database was developed using the Standard Querry Language (SQL). The modeling tool provides a friendly Graphical user interface where the user can input the required data. In general, SPECA will be of great use to investors and policymakers of Solar PV systems for drawing alternatives and conclusions based on the best compromise. The model developed will be useful, especially in addressing the trade-offs between environmental impacts and financial impacts, which aim to improve the quality and transparency in the decision-making during the deployment of Solar PV. The quantification of the social-environmental effects of Solar PV will permit for cost accounting assessment of the unforeseen cost incurred when using them for electricity generation. The SPECA modeling tool presents the LCOE, the Levelized Total Cost of Energy (LTCOE), and the Levelized Externality Cost of Energy (LECOE). LECOE is the indirect cost incurred due to the environmental and social impacts where the installation of solar PV is made. In Lodwar, the SPECA tool yields an LCOE of $11.149, while the LTCOE value is $11.214 resulting in a $LECOE of $0.065. The contribution of LCOE and LECOE to the actual cost of electricity is 95.3% and 4.7%, respectively. LECOE for Gatarakwa forms 4.06% of LTCOE while LCOE forms 95.94% of LTCOE. The SPECA tool further reveals that areas with high species yield a higher LECOE than regions with low species concentration. The indirect costs (LECOE) represent the socio-environmental burden borne by society to restore the environment. SPECA modeling tool permits for cost accounting of the indirect costs incurred while generating electricity from solar PV by including LECOE. Accordingly, LTCOE is, therefore, the true cost of energy. Finally, while attempts were made to incorporate all the relevant information about the externalities of Solar PV, not all essential aspects of solar PV were included due to scarce data, anticipated model complications, and the existing knowledge gaps. The significant shortcomings of the SPECA tool are listed, and the recommendations for future work are made.

CHAPTER ONE

INTRODUCTION

1.1 Background

The most significant portion of the energy demand worldwide is met by fossil fuels such as coal, natural gas, and crude oil (Owusu & Asumadu-Sarkodie, 2016), as shown in Figure . It is also noted that the electricity demand is increasing each day, which has caused the rapid depletion of fossil fuels. Energy production from fossil fuels emits dangerous greenhouse gases harmful to the environment. The signing of the PARIS agreement saw many nations worldwide cut down the usage of fossil fuel-related energy sources and seek alternative sources of energy. This further intensified the quest for more sustainable sources to reduce the high dependence on fossil fuels. The only viable solution to this problem was using renewable energy sources available, especially in rural areas far from the grid.

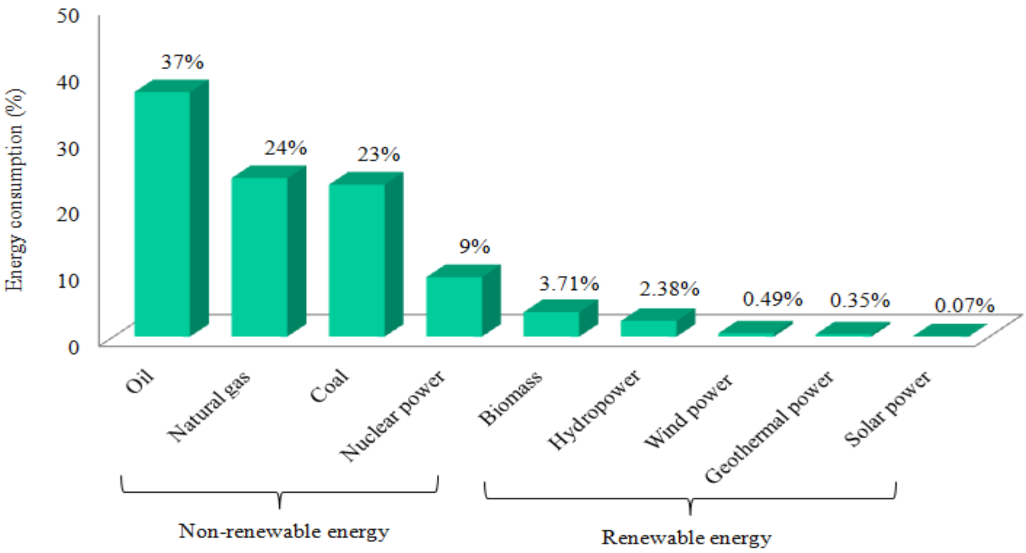

Figure 1.1: Global Share of Renewable and Non-Renewable

It is estimated that more than 2 billion people (about 44% of the world population) across the world do not have access to grid electricity connection because of the high grid connection fees, dispersed community, and the rugged terrain (Sen & Bhattacharyya, 2014)(Barley & Winn, 1996). The following section discusses, in brief, the environmental impacts of both renewable and non-renewable energy sources.

1.2 Environmental impacts of Renewable and Non-Renewable Energy Sources

Global attention has majorly focused on the negative impacts of conventional energy sources on the environment (Owusu & Asumadu-Sarkodie, 2016)(Chowdhury & Kibaara, 2016). These include the emission of greenhouse gases, oil spillage in rivers, which may interfere with aquatic life and habitat fragmentation (Owusu & Asumadu-Sarkodie, 2016). On the other hand, non-conventional sources of energy have always been regarded as clean and harmless to the environment (Chowdhury & Kibaara, 2016). It is reported that in all public discussions held regarding pollution from conventional sources of energy, the advice is that everyone should adopt renewable energy sources (Abbasi & Abbasi, 2000). But are the non-conventional sources of energy as clean and harmless as they are widely believed to be?

Despite being described as clean energy sources, coupled with the use of guaranteed feed-in tariffs and the quota targets combined with tradable green certificates in the endeavor to promote them, their utilization is low as depicted in Figure , standing at 15-20%, therefore not fully penetrating the market due to several barriers (Painuly, 2001)-(Abbasi & Abbasi, 2000)-(Madlener & Stagl, 2005). Many authors recommend the immediate removal of the production subsidies (tradable green certificates) on solar PV systems because of the high Levelized Cost of Electricity (LCOE), which ranges from 300-450 per MWh and their vast environmental impacts(Painuly, 2001)-(Abbasi & Abbasi, 2000)-(Madlener & Stagl, 2005)-(Laleman et al., 2011)-(Bo & Brod, 2019). The market prices of energy generated from fossil fuels are lower than those generated from renewable energy technologies such as solar, wind, and biofuels (El-Shimy, 2017)(Members, 2020). The barriers towards full realization and market penetration of renewable energy technologies, specifically solar PV, are majorly contributed by the underlying negative impacts on the environment, social world, high initial cost, and the technical barriers (Abbasi & Abbasi, 2000). The environmental impacts include Green House Gases (GHG) emissions which have implications on natural biota, habitats, and wildlife, groundwater contamination, visual intrusion, water use and effects, air quality, land use impacts, and soil fertility (Akella et al., 2009). The hazardous greenhouse gas emitted by renewable and non-renewable energy technologies are as shown in Table 1.1 has effects on human health, the ozone layer, and plants (Moss et al., 2014). Mostly, to ensure the sustainability of RETs, the environmental impacts must always be considered during their design to determine their economic viability in a particular locality (Akella et al., 2009).

Table 1.1:Estimated Life Cycle Emissions of Various Energy Sources

Energy Source	**CO_2 (g/kWh)**	**SO_2 (g/kWh)**	**NO_x (g/kWh)**
Coal	955	11.8	4.3
Oil	882	14.2	4.2
Solar Photovoltaic	98-167	0.2-0.34	0.18-0.30
Concentrating Solar Thermal Power	26-38	0.13-0.27	0.06-0.13
Natural gas	430	-	0.5
Wind	7-9	0.02-0.09	0.02-0.06
Geothermal	7-9	0.02	0.28
Small hydro	9	0.03	0.07
Large hydro	3.6-11.6	0.009-0.024	0.003-0.006
Diesel	772	1.6	12.3

In a nutshell and as illustrated by Table 1.1, renewable energy technologies are not as benign as they are widely believed to be. Therefore, in determining the cost of energy, aspects such as the emissions of either renewable or non-renewable must be considered, as discussed in section 0.

1.3 The Cost of Energy

The calculation of LCOE involves all the costs incurred in the daily running of the plant, including operation and maintenance costs, fuel costs, and capital (initial) costs. LCOE is the most convenient measure of the economic competitiveness of different electricity-generating technologies. It is a metric of measurement that indicates the price at which electricity must be sold to break even (Del Sol & Sauma, 2013). LCOE represents the per kWh cost of building and operating a generating plant for its entire lifespan. In economic terms, LCOE represents the price of electricity that would equalize the lifetime cash flows (Said et al., 2015). The lifetime cash flows are as defined by Equation ..(0.1) and Equation (0.2).

$$CI = \sum_{t=1}^{T} E_t * \frac{COE_t}{(1+r)}^{t} \qquad ..(0.1)$$

$$CO = \sum_{t=0}^{T} \frac{C_t}{(1+r)}^{t} \qquad (0.2)$$

Where E_t, COE_t, r ,C_t, CI, CO are respectively energy generated, cost of energy, discount rate, capital cost, cash inflow, and cash outflow.

LCOE is, therefore, the average cost of energy over the life span of the project such that the net present value (NPV) becomes zero in the discounted cash flows (DCF).

Throughout this thesis, it is found that popular economic tools such as Hybrid Optimization of Multiple Energy Sources (HOMER), Hybrid Optimization by Genetic Algorithms (HOGA), Transient System Simulation Tool (TRNSYS), Hydrogen Energy Models (HYDROGEMS), Autonomous Renewable Energy System (ARES), Simulation and Optimization Model for Renewable Energy Systems (SOMES), Integrated Simulation Language Environment (INSEL), Remote Area Power Simulator (RAPSIM) and Integrated Power System Tool (IPSYS) used for the economic evaluation and optimization of different RETs do not put enough emphasis on the environmental impacts. Instead, these tools use the capital (initial) costs, operation and maintenance costs, and the annual replacement costs to calculate the LCOE (Sen & Bhattacharyya, 2014)(Barley & Winn, 1996)(Zerihun, 2015)(Lund et al., 2010).

It is reported that the actual cost of electricity production from either renewable energy technologies or conventional sources of energy must consider the external costs incurred while generating energy (El-Shimy, 2017). Most energy market prices ignore these critical factors such as pollution and resulting problems such as damage to the ecosystem and human health, therefore declaring the LCOE a crude estimate (El-Shimy, 2017). It is further argued that the ignored damage cost resulting from electricity generation from either renewable energy technologies or Non-Renewable Energy Technology (NRETs) is valued at zero and hence not included in the electricity pricing, policy-making, or resource and site selection (Ottinger Richard, 1990). Roth & Ambs (2004a) reports that the Environmental Impact Assessment (EIA) is usually not featured in many energy modeling tools. The failure to consider the externalities of power generation renders techno-economic comparison with other energy technologies complicated (Roth & Ambs, 2004b).

This thesis identifies a need to develop a techno-economic modeling tool that fully integrates the variability of the economic and environmental impacts of solar PV. Incorporating the environmental impacts of RETs in the cost modeling tool will permit cost accounting evaluation of the indirect cost incurred while using Solar PV for electricity generation, which will further guide investors in the approximation of their economic viability.

1.4 Problem Statement

In Kenya, like the rest of the world, there are plans to increase electricity production through solar PV-based investments. Although the Environmental Impact Analysis (EIA) reports forming a large percentage in the decision-making during deployment of any technology, this work has found that the critical analytical components which form the basis for decision making are poorly performed. The EIA reports fail to identify and assess all the impacts during the construction and run of Solar PV or any other energy technology (Sandham et al., 2013).

The other limitation of the EIA reports is the failure to consider the socio-economic impacts and the non-consideration of the monetary valuation of externalities despite their importance in decision making. The Techno-Economic and sizing tools currently, including HOMER, INSEL, SAM, RETSCREEN, and SOMES, do not consider the internalization and monetization of externalities. As such, the LCOE results and other metrics are crude estimates. Therefore, this thesis develops a tool through mathematical modeling that quantifies, monetizes, and internalizes the externalities of solar PV. The principal research problem is the identification, assessment, monetary evaluation, and inclusivity of the environmental impacts in the cost modeling for the techno-economic feasibility of solar PV.

1.5 Justification

The traditional tools such as HOMER, HOGA, SAM, INSEL, RAPSIM, TRNYS, INSEL, SOMES, and ARES; among others, use the capital costs, operational and maintenance costs, replacement costs, and residual value to determine the LCOE; which is the primary metric used for the analysis of economic viability of solar PV. These tools, however, do not value and consider the environmental impacts in the cost modeling. Considering the environmental impacts will help in accounting for the external costs incurred while generating energy from USSE. This thesis, therefore, bridges the existing gap by developing a techno-economic modeling tool based on a mathematical modeling approach that acts as a decision-maker during feasibility analysis of Solar PV considering their vast environmental impacts.

1.6 Objectives

1.6.1 Main Objective

The main objective was to develop a Techno-economic and environmental modeling tool that aids in decision-making on the economic viability of Utility-Scale Solar PV Energy.

1.6.2 Specific objectives

i.) To identify, select and quantify the valued environmental impacts of solar PV.

ii.) To develop a costing model for the valuation of the identified environmental impacts.

iii.) To develop a decision support system that allows for the combined valuation of the interdependence between the various environmental impacts in generating electricity from solar PV.

1.7 Research Questions

i.) What are the current setup and capabilities of the existing techno-economic analysis tools? What are the shortfalls of these tools, and how can they be improved to achieve financial and environmental sustainability?

ii.) How do the environmental impacts influence the LCOE for Utility-Scale Solar Energy?

iii.) Considering the environmental impacts of Utility-Scale Solar Energy (USSE) technologies, what is the future optimal installation in a given region?

iv.) How much renewable energy is likely to be generated, and where will it be installed considering the environmental impacts of these technologies?

v.) To what degree does the infrastructure of the utility-scale solar impact the native species of plants and the destruction of habitats for wild animals?

vi.) What are the environmental trade-offs between allocating lands to utility-scale solar and wind energy development versus agriculture, forest, and protected areas?

1.8 Scope

This work confines itself only to the socio-environmental impacts of commercial solar photovoltaic systems whose installed capacity is 10kW$_p$ DC and above. The restoration of externalities of Solar PV in this work utilized proxy values of the ecosystem goods and services. This was necessitated because it was impossible to value all the biomes existing in a given location. The lifetime of the components such as batteries, inverters, and solar PV used in this work will be replaced only after their lifespan is over. The financial assumptions made in determining LCOE, LTCOE, and

LECOE using the SPECA are the choice of discount rate, overall system degradation rate, and the plant's lifetime. The Solar PV plant's discount rate, system degradation rate, and lifespan were assumed to be 5%, 0.5%, and 25 years, respectively.

1.9 Thesis Organization

This thesis is divided into five Chapters. The rest of the thesis is organized as follows: Chapter Two describes the literature review of the previous work done on solar PV modeling, externalities of Solar PV power generation, and the existing Techno-economic modeling tools. Chapter Three grounds this research by showing a piecewise mathematical model of the solar PV-based Power and Environmental Costing Assessment tool (SPECA) modeling tool. This involves the mathematical derivation of the solar photovoltaic systems, cost modeling of the different solar, quantification and monetization of externalities, and finally, tying all these components to make the new SPECA modeling tool. Chapter four applies the SPECA modeling tool to perform some case studies of the different regions to show the capability and working principle of the tool. Chapter five of this thesis discusses the conclusions, limitations, and recommendations for further work.

CHAPTER TWO

LITERATURE REVIEW

2.1 World Energy Scenario

Today, it is reported that 40% of the global population relies on the traditional use of biomass for meeting their energy needs (Abbasi & Abbasi, 2000). It is projected that by the year 2030 (date of the proposed goal of the universal access to clean energy services), about 1.2 billion people will still lack access to electricity (Abbasi & Abbasi, 2000)-(Saheb Koussa et al., 2012). Approximately 80% of these people without access to clean energy sources live in the rural areas of sub-Saharan Africa, India, and other Asian developing countries (Wies et al., 2004). In South-Eastern Asia, for example, the level of electrification in rural areas is about 51%, while the level of electrification in urban areas is 90% (Wies et al., 2004). The International Energy Agency estimated that about 620 million people living globally have no access to electricity(Quansah et al., 2016). It is further reported that 75% of the populations living in Africa, including Mauritania, Guinea, Burkina Faso, Chad, and Central Africa, have no access to electricity. Energy-wise, with about 15% of the population globally, Africa remains the poorest in electricity installed capacity, as shown in Table 2.1, translating to about 2.4% of the global GDP (Quansah et al., 2016).

Table 2.1: World Energy and GDP Indicators

Region	Population (Million)	% world population	GDP (Bn)$	% Global GDP	Electricity per Capita (kWh)	Per Capita against Global avg
OECD	1254	18	39490	72.3	8090.11	272
Middle East	213	3	1430	2.6	3708.92	125
Non-OECD	341	5	1644	3	4551.32	153
Europe and Eurasia						
China	1358	19	4756	8.7	3488.22	117
Asia	2320	33	3568	6.5	892.67	30
Non-OECD Americans	467	7	2369	4.3	2096.36	71
Africa	1083	15	1331	2.4	591.87	20
Totals (World)	**7036**	**100**	**54588**	**100**	**2972.57**	**100**

In Sub-Saharan Africa (SSA), the overall electricity connection stands at about 23%, with the urban and rural area figures at 51% and 8%, respectively. In the Sahelian countries (Senegal, Mali, Burkinafaso, Niger, Nigeria, Chad, Sudan, and Eritrea), energy access remains low despite the abundance of high wind speeds and high solar irradiance (Thiam, 2010). Senegal has the lowest energy consumption per capita (0.19) despite being located in a region with very high insolation of about 2kWh/m^2 and high wind speeds. In Senegal, 60% of the urban population is connected to the utility grid, while only 15% enjoy the rural areas (Thiam, 2010).

The deployment of renewable energy is potentially one of the solutions capable of alleviating the energy poverty index that is continuously experienced by about two billion people across the world. The majority of these people live in rugged terrain areas and are sparsely populated, making the utility grid connection impractical because of the high costs of reaching such regions (Thiam, 2010). These renewable energy sources of energy include solar, wind, biomass, and hydro. These energy sources are clean, inexhaustible, and environmentally friendly (Tsoutsos et al., 2005a). However, it should be noted that the weather-dependent renewable energy alternatives such as wind and solar are intermittent and volatile, therefore unable to match the load demand's time distribution (Tsoutsos et al., 2005b). Intermittent refers to the unavailability of the wind or solar for longer or extended periods.

In contrast, volatility refers to the smaller and hourly fluctuations of the current or solar within their intermittent characteristics (Machinda et al., 2011). As such, neither a wind standalone nor a solar system can provide a continuous power supply. This shortcoming not only affects the system's energy performance but also affects the battery's life. The stochastic nature of each of the resources, either sun or wind, can be partially or wholly overcome by integrating these two resources using the strengths of one resource to overcome the weakness of the other (Machinda et al., 2011). The independent use of a standalone wind, solar, or diesel results in over-sizing, making the system very costly, inefficient, and unreliable (Erdinc & Uzunoglu, 2012)(Notton et al., 2001)(D. De Groot & Wang, 2010). Section 0 discusses solar energy technologies.

2.2 Solar Energy Technologies

Matured and emerging solar energy technologies such as photovoltaic (PV) systems and Concentrating Solar Thermal Power (CSTP) use the sun's radiation in generating electricity (Erdinc & Uzunoglu, 2012)(Ho et al., 2011). The two leading solar energy technologies differ because PV converts solar energy directly into electricity. At the same time, CSTP uses the thermal effect of solar irradiation to generate steam, which is used to run a turbo-alternator to generate electricity.

2.2.1Concentrating Solar Thermal Power (CSTP)

A CSTP plant employs reflective mirrors to focus solar irradiation on an absorber carrying a heat transfer fluid (Erdinc & Uzunoglu, 2012). The heat transfer fluid undergoes a Rankine Cycle in which water is vaporized at high pressure to run the turbine connected to an electrical power generator. There are four types of CSTPs technologies: Parabolic Trough Collectors (PTC), Linear Fresnel Collectors (LFC), Solar Towers (heliostat field collectors), and Parabolic Dish Reflectors (PDR).

The parabolic trough shown in Figure 2.1is the most proven CSTP technology because of the nine large commercial-scale solar power plants operating in the California Mojave Desert since 1984 (Erdinc & Uzunoglu, 2012). They represent a total of 354MW of installed capacity (Greenpeace International et al., 2005). Parabolic trough collectors trap the sun along the East-West direction during the day. The reflected solar radiation is absorbed by absorbers which carry a heat transfer fluid used to evaporate water for steam production. The steam is used to run a turbine coupled to a generator for electricity production (Greenpeace International et al., 2005).

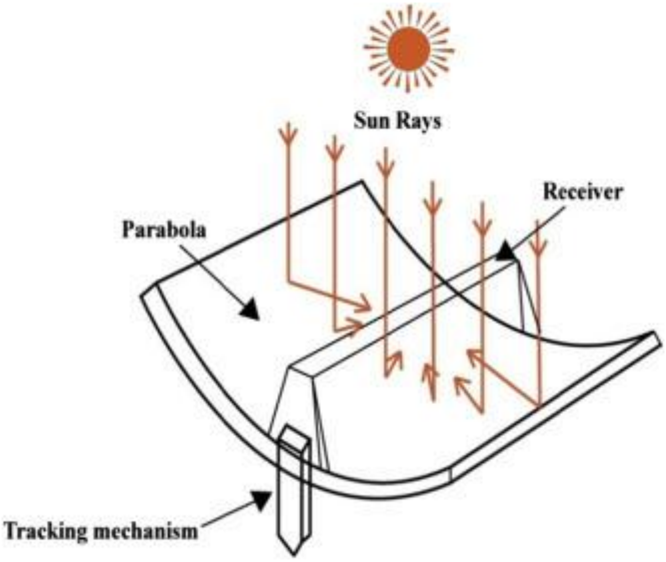

Figure 2.1: Parabolic Troughs

The power tower (heliostat field collectors) uses several heliostats mirrors to track the solar radiation on a central receiver. The sun is tracked on two axes following the azimuth and elevation angles. An HTF that passes to the receiver is heated and used to generate steam (Ho, 2008). The heliostats are about 120m^2 in area. They are usually curved, and the mirrors reflect the sun's rays to a central receiver. The receiver on the tower is designed to reduce the radiation and convectional losses. The steam in the turbine expands and produces mechanical power and electricity. The cold tank molten salts are kept at 45°C above their melting point (240°C). A single 100MW plant with 12 hours of storage requires 1000 acres of desert land to supply 50,000 homes (Greenpeace International et al., 2005)(*Concentrating solar power,* 2007). They generally use ten to fifteen acres per Mega Watt equivalent (MWe) generated. The internal cross-section of the power tower is shown in Figure 2.2 (Ho, 2008).

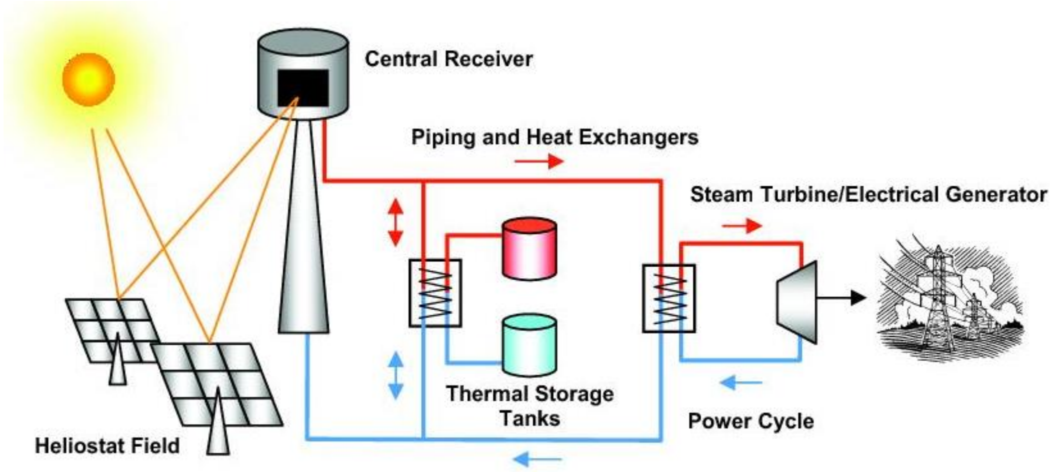

Figure 2.2: Scheme of the CSTP Plant with Power Tower

Linear Fresnel reflectors track the sun using one axis. The shape of a linear Fresnel resembles the parabolic trough. They consist of thin mirrors that focus the solar energy on fixed absorber pipes carrying a heat transfer fluid, as shown in Figure 2.3 (Pitz-Paal, 2008). It uses flat mirrors, which are easy to make (*Concentrating solar power*, 2007).

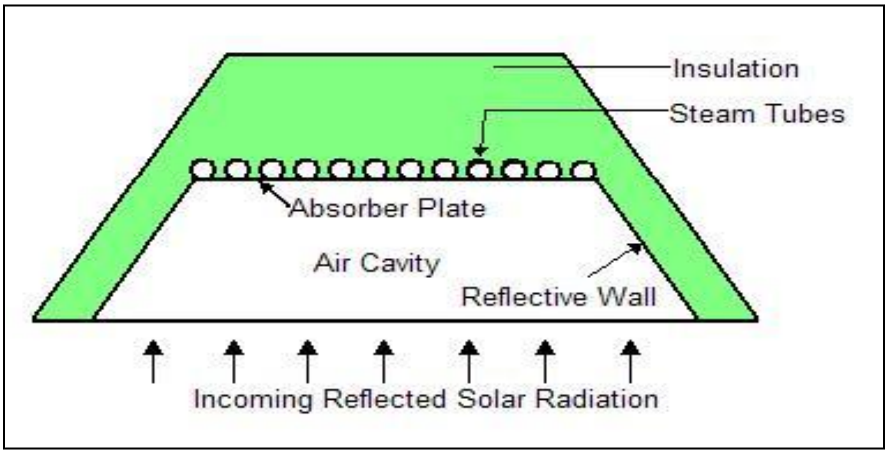

Figure 2.3: Linear Fresnel Showing Concentration of sun rays to heat HTF

The flat mirrors used in Linear Fresnel can concentrate the solar irradiance 30 times its average intensity. The heat transfer fluid absorbs the concentrated solar energy, which undergoes a heat exchanging process to generate steam to power a steam turbine generator. The reflectors are located at the base and reflect the sun rays on a linear axis similar to the parabolic trough (Pitz-Paal, 2008).

A Parabolic Dish CSTP plant concentrates solar irradiation to a single point using a point focus system. The solar irradiation is focused on the concentrator along two axes. A reflective glass or a metalized glass reflects the incident ray to a small region called the Focus. A Stirling engine, shown in Figure 2.4, is directly mounted at the base of the parabolic dish. The Stirling engine converts the concentrated heat into mechanical energy by compressing an HTF (for this case, a gas) and then expanding it through a turbine to produce work. There are no means of storage for this plant, which makes it less popular than the parabolic trough. It requires continuous changing or adjustment of its position to maintain focus (Pitz-Paal, 2008).

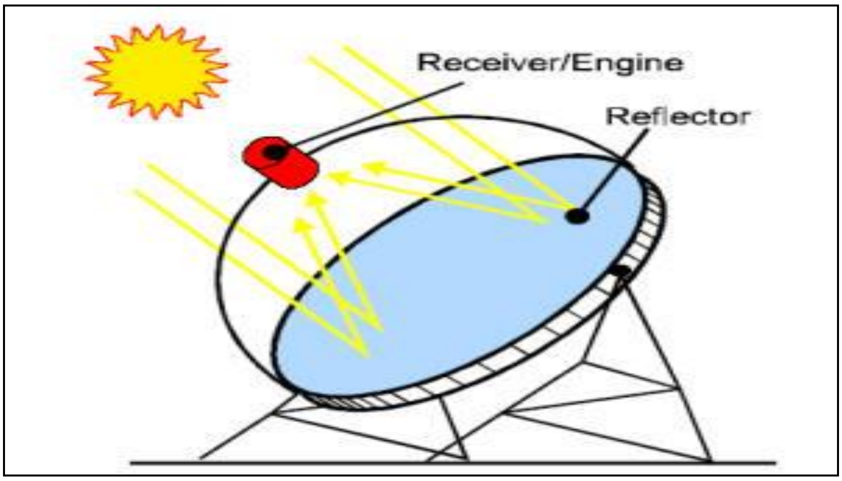

Figure 2.4: Parabolic Dish

In conclusion, concentrating solar thermal is mostly applied in areas where land is in plenty, requiring large tracts of land. This technology also uses a lot of water for cooling and mirror washing. The carbon dioxide emissions from the CSTP are as shown in Figure 2.5**Figure** (Bo & Brod, 2019).

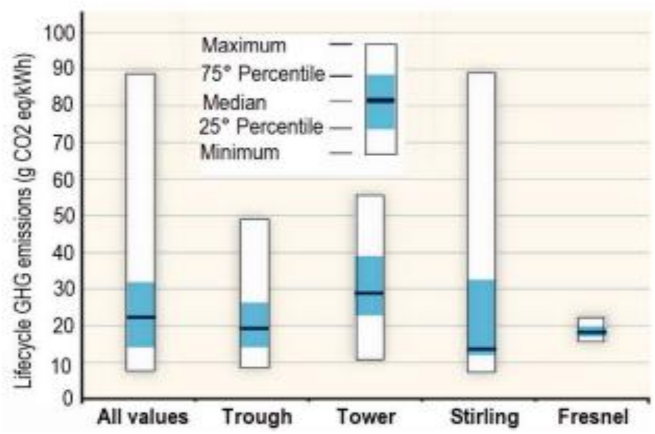

Figure 2.5: Life cycle GHG Emissions of Concentrated Solar Thermal Power

2.2.2 Types of Solar PV and their Applications

A solar cell, commonly referred to as a solar photovoltaic cell, is an electrical device that converts light energy to electrical energy through the photovoltaic effect, usually a physical and chemical phenomenon (Mohammad, 2015). Solar PV is a photoelectric cell whose electrical parameters such as current, voltage, and resistance vary with light (Mohammad Bagher, 2015). Solar cells are the building blocks of photovoltaic modules, also called solar panels. There are several types of solar panels usually named after the semiconductor material making them.

The Amorphous silicon solar cell (A-Si) is a form of non-crystalline silicon mostly used in pocket calculators, powering homes, buildings, and remote areas. They are formed due to a thin layer of silicon material deposition on a metal or glass substrate(Mohammad Bagher, 2015)(Yehezkeli et al., 2012). Amorphous silicon solar cells utilize the triple-layer system to maximize light, as shown in Figure 2.6. The advantage of these cells is their lower manufacturing costs and hence affordable for various applications(Mohammad Bagher, 2015).

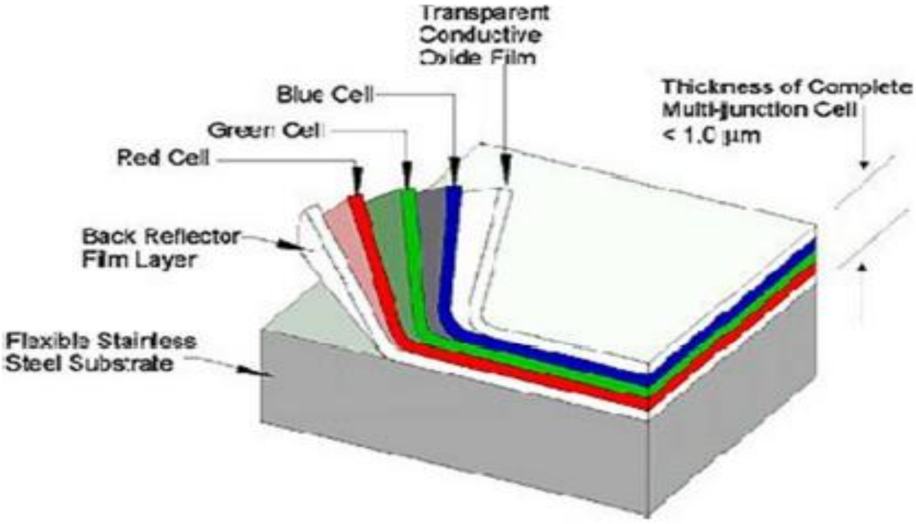

Figure 2.6: Amorphous Silicon Solar Cell

A bio-hybrid solar cell is a solar cell made up of organic and inorganic matter(Mohammad Bagher, 2015). It is made of a photoactive protein complex typically located in the thylakoid membrane, which recreates the natural process of photosynthesis to enhance the efficiency of conversion of light energy to electrical energy(Mohammad Bagher, 2015)(Yehezkeli et al., 2012). The multiple layers gather photonic energy, thus converting it to chemical energy, which creates a current that goes through the cell (Mohammad Bagher, 2015).

A Concentrating Solar PV (CPV) converts light energy to electrical energy as the other types of solar cells, except that it utilizes a more advanced apparatus, which helps capture sunlight from a wide area, focusing it on the solar cells for maximum efficiency. There are several types of CPV designs usually differentiated by their respective concentration factors. CPV utilizes lenses and curved mirrors to concentrate light on small, efficient apertures, unlike conventional photovoltaic systems. Besides, many CPVs technologies use trackers and a cooling system to increase the overall efficiency (Mohammad Bagher, 2015)(Philipps et al., 2015).

Multi-junction solar cells are cells with multiple p-n junctions made up of different materials, as shown in Figure 2.7. Each material's p-n connection produces an electric current based on the varying light energy. The advantage of multiple semiconductor materials is to increase the absorption rate of light in different wavelengths, enhancing the light-electrical conversion efficiency (Mohammad Bagher, 2015). Single junction achieves an efficiency of up to 34%, while the multi-junction solar cell can achieve an efficiency of 86.8% with a high concentration of sunlight(Mohammad Bagher, 2015).

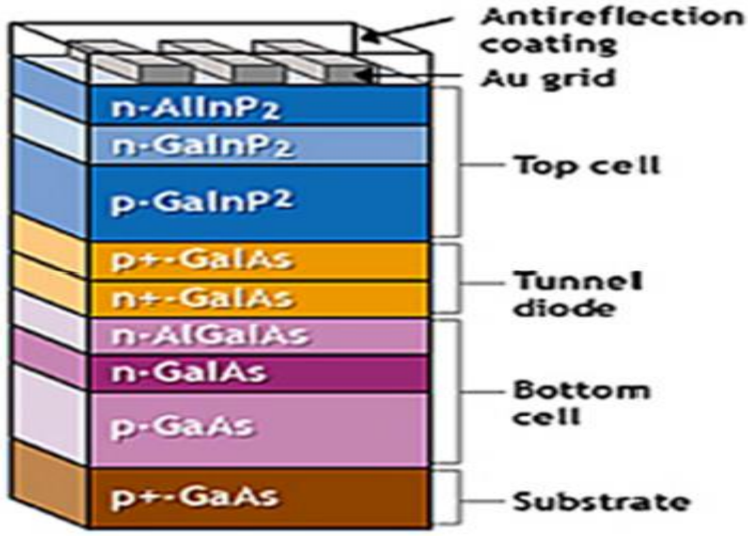

Figure 2.7: Multi-Junction Cell

2.3 Growth of Solar PV

Solar Photovoltaic power is experiencing high growth, having an installed capacity of 115GW in 2014 to 627GW in 2021, growing at a rapid rate of about 44% annually (Quansah et al., 2016)-(Turney & Fthenakis, 2013). In terms of cumulative solar PV installed capacity, the leading nations worldwide as of 2019 were Germany, China, Japan, Italy, and the USA, with installed capacities of 38.2GW, 28.41GW, 23.3GW, 18.5GW, and 18.3GW, respectively (Quansah et al., 2016). In Africa, even though most parts receive Direct Normal Irradiation above 2000kWh/m^2/year, the continent has not had substantial solar development. It is reported that the cumulative installed solar PV capacity in Germany in 2019, which is located in temperate regions, is more than the total installed capacity from all energy sources in individual Sub-Saharan African countries apart from South Africa(Quansah et al., 2016).

In countries like the US, the government has been forcing the utility companies that power generated must contain a certain renewable energy fraction. This has led to wide-scale land occupation and ecosystem damage. For instance, New Jersey has set a target of 22.5% renewable energy by 2021; New York has completed a 37MWe solar plant at Long Island, while Canadian Ontario has a complete solar plant of about 80MWe (Lovich & Ennen, 2011)(Turney & Fthenakis, 2013)(V M Fthenakis et al., 2005). Several solar PV projects are ongoing in some African countries, boosting the overall installed capacity, as shown in Table 2.2.

Table 2.2: Solar PV Projects Across Africa

Country	Capacity, MW	Project developer
Egypt	50	New and Renewable Energy Authority (NREA)
Burkinafaso	30	SONABEL, EU, EIB
Nigeria	30	Nigeria National Energy Council
Zambia	100	Energy Zambia Limited
Kenya	430MW	TARDA (Kenya), Ultra clean Energy Solutions, and Hitachi India

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Most of the published literature focusing on the impacts of solar energy mainly look into the life cycle assessment, majorly focusing on the Greenhouse Gases (GHG) and the energy payback time (EPBT) (Vasilis Fthenakis et al., 2008)(Mason et al., 2005). A small number of published works consider other impacts such as hazardous materials by Tsoutsos et al. (2005b), land use and land-use efficiency by Denholm et al. (2009) and . Fthenakis & Chul (2009), wild animals habitat fragmentation by Fthenakis et al. (2005) and Mason et al. (2005). However, these studies do not quantify nor monetize the perceived impacts.

It is further reported that solar photovoltaic installation and operation phases have received little scientific attention (Turney & Fthenakis, 2013). Most of these studies contain no quantitative information on the broader impacts of solar photovoltaic. In the most recent up-to-date LCA, it is reported that about 16-40gm/kWh of Carbon

Dioxide is emitted (Alsema et al., 2005). It is further documented in Turney & Fthenakis (2013) that only one published report collected raw data on the impacts of solar on the environment. Despite the lack of enough studies addressing the broader impacts of Solar photovoltaic, there is a significant need to address these impacts. Sub section 0 describes the different biomes that characterize installations and operation of solar PV.

2.3.1 Biomes Characteristics for PV Installation

The development of solar photovoltaic is taking place in various regions with different ecosystems/biomes worldwide. The different biomes include forested lands, desert shrublands deserts, grasslands, and farmlands. As described in Table 2.3, the biodiversity in a given biome is measured by the species density per hectare associated with solar insolation and precipitation (Hawkins et al., 2003).

Forestlands receive precipitation of not less than 50cm per year, together with the absence of sustained drought and freezing (Turney & Fthenakis, 2013). Cloud cover in forested lands reduces direct solar insolation by factors of about 25-50% (Turney & Fthenakis, 2013). The average height of trees in the forested areas ranges from 5-100m, whereas the rooting depths span 1 to 5m. The biomass density of tropical forests ranges from 100-500mg calories per hectare (Crow, 2005). The forest cover is a source of goods and services such as floods control, head of wood and pulp, filtration of pollutants from rainwater and air, habitat for wild animals, and scenic and recreational values (Crow, 2005).

Grasslands receive yearly average precipitation of about 30-50cm (X. Zhou et al., 2009). Droughts and freezing are experienced in glass lands, which leads to low tree density. The biomass density is estimated at 10-50mg calories per hectare, with most of this biomass lying on the soil surface (X. Zhou et al., 2009). Biodiversity levels are about 25% less compared to forestlands. The grasslands provide the same services as forestlands, except for wood and pulp, but they offer excellent grazing fields (X. Zhou et al., 2009).

The precipitation received in desert shrublands ranges from 5 to 30cm per year with lower cloud cover than forestlands and grasslands (X. Zhou et al., 2009). The biomass density is also lower and stands at about 10-30mg calories per Hectare. The biodiversity level is almost the same as that found in grasslands. They offer the same natural goods and services as grasslands except for low floods mitigation and low grazing capacity (X. Zhou et al., 2009).

True deserts have precipitations as low as 3mm per year with no biomass and biodiversity (Turney & Fthenakis, 2013). They include the Sahara Desert, the Arabian Desert, among others. Such environments are conducive for solar energy harvesting because they have low population density, wildlife, and biomass (Turney & Fthenakis, 2013).

Farmland is human-made (Turney & Fthenakis, 2013) and can be a built-in replacement for forested areas, woodlands, shrublands, or deserts. The cloud cover in farmlands depends on the type of land cover type. It could be a desert, forest lands, or shrublands. Biodiversity is less than grasslands, but the biomass level is almost the same (Turney & Fthenakis, 2013).

Table 2.3: Biomes characteristics

Type of Biome	**Precipitation Levels (cm/yr)**	**Biomass Density (Mg C/Ha)**
Forests	50	100-500
Grasslands	30-100	10-50
Desert shrublands	5-30	10-30
True deserts	<3	Zero

Installation of utility-scale solar photovoltaic requires the removal of trees and root balls (Turney & Fthenakis, 2013). The PV panels are mounted on Steel and Aluminum supports approximately 1m above the ground level on concrete footings. The ground level where mounting is done is kept below 5% by grading, and periodical mowing is done to prevent shading; this keeps the vegetation height below 1m. Herbicides are sometimes applied instead of mowing (Tsoutsos et al., 2005a). The Balance of Plant (BOP), the plant auxiliaries' systems such as inverters, transformers, cable channels, and access roads, also occupy surmountable space and cascaded environmental impacts. It is reported that the BOP increases the solar PV power plant footprint to be approximately 2.5 times greater than the area directly occupied by overlain panels (Paul Denholm & Margolis, 2008). The spatial density ranges from 5-8 acres of land per MWe. The water uptake for commercial solar thermal power requires 500-1000 gallons per MWe (Paul Denholm & Margolis, 2008). There is no doubt that solar power is a clean source of energy and is environment-friendly compared to conventional sources in terms of emissions. However, large-scale deployment of solar energy has negative environmental implications, which have created substantial barriers in further dissemination of these systems (Abbasi & Abbasi, 2000)(Beck et al., 2012)(Gekas, V., Frantzeskaki, N., Tsoutsos, 2002)(Yalçin & Öztürk, 2013). Subsection 0 discusses the impacts of Solar PV.

2.3.2 Impacts on Land use and Ecosystems

Utility-Scale Solar PV requires large tracks of land for installation, and no reclamation can be done until the plant is decommissioned. The term "land use" has three meanings (Dessouky, 2013). First, it means the physical nature of the land that will be affected by the installation of the project. Physical nature refers to the condition of the ground and the earth's surface. The second meaning is a quantitative one and means the total area of land occupied by the installation. The third meaning refers to the alternative use of this land apart from the solar installation.

The impacts of solar plants on earth depend on the topography of the landscape, land cover type (for example, cropland, forests), distance from archaeological sites, types of sensitive ecosystems in that land, and biodiversity (Carter & Campbell, 2011). The size of land occupied by solar power plants also depends on the technology, topography of the site, and the intensity of the solar resource availability. There are two ways to quantify the area impacted by solar energy technologies. The first is the total area, corresponding to all land enclosed by the site boundary characterized by fencing. The second area is directly occupied by access roads, solar arrays, substations, service buildings, and other infrastructure. The direct impact area is contained within the total area boundaries (Ong et al., 2013).

The size of land occupied by PV or CSTP depends on the Direct Normal Irradiation (DNI) in a given region. The ratio of the amount of energy generated to the size of land occupied is known as Land Use Efficiency (LUE) (Machinda et al., 2011). On average, utility-scale solar energy has a LUE of 35W.m^{-2}. In a study conducted by Machinda et al. (2011), CSTP is inefficient in terms of land usage. To achieve high electricity generation from them, more land is needed for more reflectors. The intensity of the solar radiation on the receivers is proportional to the number of concentrators used. Therefore, the more the concentrators, the high the power and hence the electrical energy. Mathematical expressions relating to the solar efficiency and land-use factor are described by equations (0.1), (0.2), and (0.3), respectively (Machinda et al., 2011).

$$\boldsymbol{SEE} = \frac{NEP}{DNI} \tag{0.1}$$

$$\boldsymbol{LUF} = \frac{\boldsymbol{AA}}{LA} \tag{0.2}$$

$$LUE = \boldsymbol{SEE} * \boldsymbol{LUF} \tag{0.3}$$

Where $SEE, LUF, NEP, DNI, AA, LA$ are respectively Solar Electricity Efficiency, Land Use factor, Net energy production, Direct Normal irradiation, aperture area and area of land.

In Spain, the 50MW 7.5-hour parabolic trough CSTP plant known as Andasol 1 occupies an immediate area of 510,120m^2 and a total area of 200ha (Tsuma & Kibaara, 2019). The 64MW Nevada Solar 1 plant in the Mojave Desert in California, USA, occupies 400 ha of land (Tsuma & Kibaara, 2019). Plans are also underway to install a 100MW CSTP plant near Upington, South Africa, receiving an annual DNI of approximately 2995kWh/m^2/year (Machinda et al., 2011)-(Greenpeace International et al., 2005). This plant will have an estimate of 4000-5000 heliostat mirrors, each heliostat occupying 140m^2. This implies that the plant will occupy approximately 172 acres of land. According to a report (Ho, 2008), the monetary value of such cultivatable lands in South Africa is $667/ha/year. Therefore, using it for electricity generation attracts a revenue loss of $114,724/ha/yr.

It is noted that utility-scale PV plants occupy approximately 3.5-10 acres per MW while that of utility-scale CSTP ranges between 4-16.5 acres per MW (Tsoutsos et al., 2005b) (Carter & Campbell, 2011) (Bin Zhaoa, Urs Kreuterb, Bo Lia, Zhijun Maa, Jiakuan Chena, 2004). In the endeavor to promote solar PV, the US has put aside 285,000 acres of public land for solar projects. A summary of land use requirements for PV and CSTP projects in the United States is shown in 3.4. The land cover change due to the occupation of land for several years for installing and operating solar power plants is now raising concerns over land occupancy, damage to vegetation and soil, and adverse impacts on ecosystem and biodiversity more than the fears over GHG emission (Laleman et al., 2011). It is also further reported that solar PV's Global Warming Potential (GWP) is four times higher than that of nuclear energy or wind energy (Laleman et al., 2011). It has been seen that the application of solar technologies to cultivatable land or lands that can be irrigated causes soil infertility and potential food insecurity. It is estimated that 97000ha of land in the US has pending leases to develop utility-scale solar energy. Shrub-lands ecosystems occupy the majority of this land. Some wetlands and grasslands have been approved for the same purpose (Erdinc & Uzunoglu, 2012)-(Directorate-General for Energy and Transport & Directorate-General for Research, 2007).

Table 2.4: Summary of Land Use Requirements for PV and CSTP in the United States

Technology	Direct Area		Total Area	
	Capacity-weighted average land use (acres/MW)	**Generation weighted moderate land use Acres/GWh/yr**	**Capacity-weighted average land use (acres/MW)**	**Generation weighted average land use Acres/GWh/yr**
Small PV(>1MW,<20MW)	5.9	3.1	8.3	4.1
Fixed	5.5	3.2	7.6	4.4
1-axis	6.3	2.9	8.7	3.8
2-axix flat panel	9.4	4.1	43	5.5
2-axix CPV	6.9	2.3	9.1	3.1
Large PV(>20MW)	7.2	3.1	7.9	3.4
Fixed	5.8	2.8	7.5	3.7
1-axix	9	3.5	8.3	3.3
2-axix CPV	6.1	2	8.1	2.8
CSTP	7.7	2.7	10	3.5
Parabolic Trough	6.2	2.5	9.5	3.9
Tower	8.9	2.8	10	3.2
Dish Sterling	2.8	1.5	10	5.3
Linear Fresnel	2	1.7	4.7	4

Over 20MW of utility-scale solar power plants operate, occupying 86000ha of agricultural and arid lands in California, USA (Rebecca R. Hernandez et al., 2014). In California, 28% of the utility-scale solar energy systems are located on cropland and pastures; and only 15% of the total installations are situated in incompatible areas (Hoffacker et al., 2016). Globally the monetary value of cropland and pastures is about $752/ha/yr, while the total economic value of the arid regions is $258/ha/yr (D. De Groot & Wang, 2010). Therefore, the total revenue lost from installing a CSTP plant in 86000 ha of cropland and arid areas would lose the value of $64.672 million and $22.118, respectively (Hoffacker et al., 2016).

In the South West United States (Lovich & Ennen, 2011), large areas of public land are reported to be on the evaluation stage or have been permitted for utility-scale solar energy development schemes, including areas with high biodiversity and protected species of animals and plants. This has mainly been driven by the increasing costs and demand for fossil-generated energy and the concerns about the emission of GHG gases. The Deserts in the South West, including Mojave and Sonoran, which are hosts to some potentially endangered species of animals and plants, are already under stress due to human encroachment and climatic changes. In this study, the reported potential impacts include destruction and modification of wildlife habitat, direct mortality of wildlife, landscape destruction, water consumption effects by concentrating solar thermal power plants, and pollution effects from spills (Lovich & Ennen, 2011). Globally, the USSE installations and the land cover type are as shown inTable 2.5 (Hoffacker et al., 2016).

Table 2.5: USSE Installations and Land Cover Type

Land cover type	Name Plate capacity (MW)		Area, kM	
	PV	CSTP	PV	CSTP
Barren land	2102	1000	77	34
Cultivated land	3823	280	110	8
Developed areas	2039	50	70	1
Herbaceous Wetlands	60	0	1	0
Shrubland/ scrubland	6251	744	343	32

2.4 Impacts of USSE Installation on Wildlife and Human Health

It is reported that the 10MW Solar 1 CSTP plant in the Mojave Desert killed 70 birds for 40 weeks, which equates to a mortality rate of 1.9-2.2 birds per week (Erdinc & Uzunoglu, 2012). The primary cause of death of the birds (81%) was attributed to collision with the CSTP infrastructure. In comparison, the rest (19%) died due to burning when the heliostats were oriented towards their eyes, which impaired their visual ability. Additionally, there are changes in land surface temperatures resulting from their installations, killing some insects, birds, burrowing animals, and other sensitive plants that thrive in areas they are installed. Some of these plants have medicinal values (Lovich & Ennen, 2011).

The solar tower type of CSTP is seen to have the potential of concentrating light to high intensities that could impair the eyesight of wild animals and birds. Other adverse impacts hazards from toxicants in the coolant fluids, soil erosion, and compaction, destruction of habitats of some wild animals such as antelopes, giraffes, zebras, lions, leopards (Abbasi & Abbasi, 2000)(Gekas, V., Frantzeskaki, N., Tsoutsos, 2002)(Hoffacker et al., 2016). The fragmentation of animals and birds habitats can lead to low turnover in revenues collected from tourism (Chowdhury & Kibaara, 2016). Turney & Fthenakis (2013) reports that the slow deployment of Solar PV in the deserts of the South West United States is caused by the concerns and controversies surrounding the disruption of wildlife habitats and the hefty mitigation efforts. Solar PV occupies not less than 10 acres of land to generate 1MW of power (Rebecca R. Hernandez et al., 2014).

At their inception, large-scale solar power plants are more hazardous emitting greenhouse gases and respective environmental degradation than a nuclear plants and other fossil energy generating systems (Abbasi & Abbasi, 2000). The green gas emissions are 40-55 grams per kilowatt of generation capacity for the standard silicon panels and 25-32 grams for the thin mirrored solar panel types. Other types of Solar PV panels, such as polycrystalline and monocrystalline, emit hazardous gases estimated as 2.757– 3.845 kg for CO2/kWp, 5.049–5.524 kg for SO2/kWp, and 4.507–5.273 NOx/kWp (Mahajan, 2012).

2.5 The Cost of Electricity Generating Technologies

The dollar per watt ($/W) served as an index for estimating energy costs from electricity generating stations (El-Shimy, 2017). However, the $/W evaluation does not consider the life cycle costs of energy production, interests, depreciation of equipment, discounts, and financial policies in a given region (El-Shimy, 2017). The discovery of LCOE by the US department of energy eased the evaluation and the techno-economic analysis of power generating systems (El-Shimy, 2017). The $/W traditionally used to evaluate solar Photovoltaics economic viability can be transformed to \$/kWh, a more decisive parameter.

The LCOE from the different energy-generating technologies (both renewable and non-renewable) is the metric mostly applied to compare the respective economic worthiness of these technologies. This metric relates the life cycle costs such as capital, fuel, operations, maintenance, and replacement costs with lifetime energy production (Owen, 2006). It measures the marginal cost (cost of producing an extra unit) of producing electricity over some time (El-Shimy, 2017). LCOE is also known as Levelised Energy Cost (LEC), Levelised Unit Energy Cost (LUEC), and Long Run Marginal Cost (LRMC) (El-Shimy, 2017). LCOE can then be deduced as a constant unit cost (Per kWh or MWh) of a payment stream that has the same present value as the cost of construction and running a power generating plant, as shown by Equation (0.4) (El-Shimy, 2017).

$$LCOE = \frac{C_0 - \sum_{t=1}^{n}\left\{\frac{Dep^t}{(1+r)^t}(TR)\right\} + \sum_{t=1}^{n}\frac{C_t}{(1+r)^t}(1-TR) - \frac{RV}{(1+r)^t}}{\sum_{t=1}^{n}\frac{\{((S_t)(1-d)^t)\}}{(1+r)^t}} \tag{0.4}$$

Where t is the Year Number, i.e., 0,1,2,3…. n, C_0 is the Initial Capital, S_t is the rated energy for year t, C_t is the Annual Net Cost of the Project for Year t, r is the Discount Rate, d is the Degradation Rate, RV is the Residual Value, and TR is the Tax Rate is the Depreciation.

In Table 2.6, the different LCOE of both renewable and non-renewable energy sources are shown and their forecasted LCOE.

Table 2.6: Current and Projected LCOE of Renewable and Non-Renewable Sources

Energy Source	Technology	Current cost ($ ¢ /kWh)	Expected future cost (2020) ($ ¢ /kWh)
Coal	Grid supply	3-5	Capital costs expected to go down due to technological evolution
Gas	Combined cycle	2-4	
The energy delivered to the grid from fossil fuels	Off-peak	2-3	
	Peak	15-25	
	Average	8-10	
	Rural electrification	25-80	
Nuclear		4-6	3-5
Solar	CSTP @2500kWh/m^2	12-18	4-10
Solar	Annual@1000kWh/m2	50-80	8
	Annual@1500kWh/m2	30-50	5
	Annual@2500kWh/m2	20-40	4
Geothermal	Electricity	2-10	1-8
	Heat	0.5-5.0	0.5-5.0
Wind	Onshore	3-5	2-3
	Offshore	6-10	3-5
Marine	Tidal barrage	12	12
	Tidal stream	8-15	8-15
	Wave	8-20	5-7
Biomass	Electricity	5-15	4-10
	Heat	1-5	1-5
Biofuels	Petrol, diesel	3-9	2-4
Hydro	Large hydro	2-8	2-8
	Small hydro	4-10	3-10

2.6 Control of the Environmental Externalities

Environmental externalities are defined as benefits or costs generated as a by-product of economic activity that does not accrue to the move (Aman et al., 2015). They are the benefits or costs that usually manifest themselves through changes in the physio-biological environments (Roth & Ambs, 2004b)-(Carlin, 1995). In electricity pricing, externalities refer to the costs associated with the fuel cycle that are not incorporated in the electric utility cost structure, as shown in Figure 2.8 (Carlin, 1995).

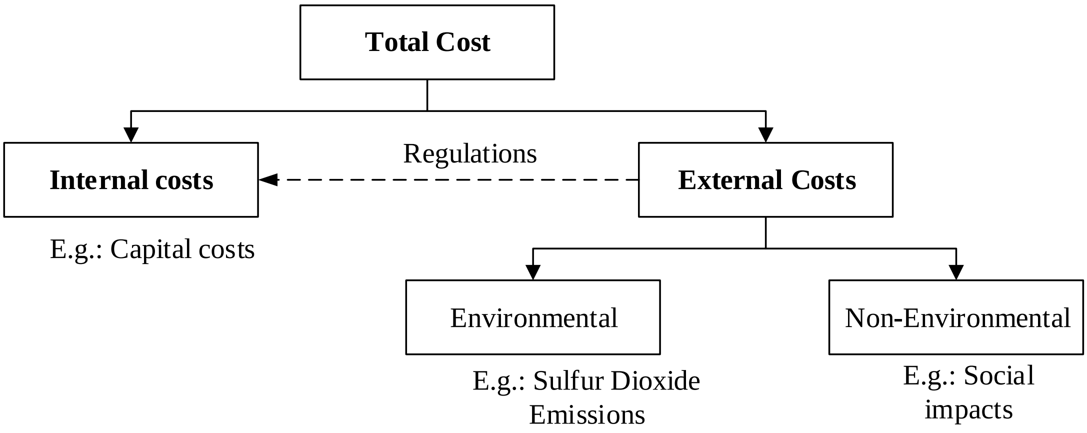

Figure 2.8: Classification of Environmental Impacts and Total Societal Burden

In this case, the fuel cycle, as defined in Aman et al. (2015), refers to the series of physical and chemical processes required to generate electricity from a particular resource, including extraction, processing, transport, storage, conversion, and disposal.

Thorough analysis and inclusion of externalities in the utility cost structure provide the most efficient generation strategy considering environmental preservation and non-environmental preservation. Environmental conservation includes encroachment to biodiversity through solar PV installation, which has cascaded impacts on habitat fragmentation and the impacts on plants. The social externalities of solar PV are the impacts that occur due to installing a solar PV plant. For example, the emitted gases pose a danger to human health. The occupation of land previously used as an archaeological site deprives the communities of a source of livelihood, eliminating herbaceous plants, which are a source of medicine (Aman et al., 2015)(Carlin, 1995).

Three pollution control techniques are usually considered as mitigation measures towards environmental damages. These include emission standards, emission charge fees, and market charge allowances (Carlin, 1995). These are discussed briefly in the next subsections.

2.6.1 Emission Standards

An emission standard is a legal emission rate or a limit of effluent an entity can emit. Some standards require pollutant emissions to be kept low, but such measures do not contribute to cost minimization (Carlin, 1995).

2.6.2 Emission Charges

These are financial penalties imposed on each unit emission from the resource. The emission source should reduce its emissions to the point where the marginal control costs equal the emission charge. In this case, it encourages emission sources to minimize the cost of control (Carlin, 1995).

2.6.3 Market Emission Allowances

This method permits the regulating bodies to precisely control the total level of emissions and reduce the control cost. In this case, each source is assigned an allowance for each unit of emission, in which the total allowance is limited to reflect the desired emissions (Carlin, 1995).

2.7 Monetization/Valuation of Ecosystems Goods and Services

The valuation of ecosystems goods and services usually considers three main attributes: ecological valuation, socio-cultural valuation, and economic valuation (De Groot et al., 2002).

In the energy markets worldwide, the market prices of fossil fuels are often lower than the prices of electricity generated from renewable energy technologies such as solar, wind, and biomass (El-Shimy, 2017). These market prices do not consider the actual costs of electricity being sold because they do not account for the external costs caused to the environment and the surroundings by pollution and its resulting problems, which include damage to human health and the ecosystems (El-Shimy, 2017). The monetary valuation of the impact of externalities carries a considerable burden of proof to the financial viability of electricity-generating technologies in a given area. It is reported that when externalities are taken into consideration during the modeling of electricity generating units, renewable electricity generation is comparable in cost to fossil fuels (Sklar-Chik et al., 2016).

Monetizing the externalities of electric generating units is important because it provides clear and understandable comparisons of direct and environmental costs (Sklar-Chik et al., 2016). Suppose these costs of energy planning are not expressed in the standard units. In that case, the comparisons become very confusing, making comparisons between the trade-offs between the economic factors and environmental costs less comprehensible(Sklar-Chik et al., 2016). The other reason for the monetization of externalities is that it allows for consistent treatment and valuation of ecological issues in a very consistent manner, which many other methods do not (Carlin, 1995). Section 0 discusses the different ways of weighing/valuing externalities.

2.8 Biodiversity/Externality Valuation Instruments

The process of monetizing the wide range of benefits ecosystems contributes to the world in monetary and non-monetary terms is generally referred to as biodiversity valuation (*Tools and Guidelines for Integrating Biodiversity Concerns in National Planning Process - Africa*, 2016). Biodiversity valuation is a crucial pillar when integrating the environmental impacts in the cost modeling of Solar PV.

There are four main approaches to externality valuation: contingent valuation, hedonic price method, travel cost method, and the restoration cost approach (Preiss & Klotz, 2008). The contingent valuation approach uses questionnaires to determine the Willing To Pay (WTP) or Willingness To Accept (WTA) of the affected individuals to avoid a negative impact. This method suffers a drawback because people have problems understanding some questions and giving a wrong impression (Preiss & Klotz, 2008)(*New Elements for the Assessment of External Costs from Energy Technologies*, 2004).

The hedonic price approach tries to find the WTP for environmental goods as expressed in related markets. This method elicits preferences from actual market information. The technique is mostly applied in noise and aesthetic effects. Thus, according to the hedonic price approach, an increase in noise pollution will reduce property values. The hedonic approach has limited applicability in diversity valuation (Preiss & Klotz, 2008).

The "travel cost approach" is mainly used for recreational impacts valuation. The method assumes that the costs incurred by the locals in traveling to the park and entrance fees paid are an indication of WTP for the recreational facilities at the expense of the environment. The travel cost approach is not suitable for biodiversity loss valuation due to energy production because only the recreational values can be valued by the travel expenditures (Preiss & Klotz, 2008).

The restoration approach looks into the cost of restoring a damaged asset to its original value. Restoration costs are the investment expenditures incurred to offset any damage done to the environment by human activity. The method assumes that replacing an ecosystem or its services is the value of that particular ecosystem and its benefits (Preiss & Klotz, 2008).

2.9 Current Status of RETs and their Environmental Impacts

The main objective of this thesis was the development of a decision-making tool for Solar PV energy technologies, herein referred to as the SPECA modeling tool. Apart from giving the respective energy output, LCOE, and other metrics, the SPECA modeling tool quantifies the monetary value of the environmental impacts of USSE. This section, therefore, reviews the strengths and weaknesses of the previous studies, evaluative literature, mathematical models, and modeling tools previously used in modeling Solar PV and its externalities

Sellami's (2014) economic modeling tool was developed based on the mathematical derivation of the structural theory of thermodynamic process cost formation for Tunisian wind farms. The proposed thermo-economic model was used to assess the environmental impacts of a hybrid solar PV, wind, and biogas reactor with a capacity of 242.6MW. The targeted externalities of these energy sources were studied in agricultural land, birds killed, and atmosphere, which the authors monitored in the areas where these plants were located. The authors found that area covered by the plants was 152,604m^2 and that the amount of annual energy produced was 2.6GWh. The estimated number of birds killed was reported as 216. The environmental cost incurred resulting from these energy sources was estimated at $2,939.4.

Rowley, Leicester, Thornley, and mander (2017) developed a probabilistic modeling technique to evaluate carbon dioxide avoided due to the UK's wide-scale integration of solar photovoltaic. The socio-economic impact considered by the authors was the change in the aesthetic value of the place. The residents were supplied with questionnaires to get feedback on their willingness to accept the changes brought about by the solar panels. There was no quantification of any emission or the impacts that were brought by this installation.

Leicester, and Goodier (2013) developed a social, economic, and environmental modeling tool using Bayesian Network to evaluate solar PV to curb energy poverty in England. The Bayesian Network estimated the technology investment, energy generated per unit area by deploying rooftop solar PVs in the houses, domestic energy consumption, and the CO2 emission avoided through solar PV installation in England. Although the authors did not show any other environmental impact in their model, they should have been minimal because the PV was erected on rooftops.

Akella et al. (2009) evaluated the environmental impacts of RETs such as small hydroelectric, wind energy, biomass, bagasse cogeneration, solar PV, and municipal solid waste in India. The authors introduced important mathematical formulae referred to as weighted average emissions to determine the emission from carbon oxides for a given installed capacity of a renewable energy plant. The authors, however, did not quantify the other negative environmental impacts, such as land usage and the destruction of the ecosystem available.

Guta (2014) developed a model based on ordinary least squares to assess the consumption of fuelwood and charcoal in Ethiopia, which has led to annual forest cover loss estimated at 140,000-200,000 ha. The study conducted was used to determine the accessibility of electricity in the rural areas of that country. The investigation was concluded by advocating a policy to subsidize alternative energy sources such as biogas obtainable from domestic animals excreta other than relying on traditional biomass, which has other adverse impacts such as deforestation and soil erosion. The authors also advocated for Solar PV installation, but the impacts were never quantified or monetized.

Katuwal and Bohara (2009) studied a hybrid of Solar PV and biogas power plants and Nepal's environmental impacts. The results obtained were based on a survey done in the rural areas of Nepal before and after the installation of 189,122 biogas plants in the nation's 75 districts. The questionnaire-based study interviewed people across these districts on the benefits of introducing hybrid systems. These benefits include health, agriculture, environmental, workload reduction, women empowerment, and employment generation. However, this study did not quantify nor monetize the impacts of the hybrid systems.

Zerihun (2015) assessed the socio-economic and environmental benefits of RETs in the rural areas of Ethiopia. The survey-based study revealed that the introduction of biogas to replace the traditional forms of biomass saved each household an average of 144 minutes per day. This time would otherwise be used for fetching firewood. The study continues by reporting that the use of biogas has saved them money worth \$100.13 for firewood, \$32.24 for charcoal, \$3.36 for baking cow dung cakes, and \$6.95 for buying kerosene.

Jaber (2014) reported that wind energy has both positive and negative impacts on the environment. The environmental impacts of wind reported were land usage, vegetation clearance, ground disturbance, destruction of animal habitats, noise intrusion, which affects human health and lowers the value of surrounding houses, aesthetic impacts, bird mortality, and television interference. The environmental benefits of wind energy include energy production, which replaces fossil energy generators, job creation, and raising living standards.

Hernandez et al. (2014) used a decision support tool, the Carnegie Energy and Environmental Compatibility (CEEC) model, to evaluate the potential land cover and land use of the utility-scale solar energy for over 160 solar installations. In this study, the utility-scale solar energy was evaluated based on their environmental impacts and technical compatibility in the installed region and their proximity to protected areas such as national parks or birds migration corridors. This study established that 28% of the installations were located in croplands and pastures, 57% were found in scrublands and shrublands, and only 15% of the total buildings were found incompatible areas. The authors, however, did not evaluate the cost of the externalities on the different environments considered in the lifespan of the USEE.

A study conducted in Scotland used the choice experiment to quantify people's preference over the socio-economic and environmental impacts of RETs(Bergmann et al., 2007). The findings in this study were that the community had to pay $72.3 more to cater to the environmental damages such as loss of landscape, wildlife habitats, and aesthetic value damage brought about by the wind turbine.

A study conducted by Owen (2006) discussed the external damage costs from CO_2 associated with electricity-generating technologies within the European Union countries. The EU range for this external cost was found to be $0.03-coal, $0.04-peat, $0.045-oil, $0.05-gas,$ 0.09-nuclear, $0.06-biomass, $0.01-hydro, $0.08-PV, and $ 0.06-wind. The authors attributed the market failure and full realization of RETs due to a lack of internalization of fossil fuel generating technologies' externalities. The internalization of total damage costs of RETs into the resulting output electricity could lead to some RETs such as wind, solar PV, and CSTP being financially competitive with fossil fuel energy sources. Using the traditional evaluation tools, it is noted that RETs are financially unattractive compared to their counterparts in fossil fuels owing to their high initial capital cost. The authors concluded the research by giving the carbon tax rates implemented in Germany, Finland, Netherlands, Norway, Sweden, and the UK.

Álvarez-Farizo and Hanley (2002) discussed the environmental impacts of wind power plants in Spain using the choice experiment, and the conjoint analysis technique was discussed. Questionnaires were created by the stakeholders, which were distributed to 488 respondents. The questionnaire described the expected attributes (impacts) of wind energy to the surrounding areas, such as loss of natural space, increasing development threats through access roads, visual impacts, and the loss of a migratory birds corridor. Using the two methods, choice experiment and conjoint analysis, it was found that the amount to be paid annually for the environmental damages caused by the wind farm was $12.34/year and 28.32/year, respectively.

Ho et al. (2011) used SOLERGY, which employs a probabilistic modeling approach to quantify the uncertainties inherent to CSTP and Solar PV, such as solar irradiation. The authors used Latin Hypercube Sampling for variable stratification and distribution. The results showed that the probabilistic analysis quantifies different performance metrics, such as annual energy and LCOE. The model developed did not consider the environmental impacts of CSTP and Solar PV and employed point values to account for interest rates, discount rates, and the degradation rates of different components.

Boukelia et al. (2015) present a study on optimization using the SAM of two 50MWe parabolic troughs integrated with thermal energy storage (TES) and a fuel backup for Algeria. The first parabolic trough plant uses the Therminol VP-1 oil, while the second utilizes the molten salt as a heat transfer fluid. Optimization is carried out for the two plants to minimize the LCOE, maximize the output energy, and compare the results based on energy production, environmental impacts, and economic viability with that of the Andasol-1. The ecological impacts studied are water consumption, land use, and the life cycle of gas emissions. The Techno-economic analysis was determined using the LCOE, the most commonly used solar energy-based generation economic analysis parameter. At a solar multiple of 2.5, the LCOE was 10.18 and

$8.51 /kWh for Therminol VP-1 oil and molten salt. In terms of land usage, the oil plant used 562 acres, while that of the salt plant was 592 acres with annual water consumption of 822,466m^3 and 800,482m^{3,} respectively. The annual CO2 emissions were 40.25 tonnes for the Therminol VP-1 oil plant and 43.577 tonnes for the molten salt plant. The shortcoming of this study was that SAM can quantify externalities such as land usage and water uptake but does not monetize the same, therefore not incorporated in the LCOE.

Del So and Sauma (2013) modeled CSTP and PV solar plants to determine their economic viability in northern Chile using *OSE2000* software. The authors considered three CSTP technologies as well as three PV technologies. The CSTP considered were parabolic trough, solar power tower, and the Stirling dish, while the PV considered were monocrystalline silicon, polycrystalline silicon, and first solar cadmium. Data for 45 CSTP and 37 PV was used to determine these solar technologies' best investment cost function. This resulted in two regression models: CSTP and PV models, because of the difference in the variables used to explain their respective investment costs. The CSTP and the PV regression models consisted of variables such as installed cost, technology, electricity generation, established country, total plant area, year of commissioning, capacity factor, and solar irradiation. The main explanatory variables that best described the CSTP were the installed capacity, type of technology, area occupied, storage capacity, and the country it is installed. After several multivariable linear regressions, the essential parameters in a PV installation were capacity, technology, year of commissioning, and the installed country. The carbon credit benefit of $18.42/Ton CO2 was added to the economic evaluations in the lifetime of these plants. After these simulations and analysis, the authors found that installing solar plants in Northern Chile is not economically viable unless the current carbon bond prices, labor rate, and component prices change.

Burtraw and Krupnick (2012) conducted a study about the actual cost of electric power and highlighted that many researchers estimate the actual cost of electric power using three methods: primary studies, benefit transfer studies, and the meta-studies. Each study forecast the exact cost using the following two ways: the damage function approach and the abatement cost approach. The damage function approach reveals the relationship between the impacts of the RETs on the environment and monetizes the accrued damages. The abatement cost approach uses the cost of reducing pollution, given the currently existing regulations, as an estimate of the damage caused.

Le et al. (2012), in their paper “Potential and future of concentrating solar power in Namibia,” used the System Advisor Model in the evaluation, potential, and future of CSTP in Namibia. The LCOE was computed as the sum of Total Life Cycle Costs (TLCC), divided by the total energy generated for 20 years. The TLCC added was the total sum of the expenses incurred, including initial investment, operation, maintenance, and infrastructure costs. In the determination of LCOE, the environmental impacts included were the impacts of GHG gases, which slightly increased the LCOE.

Table 2.7: Summary of Previous Techno-Economic Modelling of RETs

Reference	Methodology used	Environmental impacts considered	Deficiency
Sellami (2014)	Thermodynamic process cost formation	Birds killed, Land use impacts, GHG gases emitted	Non-quantification and monetization of externalities in the cost model.
P.Rowley, P.Leicester, P.Thornley, S.mander (2017)	Bayesian Network	Social-economic	Missing monetization and quantification of externalities
P.Leicester, C.Goodier (2013)	Bayesian Network	CO2	Non-monetization and quantification of externalities.
Akella et al. (2009)	Weighted average emissions	CO2	Non-quantification of externalities and LCOE modeling
Guta (2014)	Ordinary least square	Land use impacts	Missing monetization and LCOE
Katuwal & Bohara (2009)	Questionnaire based	Health impacts, environmental impacts, social impacts	Non-quantification of benefits arising from the installation, missing LCOE
Zerihun (2015)	Survey-based	Study reports on the time saved as a result of RETs installation and cascaded benefits of saving money on firewood used, kerosine, charcoal	No mathematical formulation showing how saving time and money is done. LCOE from the installed RETs is not shown.
Jaber (2014)	Survey-based study	Land use impacts, health impacts	Not quantified Non-monetization and missing LCOE
R. R. Hernandez et al., (2014)	Carnegie Energy and Environmental Compatibility (CEEC)	Land use impacts	Social impacts not considered, non-monetization of externalities
Bergmann et al. (2007)	Choice experiment	Land use impacts	Non-quantification and monetization of externalities
Owen (2006)	Report	CO2	Missing method of how the external costs were quantified.
Álvarez-Farizo & Hanley (2002)	Conjoint analysis Technique and Choice Experiment	Land use impacts	The methods used to determine the externality cost are not well defined.
Ho et al. (2011)	SOLERGY	Land use impacts quantified.	Missing monetization of land use impacts and incorporation of the same in the cost model
Boukelia et al. (2015)	SAM	Land use impacts	Land use impacts not incorporated in the cost model
Del Sol & Sauma (2013)	OSE2000	Land use impacts, CO2	Impacts not monetized
Burtraw & Krupnick (2012)	Primary studies, benefits transfer, and meta-studies	-	The study does not report on monetization and quantification of impacts
Le et al. (2012)	SAM and manual methods	GHG gases	Method of externality monetization unknown.

In conclusion, the tools and methods developed in the studies summarized in

Table do not evaluate the indirect costs incurred during electricity generation from solar PV. It has thus been identified that there is a need to develop a modeling tool that incorporates all the indirect costs emanating from the generation of electricity from solar PV. The following section discusses the assessment tools and methods for different power generation technologies.

2.10. Modeling Tools for Simulation and Optimization of Hybrid Energy Systems

This section introduces the leading simulation and optimization software tools frequently used by researchers to evaluate renewable energy technologies' economic viability. For each software tool, a brief description of its background, functionality, and the works done by these tools are briefly described.

2.10.1 HOMER

HOMER (Hybrid Optimization Model for Electric Renewables), developed by National Renewable Energy Laboratories (NREL), is the most applied modeling tool in hybrid renewable energy systems because of its user-friendliness (Gsma, 2010). HOMER has extensively optimized standalone and grid-connected hybrid systems: wind generators, photovoltaic generators, batteries, hydraulic turbines, AC generators, fuel cells, electrolyzers, hydrogen tanks, and AC-DC bidirectional converters, and the boilers (Zhou et al., 2010). The loads used by HOMER can be either AC or DC loads (Bernal-Agustín & Dufo-López, 2009). It is reported that for successful analysis using HOMER, the information on resources such as electrical loads, economic constraints, current, and future equipment costs, and the control strategies must be known first hand (Zoulias & Lymberopoulos, 2007). Other inputs such as component type, capital cost, replacement, operation and maintenance costs, efficiency, and operational life are also incorporated. Simulation using HOMER considers one year with a minimum step size of 1 minute (Zoulias & Lymberopoulos, 2007). HOMER evaluates the most suitable option set of energy sources to meet a given load considering the cost and the availability of the resources. The architecture of HOMER is as shown in Figure .

Zoulias and Lymberopoulos (2007) used HOMER to simulate and optimize the replacement of conventional technologies employing diesel and batteries with hydrogen technologies such as fuel cells to provide electricity to remote rural communities. This analysis proved that replacing conventional-based generators with hydrogen-based technologies is feasible but not viable because of the high costs of hydrogen technology.

Rehman et al. (2007) used the HOMER modeling tool to perform a feasibility analysis of wind penetration in a standalone diesel generator in a remote village in the South-Eastern part of Saudi Arabia. The results were that for wind speeds less than 6m/s, the diesel plant is the only feasible solution over the range of other fuels used in the simulation. The hybrid wind /diesel became possible when the wind speed was 6m/s or more at a fuel price rate of 0.1$/L.

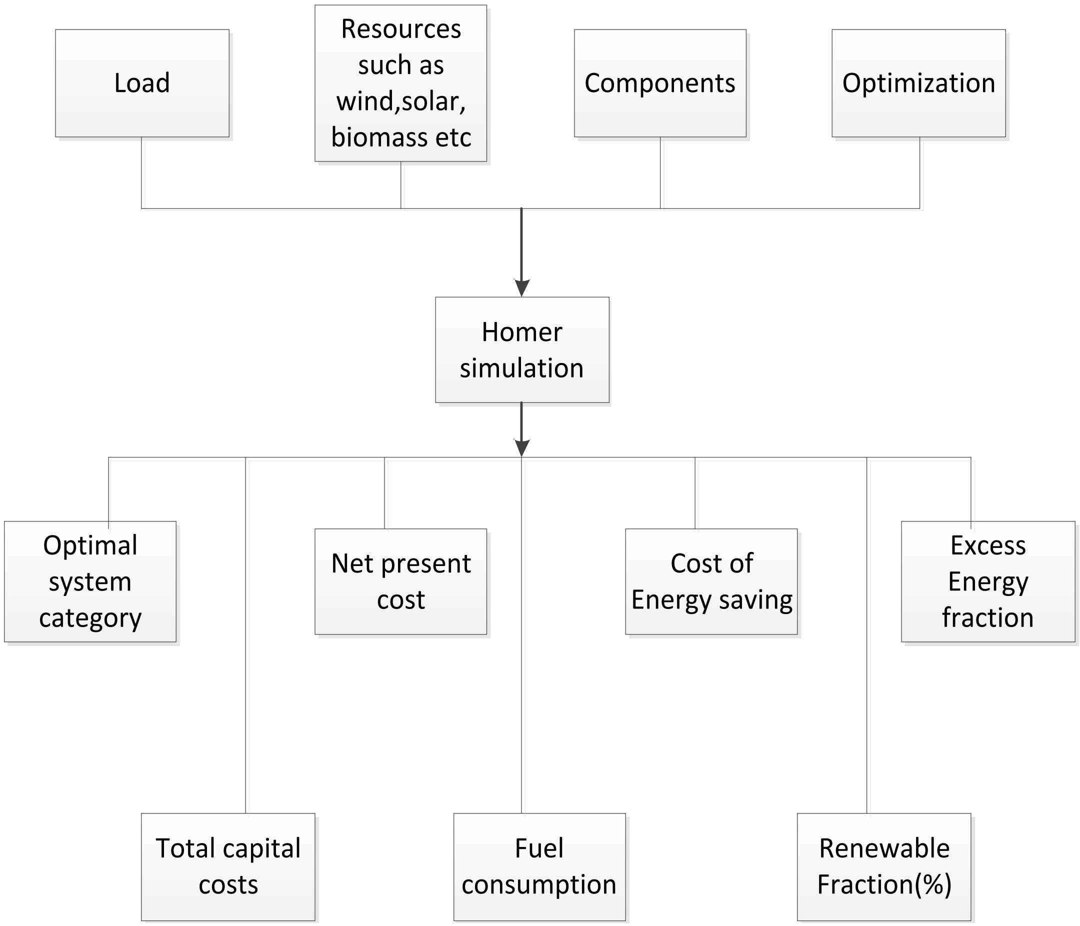

Figure 2.9: HOMER Model Architecture

Shaahid and Elhadidy (2007) used the HOMER modeling tool to carry out the techno-economic viability of a typical commercial building's hybrid PV/diesel battery energy with an annual electricity demand 620MWh. The hybrid configuration results revealed that the diesel generator's operational hours decreased with increased PV capacity. The hybrid PV-battery –diesel has advantages such as system load satisfaction in the most optimal way, maximization of diesel efficiency, and minimizing diesel operation and maintenance costs. The authors also recommend investing in solar energy technologies to decrease the over-reliance on depleted fossil fuels to diminish the energy crisis in the future.

The main restrictions/ limitations of HOMER are that it does not allow the user to intuitively select the relevant components for a given system because the procedures, algorithms, and calculations used are not available or visible to the user. The other shortcoming of HOMER is that it does not calculate the number of solar panels and their type. Instead, HOMER gives a PV array power from the ones selected by the user. The user must choose the battery type, and there is no optimization amongst the dissimilar battery types. The environmental impacts of renewable energy considered by HOMER are only carbon dioxide (Bergmann et al., 2007).

2.10.2 HYBRID2

HYBRID2 was developed by the Renewable Energy Research Laboratory (RERL) of the University of Massachusetts (Sinha & Chandel, 2014). It is a hybrid simulation software. It is very precise and is capable of defining time intervals from 10 minutes to 1 hour. NREL recommends that optimization of the system using HOMER and improving the design using HYBRID2. The hybrid systems to be simulated using HYBRID2 may include three electrical loads, multiple wind turbines of different types and sizes, photovoltaic generators, numerous diesel generators, battery storage, and four conversion system devices (Bernal-Agustín & Dufo-López, 2009). The limitation of this software is that it does not perform any form of environmental modeling associated with the impacts of the hybrid renewable energy systems. Also, some component inputs are limited, such as the types of loads and the conversion system types (Bernal-Agustín & Dufo-López, 2009)(Dufo-López & Bernal-Agustín, 2005).

2.10.3 HOGA

HOGA (Hybrid Optimization by Genetic Algorithms) is a hybrid system optimization tool developed by the Electric Engineering Department of the University of Zaragoza (Spain) (Lovich & Ennen, 2011) (Dufo-López & Bernal-Agustín, 2005). The optimization is carried out using Genetic Algorithms (GA) and can be mono-objective or Multi-objective.

HOGA allows optimization of Hybrid renewable Energy systems consisting of a photovoltaic generator, batteries, wind turbine, hydraulic turbine, AC generator, fuel cells, electrolyzer, hydrogen tank, rectifier, and inverter. The system loads can be AC or DC. Simulation is carried out in a time step of 1 hour, during which all the parameters remain constant (Dufo-López & Bernal-Agustín, 2005). The limitations of HOGA include the lack of probabilistic analysis and the inability to perform the sensitivity analysis and environmental impact analysis.

2.10.4 TRNSYS

TRNSYS (Transient Energy System Simulation Program) was developed in 1975 by the University of Wisconsin and the University of Colorado (USA) (Sinha & Chandel, 2015). The program runs in the FORTRAN language. It has an open modular structure, which is open source capable of simulating electricity and heat sectors of an energy system. The program was developed for the analysis of single community projects. Over the years, TRNSY has been upgraded and can now simulate hybrid systems, including solar photovoltaic, solar thermal power, among others. The software does not perform optimization and environmental analysis.

2.10.5 HYDROGEMS

HYDROGEMS is not a program but a time series of libraries suitable for simulating integrated hydrogen, mainly standalone renewable energy systems. HYDROGEMS was developed by IFE Institute, Norway(Bernal-Agustín & Dufo-López, 2009). The libraries developed by HYDROGEMS include photovoltaic generators, wind energy conversion systems, diesel generators, polymeric and alkaline fuel cells, electrolyzers, hydrogen gas storage tanks, lead-acid batteries, power conditioning equipment, diesel engine generators, and AC/DC converters. The software can analyze hydrogen energy systems down to 1-minute time steps (Bernal-Agustín & Dufo-López, 2009). The drawback of this tool is that it does not include the environmental impacts inherent to renewable systems throughout its modeling procedures.

2.10.6 HYBRIDS

It is a commercially available modeling tool produced by Solaris Home (Lund et al., 2010). It can simulate and perform an economic analysis of PV-Wind-diesel and battery systems. It utilizes a 1-hour step to determine the net present cost of the hybrid energy systems. A Microsoft excel database founded renewable energy system valuation, application, and design, which entails daily average load and environmental data for each month. The limitation of HYBRIDS is that it can only simulate a single configuration at a time without optimization (W. Zhou et al., 2010). The tool does not quantify the externalities of hybrid renewable energy systems.

2.10.7 INSEL

INSEL was developed by the University of Oldenburg (Lund et al., 2010). It has a library where the user selects blocks and connects them to define the system's structure. The user specifies the system analysis and simulation time. The INSEL program only simulates the chosen energy method but does not optimize (W. Zhou et al., 2010). This tool does perform environmental analysis in its simulations.

2.10.8 System Advisor Model (SAM)

System Advisor Model (SAM) is a modeling tool developed by the National Renewable Energy Laboratory (NREL) (Dobos et al., 2014)(XU, 2012). It is widely used across commercial, research, and academic fields for cost evaluation and performance estimation (Dobos et al., 2014). SAM performs time-step by time-step calculations from user-defined system performance input parameters such as climate data, plant specifications, parasitic losses, and dispatch control schedule. Cost and finance parameters such as capital cost, costs of operation and maintenance, state taxes, and depreciation are also taken into the calculations (Dobos et al., 2014). SAM can determine the land occupied and water usage for installation but does not monetize the cascaded environmental impacts such installations pose.

2.11 Summary of Strengths and Weakness of Traditional Software Tools

The economic indicators and software tools mostly use fuel costs, capital costs, and the plant life cycle to estimate the most affordable method of power generation. These methods and tools considerably limit the indirect costs incurred while generating electricity, such as environmental damage, transmission and distribution costs, energy security, and social costs, as shown in Table 2.8. The failure by these methods to include these externalities in the energy models and the fact that the consumers do not pay for them directly is viewed as inefficiency (Roth & Ambs, 2004b) (Sinha & Chandel, 2014)(Markovic et al., 2011).

Table 2.8: Comparison of the Different Modelling Tools

Tool	Reference	Optimization	Financial evaluation	Externality Evaluation	Damage cost analysis
Hybrid 2	(Sinha & Chandel, 2015)	NO	YES	NO	NO
HOMER	(Lund et al., 2010)	YES	YES	YES (Carbon dioxide)	NO
IHOGA	(Lovich & Ennen, 2011)	YES	YES	Carbon dioxide	NO
RETSCREEN	(Sinha & Chandel, 2014)	NO	YES	Carbon dioxide	NO
TRNSYS	(Sinha & Chandel, 2015)	NO	NO	NO	-
SAM	(Dobos et al., 2014)	YES	YES	Land usage, water consumption	No
INSEL	(Connolly et al., 2010)	YES	YES	NO	NO
HYBRIDS	(Lund et al., 2010)	NO	YES	NO	NO
HYDROGEMS	(Bernal-Agustín & Dufo-López, 2009)	-	NO	NO	NO

2.12 Power Generation Techno-Economic Assessment Tools and Methods

There exist several economic and financial indicators used to determine the financial worthwhile of different energy systems. These methods combine the capital costs, operation and maintenance costs, fuel costs, and the energy output, which, when computed, provide the necessary metrics which are indicators of project viability (El-Shimy, 2017) (Sklar-Chik et al., 2016)(Masters, 2004). As shown in Table 2.9, these methods are classified into three main categories: financial analysis methods, impacts analysis methods, and systems analysis methods (Tran, 2007)(*Measuring the Social Costs of Coal-Based Electricity Generation in South Africa*, 2015).

Table 2.9: Power Generation Technology Assessment Tools and Methods

Financial Analysis	Impact Analysis	Systems Analysis
Life cycle cost analysis	Damage cost approach	Systems dynamics
Levelized cost of electricity	Abatement cost approach	System optimization technique
Simple payback period	Benefit transfer technique	Linear programming
Discounted payback period	Simple unit transfer	Integer programming
Internal rate of return	Meta-analysis	Dynamic programming
Modified internal rate of return	Benefit function transfer	Energy systems analysis models
Net present value	Life cycle assessment	HOMER
	Hybrid LCA	RET Screen
	Environmental impact assessment	MARKAL
	Ecological impact assessment	EnergyPLAN
	Health impact assessment	
	Social impact assessment	

In the following section, economic performance methodologies for energy systems are discussed.

2.12.1 Simple Payback Period

The simple payback methods have been widely used to determine the economic viability of projects (El-Shimy, 2017). It is expressed as a ratio of the additional costs to the annual savings, as shown by equation (0.5).

$$SPB = \frac{\Delta p\ (\$)}{S\ \left(\frac{\$}{yr}\right)} \tag{0.5}$$

where $SPB, \Delta p,$ and S are simple payback time, additional costs incurred while generating energy, and S is the net savings per year.

The advantage of the simple payback period method is that it is simple and easy to understand. Still, the disadvantage is that it does not explore all the variables of concern for the economic viability of projects, such as environmental impact analysis (El-Shimy, 2017). This method is also considered one of the most misleading ways since it does not include the project's lifespan (El-Shimy, 2017; Masters, 2004).

2.12.2 Initial (Simple) Rate of Return

Equation (2.6) shows that the initial rate of return is reciprocal of the simple payback and thus defined as the proportion of the yearly savings to the additional original costs.

$$IRR = \frac{S\ \left(\frac{\$}{yr}\right)}{\Delta p\ (\$)} \tag{0.6}$$

Where IRR is the initial rate of return. If the project's lifetime is sufficient, the initial rate of return is considered an excellent pointer to the economic worthiness of the project (El-Shimy, 2017)(Masters, 2004).

2.12.3 Net Present Value

The Present Net Value (NPV) is defined as the variance between cash inflows and cash outflows. NPV is usually used to evaluate the cost-effectiveness of an investment. The NPVof all the costs incurred during construction, generation, and residual value during decommissioning; that is; present and future expenses are regarded as the life cycle costs. The difference in the cash inflows and the cash outflows determines the economic viability of a project. The NPV is calculated using Equation (0.7).

$$NPV = \sum_{t=1}^{T} \left\{\frac{C_t}{(1+r)^t}\right\} - C_0 \qquad (0.7)$$

Where C_t is the total net cash inflow in year t, r is the discount rate, T is the projected lifespan of the project and C_0 is the initial capital cost. Since most projects are built for profit-making, a negative NPV would indicate a loss (El-Shimy, 2017)(Masters, 2004).

2.12.3 Internal Rate of Return (IRR)

This metric is used in assets accounting to determine the cost-effectiveness of investments. IRR is a mark-down requisite rate to make the NPV zero shown by equation (0.8).

$$NPV = P_0 + \frac{P_1}{(1+IRR)_1} + \frac{P_2}{(1+IRR)_2} + \cdots \frac{P_n}{(1+IRR)_n} \qquad (0.8)$$

Where P_i represents the cash flows in a year i where i= 0,1,2... n and IRR is the Initial Rate of Return

2.12.4 Levelized Cost of Electricity (LCOE)

The Levelized Cost of Electricity (LCOE) of an electricity generating unit is the per-unit cost of power calculated for comparison purposes between the cost of generating a unit with other types of energy generators over a similar lifespan with comparable operational profiles and system value (El-Shimy, 2017). It is an economic assessment of the cost of an energy-generating system that includes all the life cycle costs. The life cycle costs that are included in almost all LCOE calculations are the initial capital costs, cost of fuel, operations and maintenance costs (both variable and fixed), interest on financing costs, residual value, replacement costs, and the assumed capacity factor as shown by Equation (0.9) (El-Shimy, 2017) (Aman et al., 2015)(Sklar-Chik et al., 2016).

$$LCOE = \frac{Total\ life\ cycle\ cos\ t\ s}{Total\ life\ time\ energy\ production} \qquad (0.9)$$

LCOE is a representation of the cost of electricity that would match the cash flows, that is; the inflows and the outflows; which are usually normalized over a certain period and allow the Independent Power Producers (IPPs) to fully recover all the costs over a predetermined financial lifespan (El-Shimy, 2017)(*Assessing the economic value of new utility-scale renewable generation projects*, 2013). It is mostly useful in many diverse evaluative resolves such as utility resource choice, dispatch choices, electricity valuing, energy conservation programs, Research and development inducements, funding determination, and impact planning (Aman et al., 2015). LCOE is usually determined when all the discounted proceeds balance with all the discounted costs as described by Equation (0.10).

$$\sum_{t=1}^{T} \frac{R_t}{(1+r)^t} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (0.10)$$

Where R_t is the revenue generated for the period t and C_t is the total of costs incurred for the period t. Considering that

$$R_t = LCOE_t * E_t \qquad (0.11)$$

Where E_t is the amount of energy generated for the period t, then Equation (0.11) becomes

$$\sum_{t=1}^{T} \frac{LCOE_t * E_t}{(1+r)^t} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (0.12)$$

Making $LCOE_t$ the subject of the formulae from Equation (0.12) yields Equation (0.13).

$$LCOE_t = \frac{\left\{\sum_{t=0}^{T} \frac{C_t}{(1+t)^t}\right\}}{\left\{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}\right\}} \qquad (0.13)$$

2.13 Aspects not covered by the LCOE and other Methodologies

In determining the LCOE, some aspects, such as environmental and impact cost (externalities), are omitted (Roth & Ambs, 2004b). The externalities, as mentioned earlier, are costs and benefits that do not accrue to the stakeholders. They include damage to human health and the environmental impact costs. The environmental impacts cost includes ecosystem damage, habitat fragmentation, and soil erosion (Roth & Ambs, 2004b).

2.14 External Costs of Power Generation Systems

All electricity generation technologies have, apart from their benefits, some adverse consequences such as environmental degradation. Electricity production influences a wide set of endpoint impacts, including soil compaction, visibility, global climate through emissions of Greenhouse Gases (GHG), ecosystem damage, and human health. These impacts are not accounted for by the producers or consumers of electricity (Roth & Ambs, 2004b). There are about 20 GHG responsible for the process of absorption that naturally warms the earth (greenhouse effect). The common GHG that draw a lot of concern is the Particulate Matter (PM), Ozone layer (O3), Carbon Monoxide (CO), sulfur dioxide (SO_2), Nitrous Oxide (N_2O), methane (CH_4), Lead (Pb) and the Volatile Organic Compounds (VOC) (Roth & Ambs, 2004b). The proportionate contribution to the global warming potential is 61% for CO_2, 15% for CH_4,12% for CFCs, 4% for N_2O, and 8% for all other gases(Goedkoop et al., 2009).

The PM causes health problems as it reaches the upper part of the airways and lungs when inhaled. The PM is formed in the air from SO_2, Ammonia (NH_3), and N_2O. The inhalation of PM results in various health problems (Goedkoop et al., 2009).

Ozone is formed due to photochemical reactions of the N_2O and the Non-Methane Volatile Organic Compounds (NMVOC). Ozone is a health hazard to human beings as it inflames the airways and damages the lungs. Ozone concentrations lead to an increased frequency in humans with respiratory problems such as asthma and chronic obstructive pulmonary diseases (COPD) (Goedkoop et al., 2009). The damage cost must be evaluated in monetary terms to appreciate the environmental impacts/ externalities of electricity generation. The health and environmental impacts of the different effluents of USSE are discussed in Table 2.10.

Table 2.10: Health and Environmental Effects of USSE

Impact category	Pollutant	Effects included
Public health-Mortality	PM_{10},SO_2 , O_3	Reduction in life expectancy due to acute and chronic mortality
Public Health-Morbidity	PM_{10}, O_3	Respiratory hospital admissions, restricted activity days, cardiovascular admissions, bronchitis, asthma, respiratory symptoms
Material damage	SO_2, acid deposition	Aging of galvanized steel, limestone
Crops	SO_2,O_2 ,acid deposition	Yields change in wheat, barley, potato O_3 causes loss of wheat, barley, rice, tobacco

2.15 Accounting for Human Health Damages from USSE

The characterization factors for chronic toxicological effects, referred to as the Human Toxicity Potentials (HTF) and Human Damage Factors (HDF), provide a cumulative amount of toxicological impacts per unit mass emitted to the environment. The HDF of emission is expressed in Disability Adjusted Life Years (DALY) per kg emitted as shown by Equation (0.14**)**.

$$HDF_i = IF_i * EF_i = IF_i * \beta_i * D_i \qquad (0.14)$$

Where HDF_i is the Human damage Factor, IF_i is the Intake Fraction, EF_i is the Effect Factor,β_i is the dose-response slope factor while D_i is the severity factor, also called the DALY.

The intake fraction of the mass of a chemical released by USSE to the environment and taken up by human beings through inhalation, dermal exposure, or ingestion expressed in kg absorbed/kg emitted as shown in Equation (0.15), while (EF_i) is the effect factor.

$$IF(total, air) = IF(inhalation, air) + IF(ingestion, air) + IF(dermal, air) \quad (0.15)$$

The number of toxic pollutants getting into the human body from all the exposure routes (inhalation, ingestion, and dermal) is expressed by Equation (0.16).

$$IF = \frac{\frac{mg}{kg} - \frac{BW}{day}}{\frac{mg}{day}} * BW * p \quad (0.16)$$

Where $\frac{mg}{kg} - \frac{BW}{day}$ is the intake rate per unit emission $\frac{mg}{day}$ and p is the population.

EF_i is the effect factor, which is the product of the dose-response slope factor β (risk of incidence per kg intake) and the severity D (in Disability Adjusted Life Years

(DALY) per incidence). The effect factor (EF_i) is estimated using Equation (0.17).

$$EF_i = \left[\beta ED10h^{-1} * \frac{1}{BW.LT_h.N_{365}}\right].DALY_p \quad (0.17)$$

Where EF_i is the effect factor of substance I (years lost/mass intake), $\beta ED10h^{-1}$ is the slope factor of substance I (risk per mass/kg per day) where β =0.1,$BW$is the body weight (kg/person); 70 kg per person, $LT_h$is the lifetime of human beings; 70 years, N_{365} are the number of days in one year, $DALY_p$ is the Disability-adjusted life years per incidence (years/ incidence).

The carcinogenic and non-carcinogenic (human toxicity), respiratory effects (organic and inorganic substances), ozone layer depletion, and radiation ionization are contributory factors to human health damage (Jolliet et al., 2003). The toxicity can be expressed in terms of Disability Adjusted Life Years (DALY per kg emission). Table 2.11 shows the characterization factors damage factors of different substances on human health (Jolliet et al., 2003).

Table 2.11: Reference Damage factors for Human Health

Category	Damage factor	Units
Carcinogens	1.45E-06	DALY/kg chloroethlyne
Non-carcinogens	1.45E-06	DALY/kg chloroethlyne
Respiratory inorganics	7.00E-06	DALY/kg PM 2.5
Ozone layer	1.05E-03	DALY/kg CFC-11

Respiratory Organics	2.13E-06	DALY/kg ethylene
Radiation	2.10E-10	DALY/Bq carbon-14

The number of toxic substances entering the human body, commonly referred to as the intake fraction, IF, is the total intake from a source such as power plants, refineries, etc. and summed over all individuals exposed for in a given time per unit of emission as described by equation (0.18).

$$IF = \frac{P}{m} \qquad \textbf{(0.}18\textbf{)}$$

Where P is the pollutant emission inhaled by human beings and m is the mass intake of the pollutant. Therefore, the Intake Fraction is the amount of pollutant absorbed by the target; for this case, human beings through inhalation, ingestion, and dermal exposure.

2.15.1 Disability Adjusted Life Years

The burden of a disease is the impact on health across the human population, which is mainly described by mortality, morbidity, and the financial cost (Goedkoop et al., 2009) (Crettaz et al., 2002)(Huijbregts et al., 2017). A line is drawn between mortality and morbidity in terms of Years of Life Lost (YLL) and Years of Life Disabled (YLD), as shown in Equation (0.19**)**.

$$DALY = YLL + YLD \qquad (0.19)$$

The number of years lived with a disability is expressed by Equation (0.20) which indicates the decreased quality of life due to the disease burden.

$$YLD = w * D \qquad (0.20)$$

Where w is the severity factor of the disability/ disability weight, which ranges between 0 for complete health and 1 for dead, D is the duration of the disease/disability, and YLD is the years of life lived with a disability per affected person (year/incidence)(Crettaz et al., 2002).

YLL for an individual can not be predicted but assumed to conform to the reference population(Tsoutsos et al., 2005b)(Allan D. Lopez, Collin D. Mathers, Majd Ezzati, Dean T. Jomison, Christopher J, 1996). Accordingly, YLL is defined as shown in Equation (0.21)

$$YLL \quad (c, a, s) = \frac{N(c, a, s)}{L(a, s)} \qquad (0.21)$$

where $L(a, s)$ is the years of life lost per affected person for age a and sex s

$N(c, a, s)$ is the total number of deaths (incidences) due to causing c for given age $a$and sex $s$and $YLL \quad (c, a, s)$ is the years of life lost per affected person in a population (years/ incidence)

The DALY of cancer in the different human body parts is shown in Table 2.12 using the world data (Crettaz et al., 2002).

Table 2.12: Disability Adjusted Life Years for Various types of Tumors in affecting the Human body across the World

	Disability			**Death**			**Disability +Death**
Type of cancer	W	D	YLD=w.D	L	N	YLL=L/N	DALY=YLL+YLD
Mouth and oropharynx	0.145	4.3	0.62	$3.2x10^{6}$	$1.1x10^{6}$	2.9	3.5
Oesophagus	0.217	1.7	0.37	$3.4x10^{6}$	$3.8x10^{5}$	8.9	9.3
Stomach	0.217	2.9	0.63	$7.0x10^{6}$	$1.1x10^{6}$	6.5	7.2.
Colon	0.217	3.7	0.8	$3.9x10^{6}$	$9.9x10^{5}$	3.9	4.7
Liver	0.239	1.6	0.38	$6.3x10^{6}$	$5.4x10^{5}$	11.6	12
Pancrease	0.301	1.2	0.37	$1.5x10^{6}$	$1.9x10^{5}$	7.9	8.3
Trachea	0.146	1.8	0.26	$8.3x10^{6}$	$1.1x10^{6}$	7.9	8.2
Melanoma	0.045	4.2	0.19	$5.1x10^{5}$	$1.7x10^{5}$	3.1	3.2
Breast	0.069	4.2	0.29	$3.8x10^{6}$	$1.1x10^{6}$	3.6	3.9
Cervix Uteli	0.066	3.8	0.25	$2.7x10^{6}$	$4.5x10^{5}$	6	6.2
Corpus uteri	0.066	4.5	0.3	$5.8x10^{5}$	$3.1x10^{5}$	1.9	2.2
Ovary	0.081	3.4	0.28	$1.3x10^{6}$	$2.0x10^{5}$	6.4	6.7
Prostrate	0.113	4.2	0.47	$1.1x10^{6}$	$6.8x10^{5}$	1.6	2.1
Bladder	0.085	4.2	0.36	$9.8x10^{5}$	$4.6x10^{5}$	2.1	2.5
Leukemia	0.112	3.1	0.35	$4.4x10^{6}$	$3.1x10^{5}$	14.3	14.6

2.16 Ecosystems Functions, Ecosystems Services, and Value Assignment

Ecosystems functions refer to the habitat, organic, or system properties or processes of biotas. Ecosystems goods and services refer to the benefits human beings and animals derive directly or indirectly from ecosystem functions (Costanza et al., 1997). Ecosystems functions and services are further classified as direct and indirect use assets (Eade & Moran, 1996). The natural use assets are generally hypothetical and require some capital investment and market identification to realize their potential fully. The indirect use assets are the environmental goods and services where human beings benefit indirectly. In this case, the are no capital investment for maintenance of their productivity.

The ecosystem functions and services include nutrient cycling, carbon sequestration, air, and water filtration, flood amelioration, shading, habitat to world animals, and pollination (Bin Zhaoa, Urs Kreuterb, Bo Lia, Zhijun Maa, Jiakuan Chena, 2004).

Globally different land-use types and biomes are valued according to the willingness to pay for ecosystem services. Some of the ecosystem services, functions, and biomes are valued, as shown in Table 2.13 (Costanza et al., 1997).

Table 2.13: Biome Equivalents, Land use Categories, and Corresponding

Land Cover Type	**Equivalent Biome**	**Ecosystem Service Coefficient ($/ha/yr)**
Aquaculture	Lakes and rivers	8498
Farmland	Cropland	92
Orchard	Forest	969
Wetland	Estuaries	22,832
Rangeland	Grasslands	232
Woodlands	Temperate forests	302

Ecosystems Values

The ecosystem functions and their associated goods and services are categorized into four primary categories, as discussed in section 0.

2.17 Classification of Ecosystem Goods and Services

The ecosystem goods and services are divided into four different categories according to the functions and their contribution to the coexistence of biodiversity. The various functions are categorized into four main attributes: regulation functions, habitat functions, production services, and information functions, as described in Table 2.14 (R. S. De Groot et al., 2002).

Table 2.14: Ecosystem Functions, Goods and Services

Functions	**Ecosystem processes and components**	**Goods and services**
Regulation functions: Maintenance of essential ecological processes and life support systems		
Gas regulation	Role of the ecosystem in biogeochemical cycles, e.g., CO_2, O_2 balance	Maintenance of good air quality UV protection by O_3.
Climate regulation	Influence on land cover type	Maintenance of favorable climate for human habitation, health, cultivation
Disturbance prevention	Influence of ecosystem structure on dampening env. disturbances	Storm protection by coral reefs and flood control by wetlands and forests
Water regulation	Role of land cover in controlling runoff and river discharge	Drainage and natural irrigation, the medium of transport
Water supply	Filtering, retention, and storage of freshwater	Provision of water for consumption
Soil retention	Role of vegetation root matrix and soil biota in soil retention	Maintenance of arable land, soil erosion prevention
Nutrient regulation	Role of biota in nutrient cycling	Maintenance of healthy soils and productive ecosystems
Pollination	Role of biota in the movement of floral gametes	Pollination of wild plants species, pollination of crops
Biological control	biological control through dynamic trophic relations	Control of pests and diseases, reduction of crop damage
Habitat functions: Providing suitable Habitat for wild plants and animal species		
Refugium functions	Living space for wild plants and animals	Maintenance of biological and genetic diversity
Nursery function	Suitable reproduction habitat	Maintenance of commercially harvested species
Production functions: Provision of natural resources		
Food	Conversion of solar energy to edible plants	Hunting, gathering of fish, game, fruits, small scale farming
Raw materials	Conversion of solar energy into biomass for construction and other uses	Building, manufacturing, fuel, energy, fodder, fertilizer
Genetic resources	Genetic material and evolution in wild plants and animals	Improves crop resistance to pathogens and pests
Medicinal resources	Variety in biochemical substances, medicinal uses	Drugs and pharmaceuticals, chemical models and tools
Information functions: providing opportunities for cognitive development		
Aesthetic information	Beautiful scenery	Enjoyment of scenery
Recreation	Variety of landscapes with recreation uses	Traveling to the natural ecosystem, eco-tourism, and outdoor sports
Cultural, spiritual, and artistic information	Variety in natural features with cultural, artistic, spiritual, and historical value	Films, the motive in books, national symbols
Science and education	Variety of features with scientific value	Use of natural biota for an excursion

The categories are briefly discussed in subsections 0, 0, 0, and 0 below.

2.17.1 Regulation Functions

This group of ecosystem goods and services refers to the ability and capacity of the natural and semi-natural ecosystems goods and services to regulate ecological processes through bio-spheric and biogeochemical cycles. Additionally, these regulation functions provide services that directly or indirectly are beneficial to human beings' health and other living organisms at large such as clean air, water purification, soil retention, and biological control services (R. S. De Groot et al., 2002).

2.17.2 Habitat Functions

Natural ecosystems provide refugium services and reproduction/breeding habitats to wild animals and plants, thereby contributing to conservation of biological and genetic diversity.

2.17.3 Production Services

The process of photosynthesis and nutrient uptake by plants and the eventual conversion of carbon dioxide, energy, water, nutrients into carbohydrate structures converted into biomass by other secondary producers. The broad range of carbohydrates structures provides various ecosystem goods for human consumption, such as food and raw materials to energy resources and genetic materials (R. S. De Groot et al., 2002).

2.17.4 Information Functions

Human beings depend on plants and animals as sources of medicine, food, archaeological sites, cognitive development, recreation services, and aesthetic experience(R. S. De Groot et al., 2002). section 0 discusses land use and life cycle assessment.

2.18 Land Use and Life Cycle Assessment (LCIA)

The main drivers of biodiversity loss and reduction across the globe are land use. Accordingly, three types of land use are characterized as the transformation impact, the occupation impact, and the permanent impacts.

The transformational effects are applied in quantifying the original change in biodiversity due to a shift in their natural habitat and include the restoration time it will take to regain its natural state (Science et al., 2013)(Mueller et al., 2014).

The occupation impact occurs due to preventing the recovery to the natural state due to human encroachment through farming and building energy-generating plants. It results in the destruction of bleeding zones and eventual habitats change (Science et al., 2013).

The permanent impacts account for the irreversible damages that happen as a result of land occupancy. The side effects of the permanent effects are incomplete biodiversity recovery. The results of such impacts are the extinction of certain biodiversity species (Science et al., 2013).

2.18.1 Life cycle impact assessment (LCIA)

Life cycle impact assessment (LCIA) is a methodology used to quantify the environmental impacts resulting from land-use change. LCIA highlights the eventual reduction of ecological goods and services and highlights the remedial action to restore. The existing LCIA models quantify biodiversity loss as the difference in the local species richness in the different land-use types (Science et al., 2013)(Mueller et al., 2014).

2.19 Quantification of Land Use Impacts on Biodiversity

The loss of biodiversity resulting from the occupation of previously natural land and harboring ecosystem goods and services must be accounted for. Three main methods have been applied for the quantification of the lost biodiversity. These are the

Species Area Relationship (SAR) model, the Countryside SAR model, and the Matrix SAR model (Science et al., 2013)(Chaudhary et al., 2015).

The SAR model is mostly applied in regions where species may be driven out of extinction due to land occupancy. The SAR model is derived from the island biogeography theory described by Equation (0.23).

$$S = cA^z \tag{0.22}$$

Where S is the number of species in a given geographical location, c is the constant that describes the species richness for a particular location, z =constant that describes the species accumulation rate

The number of species remaining after land occupancy is determined by Equation (0.23).

$$\frac{S_{new}}{S_{org}} = \frac{A_{new}}{A_{org}} \tag{0.23}$$

Where S_{new} is the number of species remaining after land occupancy, S_{org} is the original number of species in the original area, A_{new} is the new area occupied by USSE, A_{org} is the original area.

The main disadvantage of the SAR model is that it majorly focuses on natural land and assumes that no species exists in the human-modified habitats (Chaudhary et al., 2015). However, this is not the case because some species remain and survive after land use has changed.

The countryside SAR model predicts the number of species lost ($S_{lost_{,g,j}}$) in a given geographical location consisting of taxa g in the region j (Chaudhary et al., 2015). This is described in Equation (0.24).

$$S_{lost,g,j,regional} = S_{org,g,j}\left[1 - \left(\frac{A_{new,j} + \sum_{i=1}^{n} h_{g,i,j}A_{i,j}}{A_{org,j}}\right)^{z_j}\right] \quad (0.24)$$

Where $S_{org,g,j}$ is the original number of species occurring in the natural habitat $A_{org,j}$, $A_{new,j}$is the remaining natural habitat in a region, $A_{i,j}$ is the current area of land use type i, z_j is a constant that represents the species accumulation rate

The matrix SAR model provides unrealistic results (100 % species loss) for regions whose land use occurs. The method also treats all the species equally, whether critically endangered or not (Chaudhary et al., 2015). Section 0 discusses the environmental impact assessment of lead-acid batteries.

2.20 Battery Recycling in Solar Projects

Lead-acid batteries are widely used for various applications for power supply, such as automotive, traction services, uninterruptible power supply, among others (Zhang et al., 2016). It is estimated that 3 million tons of waste per year are generated from lead-acid batteries. These batteries consist of electrolytes, lead paste, organics, and highly flammable plastics. These materials pose a significant danger if not correctly disposed of (Zhang et al., 2016). The lead-acid pollutants are as shown in Table 2.15 (Zhang et al., 2016).

Table 2.15: Risk and Pollutants of Lead Acid Batteries

Materials	Risk	Physical state	Source
Lead compounds	Toxicity	Solid	Electrode and grid
Antimony	Toxicity	solid	Plates
Sulfuric acid	Corrosion	liquid	Electrolyte
Hydrogen	Explosiveness	Gas	Water electrolysis

The main environmental impacts of batteries encountered during mining, usage, and decommissioning solar PV plants are shown in Table 2.16 (Zhang et al., 2016).

Table 2.16: Environmental Impacts during Life of Batteries

	Mining	Production	Decommissioning
Exhaustion of raw materials		Medium	
Energy needed	Medium	Medium	Low
Global warming	Low	Low	Medium
Waste	Medium	High	High
Land use	Low	Low	Medium

2.21 Research Gap

While many models previously developed can give valuable insights into the economic modeling of renewable energy technologies, they cannot account for the environmental impacts of RETs. The cost modeling's quantification and inclusivity of the ecological impacts are practically absent in all LCOE calculations (Darling et al., 2011). Given the above, there arises a need to develop a versatile economic modeling tool that fully incorporates the environmental impacts of solar PV and the complex interdependence between them to provide a coherent valuation of their impacts, including synergies and side effects. The Techno-Economic model developed in this thesis will thus aid in the decision-making about site considerations and the economic viability of solar PV. Incorporating the environmental impacts of solar PV explicitly into the electricity tariff would give proper guidance and projections on the future of Solar PV.

2.22 Chapter Conclusion

In summary, the model developed by Sellami (2014) has quantified the area impacted but does not break down the respective values of the ecosystem in the impacted area, such as the value of land and the value of wildlife in such an environment. The models developed in Sellami (2014) and R. R. Hernandez et al. (2014) only consider the CO_2 avoided or emitted by RETs. These models do not perform the monetary valuation of CO_2 and other environmental impacts. The models do not also show any cost modeling. Erdinc and Uzunoglu (2012) and Guta (2014) evaluate the ecosystem in the impacted area and the cost modeling of energy. The models developed by Bergmann et al. (2007) and Álvarez-Farizo & Hanley (2002) calculated the revenue as payback to the impacted land, wildlife, etc. Still, they did not show how much has been included in the cost model. Owen (2006) compared the different external costs per kilowatt-hour of electricity generated from conventional and non-conventional sources, but their study was limited to the carbon tax. The environmental impacts such as the area of land utilized, water consumed, and CO_2 emitted have been simulated using SAM (Yun & Baker, 2009). Still, their respective monetary value is not computed and, therefore, not incorporated in the LCOE determination. Although the environmental impacts were not considered by Vujić et al. (2012), which would perhaps have made the energy production from solar more unaffordable, the installation of PV and CSTP were found unsuitable in Chile on the grounds of labor, carbon bond prices, and the component prices.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This work's ultimate purpose is to develop the Solar-PV-based Power and Environmental Cost Assessment (SPECA) modeling tool that provides information on Solar photovoltaic-based generation and its interactions with the resource inputs, private costs, externalities economic impacts over its lifetime. Section **Error! Reference source not found.** describes the research approach followed in this thesis.

3.2 Research Approach

The literature review unveils all the unplanned, unwanted, or unanticipated externalities during Solar PV construction and running. The target environmental impacts are land usage, emissions, human health, water, and wildlife. The aim of this work is thus to develop a mathematical modeling tool for the techno-economic and environmental impacts of solar photovoltaic systems. The modeling tool developed quantifies and incorporates the monetary value of the impacts and other important parameters in the decision-making for utility-scale solar deployment.

The underlying philosophy in this work is to consider the socio-environmental impacts in the decision to install and test the techno-economic viability of solar PV. Therefore, in developing a modeling tool for this research work, the environmental impacts of solar PV will be identified and quantified according to their estimated monetary value. These impacts vary according to the technology used and resource availability in a given location. Just to name a few, solar PV consumes water for washing the mirrors, effectively posing a danger to the water security of the surrounding ecosystems, including human beings. Therefore, the quantifiable element will be the value of the water used for electricity generation in this case.

3.3 Formulation of the Speca Modelling Tool

The central block diagram of the solar PV-based Power and Environmental Costing Assessment tool (SPECA) is shown in Figure . The inputs to this tool include the location, Direct Normal Irradiation (DNI), load data, environmental and non-environmental data, components, their respective cost characteristics, and the energy model of solar PV. The SPECA tool analyses and computes the input data yielding the total system output, including the LCOE, Net Present Cost (NPC), IRR, cash inflow, cash outflow, and total energy output.

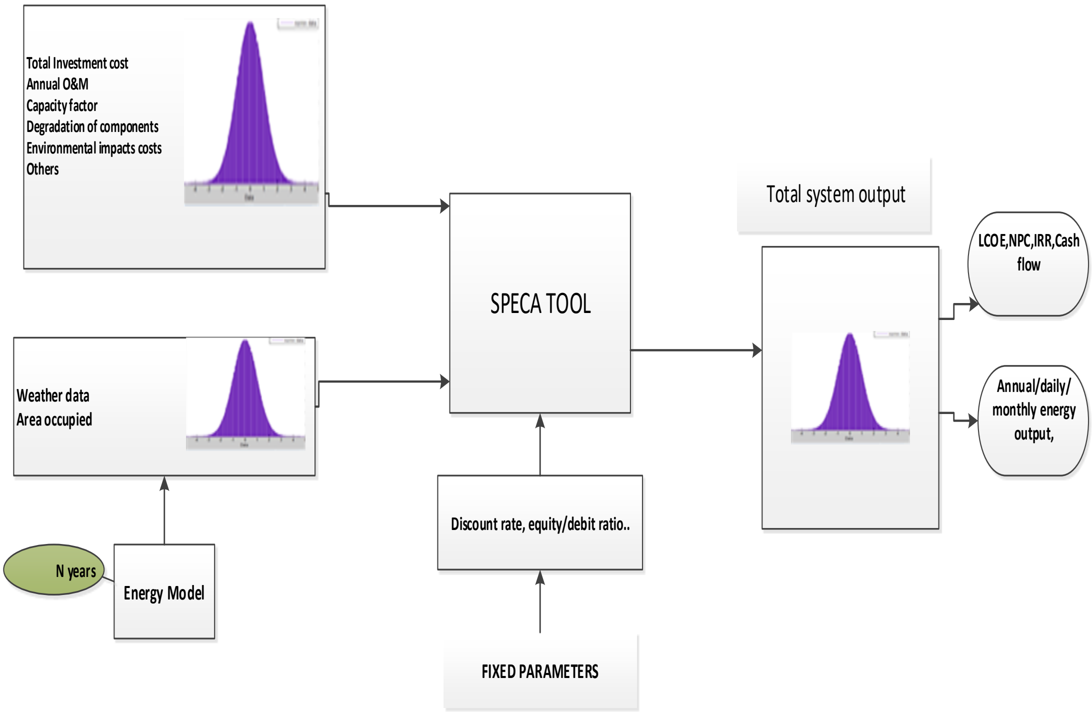

Figure 3.1: Main Block Diagram of the SPECA Model

As discussed in previous chapters, the tool is developed to overcome the failure of other tools to include the environmental impacts of Solar PV in the determination of the system metrics such as annual energy generated in a given region, Energy payback time, Net present value, Levelized cost of electricity, Levelised Externality Cost of Energy (LECOE) and Levelised Total Cost of Energy (LTCOE). LTCOE defines the amount of money paid per kWh of energy when externalities are incorporated, while LECOE defines the externalities per kWh of energy generated, as discussed in section 0. The SPECA modeling tool is implemented using basic visual programming. A graphical user interface (GUI) provides an interactive user platform. The Structured Query language (SQL) is used for database development. The SPECA modeling tool, therefore, has the Graphical user interface (GUI) and the database.

The GUI is window-based and provides functions to manipulate the data according to the requirements. The interface calls stored procedures in the database for data processing and data retrieval. Finally, the database keeps all system data enhancing data integrity. The database used is a relational database management system, which is a Microsoft SQL Server. The database stores the tabular files of DNI, the cost of equipment used for solar photovoltaic and their types, different environmental aspects of the other regions in Kenya. The process flow diagram of the SPECA model is described in Figure .

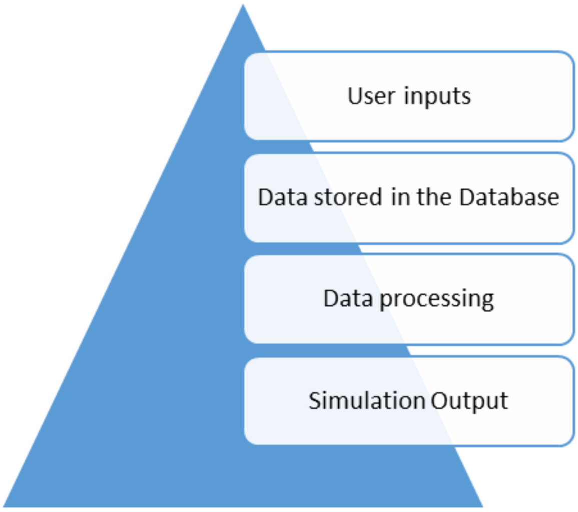

Figure 3.2: SPECA Model System Architecture

3.4 The Levelized Cost of Electricity (LCOE) Versus the SPECA Modelling Tool

LCOE methodology has been applied in almost all USSE modeling. As was reported in Chapter Two in this study, LCOE does not take care of the environmental impacts of USSE and, therefore, does not reflect the actual cost of electricity (El-Shimy, 2017). LCOE is calculated for each year using the Levelized lifetime cost methodology since it is considered one of the most important indicators of the financial viability of power generating systems. According to this methodology, the Levelized lifetime cost per unit of electricity generated is the lifetime cost and expenses ratio versus the total expected lifetime energy output (Rentizelas et al., 2012).

In this thesis, the SPECA modeling tool, which is a modification of the LCOE methodology, has been applied with an amendment to include the environmental impacts instead of the other traditional methods and tools such as NPV, HOMER, INSEL, IHOGA, SAM, IRR, SOMES, HYBRIDS, RETSCREEN, and HYBRID2. Unlike the LCOE methodology and NPV analysis, the SPECA modeling tool can transform the investment and the lifetime series of expenditures, externalities, and incomes in the asset period to equal annuities discounted in the present value. Thus, the SPECA modeling tool will allow a fair comparison of electricity generation costs from Solar PV. Section 0 describes the SPECA modeling tool formulation.

3.5 SPECA Modelling Tool Formulation

The SPECA modeling tool is a mathematical development that utilizes the LCOE methodology. From the first principles, LCOE is expressed as a fraction of the lifetime energy production cost as described by Equation (0.1).

$$LCOE = \frac{Total\ life\ cycle\ cost}{life\ time\ energy\ production} \tag{0.1}$$

The summation of the cost of electricity (COE_t) multiplied by the total amount of

energy generated should be equivalent to the discounted net present cost (NPV) or the cash inflows. The input and output cash flows are defined by Equations (0.2) and (0.3).

$$Lifetime\ cash\ inf\ l\,ow = \frac{\sum_{t=1}^{T} E_t * COE_t}{(1+r)^t} \tag{0.2}$$

$$cash \rightleftarrows outflow = \frac{\sum_{t=0}^{T} C_t}{(1+r)^t} \tag{0.3}$$

Making COE_t the subject of the formulae from Equation (0.2) yields Equation (0.4).

$$COE_t = \frac{(1+r)\ \ lifetime\ \ cash\ \ inflow}{\sum_{t=1}^{T} E_t} \tag{0.4}$$

Where r is the % discount rate, $E_t$is the amount of energy generated in year t, C_t is the annual cost of energy for year t, COE_t is the cost of Energy in year t, T is the project lifetime

As shown in Equation (3-3), the summation starts from t=0 to integrate all the costs incurred at the commencement of the project. $COE$is; therefore, time-dependent as defined by equation (3-3), while $LCOE$ is usually a constant time-independent value (El-Shimy, 2017).

LCOE is determined as the lifetime energy cost. In the life cost analysis, the breakeven point is established when the sum of the discounted revenues equals the value of the discounted costs, as detailed in equation (0.5**)** (El-Shimy, 2017).

$$\boldsymbol{LCOE = P_{elec} = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}} \qquad (0.5)$$

Therefore, the efficiency and output of the solar photovoltaic (generally referred to as output degradation) reduces with time, and this applies to all energy-generating technologies. The amount of energy generated in the year t (E_t) equals the initial energy generated (E_0) multiplied by the annual system degradation rate d. The amount of energy produced, therefore, reduces as the solar PV ages. Equation 3-5 further disintegrates to Equation (0.6**)**.

$$LCOE = P_{elec} = \frac{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_0\,(d)^t}{(1+r)^t}} \qquad (0.6)$$

Where $d$is the systems degradation rate

The main costs in any electricity generation which constitute the total life cycle costs C_t as indicated by Equation (0.7) include the initial capital cost IC, operations and maintenance costs$O\&M$, residue value,RV and the replacement costsRC.

$$C_t = C_0 + O\&M + RV + RC \qquad (0.7)$$

Where C_0 is the initial capital, $O\&M$ is the operations and maintenance costs, RV is the Residual Value, RC is the Replacement Cost

The total costs C_t, of Equation (0.7) once enjoined in Equation (0.6) yields Equation (0.8).

$$LCOE = P_{elec} = \frac{\sum_{t=0}^{T} \frac{C_0 + O\&M_t + RC_t + RV}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_0 (d)^t}{(1+r)^t}} \qquad (0.8)$$

To capture the Externality Cost (EC) of solar PV, the LCOE methodology is further restructured to yield the Levelised Total Cost of Energy (LTCOE) as defined by Equation (0.9). In this thesis, the difference between LTCOE and LCOE is referred to as Levelised Externality Cost of Energy (LECOE) as defined by Equation (0.10).

$$LTCOE = \frac{\sum_{t=0}^{T} \frac{C_0 + O\&M_t + RC_t + RV}{(1+r)^t} + \frac{\sum_{i=1}^{k} \mathrm{EC}}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_0 (d)^t}{(1+r)^t}} \qquad (0.9)$$

$$LECOE = \frac{\sum_{t=0}^{T} \frac{C_0 + O\&M_t + RC_t + RV}{(1+r)^t} + \frac{\sum_{i=1}^{k} \mathrm{EC}}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_0 (1-d)^t}{(1+r)^t}}) - (\frac{\sum_{t=0}^{T} \frac{C_0 + O\&M_t + RC_t + RV}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_0 (1-d)^t}{(1+r)^t}}) \qquad (0.10)$$

Where $\sum_{i=1}^{k} \mathrm{EC}$ represents the aggregated environmental and non-environmental impacts the cost of the USSE, and k represents the affected impacts

The following section explains the mathematical modeling of energy harvesting from solar photovoltaics and components sizing.

3.6 Electricity Generation from Solar Photovoltaic

This section presents models for the estimation of power generation from solar Photovoltaics. These models can also be used in the profitability analysis or the determination of the best site for the deployment of solar photovoltaics.

The output of solar photovoltaic cells is estimated by Equation (0.11**)** (El-Shimy, 2017).

$$P_{pv}(t) = Y_{pv} f_{pv} \frac{G_T(t)}{G_{T,STC}} \tag{0.11}$$

Where $P_{pv}(t)$ is the output power of a solar photovoltaic (kW), Y_{pv} is the rated capacity of the solar PV array (kW), $f_{pv}$is the solar PV derating factor (%), $G_T(t)$ is the solar irradiance incident on the PV array (kWh/m^2), $G_{T,STC}$ is the incident radiation at standard test conditions.

The rated capacity of the solar PV (Y_{pv}) is given by Equation (0.12**)**.

$$Y_{pv} = \frac{\eta_{pv} A_{pv}}{G_{T,STC}} \tag{0.12}$$

Therefore Equation (0.12**)** yields Equation (0.13**)**.

$$P_{pv}(t) = f_{pv} \eta_{pv} A_{pv} G_T(t) \tag{0.13}$$

Where η_{pv} is the efficiency of solar PV technology and A_{pv} is the total area of the solar PV array.

If the temperature variations on the output power for solar PV are considered, Equation (0.13) yields Equation (0.14).

$$P_{pv}(t) = Y_{pv} f_{pv} \frac{G_T(t)}{G_{T,STC}} \{1 + \alpha_p (T_C(t) - T_{C,STC})\} \quad (0.14)$$

Where α_p is the temperature coefficient of power. The average value of this figure depends on solar PV technology. 0.48 for mono-silicon and -0.46 for poly-silicon, $T_C(t)$ is the solar PV cell temperature in the current time step, $T_{C,STC}$ is the solar PV cell temperature under standard test conditions.

3.7 Solar PV System Sizing

The solar PV system includes different components that should be selected according to the system type, site location, and applications. The major components for the solar PV system are the PV module, the inverter, and the battery bank.

3.7.1 Sizing of a standalone PV system

To conveniently and accurately size a PV system, the specific area, Direct Normal Irradiance (DNI) data, and the anticipated load must be defined. The capacity of the PV system, size, and the total number of PV units, and the number of batteries are then calculated. The several factors considered in the design are the amount of energy (kWh) that the solar PV can generate to meet the load demand, kWh/yr generated by the PV system, and the Ah of the batteries required, the area the system will occupy and the cost of production.

The different sizing techniques reported in the literature include intuitive, numerical, analytical, commercial computer tools, artificial intelligence, and hybrid methods (Khatib et al., 2016). This Thesis utilizes the numerical technique for sizing the PV array, batteries, and inverters because of its accuracy coupled with its capability of using linear functions, unlike other methods based on complex algorithms (Khatib et al., 2016).

The energy delivered by a solar PV array aligned in the field is given by Equation (0.15).

$$P_{ac} = P_{dc,STC} * \eta \qquad (0.15)$$

where P_{ac} is the actual ac power delivered, $P_{dc,STC}$ is the rated DC power output under standard test conditions,η is the conversion efficiency, accounting for inverter efficiency and mismatched modules.

3.7.2 Steps followed in sizing the PV array

The insolation data (kWh/m^2) was obtained from the NASA websites for the different sites considered. The worst month (month with the lowest solar irradiance) is designed as it is the minimum guaranteed generation. As shown by Equation **(**0.16), identification of a PV module and using its rated current I_R together with its column efficiency of about 0.9 and a derating factor of 0.9 and the solar insolation of the design month (DNI) yields the Ah/day produced by each solar PV string.

$$Ah = DNI\left(\frac{kWh}{m^2}\right) * I_R * DF \qquad (0.16)$$

Where Ah, DNI and DF are respectively ampere-hours, Direct Normal radiation, and the Derating factor. The number of parallel strings is given by the relation (0.17).

$$Strings\ in\ parallel = \frac{design\ month\ load\ \left(\frac{Ah}{day}\right)}{\frac{Ah}{day}\ per\ \ mod\,u\,le\ in\ design\ month} \qquad (0.17)$$

The number of PV modules in series is determined by the relation (0.18).

$$mod\,u\,les\ in\ series = \frac{system\ \ voltage\ (V)}{No\,min\,a\,l\ \ mod\,u\,le\ voltage\ (V)} \qquad (0.18)$$

3.7.3 Determination of Collector Area

The area occupied and the number of PV cells vary according to type, as each has different parameters. The cell temperature of a PV module is estimated using Equation (0.19).

$$T_{cell} = T_{ambient} + \left(\frac{NOCT - T_{av}}{0.8}\right) * S \qquad (0.19)$$

Where$S$is the insolation under standard test conditions, $NOCT$ is the Nominal

Operating Cell Temperature, T_{av} is the average maximum daily temperature, while S

is the solar insolation (kWh/m^2).

The DC output of a solar photovoltaic panel is defined by Equation (0.20)

$$P_{dc} = PV_{rating}[1 - P_l](T_{cell} - T_{av}) \qquad (0.20)$$

Where P_{dc} is the Solar PV DC output power, PV_{rating} is the rating of the solar PV and P_l is the power loss per degree above T_{ov}

Including the dirt, mismatch, and inverter efficiencies will result in an estimated ac rated capacity of the solar photovoltaic (P_{ac}) described by relation (0.21).

$$P_{ac} = P_{dc} * mismatch * dirt * inverter\ efficiency \qquad (0.21)$$

The energy delivered per year is governed by the Equations (0.22),(0.23),(0.24) and (0.25) as shown.

$$\frac{ED}{yr} = P_{ac} * \frac{DNI_{site}}{day} * CF * 365\ days \qquad (0.22)$$

$$P_{ac} = \frac{\frac{ED}{yr}}{\frac{DNI_{site}}{day} * CF * 365 days} \qquad (0.23)$$

$$P_{dc} = \frac{P_{ac}}{Mismatch * dirt * inverter\ efficiency} \qquad (0.24)$$

$$Area\ occupied = \frac{P_{dc}}{\frac{DNI_{site}}{year} * collector\ efficiency} \qquad (0.25)$$

In the model developed in this thesis, the types of PV modules used are shown in Table 3.1 (Masters, 2004)(Islam et al., 2013)(*Capital Cost Estimates for Utility Scale Electricity Generating Plants*, 2016).

Table 3.1: High Power PV Modules characteristcs

Module type	**Sharp NE K125U2**	**Kyocera KC158G**	**Shell SP150**	**Uni-solar SSR256**
Material	Polycrystal	Multi-crystal	Monocrystal	Triple junction
Rated power (P_{dc}) (W)	125	158	150	256
Voltage at max power (V)	26	23.5	34	66
Current at max power (A)	4.8	6.82	4.4	3.9
Open circuit voltage (V)	32.3	28.9	43.4	95.2
Short circuit current (A)	5.46	7.58	4.8	4.8
Length (m)	1.19	1.29	1.619	11.124
Width (m)	0.792	0.99	0.814	0.42
Efficiency (%)	13.3	12.	11.4	5.5
Capital cost ($)	525	663.6	630	1075
Derating factor (%)	90	90	90	90
Replacement cost ($)	525	663.6	630	1075
Lifespan (years)	25	25	25	25
O&M cost ($)	121.25	153.26	145.5	248.32

3.7.4 Solar PV Costing

The initial cost of the solar PV module based on Table 3.1 is defined by Equation (0.26).

$$init\ \ cos\,t_{pv} = X_{pv,series} * cos\,t_{pv}\,(type).\left(1 + \%CC_{pv}\right) + fixed \rightleftarrows\ \ cos\,t\,s_{pv} \tag{0.26}$$

Where $init\ \ cos\,t_{pv}$ is the initial cost of a solar photovoltaic module $X_{pv,series}$ is the number of PV panels in series, $cos\,t_{pv}$ is the cost of solar PV, $\%CC_{pv}$ is the percentage of capital costs added to the BOP while $fixed\ \ cos\,t\,s_{pv}$is the fixed cost of Solar PV

The operation and maintenance costs of Solar PV are defined by Equation (0.27), which are percentages of the capital cost of the component.

$$OP_{cost},PV(x,years) = fixedper \rightleftarrows year_{per \rightleftarrows annum},pv * OP\%\ CC_{per,PV}) * R_{yearly}(x\ years) \tag{0.27}$$

Where $fixedper \rightleftarrows year\ OP\%\ CC$and R_{yearly} are the yearly fixed operation and maintenance costs emanating from solar PV, the percentage of capital costs arising from PV operation each year, and the discount rate. In this thesis, the replacement cost of solar PV is after every 30 years, and as such, for a project whose lifetime is 25 years, the replacement cost is zero. The replacement cost of solar PV is as described by Equation (0.28).

$$Re\,p\,lacement\ \ cos\,t_{pv} = initial\ \ cos\,t_{pv} * \frac{1}{(1+r).Re\,p\,lacement\ \ year,PV} \tag{0.28}$$

Where $Re\,p\,lacement\ \ cos\,t_{pv}$ is the overall PV replacement costs, $initial\ \ cos\,t_{pv}$ is the PV initial costs is the $Re\,p\,lacement\ \ year,PV$ defines the year when solar photovoltaic panels are replaced.

3.7.5 Inverters

The inverters used in this thesis are shown in Table (Masters, 2004) (*Capital Cost Estimates for Utility Scale Electricity Generating Plants*, 2016) (Islam et al., 2013). They were chosen for this work because they are readily available in the market. The inverter costs are described by Equation (0.30).

$$init\ \ cos\,t\,s = \sum_{i=1}^{no\ of\,inv} n, inv, i, series * inv\ in\ series, i, parallel * cos\,t_{inv} * (1 + \%CC_{inv}) + fixed\ \ cos\,t\,s_{inv} \qquad (0.29)$$

Where $n, inv, cos\,t_{inv}, \%CC_{inv}, fixed\ \ cos\,t\,s_{inv}$ is the number of inverters in series

or parallel, cost of inverters, and percentage capital cost of the inverter, respectively.

The replacement costs of the inverters depend on the lifespan of each inverter, as shown by Equation (0.30).

$$replacement\ \ cos\,t\ \ inv = \sum_{i=1}^{No\ of\ repl\ inv} init\ \ cos\,t\ \ inv.\frac{1}{(1+r)^{repl,year,inv}i} \qquad (0.30)$$

Table 3.2: Cost and other Parameters for the Inverters

Model Type	**STXR1500**	**STXR2500**	**PV-10**	**SB2000**	**SB2500**
Power (kW)	15	25	100	20	25
Efficiency (%)	92	94	95	96	94
Capital cost ($)	1800	3000	12000	2400	3000
O&M cost ($)	79.12	79.12	79.12	79.12	79.12
Replacement cost ($)	1800	3000	12000	2400	3000
Lifetime (years)	10	10	10	10	10

3.7.6 Battery sizing

The total Ah determines the storage required to meet the load (Ah/day) throughout (both day and night) and the number of storage hours needed. To find the correct size of the battery bank used, the following steps were followed.

i.) The total watt-hours consumed by electric appliances for households and other facilities such as hospitals and churches are determined.

ii.) The total electric load obtained in item (i) is divided by the inverter efficiency to achieve the required DC load, as shown in Equation (0.31).

$$DC \rightleftarrows load\left(\frac{kWh}{day}\right) = \frac{AC\ load}{Inverter\ efficiency} \tag{0.31}$$

iii.) Item (ii) is divided by the maximum depth of discharge (MDOM) to obtain the usable battery capacity. For most batteries, this value is fixed at 0.8.

iv.) The value in item (iii) is divided by the nominal voltage (for this thesis, 24V is considered nominal voltage as most appliances nowadays are designed for this voltage). This is done to obtain the load the batteries are supposed to supply.

v.) The quotient of item (iv) is multiplied by the number of days the system can operate when there is no power produced by the Photovoltaic solar panels (day of autonomy). This is done to obtain the total battery, Ah. This is shown by, as shown by relation of Equation (0.32).

$$usable\ storage\ (Ah) = total\ load\left(\frac{Ah}{day}\right) * days\ of\ storage\ (days) \tag{0.32}$$

Therefore, battery storage will be calculated using Equation (0.33).

$$battery\ storage\ capacity = \frac{\frac{Ah}{day} * no\ of\ days\ of\ storage}{MDOM * DR} \tag{0.33}$$

Where $MDOM$ is the maximum depth of discharge and DR is the % discharge rate

The different types of batteries considered for the design of the SPECA modeling tool are as shown in Table 3.3 (Masters, 2004). The choice of the battery was based on its availability locally and has been extensively used in the literature surveys.

Table 3.3: Different Battery Characteristics

Battery	**MDOD (%)**	**Cycle life (cycles)**	**Lifespan (Years)**	**Efficiency%**	**Cost ($/kwh)**
Lead acid	20	500	1-2	90	50
Golf cart Lead	8	1000	3-5	90	60
Deep cycle lead	80	2000	7-10	90	100
Nickel-cadmium	100	1000-2000	10-15	70	1000
Lithium ion	80-95	300-500	2-3	95	140
Nickel-metal Hydride	100	1000-2000	8-10	70	1200

3.7.7 Battery Costing

The initial investment in the battery bank is described by Equation (0.34).

$$Ini\ \ cost_{bat}\,(n\ years) = \sum_{i=1}^{no\ of\ bat\ banks} n_{bat,i,series}.x\ Bat,i,parallel.cost_{bat}\left(x_{size,bat,i}\right).\left(1+\%CC_{bat,i}\right) + fixed\ \ costs_{Bat,i,bank} \qquad (0.34)$$

Where $n_{bat,i,series}$ is the number of batteries in series, $x\ Bat,i,parallel$are the number of batteries in parallel, $\%CC_{bat,i}$ represents the percentage of the capital costs of the batteries $fixed\ \ cos\,t\ s_{Bat,i,bank}$. The installation cost and the balance of plant costs are accounted for in the fixed costs. The battery operation and maintenance costs are defined by Equation

(0.35).

$$O\&M\ \ cos\,t_{bat}\ (n\ years) = \sum_{i=1}^{no\ of\ bat\ banks} \left(fixed\ \ cos\,t_{per,yr,bat,i} + O\&M\%CC_{bat,i}\right) \quad (0.35)$$

$$+fixed\ \ cos\,t\ s_{per,yr,bat,i}$$

The replacement costs of the battery are done whenever the battery is faulty and requires replacement. The governing cost equation for the battery is as shown by Equation (0.36).

$$Replacements_{Bat} = \sum_{i=1}^{m}\sum_{j=1}^{n}(\text{initial cost}\ , Bat, bank, i)\,.\left(\frac{1}{(1+r)^{j(repl,year,bat,i)}}\right) \quad (0.36)$$

Where i=1,2,3…m is the number of battery banks to be replaced, j=1,2,3…n is the replacement cost

3.8 Electric Load Estimation

The design process of the PV system to serve a given region starts with load estimation. This research work will design a solar PV for middle-class households. Table 3.4 is a tabulation estimate per household power consumption in Kenya.

Table 3.4: Electric Load Estimation

Appliance	Quantity	Power rating(kW)	Period of usage(hrs/day)	Annual consumption (kWh)-365 days
Fridge (14.cu ft)	1	0.3	24	2628
Television (19-in)	2	0.068	8	397.12
Electric Kettle	1	1	0.5	182.5
Desktop computer	1	0.3	6	657
Laptop	2	0.036	6	157.68
Lights	10	0.03	5	547.5
Security Lights	2	0.045	8	262.8
Geyser	1	3	1	1095
Heater	2	2	3	4380
Microwave	1	1	0.33	120.45
Annual consumption				10,428.05

3.9 Energy Payback Time (EPBT) and Energy Return on Energy Invested (EROI)

The energy payback time (EPBT) is defined as the years required by an energy resource to generate the same amount of energy to compensate for the energy used throughout its lifecycle (Peng & Lu, 2013). Energy Return on Energy Invested (EROI) aggregates the amount of energy produced by an energy system in its entire life compared to the amount of energy required to create and implement such a system (Bhandari et al., 2015). EROI is a dimensionless ratio of the amount returned to society to the amount needed to make that energy (embedded energy) (Bhandari et al., 2015). The EPBT and EROI are calculated, as shown by Equations (0.37) and Equation (0.38).

$$EPBT\ (year) = \frac{Embedded\,(primary)\,Energy(MJm^{-2})}{Annual(primary)\ generated\ bysystem\,(MJm^{-2}yr^{-1})}$$

$$= \frac{W_1\,(MJm^{-2})}{W_2\,(MJm^{-2}yr^{-1})} = \frac{W_1}{\left(DNI * \eta * \frac{PR}{}\,\varepsilon\right)} \quad (0.37)$$

$$EROI = lifetimeEnergy\ \frac{output}{Embedded}\ energy$$

$$\frac{W_3\,(MJm^{-2})}{W_1\,(MJm^{-2}yr^{-1})} = \frac{W_2\,(MJm^{-2}) * LT(\,year)}{W_2\,(MJm^{-2}yr^{-1}) * EPBT(year)} = \frac{LT(year)}{EPBT(year)} \quad (0.38)$$

Where W_1 is the Embedded (primary) energy (MJ m^{-2}), W_2 is the annual energy generated by the system expressed as primary energy (MJ m^{-2} yr^{-1}), W_3 is the total energy generated by the system over its lifetime expressed as primary energy (MJ m^{-2}) and ε is the electrical to the primary energy conversion factor

DNI is the total solar insolation incident on a surface per year (MJ m^{-2} yr^{-1}), η is the average module efficiency (%), PR is the system performance ratio (%), $LT$is the lifetime of the system (years). The commonly used EPBT and EROI values for Solar PV generation are as shown in Table 3.5 (Bhandari et al., 2015).

Table 3.5: EROI and EPBT Constants

Parameter	**Value**
Conversion factor (ε)	0.35
Average module efficiency (η)	0.15

Performance Ratio (PR)	0.75
Direct Normal Irradiation (DNI)	Depends on the region
A lifetime of the energy system (LT)	25 years

The EPBT and EROI are considered only in the two phases: the operational phase and the decommissioning phase. During normal operations of solar PV, there is no external source of energy for the PV modules, structures, cables, and electronic devices. The control devices draw power from the solar PV module itself. The charge controller and the inverter are assumed to consume 52.5kWh/year and 31.5kWh/year, respectively (Miguel & Martı, 2009). The per-unit cost of recycling, Solar PV systems, and lead-acid batteries is estimated at $8.81/kWh.

At the end of the lifespan of the solar photovoltaic, decommissioning takes place. During this, the solar PV modules would be buried in landfills, and only the aluminum frames will be recycled, and all electronic equipment is not recycled. The burying of solar PV panels in landfills is unlikely to adversely affect human health (Miguel & Martı, 2009). Table shows the energy requirement during the decommissioning phase of a solar photovoltaic (Miguel & Martı, 2009).

Table 3.6: Energy Requirement in the Decommissioning phase for Solar PV facility (kWh)

Element	Recycling process	Transport to recycling plants	Totals
PV frames	125	0.60	125.60
Supporting structures	1405.18	5.62	1410.80
Cables	611.84	0.44	612.28
Lead-acid batteries	3316.77	48.24	3365.01
Totals	5458.79	54.9	5513.69

Section 0 describes the site selection procedure.

3.10 Location Selection Procedure

The Techno-Economic model developed in this thesis will make the site selection considering the resource availability and the potential environmental impacts, as shown by the flowchart in Figure 3.3. To select the best site for solar PV deployment, the SPECA modeling tool uses two different criteria that are, Direct Normal Irradiation (DNI), land use, and location, as described in Table 3.7. DNI is the most crucial aspect as it defines the potential electric production from a given site expressed in kW/hr/m^2. Land use establishes the land use types in a given location. In this thesis, land utilization and occupancy are described in \$/ha.

Table 3.7: Criteria, Factors, and Indicators for Site Selection

Criteria	Factors	Indicators
Land-Use Type (LUT)	Species richness	3-8 plants/m^2-poor species richness-land already in use 8-15 plants/m^2 for medium species richness- land used and left 15-28 plants/m^2 high species richness- natural land
Direct Normal irradiation (DNI)	Solar irradiation potential (kWh/m^2/yr)	741–1414 1414–1563 1563–1640 1640–1717 1717–above

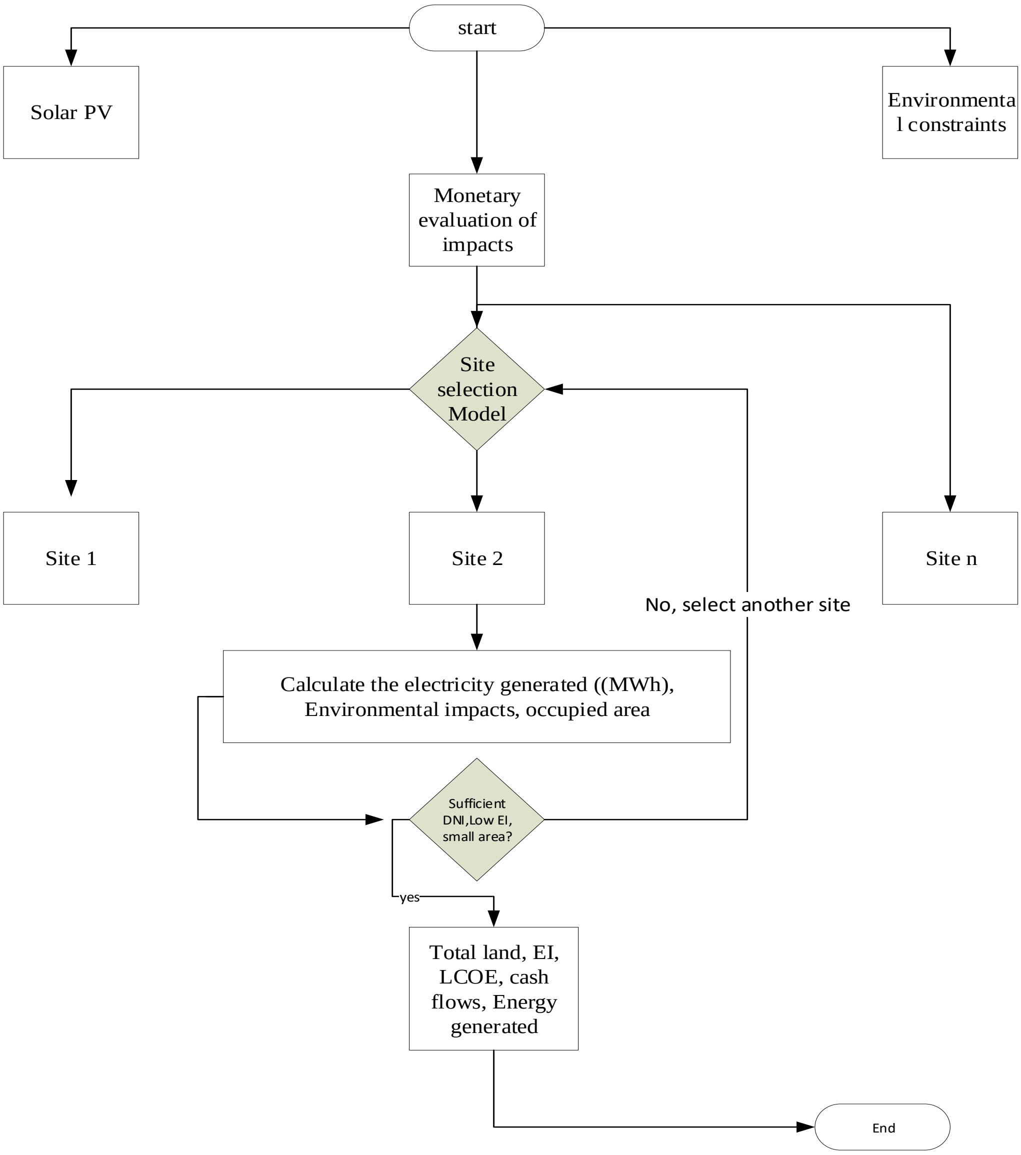

Figure 3.3: Flow Chart for Site Selection Criteria

Accordingly, using Table 3.7 and Figure 3.3, the SPECA modeling tool selects the best site for Solar PV deployment. Areas with the best DNI and lowest species richness are considered best for Solar PV deployment, while sites with the lowest DNI and high species richness factor are not favorable for deployment.

3.11 Environmental Impact Assessment of USSE

The environmental impact assessment involves impacts of USSE taking into account the following:

i.) Ecological impacts that are likely to occur as a result of installing USSE in a given location for a given duration of time
ii.) The severity of the impact on the environment in a particular region.
iii.) Whether the changes to the environment as a result of installation are redeemable and minimize these impacts.

The impacted biodiversity resulting from the installation has been gathered from the available current literature, the Ecosystem Service Value Database (EVSD), and the environmentalists. Predicting the likely environmental impacts of Solar PV and the valuation of their monetary value forms the core of the environmental impact assessment process. The prediction of environmental impacts considers the magnitude of impact, the extent of the impact, duration, and significance.

The importance of the impact is defined by the severity of each potential impact, which further indicates whether the impact is reversible or irreversible. The extent of the impact looks into the zone of influence of the impact considered. In this thesis, the environmental impacts are limited to the site in which the USSE is installed. The environmental impacts will be considered for the whole life span of the USSE. The impact significance is evaluated using the cost of mitigation, generally referred to as the restoration cost approach (Goedkoop et al., 2009). The importance of environmental impacts has been assessed using their respective monetary terms. The structure of the methodology of identification and assessment is as shown in Figure 3.4.

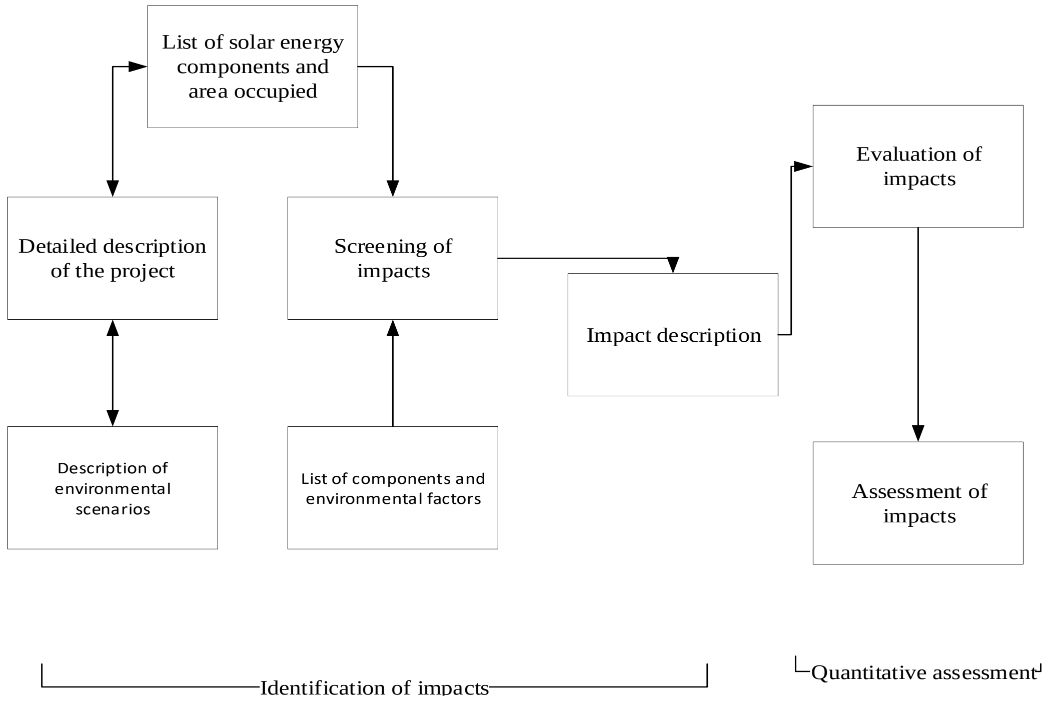

Figure 3.4: Methodology for the Environmental Impact Assessment

The methodology followed in the quantification and monetary valuation of externalities in this thesis is based on the Impact Pathway Approach (IPA) used by the European Union (EU) to undertake the Externalities of an Energy project, famously referred to as the ExternE (Alex & Pouris, 2008). This methodology is applied in the life cycle of energy production and the impacts associated with energy production. The valuation of externalities has been deduced in the damage function associated with a particular impact described in Equation (0.39).

$$ESV = \sum A_k * VC_k \qquad (0.39)$$

Where ESV is the ecosystem service value estimate, A_k is the area in hectares, VC_k is the value coefficient of the ecosystem ($/ha/year)

The different values of VC_k used as proxies for the different biomes were obtained from (R. S. De Groot et al., 2002). Section 0 discusses the different environmental impact categories.

3.12 Environmental Impact categories

The externalities of solar PV in this thesis has been classified according to the following:

i.) Air pollution emissions include SO_2, NO_x, PM_{10}, and some heavy metals. These air pollutants have direct impacts on human health, flora, and fauna. Greenhouse gases, including CO_2, methane, chlorofluorocarbons, contribute to global climate change, human health, and impacts on agriculture.

ii.) Water use and water quality. Water is affected by electricity production through massive consumption and thermal pollution, which may affect aquatic life.

iii.) Land use impacts include the occupation of land that would have otherwise been used for other economic activity, waste disposal harmful to the soils, and impacts on wild animal habitats.

3.13 Quantification and Mapping of the Economic Service Value of Biodiversity Goods and Services

3.13.1 Ecosystem Goods and Services Sub-Model

This sub-model is concerned with evaluating the opportunity cost of the lost ecosystem goods and services resulting from the installation of the PV system. The value of the different ecosystem goods and services per biome in the regions considered were adopted from (R. S. De Groot et al., 2002). They are divided into four diverse ecosystem services: regulating functions, provisioning services, production services, and information functions. Each of the four is also divided into different subcategories, as shown in Table 3.8 (R. S. De Groot et al., 2002).

Table 3.8: Valuation of Ecosystem Goods and Services

Ecosystem goods and Services	**Monetary Valuation ($/ha/year)**		
Regulating functions of Ecosystems	Min	Median	Max
Regulating air	7-265	139.5	265
Climate change	88-268	178	268
Disturbing ecosystems goods and services	2-7240	3622	7240
Water uptake and usage	2-5445	2723.5	5445
Water supply	3-7600	3801.5	7600
Soil erosion	29-245	137	245
Soil maturity and formation	1-10	5.5	10
Soil nutrients recycling	87-21,100	10593.5	21100
Plants pollination	14-25	19.5	25
Biological control	2-78	40	78
Habitat provision			
Habitation services	3-1523	763	1523
Nursery function	142-195	168.5	195
Production functions			
Food	6-1014	510	1014
Raw materials such as wood, charcoal	6-1014	510	1014
Genetics	6-112	59	112
Medicinal value	6-112	59	112
Information functions			
Aesthetic information	7-1760	883.5	1760
Recreation and tourism	2-6000	3001	6000
Cultural and artistic	1-25	13	25
Spiritual and Historic	1-25	13	25
Spiritual and Historic	1-25	13	25
Science and Education	1-25	13	25

The total value of the ecosystem goods and services for each biome is computed according to Equation **(0.40**)

$$UVE = UVE + \Delta UVE \qquad (0.40)$$

Where UVE is the per-unit value of the ecosystem goods while ΔUVE is the escalation cost of the ecosystem goods. The amount of ecosystem services is defined by Equation (0.41).

$$UVS = UVS + \Delta UVS \qquad (0.41)$$

Where UVS is the per-unit value of the ecosystem services offered by plants and animals while ΔUVS in the unit value of the ecosystem services provided by plants and animals.

3.13.2 Biodiversity Loss and Monetary Valuation due to Airborne Emissions Pollutants

As was depicted in section 0, the common GHG gases that draw a lot of concern to the biodiversity loss and cascaded reduction in crop harvest, species extinction is the particulate matter (PM), ozone layer (O3), carbon monoxide (CO), Sulphur dioxide (SO_2), Nitrous oxide (N_2O), methane (CH_4), lead (Pb) and the volatile organic compounds (VOC) (Roth & Ambs, 2004b) (Diakoulaki, 1997). The number of species in a given area is estimated using the species-area relationship (SAR) model described by Equation (0.42) (Chaudhary et al., 2015).

$$S = cA^{z} \qquad (0.42)$$

Where S were number of species in a given biome, c is the species richness factor, A is the area occupied and z is a constant that depends on the sampling regime and scale

The constants of the species-area relationship, that is, species richness factor (c) and the sampling regime(z), are shown in Table 3.9 (Pereira HM, 2006)(Koellner & Scholz, 2008).

Table 3.9: Constants of the Species Area Relationship

Parameter name	**Values derived**
Species richness factor ( )	3-8 plants/m^2-poor species richness-land already in use 8-15 plants/m^2 for medium species richness- land used and left 15-28 plants/m^2 high species richness- natural land
taxonomic group constant (z)	0.35

The number of species disappearing due to land-use change is referred to as the Potentially Disappeared Fraction (PDF)(Preiss & Klotz, 2008). PDF will be used as a characterization factor and measure the species (flora and fauna) missing in a particular area relative to the reference. It can be interpreted as the relative decline in biodiversity as a result of land-use change. The PDF of a species is mathematically expressed as a difference between the number of species under the reference conditions created by the conversion, as shown by Equation (0.43) (Preiss & Klotz, 2008).

$$PDF = \frac{1-S_1}{S_0} \qquad (0.43)$$

where S_0 denotes the initial species density in the area occupied by USSE and S_1 is the species richness after USSE occupation. The PDF of various biomes considered in this thesis was adopted from (Preiss & Klotz, 2008) and are shown in Table 3.10 (Preiss & Klotz, 2008).

Table 3.10: Biomes Characteristics

Land-use type	Species per Sqm	PDF
Conventional arable	10	0.74
Fibre crops	11	0.73
Fibre/energy crops	15	0.63
Heathland	18	0.56
Peat bog	19	0.53
Less intensive meadow	19	0.53
Semi-arid plants	23	0.43
Rail fallow	24	0.4
Rural settlement	25	0.38
Green urban	29	0.27
Rail embankments	26	0.2
Mining fallow	38	0.04
Natural grassland	39	0.02

The externality cost XC ($/kWh) for each pollutant emission is determined using equation (0.44) and shown in

Air Pollutant	Estimate damage factor ($/ton)	Emission factor (EF) Modules (kg/kWh)	Emission factor (EF) BOS(kg/kWh)
CO_2	26.4	1.94E-02	7.49E-03
SO_2	1869.77	8.96E-05	2.94E-02
NO_x	7919.03	1.46E-12	4.72E-05

$PM_{2.5-10}$	4839.41	3.16E-06	5.08E-08
VOC	5265.79	1.94E-05	1.22E-05
Co	1055.87	0.082	0
Pb	17,760,000	7.56E-08	6.08E-08
PM10	13012	7.06E-11	3.74E-08
PM2.5	21688.29	3.16E-06	5.08E-08
As	88,800	1.46E-09	9.94E-09
Cd	43290	1.40E-09	9.94E-09
Cr	34965	3.55E-09	4.00E-08
Nitrates	6440.22	9.86E-11	3.78E-10

Table .

$$\boldsymbol{XC = DC * EF} \qquad (0.44)$$

Where DC is the Damage Cost ($/ton of pollutant), EF is the Emission Factor

$(\frac{ton_{pollu\ tan\ t}}{kwh})$.

The total $EF$is the summation originating from the modules and from the BOP, XCis

the Monetary valuation of the global warming potential of the different pollutant emissions defined as the cumulative radioactive forcing between the present and future time horizon.

Table 3.11: Valuation of External Costs of Solar Photovoltaics Based on the Damage Factor Approach from GHG

Air Pollutant	Estimate damage factor ($/ton)	Emission factor (EF) Modules (kg/kWh)	Emission factor (EF) BOS(kg/kWh)
CO_2	26.4	1.94E-02	7.49E-03
SO_2	1869.77	8.96E-05	2.94E-02
NO_x	7919.03	1.46E-12	4.72E-05
$PM_{2.5-10}$	4839.41	3.16E-06	5.08E-08
VOC	5265.79	1.94E-05	1.22E-05
Co	1055.87	0.082	0
Pb	17,760,000	7.56E-08	6.08E-08
PM10	13012	7.06E-11	3.74E-08
PM2.5	21688.29	3.16E-06	5.08E-08
As	88,800	1.46E-09	9.94E-09
Cd	43290	1.40E-09	9.94E-09
Cr	34965	3.55E-09	4.00E-08
Nitrates	6440.22	9.86E-11	3.78E-10

3.14 Morbidity and Mortality Submodel

This section discusses the morbidity and mortality that occurs during construction, operation, and the decommissioning stage of USSE. The work-related and non-work-related accidents considered in this thesis are for the non-organization for Economic Corporation and Development countries where Kenya is classified (N.Nkambule, 2017). The per-unit prices for treating persons suffering injuries or mortalities while working with USSE were based on the studies done by (Preiss & Klotz, 2008). This sub-model consists of two variables, viz. unit morbidity value, and the unit mortality value. The per-unit morbidity value UV_{mob} ($/person) is estimated using Equation (0.45).

$$UVmobmob_{mob} \qquad (0.45)$$

Where $\Delta UV_{mob}(t)$ is the discounted change in morbidity value

The unit mortality values (UV_{mot},$/person) in this thesis were obtained from N.Nkambule (2017) and are described by Equation (0.46)

$$UV_{mot}(t) = UV_{mot}(17413) + \Delta UV_{mot}(t) \qquad (0.46)$$

The unit mortality and morbidity values derive their costs from USSE construction, operation/phase, and decommissioning phases. The parameters used for the fatalities/mortality and morbidity modeling are shown in Table 3.12 (N.Nkambule, 2017)(Pv, n.d.). The number of fatalities and morbidity occurring during the plant's lifespan is approximated by Equations (0.47) and Equations (0.48).

$$No\ of\ fat = fat/(MWh * MWh_{gen}) \qquad (0.47)$$

Where$No\ of\ fat$ is the number of fatalities for the lifespan of the solar PV system (25 years), $\frac{fat}{MWh}$is the number of fatalities per MWh ,MWh_{gen} is the total energy generated for the lifespan of the plant, $no\ of\ morb$is the total number of morbidity for the total lifespan

$$No\ of\ Mob = \frac{Mob}{MWh * MWh_{gen}} \qquad (0.48)$$

Where $No\ of\ Mob$ is the number of disabilities/morbidities for the lifespan, $\frac{Morb}{MWh}$ is the disabilities per MW.

Table 3.12: Universal Damage Restoration Values used for Morbidity and Fatalities model

Parameter	Unit	Value
Unit mortality value	$/person	17413
Unit Morbidity	$/person	1804
Fatalities per million tons of concrete	Persons/million tons	0.159
Fatalities per million tons of steel	Persons/million tons	2.0158923
Fatalities per million tons of limestone	Persons/million tons	0.2906977
Fatalities per MWh	Persons /MWh	2.6E-5
Injuries per MWh	Persons /MWh	1.0E-5

3.15 Chapter Conclusion

The development of the SPECA modeling tool has been described in this chapter. The component sizing procedure, the SPECA costing methodology, and externalities valuation procedures were presented. The chapter employs mathematical formulation of all the strategies done to achieve the LCOE methodology by incorporation of externalities of solar PV. The source codes for the SPECA modeling tool are written in visual basic while the database has been developed using the Structured Query language (SQL). SPECA model derives the interactions of the solar photovoltaic system with the externalities.

CHAPTER FOUR

RESULTS, ANALYSIS, AND DISCUSSION

4.1 Introduction

In Chapter Three, a detailed analysis of the mathematical description and background of the SPECA modeling tool was done using the LCOE methodology as a benchmark. SPECA modeling tool has a GUI and a database. The SPECA modeling tool was developed using the Visual Basic programming language computing platform. Visual Basic programming is an object-oriented, robust, and independent language. The reference database used was a relational database developed using the Structured Query Language (SQL). Section 0 describes the structure of the SPECA modeling tool.

4.2 Structure of the SPECA Modelling Tool

The SPECA modeling tool developed is used for sizing and determining the economic viability of solar PV systems in a given location. The input parameters to the SPECA modeling tool include weather data, load demand, ecosystem goods and services, and the solar photovoltaic component characteristics and costs. After computation, the software results output includes energy generated, LCOE, net present value (NPV), number of panels used, the total area occupied by the plant and the BOP, and the number of batteries. The SPECA modeling tool incorporates and synthesizes the externality cost of solar photovoltaics. The SPECA modeling tool's most outstanding achievement is its ability to incorporate the externalities (associated environmental costs) in the output metrics referred to as LECOE and LTCOE. The user guide of the SPECA modeling tool is described in Appendices.

4.3 Baseline Results

The SPECA modeling tool demonstrated through simulations how monetization and incorporation of externalities of USSE were achieved using the advanced LCOE methodology. The externalities that have been monetized and incorporated in the modeling of Solar PV using the SPECA modeling tool are divided into two major categories: techno-economic and environmental indicators, as shown in Table . The Techno-economic indicators measure the plant's performance, anticipated costs incurred by investors of USSE and the surrounding communities. On the other hand, the environmental indicators reflect the externalities of USSE, which were quantified and monetized in this thesis.

Table 4.1: Techno-Economic and Environmental Indicators

Techno-Economic indicators	Environmental Indicators
• Energy Generated in the whole lifespan • Cost of energy production • Levelised cost of electricity (LCOE) • Levelised externality cost of electricity • Net present value • PV externality cost	• Water pollution • Fatalities and morbidity • Ecosystems service loss • Total emissions

As earlier explained in Chapter Three, the SPECA modeling tool is a techno-economic assessment of the viability of solar energy utilization in the different regions of Kenya. Therefore, the software generates results according to the inputs given, including the location, Solar PV components, land use type, and biodiversity type. Accordingly, the SPECA modeling tool results are achieved through case studies of the different regions incorporated in the tool. Section 0 discusses two case studies using the SPECA modeling tool for simulating and sizing solar PV for Lodwar, Turkana county, and Mahiga, Nyeri County. The data considered for the two case studies is as shown in table 4.2.

Table 4.2: Parameters of Simulation for Gatarakwa and Lodwar

Location	**DNI kWh/m^2/yr**	**Land Cost ($)**	**SAR Species/ m^2**	**Battery used Golf cart**	**PV used Kyocera**
Gatarakwa, Nyeri County	1600	10,000	8-15	Golf cart	Kyocera
Lodwar, Turkana County	1800	4800	3-8	Golf cart	Kyocera

4.4 SPECA Modelling Tool Application and Results of Lodwar and Nyeri Kenya

4.4.1 Electricity production

Several factors influence the amount of electricity generated, including plant availability hours, load factor, idle capacity, BOP, and plant capacity. An increase in the load factor, availability hours, and plant capacity positively affect power generation. On the other hand, an increase in idle capacity and BOP affects electricity generation negatively. In coming up with the SPECA modeling tool, the load factor was assumed to be 25%, while the BOP was considered 20% (Miller & Keith, 2018), which is mainly applied in many photovoltaic studies.

Among other metrics, the SPECA modeling tool calculates for a lifespan of 25 years assumed in this work are the yearly energy generated, LTCOE, LCOE, LECOE, cashflows, area occupied, number of batteries, and the number of solar panels as shown in table 4.3. As shown byFigure 4.1, the yearly energy delivered varies according to the DNI, estimated at an average of 1800kWh/m^2/yr. The cumulative energy production in Turkana for the lifespan of 25 years was 790,338.201 MWh. The area required for installation to meet the electricity demand was estimated to be

194594.6 m^2 of land that required about 116,944 solar photovoltaic panels and 13350 batteries for an estimated load of 2000 houses.

Table 4.3: Comparison of Electricity production and land use factor for Mahiga and Lodwar

Location	**Cumulative energy delivered (MWh)**	**No of solar photovoltaics**	**Number of batteries**	**The area occupied (m^2)**	**DNI kWh/m^2/yr**
Gatarakwa, Nyeri County	505,617.549	116,944	13350	222,144	1600
Lodwar, Turkana County	790,338.201	70894	20025	194,594	1800

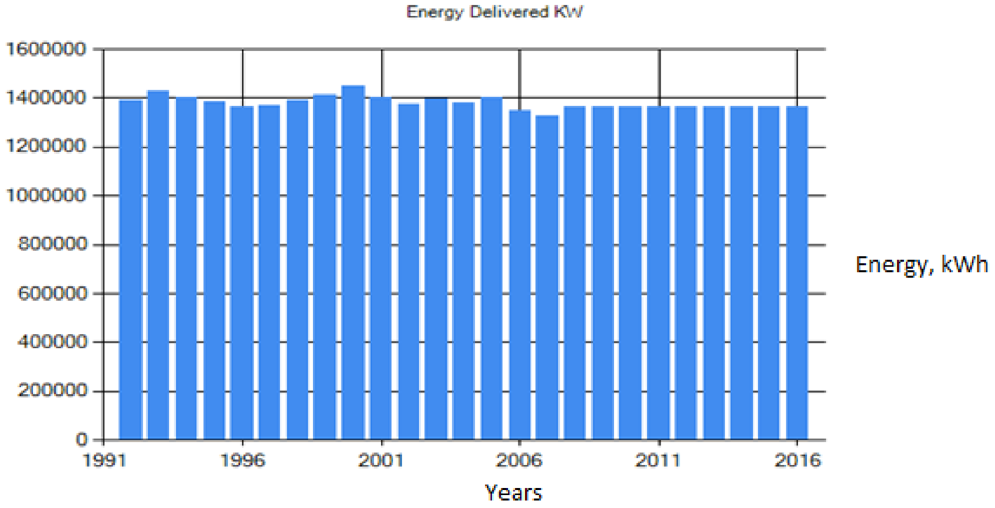

Figure 4.1: Yearly Energy Generated (Lodwar)

4.5 Cost of Electricity Production Using the SPECA modeling Tool

The techno-economic indicators linked to energy production with USSE include electricity generation costs made up of capital costs, residual value, operation and maintenance costs, and replacement costs. LTCOE, LECOE, and LCOE are capital cost, operation and maintenance costs, replacement cost, residue value, and energy production. In contrast, the Net Present Value (NPV) comprises cumulative PV and the incremental present value cost. The cost of electricity production from USSE using the SPECA modeling tool is shown in Table 4.4.

Table 4.4: SPECA software outcome for the Life cycle costs of Gatarakwa and Lodwar USSE

Output variable	**Units**	**Lodwar**	**Gatarakwa**
Capital cost	$ million	153.5	164.53
Operation & maintenance cost	$ million	20.5	22.072
Replacement cost	$	46,496.93	46,662.83
The total cost of Generation	$ million	174.009	187.4
LCOE	$/kWh	11.149	20.629
LTCOE	$/kWh	11.799	21.501
LECOE	$/kWh	0.65	0.872
DNI	kWh/m^2/yr	1800	1565

The SPECA modeling tool estimates the total electricity generation costs in Lodwar and Gatarakwa at about $ 174 million and $187.4 million, respectively. The generating cost components contributing significantly to the overall generation cost are the capital and O&M costs, which constitute 88.1 % and 11.7% individually. In comparison, the replacement cost accounts for 0.2% for Lodwar. The capital, O&M, and replacement costs in Gatarakwa are 87.8%,12.1%, and 0.4%.

The LTCOE, LECOE, and LCOE computations over the 25 years lifespan of the solar PV were arrived at by discounting all the life cycle costs to present values. A discount rate of 5% was used in this thesis. The LCOE, LTCOE, and LECOE for generating electricity in the Lodwar district were each found to be \$11.149 , \$11.214, and \$0.065, respectively. All the three costs computations done using the SPECA model are nominal (current), meaning that the inflation rates are taken into account while determining the future costs of USSE. LCOE, LTCOE, and LECOE are further discussed in section 0.

The SPECA modeling tool computes the NPV, which examines the cash inflows and cash outflows, as shown in Figure 4.2 and Figure 4.3. The cash inflow indicates the revenue generated from selling energy, while the cash outlow is the cumulated yearly expenditure over the plant's lifespan. The two cash flows decrease as the plant approaches its operational lifetime of 25 years. This is caused by components degradation rates such as the core generation components such as the solar PV and the batteries, which increases the variable costs, fixed operation, and maintenance costs, reducing the net income earned from the sale of energy.

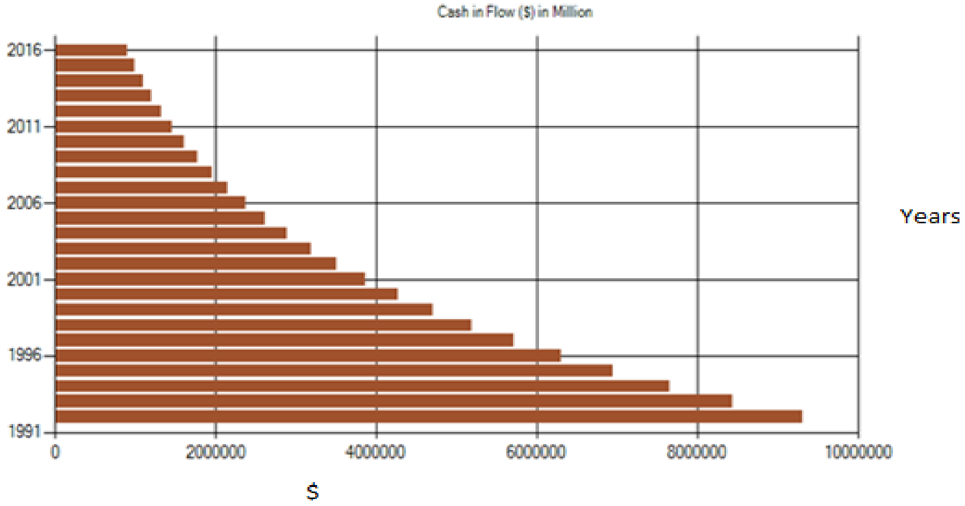

Figure 4.2: Cash inflow for Lodwar

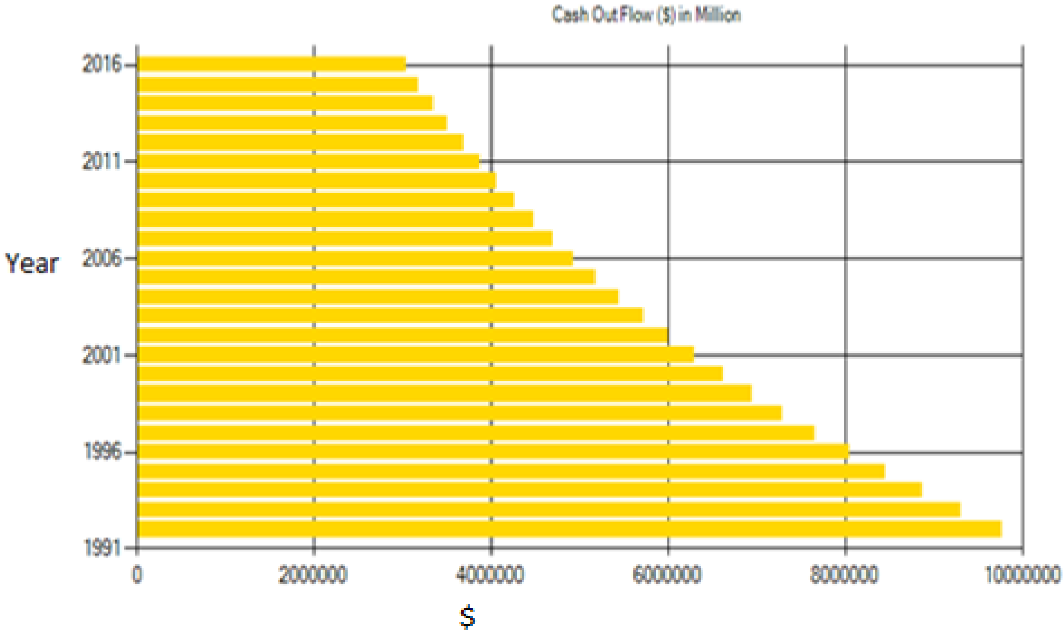

Figure 4.3: Cash outflow for Lodwar

4.5.1 Externalities of USSE

The externalities quantified, monetized, and incorporated in the SPECA modeling tool include water use, pollution, human health (fatalities and morbidity), ecosystem goods and services loss (biodiversity loss), and GHG emissions. The SPECA modeling tool examined and incorporated the externalities of solar PV exclusively in the generation phase.

The fatalities and morbidity values indicate the number of deaths and injuries during the USSE life cycle. SPECA model estimates about 24 deaths likely to happen to the personnel working in the USSE sites and the general public during its life cycle. The model further estimates that nine persons are likely to suffer injuries during the construction and operation of USSE.

On the other hand, land use and land-use efficiency were also computed by the SPECA model. The SPECA model calculates the total land area occupied by considering the total area occupied by the solar PV panels and an additional 30% of the space attributed to the BOP. The BOP includes land used for the roads and buildings. The tool estimates the PDF based on the land use type that existed before the installation of USSE. SPECA modeling tool estimates the total number of species and the PDF for the different land-use types, as shown in Table 4.5. Accordingly, the species per Sqm are the number of species occurring in a given land use type per square metre, and PDF denotes the number of species that are likely to be lost or displaced when USSE is installed. SPECA modeling tool calculates the total number of species likely to be in a given land use type, the displacement when USSE is installed, and the number of species that remain after installation and running of the USSE.

Table 4.5: Potentially Disappeared Fraction and Land Use Types

Land-Use Type	Species per Sqm	PDF	Remaining Species	Displaced Species	Total number of Species
Conventional arable	10	0.74	577577	1643872	2221449
Fibre crops	11	0.73	659770	1783823	2443594
Fibre/energy crops	15	0.63	1232904	2099269	3332173
Heath land	18	0.56	1759387	2239220	3998608
Peat bog	19	0.53	1983754	2236999	4220753
Less intensive meadow	19	0.53	1983754	2236999	4220753
Semi-arid plants	23	0.43	2912319	2197013	5109332
Rail fallow	24	0.4	3198886	2132591	5331477
Rural settlement	25	0.38	3443246	2110376	5553622
Green urban	29	0.27	4702807	1739394	6442202
Rail embankments	32	0.2	5686909	1421727	7108636
Mining fallow	38	0.04	8103845	337660	8441506
Natural grassland	39	0.02	8490377	173273	8663650

Other environmental indicators considered by the SPECA modeling tool are GHG gases. They include SO_2 , NO_x, PM, CO_2 , CO, Pb, VOC, Cd, As, and Cr are emitted by the panels during power generation. The total amount of effluents emitted by the GHGs and their respective externality cost are discussed in Section 0.

4.6 Monetization of Externalities.

The externalities of USSE discussed in Chapter Two are monetized in this section. Monetizing externalities in this thesis involves estimating the damage cost or the restoration of value to the affected ecosystem existing in the different land-use types. Regarding land use and land occupancy, the establishment and operation of USSE lead to loss of farmlands, grasslands, and other land-use types.

The opportunity cost of farming, grazing, tourism, aesthetic values, soil erosion prevention is, therefore, is the foregone alternative derived from the agricultural production and tourism in the grasslands. The per hectare market price of the ecosystem goods and services derived from the different land-use types was derived from a study (R. S. De Groot et al., 2002). The SPECA modeling tool estimates an externality cost in the plant's entire life based on the region selected. Different areas have varying richness levels of ecosystems, goods, and services. The SPECA modeling tool developed herein sets the richness levels depending on the available biodiversity in a region as such dry areas are associated with low farming activities, fewer wild animals, trees, etc.

Therefore, the SPECA modeling tool uses the proxy of the per hectare value of the ecosystem goods and services. The proxy values attached to the different environments are classified as low, medium, or rich. The externality associated with a specific land-use type is quantified and monetized according to the area occupied, and the result is summed up in the LTCOE equation. The damage cost that emanates from GHG gases is estimated using the damage cost per tonnage of effluents emitted described in Table 4.6. The total emissions in the lifetime of USSE is shown in Figure 4.4.

Table 4.6: Quantified and Monetized GHGs

GHG Gas	Amount (Kg/kWh)	Damage Cost($)
As	10.57661851	943571.45
Cd	1.24692765	58347.26
CO	7607.74317	8037155.53
CO2	24947830.96	658627105
Cr	68.23774516	2390300.48
Nitrates	0.44217687	7215.43
NOx	43790.91191	346797736.4
Pb	126.5483132	2247502411
PM10	34.69873104	455867.68
PM2.5	2978.895338	64611513.75
PM2.5-10	2978.895338	14420463.62
SO2	28107827.69	52555177355
VOC	29317.64441	154384926.6

The GHG with the highest emission rates per kWh are VOC, NO$_x$, CO$_2$, and SO$_2$, while the lowest comes from PM, CO, Pb, Cd, As, and Cr.

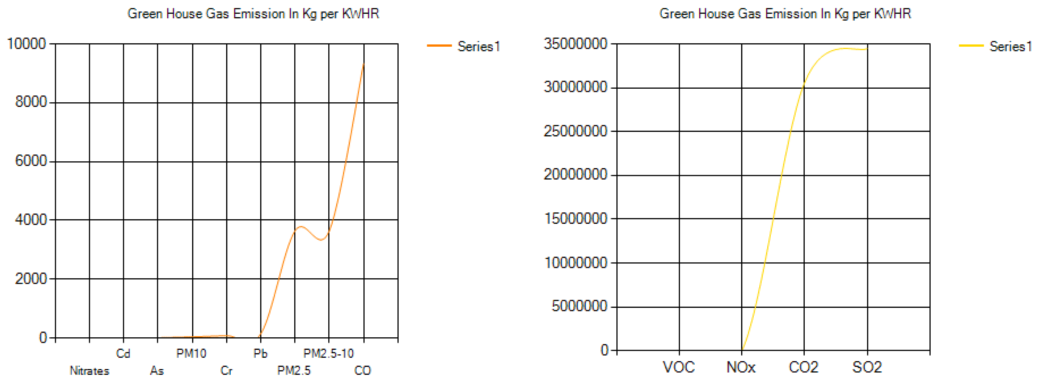

Figure 4.4: GHG Emissions

The health cost is based on the Disability-adjusted life years (DALY), which describes the value of a life lost due to air pollution. Using DALY to value human life is advantageous overvaluations based on accidental death. The former uses a change in the life expectancy, which automatically factors in that death will come irrespective of pollution. The SPECA determines the cost of a disease burden using two functions described in section 0: unit morbidity value and unit mortality values. The SPECA modeling tool estimates the health cost that originates from GHG gases using the disease burden, as shown in Table 4.7. The EF of each disease indicates the risk of incidence associated with each disease. The higher the effect factor, the higher the DALY , morbidity, and mortality rates.

Table 4.7: Disease Burden

Diseases	DALY	Effect Factor	Unit Morbidity	Unit Mortality
Bladder	2.5	0.00121	29344.315	283244.2113
breast	3.9	0.00188	29361.904	283413.988
Colon and rectum	4.7	0.00227	29373.63	283527.1725
Corpus uteri	2.2	0.00106	29344.315	283244.2113
Melanoma	3.2	0.00154	29356.041	283357.3958
Mouth and oropharnyx	3.5	0.00169	29361.904	283413.988
Oesophagus	9.3	0.00448	29432.26	284093.095
Ovary	6.7	0.00323	29397.082	283753.5415
Pancreas	8.3	0.004	29420.534	283979.9105
Stomach	7.2	0.00347	29408.808	283866.726
Trachea	8.2	0.00395	29420.534	283979.9105

As earlier discussed in the methodology, LCOE is one of the most critical metrics in electricity generation. It compares the life cycle cost of a plant in its lifespan. In this research, the LCOE equation in the SPECA modeling tool was amended to incorporate the externalities of solar energy, which is never done by other software. The SPECA modeling tool can then be used for simulation from different parts of

Kenya with different solar irradiation levels and diverse biodiversity to fully understand how the incorporation of externalities affects the LCOE.

The difference between the normal LCOE without incorporating externalities of utility-scale solar and the LTCOE when externalities are included is the Levelized Externality cost of Energy (LECOE). Incorporating the externalities in the cost modeling of USSE in Lodwar and Gatarakwa using the SPECA model yields a levelised externality cost of energy (LECOE) of \$0.65 and \$0.872, respectively. The LCOE of the two regions, Lodwar and Gatarakwa, are each \$11.149 and \$20.629. The actual cost of energy in this thesis herein referred to as LTCOE for Lodwar and Gatarakwa was found to be \$11.799 and \$21.501. The LCOE of Lodwar was therefore 95.94 % of the actual cost of electricity (LTCOE) from USSE, while LECOE forms about 4.05% of the LTCOE. It is, therefore, clear that 4.05% of the actual cost of electricity is not reflected on the utility bill and therefore borne by society.

Figure 4.5 shows the yearly cost of energy (COE) derived in Section 0 and the Total Cost of Energy (TCOE). TCOE is the annual total cost of energy when externalities are included in the modeling of Solar PV using the SPECA modeling tool. At the same time, COE is the yearly cost of energy when externalities are not included. In this thesis, TCOE is 30% higher than COE because of the incorporated externality cost.

LECOE in Gatarakwa is slightly higher than in Lodwar by about 46.72%, attributed to the higher solar insolation in Lodwar (1800kWh/m^2/yr) compared to 1565kWh/m^2/yr for Gatarakwa as described in Table 4.4. The increased solar insolation in Lodwar of about 1800kWh/m^2/yr translates to fewer panels to meet the demand. Externalities in Gatarakwa are slightly higher because the value of biodiversity in Gatarakwa differs significantly from Lodwar. Land in Gatarakwa has major economic activities such as grazing, maize farming, and tree planting. SPECA modeling tool classifies this region as ‘high rich’ as was described in section 0, Table 3.7. On the other hand, Lodwar has poor species per unit area and hence a lower LECOE. Therefore the foregone alternatives have significant economic values that must be incorporated in modeling.

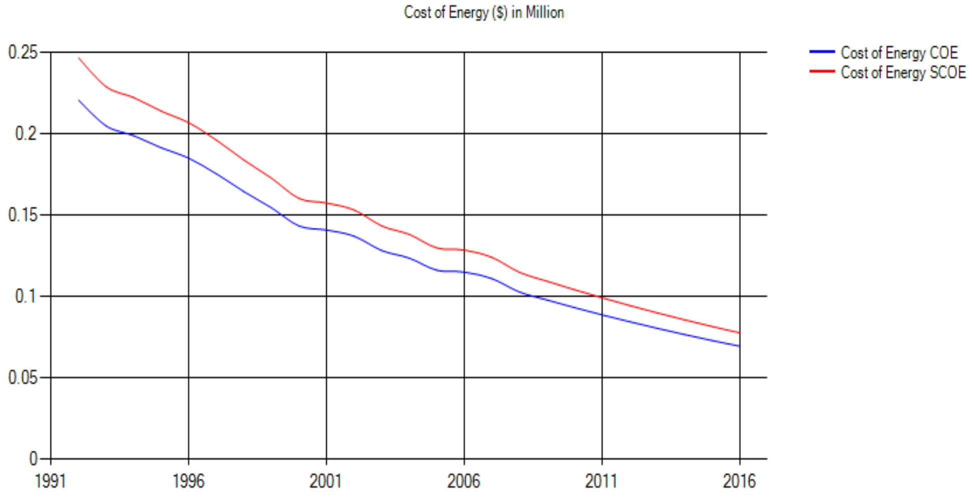

Figure 4.5: Yearly cost of Energy for Lodwar

4.7 Validation of the SPECA Modelling Tool

Validation of any model involves performing repeated tests and confidence establishment in the model (Gass, 2011). Although model validation is essential, no known test can thoroughly validate any model, but the confidence in a model is ascertained as it passes through some steps (Gass, 2011). Gass (2011) emphasizes that model validation is judged about a particular purpose; it is invalid if the model is detached from the goal. The SPECA modeling tool, as compared to other modeling tools, can accommodate the external costs of energy generation, which in this case are the environmental costs and the social costs.

The SPECA modeling tool was validated against other existing modeling tools such as HYBRID2, HOMER, TRNSYS, IHOGA, RETSCREEN, SAM, SOMES using their valuation capabilities categorized under financial valuation, externality valuation, sizing, and monetization of externalities. The validation of the SPECA model against the others has been achieved through model comparison in the existing literature and modeling using the HOMER modeling tool. HOMER software has been referred to as a global standard for renewable energy microgrids because of its extensive use in modeling. However, despite being branded the global standard, HOMER does not account for the externalities of solar energy or other technologies as SPECA does. The other disadvantage of HOMER software, as reported in the literature, is that it does not provide a transparent analytical approach to the sizing of the microgrid (Amevi Acakpovi et al., 2015). The simulations results for Lodwar using HOMER, SAM, and SPECA are shown in Table . The LCOE values of HOMER and SAM are 36.85% and 53.98 % lower than that of the SPECA modeling tool. This has been attributed to the non-incorporation of the indirect costs incurred while generating energy from Solar PV. It is also important to note that HOMER does not estimate the number of components used, such as solar PV panels and batteries.

Table 4.8: Validation of SPECA Modelling Tool Against HOMER and SAM

TOOLS	HOMER	SAM	SPECA
LCOE ($ cents)	7.04	5.13	11.149
LTCOE ($ cents)	-	-	11.214
LECOE ($ cents)	-	-	0.065
O&M ($)	154,402	180,008	200,005
NPV (Million $)	8.05	-	20.5
Initial cost (Million $)	66	-	174.009

CHAPTER FIVE

CONCLUSIONS, RECOMMENDATIONS, AND LIMITATIONS

5.1 Conclusion

The primary contribution of this thesis was mainly to develop a techno-economic modeling tool capable of internalizing the externalities of solar PV. This necessitated the understanding of solar PV and its interactions with environmental and social impacts. Consequently, the SPECA modeling tool was developed, which incorporates externalities of solar PV yielding outputs such as energy generated, cost of electricity production, life cycle costs, Levelized Cost of Electricity (LCOE), Levelized Externality cost of Electricity (LECOE), and the Levelized Total cost of Electricity (LTCOE).

Having pointed out the inadequacies of the existing modeling tools, the SPECA modeling tool is among the first tools known to accommodate the quantification and monetization of solar PV energy generation externalities. The underlying reasons behind the development of the SPECA model software were two-fold- Firstly, there was a need to inform decision-makers and investors of solar photovoltaics in making informed decisions on their financial viability. The second reason was to educate investors on solar PV with a modeling tool that detects and informs of the main drivers of USSE and their societal burdens and external costs, which yields important information on the environmental tradeoffs.

The SPECA modeling modifies the LCOE methodology to include the externalities of solar PV during modeling. The source codes of the software model were written using visual basic (VB) programming, while the joint evaluation database was written in the Structured Querry Language (SQL). A graphical user interface (GUI) provides an interactive user platform where the inputs are made or selected.

The literature review revealed that most of the techno-economic modeling tools of solar PV do not consider the quantification and monetization of their externalities. The study further disclosed that decision-making on electricity generation technologies adoption is based on the technology with the least LCOE, life cycle cost (LCC), simple payback time added to those plants with high NPV, and initial rate of return (IRR). The review further unveiled that the HOMER software was more widely used for techno-economic analysis of USSE than any other software tool. Some studies refer to HOMER as a global standard for microgrid design (Amevi Acakpovi et al., 2015). HOMER quantifies carbon dioxide but does not monetize the same impacts on the environment or human health. The literature review has further unveiled that no tool looked into the actual cost of electricity, the cost burden borne by the community.

The SPECA modeling tool has revealed that the society of energy always bears a cost from solar PV. The LCOE of solar PV in Lodwar is 95.3 % of the actual value, while LECOE forms about 4.7%. LECOE originates from the quantification and monetization of externalities attributed to the different land-use types. The externalities were quantified based on the biodiversity loss (flora and fauna), normally referred to as loss of ecosystem goods and services. The value of the different ecosystem goods and services was adapted from a study done by R. S. De Groot et al. (2002), where they are converted to proxies of land use per hectare.

This research's main outcomes show that while solar PV technologies' investment is worthwhile, the non-inclusivity of social and environmental burden in the analysis renders the LCOE obtained a crude estimate. The LCOE obtained from generating electricity from Lodwar was $11.149, while LECOE was $0.065. LECOE is the cost borne by society. Therefore, the actual cost of energy (LTCOE) is $11.214. LECOE stems up from global warming damages, health burden, and the impacted biodiversity. The LCOE of Gatarakwa is slightly higher than that of Lodwar because the region has low solar insolation. Therefore more solar panels and other components translate to more capital outlay. On the other hand, the SPECA model arrived at an LTCOE of $ 0.122 higher than one found in Lodwar.

The main finding of this thesis are as follows

- The analysis of the externalities of solar PV unveiled that about 4.7% of the actual cost of electricity from solar PV is never reflected in the balance sheet of the utility company but is borne by society. The accounting of the indirect costs (externalities) makes the estimation of LCOE from Solar PV more expensive than traditional tools such as HOMER. The indirect cost stems from three externalities: the global warming damages of flora and fauna, air pollution health costs, and water use. The indirect costs were accounted for using the restoration cost approach of the lost ecosystem goods and services.

- The existing techno-economic modeling tools majorly consider the costs of capital, operations, maintenance, and replacement in determining the LCOE. They, therefore, do not consider the indirect costs and impacts incurred while generating electricity from solar energy. SPECA modeling tool that has been developed in this work bridges this gap. The tool can quantify and monetize the resulting impacts of solar PV.

5.2 SPECA Software Limitations

The SPECA model, while it attempted to incorporate all the impacts of Solar PV to the environment, it does not capture all the intrinsic aspects of solar PV energy. The limitations of the SPECA model are:

- The non-incorporation of crucial burdens due to lack of data such as (i) noise pollution, (ii) damages to roads, (iii) injuries, and (iv) fatalities during manufacturing processes;
- The non-incorporation of significant burdens due to the anticipated and unnecessary complications they may pose to the model, such as the materials used to manufacture components used in a solar photovoltaic plant and the ecosystem goods and services lost for the resource inputs for building the solar PV.
- Due to the model limitations, the non-incorporation of the influence of energy demand on the overall plant investment (SPECA modeled the investment capacity exogenously).
- It is hard to compare LCOE from previous studies and models due to the various assumptions, such as plant capacity, discount rates, inflation and

interest rates, DNI patterns, and the non-consideration of environmental impacts.

5.3 Recommendations

It is recommended that future work should be geared towards further improvement of the SPECA model to quantify and monetize externalities of other renewable and non-renewable energy technologies. It would also be interesting to see the externalities of a hybrid power plant, either a hybrid of two renewables, such as solar and wind, or a hybrid of a renewable and a non-renewable and the respective contribution ratio of the LECOE. It is further recommended that LCOE incorporate transmission and distribution upgrades and the incorporation of time of use pricing and market dynamics.

REFERENCES

Abbasi, S. A., & Abbasi, N. (2000). The likely adverse environmental impacts of renewable energy sources. *Applied Energy*, *65*(1–4), 121–144.

Akan, M. Ö. A., Selam, A. A., & Firat, S. Ü. O. (2016). Renewable energy sources: Comparison of their use and respective policies on a global scale. In *Handbook of Research on Green Economic Development Initiatives and Strategies* (Issue June). https://doi.org/10.4018/978-1-5225-0440-5.ch0011

Akella, A. K., Saini, R. P., & Sharma, M. P. (2009). Social, economical and environmental impacts of renewable energy systems. *Renewable Energy*, *34*(2), 390–396.

Alex, G., & Pouris, A. (2008). *Aggregation and Internalisation of Electricity Externalities in South Africa*. *1*(1), 1–39.

Allan D. Lopez, Collin D. Mathers, Majd Ezzati, Dean T. Jomison, Christopher J, L. M. (1996). *Global Burden of Disease and Risk Factors* (Vols. 1 & 2).

Alsema, E. A., Wild-scholten, M. De, & Researcher, I. (2005). *The real environmental impacts of crystalline silicon PV modules : an analysis based on up-to-date manufacturers data*. *January*.

Álvarez-Farizo, B., & Hanley, N. (2002). Using conjoint analysis to quantify public preferences over the environmental impacts of wind farms. An example from Spain. *Energy Policy*, *30*(2), 107–116.

Aman, M. M., Solangi, K. H., Hossain, M. S., Badarudin, A., Jasmon, G. B., Mokhlis, H., Bakar, A. H. A., & Kazi, S. N. (2015). A review of Safety, Health and Environmental (SHE) issues of solar energy system. *Renewable and Sustainable Energy Reviews*, *41*, 1190–1204.

Amevi Acakpovi, Hagan, E. Ben, & Michael, M. B. (2015). *Cost Benefit Analysis of*

Self-Optimized Hybrid Solar- Wind-Hydro Electrical Energy Supply as compared with. *114*(18), 32–38.

Barley, C. D., & Winn, C. B. (1996). Optimal dispatch strategy in remote hybrid power systems. *Solar Energy*, *58*(4–6), 165–179.

Beck, M. W., Claassen, A. H., & Hundt, P. J. (2012). Environmental and livelihood impacts of dams: Common lessons across development gradients that challenge sustainability. *International Journal of River Basin Management*, *10*(1), 73–92.

Bergmann, E. A., Colombo, S., & Hanley, N. (2007). The Social-Environmental Impacts Of Renewable Energy Expansion In Scotland . *The Agricultural Economics Society's 81st Annual Conference*, *April*, 1–33.

Bernal-Agustín, J. L., & Dufo-López, R. (2009). Simulation and optimization of stand-alone hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *13*(8), 2111–2118.

Bhandari, K. P., Collier, J. M., Ellingson, R. J., & Apul, D. S. (2015). Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis. *Renewable and Sustainable Energy Reviews*, *47*, 133–141.

Bin Zhaoa, Urs Kreuterb, Bo Lia, Zhijun Maa, Jiakuan Chena, N. N. (2004). An ecosystem service value assessment of land-use change on Chongming Island, China. *Buffalo Bulletin*, *32*(Special issue 2), 139–148.

Bo, M., & Brod, S. (2019). *Environment impact of a concentrated solar power plant*. *Tehnički glasnik*, *13*(1), 68-74.

Boukelia, T. E., Mecibah, M. S., Kumar, B. N., & Reddy, K. S. (2015). Optimization, selection and feasibility study of solar parabolic trough power plants for Algerian conditions. *Energy Conversion and Management*, *101*, 450–459.

Burtraw, D., & Krupnick, A. (2012). *The True Cost of Electric Power*. *June*, 17.

Carlin, J. (1995). Environmental Externalities in Electric Power Markets: Acid Rain, Urban Ozone, and Climate Change. *Renewable Energy Annual*, *1990*(4), 1–14.

Carter, N. T., & Campbell, R. J. (2011). Water issues of concentrating solar power (CSP) electricity in the U.S. Southwest. *Energy Demands on Water Resources: Analysis of Competitive Concerns*, 157–173.

Chaudhary, A., Verones, F., De Baan, L., & Hellweg, S. (2015). Quantifying Land Use Impacts on Biodiversity: Combining Species-Area Models and Vulnerability Indicators. *Environmental Science and Technology*, *49*(16), 9987–9995.

Chowdhury, S., & Kibaara, S. K. (2016). Review of economic modelling for quantifying the environmental impacts of renewable energy sources. *IEEE PES PowerAfrica Conference, PowerAfrica 2016*, 280–284.

Connolly, D., Lund, H., Mathiesen, B. V, & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy*, *87*(4), 1059–1082.

Concentrating solar power, 1 European Commision ___ (2007).

Costanza, R., Arge, R., Groot, R. De, Farber, S., Grasso, M., Hannon, B., Limburg, K., … & Sutton, P. (1997). The value of the world’s ecosystem services and natural capital. *Ecology and Society*, *387*(May), 1–8.

Crettaz, P., Pennington, D., Rhomberg, L., Brand, K., & Jolliet, O. (2002). *Assessing Human Health Response in Life Cycle Assessment Using ED 10 s and DALYs : Part 1 — Cancer Effects*. *22*(5).

Crow, P. (2005). The Influence of Soils and Species on Tree Root Depth. *Forestry Commission Information Note*, 1–8.

Darling, S. B., You, F., Veselka, T., & Velosa, A. (2011). Assumptions and the levelized cost of energy for photovoltaics. *Energy and Environmental Science*, *4*(9), 3133–3139.

De Groot, R. S., Wilson, M. A., & Boumans, R. M. J. (2002). A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*, *41*(3), 393–408.

Del Sol, F., & Sauma, E. (2013). Economic impacts of installing solar power plants in northern Chile. *Renewable and Sustainable Energy Reviews*, *19*, 489–498.

Denholm, P., Hand, M., Jackson, M., & Ong, S. (2009). Land Use Requirements of Modern Wind Power Plants in the United States. *National Renewable Energy Laboratory*, *Technical*(August), 46.

Denholm, P., & Margolis, R. M. (2008). *Impacts of array configuration on land-use requirements for large-scale photovoltaic deployment in the United States* (No. NREL/CP-670-42971). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Dessouky, M. O. (2013). The environmental impact of large scale solar energy projects on the MENA deserts: Best practices for the DESERTEC initiative. *IEEE EuroCon 2013*, *July*, 784–788.

Diakoulaki, D. (1997). Multicriteria analysis vs. externalities assessment for the comparative evaluation of electricity generation systems. *European Journal Of Operational Research*, *2217*(97).

Directorate - General for Energy and Transport, & Directorate - General for Research. (2007). Concentrating Solar Power - From Research To Implementation. In *Spring*.

Dobos, A., Neises, T., & Wagner, M. (2014). Advances in CSP simulation technology in the System Advisor Model. *Energy Procedia*, *49*, 2482–

2489.

Dufo-López, R., & Bernal-Agustín, J. L. (2005). Design and control strategies of PV-diesel systems using genetic algorithms. *Solar Energy*, *79*(1), 33–46.

Eade, J. D. O., & Moran, D. (1996). *Spatial Economic Valuation : Benefits Transfer using Geographical Information Systems*. 97–110.

EIA, U. (2016). Capital Cost Estimates for Utility Scale Electricity Generating Plants; US Department of Energy. Washington, DC, USA: Energy Information Administration.

El-Shimy, M. (2017). Economics of Variable Renewable Sources for Electric Power Production. In *Lambert Academic Publishing / Omniscriptum Gmbh & Company Kg* (p. 566).

Erdinc, O., & Uzunoglu, M. (2012). Optimum design of hybrid renewable energy systems: Overview of different approaches. *Renewable and Sustainable Energy Reviews*, *16*(3), 1412–1425.

New Elements for the Assessment of External Costs from Energy Technologies, Energy Report (2004).

Fthenakis, V., & Chul, H. (2009). *Land use and electricity generation : A life-cycle analysis*. *13*, 1465–1474.

Fthenakis, V M, Fuhrmann, M., Heiser, J., Lanzirotti, A., Fitts, J., & Wang, W. (2005). *Emmisions and Encapsulation of Cadmium in CDTe PV Modules during Fires*. *January*. Retrieved from https://doi.org/10.1002/pip.624

Fthenakis, Vasilis M, Kim, H. C., & Alsema, E. (2008). *Emissions from photovoltaic life cycles*. *January*. Retrieved from https://doi.org/10.1021/es071763q

Gass, S. I. (2011). Profiles in Operations Research. *Profiles in Operations Research: Pioneers and Innovators*, *147*(September), 217–240.

Gekas, V., Frantzeskaki, N., Tsoutsos, T. (2002). Environmental Impact Assessment of Solar Energy Systems. *Proceedings Fo the International Conference "Protection and Restoration of the Environment VI," August*, 1569–1576.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. De, Struijs, J., & Zelm, R. Van. (2009). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. *Potentials*, *January*, 1–44.

Greenpeace International, ESTIA, & SolarPACES. (2005). *Concentrated solar thermal power - Now! January 2005*.

Groot, D. De, & Wang, Y. (2010). *The TEEB Valuation Database : overview of structure , data and results The TEEB Valuation Database : overview of structure , data and results*. *December*.

Groot, R. S. De, Wilson, M. A., & Boumans, R. M. J. (2002). *Framework for Integrated Assessment and Valuation of Ecosystem Functions , Goods and Services*. *May*, 1–20.

Gsma. (2010). HOMER Software: Training Guide for Renewable Energy Base Station Design | Mobile for Development. *Green Power for Mobile*.

Guta, D. D. (2014). Effect of fuelwood scarcity and socio-economic factors on household bio-based energy use and energy substitution in rural Ethiopia. *Energy Policy*, *75*, 217–227.

Hawkins, B. A., Field, R., Cornell, H. V., Currie, D. J., Guégan, J. F., Kaufman, D. M., Kerr, J. T., Mittelbach, G. G., Oberdorff, T., O'Brien, E. M., Porter, E. E., & Turner, J. R. G. (2003). Energy, water, and broad-scale geographic patterns of species richness. *Ecology*, *84*(12), 3105–3117.

Hernandez, R. R., Easter, S. B., Murphy-Mariscal, M. L., Maestre, F. T., Tavassoli, M., Allen, E. B., Barrows, C. W., Belnap, J., Ochoa-Hueso, R., Ravi, S.,

& Allen, M. F. (2014). Environmental impacts of utility-scale solar energy. *Renewable and Sustainable Energy Reviews*, *29*, 766–779.

Hernandez, Rebecca R., Hoffacker, M. K., & Field, C. B. (2014). Land-use efficiency of big solar. *Environmental Science and Technology*, *48*(2), 1315–1323.

Ho, C. K. (2008). Software and Codes for Analysis of Concentrating Solar Power Technologies. *Sandia National Laboratories, Report SAND2008-8053, December*, 1–35.

Ho, C. K., Khalsa, S. S., & Kolb, G. J. (2011). Methods for probabilistic modeling of concentrating solar power plants. *Solar Energy*, *85*(4), 669–675.

Hoffacker, K., Murphy-mariscal, M. L., Wu, G. C., Hernandez, R. R., Hoffacker, M. K., Murphy-mariscal, M. L., Wu, G. C., & Allen, M. F. (2016). Correction for Hernandez et al., Solar energy development impacts on land cover change and protected areas. *Proceedings of the National Academy of Sciences*, *113*(12), E1768–E1768.

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, *22*(2), 138–147.

Islam, A., Shima, F. A., & Khanam, A. (2013). *Analysis of Grid Connected Solar PV System in the Southeastern Part of Bangladesh 1*. *49*(2), 116–123.

Jaber, S. (2014). Environmental Impacts of Wind Energy. *Journal of Clean Energy Technologies*, *1*(3), 251–254.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., & Rebitzer, G. (2003). *Presenting a New Method IMPACT 2002 + : A New Life Cycle Impact Assessment Methodology*. *8*(6), 324–330.

Katuwal, H., & Bohara, A. K. (2009). Biogas: A promising renewable technology and its impact on rural households in Nepal. *Renewable and Sustainable Energy Reviews*, *13*(9), 2668–2674.

Khatib, T., Ibrahim, I. A., & Mohamed, A. (2016). A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system. *Energy conversion and management*, *120*, 430–448.

Koellner, T., & Scholz, R. W. (2008). Land Use in LCA (Subject Editor : Llorenç Milà i Canals) Assessment of Land Use Impacts on the Natural Environment Part 2 : Generic Characterization Factors for Local Species Diversity in Central Europe. *International Journal of Life Cycle Assessment*, *13*(1), 32–48.

Laleman, R., Albrecht, J., & Dewulf, J. (2011). *Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation*. *15*, 267–281.

Le, Y., Dipl, F., & Gef, R. U. (2012). Potential and Future of Concentrating Solar Power in Namibia. *Growth (Lakeland)*, *24*(1), 1–13.

Lovich, J. E., & Ennen, J. R. (2011). Wildlife Conservation and Solar Energy Development in the Desert Southwest, United States. *BioScience*, *61*(12), 982–992.

Lund, H., Connolly, D., Lund, H., Mathiesen, B. V, & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems A review of computer tools for analysing the integration of renewable energy into various energy systems. *Journal of Applied Energy*, *87*(4), 1059-1082.

Machinda, G. T., Chowdhury, S., Arscott, R., Chowdhury, S. P., & Kibaara, S. (2011). Concentrating solar thermal power technologies: A review. *2011 Annual IEEE India Conference: Engineering Sustainable Solutions, INDICON-2011, December 16, 2011 - December 18, 2011*, Birla Institute of Technology and Science, Pilani.

Madlener, R., & Stagl, S. (2005). Sustainability-guided promotion of renewable electricity generation. *Ecological Economics, 53*(2), 147–167.

Mahajan, B. (2012). *Negative environment impact of Solar Energy*. *December 2012*, 5.

Markovic, D., Cvetkovic, D., & Masic, B. (2011). Survey of software tools for energy efficiency in a community. *Renewable and Sustainable Energy Reviews*, *15*(9), 4897–4903.

Mason, J. E., Fthenakis, V. M., Hansen, T., & Kim, H. C. (2005). *Energy Pay-Back and Life Cycle CO 2 Emissions of the BOS in an Optimized*.

Masters, G. M. (2004). *Renewable and Efficient Electric Power Systems*. Retrieved from https://doi.org/10.1002/0471668826

Members, R. E. N. (2020). *Renewables 2020 global status report 2020*.

Tools and Guidelines for Integrating Biodiversity Concerns in National Planning Process - Africa, (2016).

Miguel, C., & Martı, R. (2009). Life cycle assessment study of a 4 . 2 kW p stand-alone photovoltaic system. *Solar Energy*, *83*, 1434–1445.

Miller, L. M., & Keith, D. W. (2018). Observation-based solar and wind power capacity factors and power densities. *Environmental Research Letters, 13*(10), 1–20.

Mohammad Bagher, A. (2015). Types of Solar Cells and Application. *American Journal of Optics and Photonics, 3*(5), 94.

Moss, J., Coram, A., & Blashki, G. (2014). *Solar Energy in Australia : Health and environmental Costs and Benefits of Solar energy in Australia*. *December*.

Mueller, C., Baan, L. De, & Koellner, T. (2014). *Comparing direct land use impacts on biodiversity of conventional and organic milk — based on a Swedish case study*. *January*. Retrieved from https://doi.org/10.1007/s11367-013-0638-5

N.Nkambule. (2017). Externality costs of the coal-fuel cycle : The case of Kusile Power Station. *Jounal of Sustainable Energy*, *113*(9), 1–9.

Assessing the economic value of new utility-scale renewable generation projects, (2013).

Measuring the Social Costs of Coal-Based Electricity Generation in South Africa, (2015).

Notton, G., Cristofari, C., Poggi, P., & Muselli, M. (2001). Wind hybrid electrical supply system: behaviour simulation and sizing optimization. *Wind Energy*, *4*, 43–59.

Ong, S., Campbell, C., Denholm, P., Margolis, R., & Heath, G. (2013). *Land-Use Requirements for Solar Power Plants in the United States*. *June*. Retrieved from https://doi.org/10.2172/1086349

Ottinger Richard. (1990). External Environmental Costs of Electric Power. In *Springer* 53(9). 5324-5342

Owen, A. D. (2006). Renewable energy: Externality costs as market barriers. *Energy Policy*, *34*(5), 632–642.

Owusu, P. A., & Asumadu-Sarkodie, S. (2016). A review of renewable energy sources, sustainability issues and climate change mitigation. *Cogent Engineering*, *3*(1), 1–14.

P.Leicester, C.Goodier, P. R. (2013). *Using Bayesian Network to Evaluate the Social, Economic and Environmental Impacts of Community Deployed Renewable Energy*.

P.Rowley, P.Leicester, P.Thornley, S.mander, C. J. (2017). *Wise PV: Whole system and Socio-economic Impacts of Wide Sclae PV integration*. 4156–4160.

Painuly, J. P. (2001). Barriers to renewable eneryg penetration; a framework for analysis. *Renewable Energy, 24*(1), 73–89.

Peng, J., & Lu, L. (2013). Investigation on the development potential of rooftop PV system in Hong Kong and its environmental bene fi ts. *Renewable and Sustainable Energy Reviews, 27*, 149–162.

Pereira HM, D. G. (2006). Modeling biodiversity dynamics in countryside landscapes. *Ecology, 524*(1), 1877–1885.

Philipps, S. P., Bett, A. W., Horowitz, K., & Kurtz, S. (2015). Current Status of Concentrator Photovoltaic (CPV) Technology. *National Renewable Energy Laboratory*, 1–25. Retrieved from https://doi.org/http://www.ise.fraunhofer.de/en/publications/veroeffentlichungen-pdf-dateien-en/studien-und-konzeptpapiere/current-status-of-concentrator-photovoltaic-cpv-technology.pdf

Pitz-Paal, R. (2008). Concentrating solar power. *Future Energy: Improved*. Retrieved from https://doi.org/10.1016/B978-0-08-054808-1.00010-7

Preiss, P., & Klotz, V. (2008). *NEEDS - New Energy Externalities Developments for Sustainability*. *6*(9), 1–95.

Pv, U. (n.d.). *Osh and Small Scale Solar Energy Applications*. 1–8.

Quansah, D. A., Adaramola, M. S., & Mensah, L. D. (2016). Solar Photovoltaics in Sub-Saharan Africa - Addressing Barriers, Unlocking Potential. *Energy Procedia, 106*, 97–110.

Rehman, S., El-Amin, I. M., Ahmad, F., Shaahid, S. M., Al-Shehri, A. M., Bakhashwain, J. M., & Shash, A. (2007). Feasibility study of hybrid retrofits to an isolated off-grid diesel power plant. *Renewable and*

Sustainable Energy Reviews, *11*(4), 635–653.

Rentizelas, A. A., Tolis, A. I., & Tatsiopoulos, I. P. (2012). Investment planning in electricity production under CO2price uncertainty. *International Journal of Production Economics*, *140*(2), 622–629.

Roth, I. F., & Ambs, L. L. (2004a). *Incorporating externalities into a full cost approach to electric power generation life-cycle costing*. *29*, 2125–2144.

Roth, I. F., & Ambs, L. L. (2004b). Incorporating externalities into a full cost approach to electric power generation life-cycle costing. *Energy*, *29*(12-15 SPEC. ISS.), 2125–2144.

Saheb Koussa, D., Koussa, M., & Hadji, S. (2012). A Technical, Economic and Environmental Assessment of Decentralized Systems Connected to the Algerian Grid. Case Study: Adrar Site. *Energy and Power*, *2*(4), 55–60.

Said, M., EL-Shimy, M., & Abdelraheem, M. A. (2015). Photovoltaics energy: Improved modeling and analysis of the levelized cost of energy (LCOE) and grid parity - Egypt case study. *Sustainable Energy Technologies and Assessments*, *9*, 37–48.

Sandham, L. A., van Heerden, A. J., Jones, C. E., Retief, F. P., & Morrison-Saunders, A. N. (2013). Does enhanced regulation improve EIA report quality? Lessons from South Africa. *Environmental Impact Assessment Review*, *38*(July 2018), 155–162.

Science, E., Baan, L. De, Mutel, C., Hellweg, S., & Koellner, T. (2013). *Land Use in Life Cycle Assessment: Global Characterization Factors Based on Regional and Global Potential Species Extinction*. *July*. Retrieved from https://doi.org/10.1021/es400592q

Sellami, M. H. (2014). A modeling approach to quantify the socioeconomic and environmental impacts of renewable energy installations. Case studies for wind energy and biogas reactor. *IREC 2014 - 5th International*

Renewable Energy Congress, 1–4.

Sen, R., & Bhattacharyya, S. C. (2014). Off-grid electricity generation with renewable energy technologies inIndia: An application of HOMER. *Renewable Energy*, *62*, 388–398.

Shaahid, S. M., & Elhadidy, M. A. (2007). Technical and economic assessment of grid-independent hybrid photovoltaic-diesel-battery power systems for commercial loads in desert environments. *Renewable and Sustainable Energy Reviews*, *11*(8), 1794–1810.

Simon, S. (2003). Sustainability Indicators. *Management*, *2*(February), 1–10.

Sinha, S., & Chandel, S. S. (2014). Review of software tools for hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *32*, 192–205.

Sinha, S., & Chandel, S. S. (2015). Review of recent trends in optimization techniques for solar photovoltaic – wind based hybrid energy systems. *Renewable and Sustainable Energy Reviews*, *50*, 755–769.

Sklar-Chik, M. D., Brent, A. C., & De Kock, I. H. (2016). Critical Review of the Levelised Cost of Energy Metric. *South African Journal of Industrial Engineering*, *27*(4), 124–133.

Thiam, D. R. (2010). Renewable decentralized in developing countries: Appraisal from microgrids project in Senegal. *Renewable Energy*, *35*(8), 1615–1623.

Tran, T. A. (2007). Review of Methods and Tools Applied in Technology Assessment Literature. *PICMET,Portland, Oregon*, 5–9.

Tsoutsos, T., Frantzeskaki, N., & Gekas, V. (2005a). *Environmental impacts from the solar energy technologies*. *33*, 289–296.

Tsoutsos, T., Frantzeskaki, N., & Gekas, V. (2005b). Environmental impacts from the solar energy technologies. *Energy Policy*, *33*(3), 289–296.

Tsuma, M., & Kibaara, S. (2019). *A Review of Levelized cost of Electricity for Photovoltaic systems combining with their Environmental Impacts*. 219–224.

Turney, D., & Fthenakis, V. (2013). Environmental impacts from the installation and operation of large-scale solar power plants. *Renewable and Sustainable Energy Reviews*, *15*(6), 3261–3270.

Vujić, J., Antić, D. P., & Vukmirović, Z. (2012). Environmental impact and cost analysis of coal versus nuclear power: The U.S. case. *Energy*, *45*(1), 31–42.

Wies, R. W., Johnson, R. a., Agarwal, a. N., & Chubb, T. J. (2004). Economic analysis and environmental impacts of a PV with diesel-battery system for remote villages. *IEEE Power Engineering Society General Meeting, 2004.*, *20*(2), 692–700.

XU, P. (2012). Investigation of Thermal Storage Options for Concentrating Solar Power Plants. *University Power Engineering Education*, 6.

Yalçin, L., & Öztürk, R. (2013). Performance comparison of c-Si, mc-Si and a-Si thin film PV by PVsyst simulation. *Journal of Optoelectronics and Advanced Materials*, *15*(3–4), 326–334.

Yehezkeli, O., Tel-Vered, R., Wasserman, J., Trifonov, A., Michaeli, D., Nechushtai, R., & Willner, I. (2012). Integrated photosystem II-based photo-bioelectrochemical cells. *Nature Communications*, *3,* 564 - 674

Yun, T., & Baker, R. D. (2009). Analysis of a power plant investment opportunity under a carbon neutral world. *Investment Management and Financial Innovations*, *6*(4), 155–163.

Zerihun, Y. A. (2015). The benefits of the use of biogas energy in rural areas in

Ethiopia: A case study from the Amhara National Regional State, Fogera District. *African Journal of Environmental Science and Technology*, *9*(4), 332–345.

Zhang, J., Chen, C., Zhang, X., & Liu, S. (2016). Study on the Environmental Risk Assessment of Lead-Acid Batteries. *Procedia Environmental Sciences*, *31*, 873–879.

Zhou, W., Lou, C., Li, Z., Lu, L., & Yang, H. (2010). Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems. *Applied Energy*, *87*(2), 380–389.

Zhou, X., Talley, M., & Luo, Y. (2009). Biomass, litter, and soil respiration along a precipitation gradient in southern Great Plains, USA. *Ecosystems*, *12*(8), 1369–1380.

Zoulias, E. I., & Lymberopoulos, N. (2007). Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems. *Renewable Energy*, *32*(4), 680–696.

APPENDICES

Appendix I: Overview of the SPECA Software Operating Environment

SPECA software is a techno-economic modeling tool that simulates the technical and economic viability of solar photovoltaic systems. In the design of power systems, various decisions must be made, including the intended system size, the components to be used, the number of components, and the size, among others. In addition to these, the interaction of the designed system with the environment must also be assessed. SPECA modeling tool helps evaluate the energy generated, cost of energy generated, and monetize the possible environmental, social, and economic impacts of solar photovoltaics.

How to use the SPECA Software

To use the SPECA software, the user provides the model inputs, which describe the technology option, in this case, Solar photovoltaics, components costs and types, solar energy availability, endangered flora and fauna, and the interactions of the solar photovoltaics with the environment.

Simulation using the SPECA modeling tool

The SPECA software simulates the operation of a solar photovoltaic using the energy balance calculations for each year. After the calculations, the SPECA software determines if the configuration selected is feasible, i.e., to meet the load demand under the specified conditions. The software then calculates the cost of energy (COE) for the entire lifetime of the project. The system costs account for operation and maintenance costs, capital costs, replacement costs, and the total interest.

System Architecture

The system has a user interface and a database. The user interface is window-based that provides functions to manipulate the data according to the requirements. The interface calls stored procedures and views heavily for data processing and data retrieval. Finally, the database stores all system data, and none is held outside the database, enhancing data integrity.

The database used is a relational database management system which is Microsoft SQL Server.

System Requirements

Table 0-1: System Requirements

Hardware	**Properties**
1. CPU/Laptop	2 Ghz Minimum
2. RAM	4 GB
3. Disk Space	15 GB Free space
4. Keyboard	Standard
5. Mouse	3-mouse button with roller button
Software	
1. OS	Windows XP and Above
2. Browser	Internet Explorer v. 7 or higher
3. .NET Framework	3.5 and above

Appendix II: Introduction and Getting started

The flow chart process of the SPECA modeling tool is as described in ()

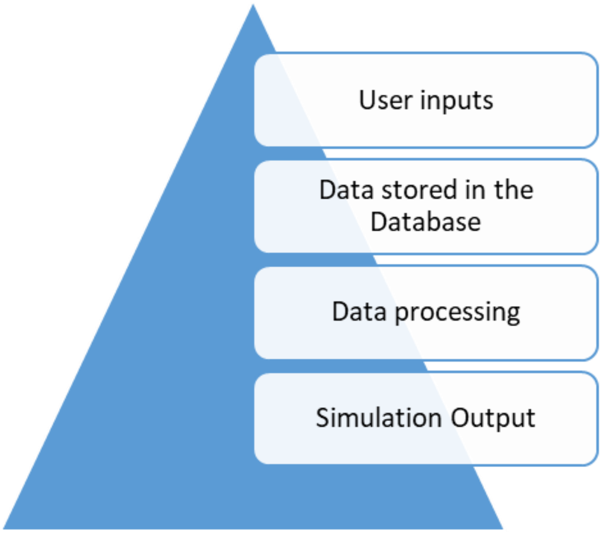

Figure 0.1: SPECA Modelling tool system architecture

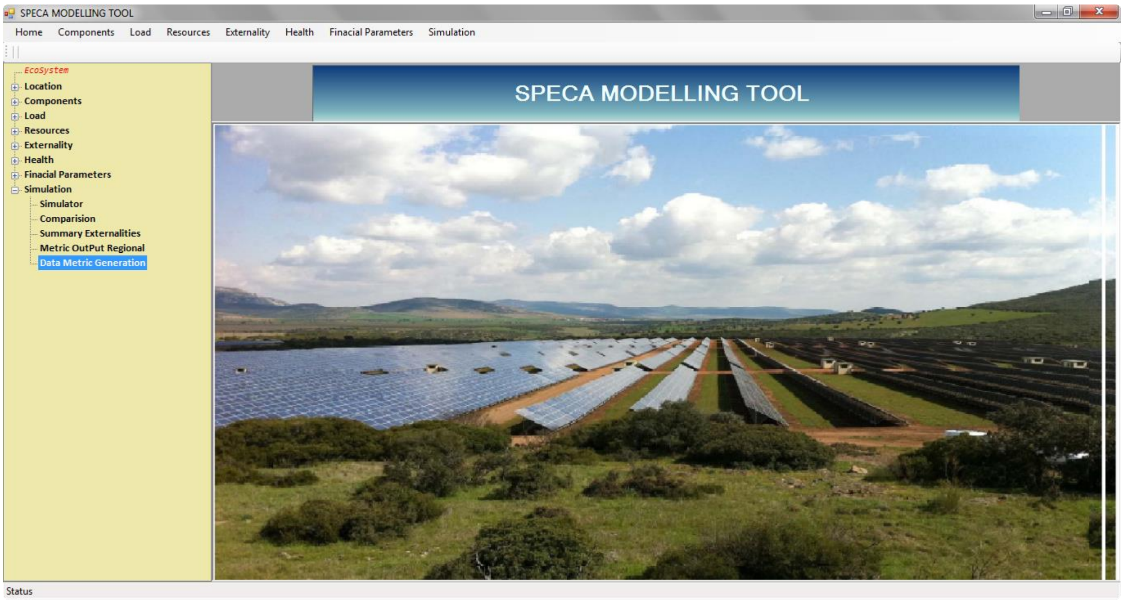

Figure 0.2: Home page of SPECA modeling tool

How to set location

A drop-down arrow appears with the various Kenya locations containing the different DNI resources when the icon location is chosen. After choosing a certain location, say ‘Nyeri’, two graphs that show the DNI pattern and the temperature for the range of years selected on the same page. The Direct Normal Irradiance (DNI) data for this research work was gathered from SWERA websites equipped with GIS. Clicking the ‘set location’ button as shown by Figure 0.3 saves this location and the range of years selected. The source code at the background picks the solar data for the location selected and the years specified, as shown in Figure 0.4 and Figure 0.5.

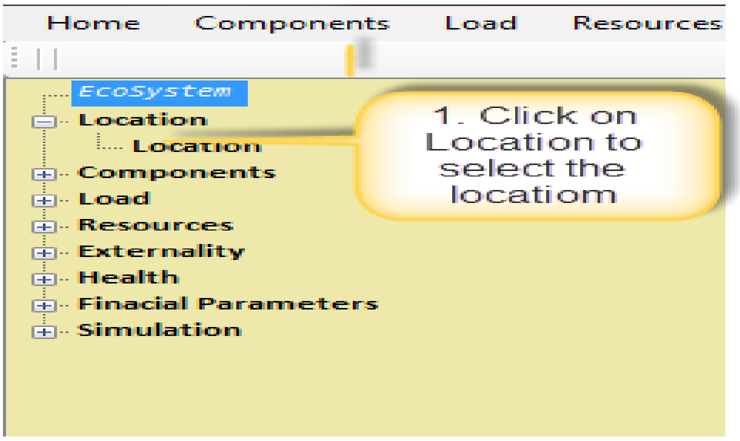

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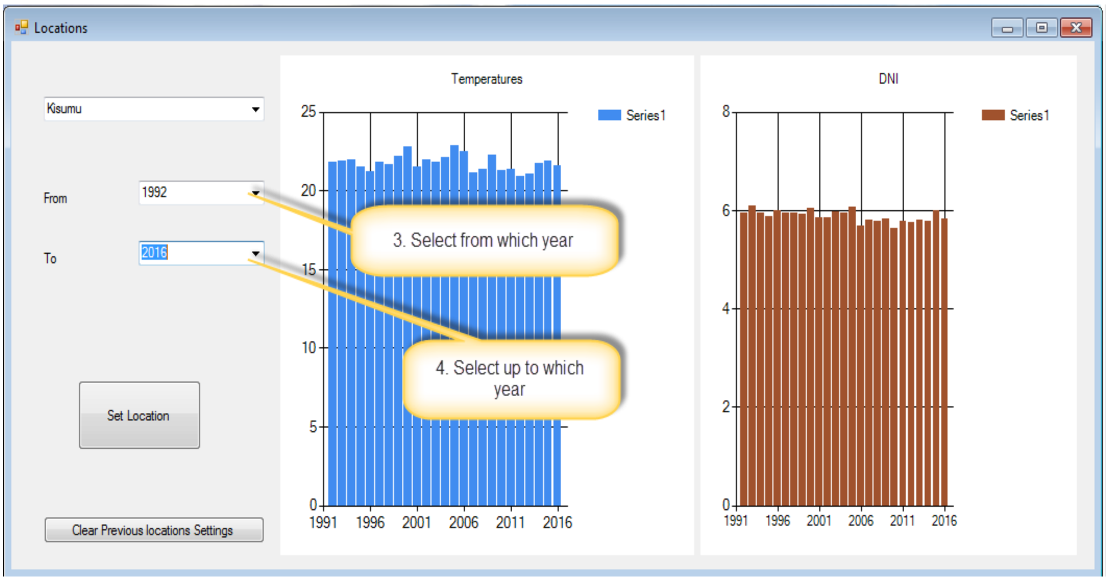
Figure 0.3: Location Selection



Kisumu

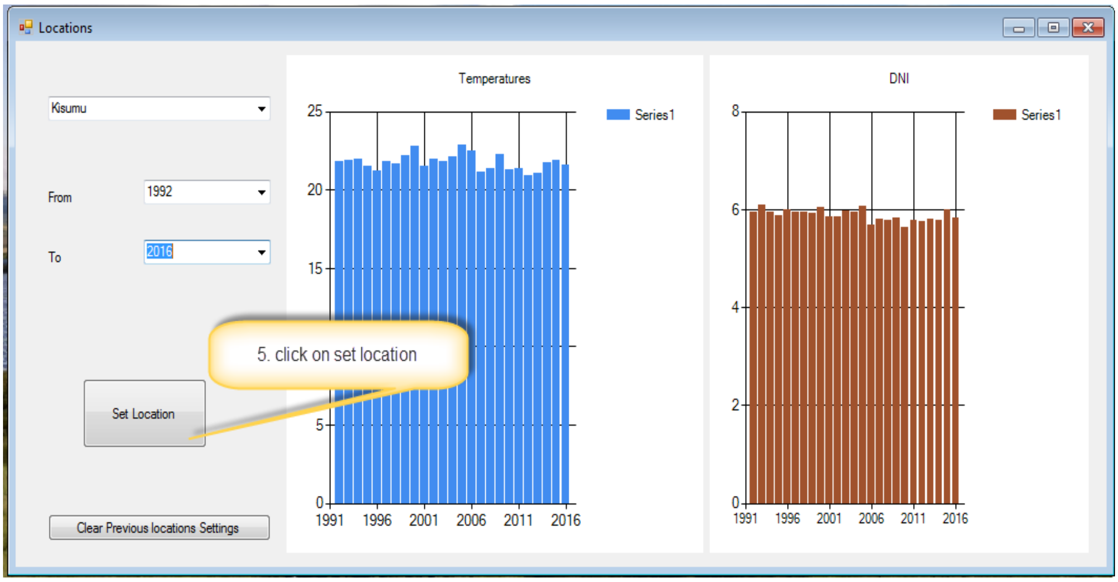
From 1992

To 2016

3. Select from which year

4. Select up to which year

Figure 0.4: Selection of plant operation Lifespan



Kisumu

From 1992

To 2016

5. click on set location

Figure 0.5: Setting Location

Component Selection

In this window, all the components to be used for the simulation of solar photovoltaics are selected, as shown in Figure 0.6. When a component is selected, say PV, a drop-down arrow appears, containing the different types of solar photo voltaics and their respective details such as their capital cost, replacement cost, operation and maintenance cost, lifespan, and degradation rate as described by Figure 0.7 and Figure 0.8. Once each component is selected, its data is filled in and saved for the simulation. The same is done for converters and batteries.

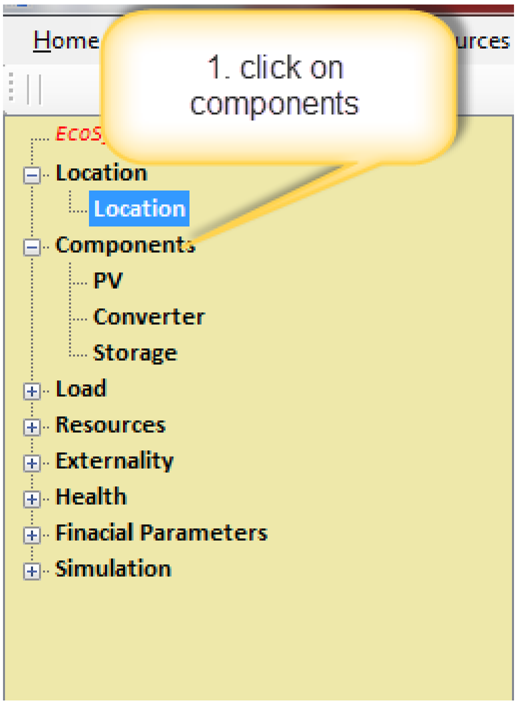
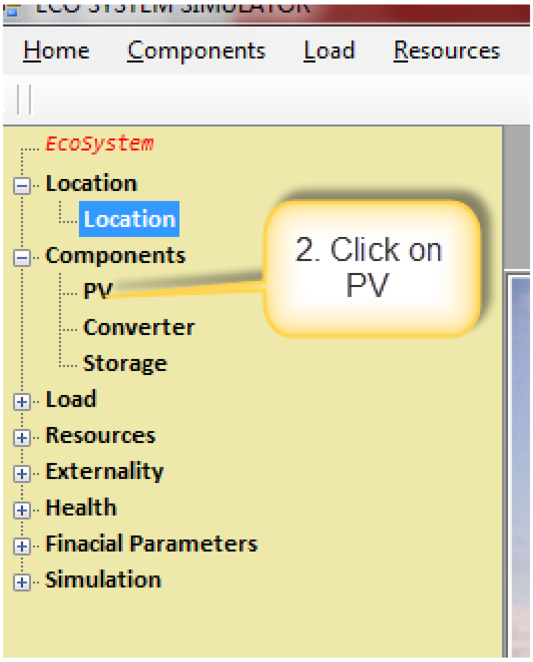
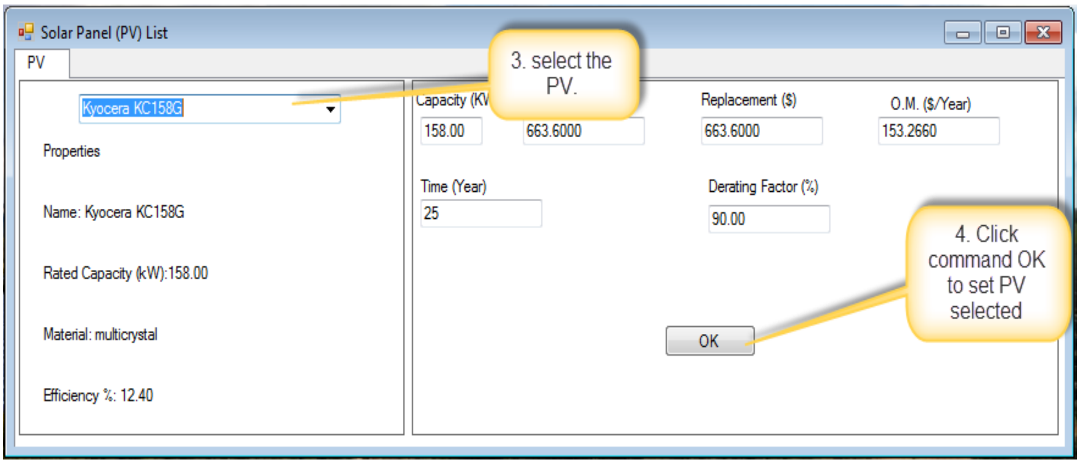


Figure 0.6: Component Selection Procedure



2. Click on PV

Figure 0.7: Solar PV Selection



3. select the PV.

Kyocera KC158G

Properties

Name: Kyocera KC158G

Rated Capacity (kW):158.00

Material: multicrystal

Efficiency %: 12.40

Capacity (KV: 158.00

663.6000

Replacement ($): 663.6000

O.M. ($/Year): 153.2660

Time (Year): 25

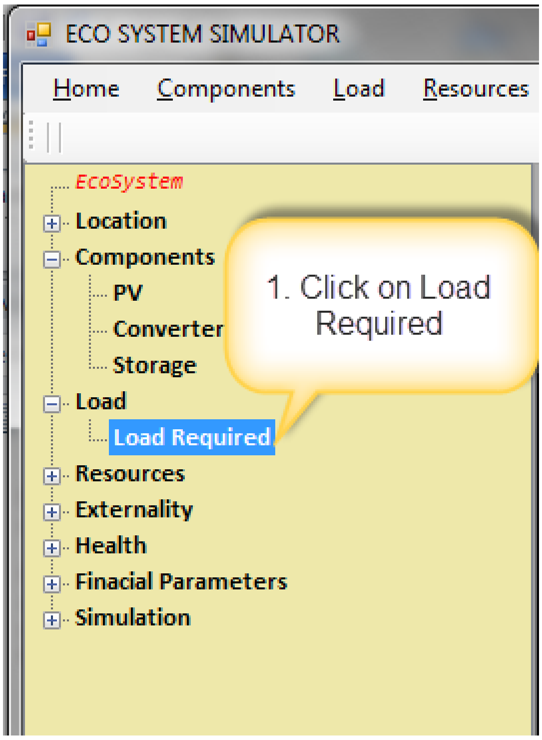
Derating Factor (%): 90.00

4. Click command OK to set PV selected

Figure 0.8: Solar PV Types and Characteristics

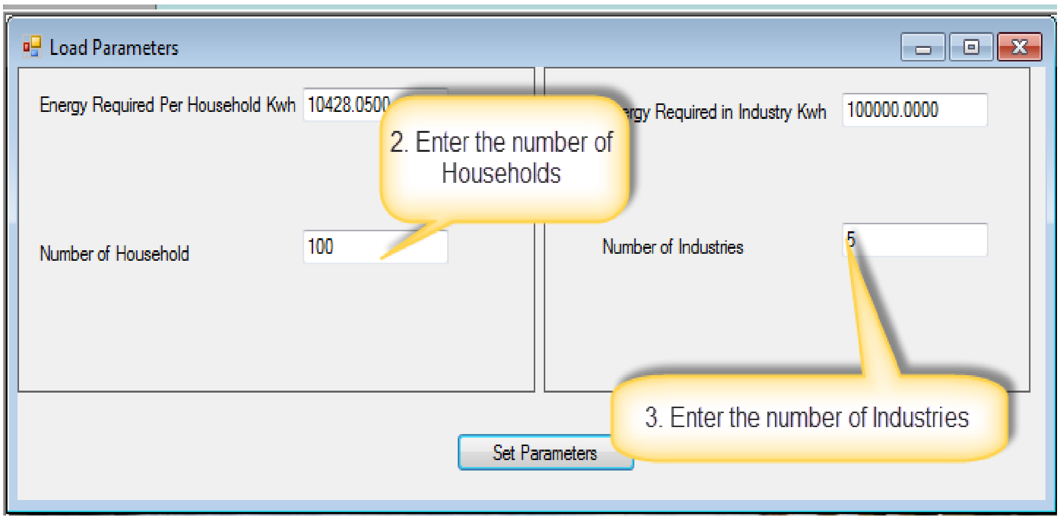
Load Requirement

The load size determines the size of the Solar PV and the number of batteries. The SPECA modeling tool has been designed for rural applications, and the determination of the plant size is based on a household hypothetical load profile. The load is selected, and the user inputs the number of households in a particular locality inserted as shown by Figure 0.9, Figure 0.10, and Figure 0.11.



1. Click on Load Required

Figure 0.9: Load Selection



Energy Required Per Household Kwh 10428.0500

Number of Household 100

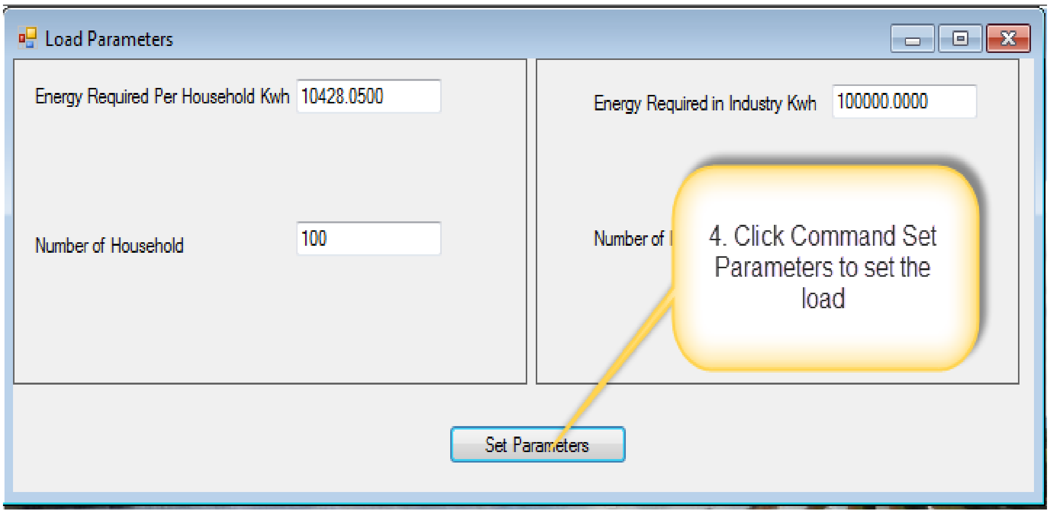
rgy Required in Industry Kwh 100000.0000

Number of Industries 5

2. Enter the number of Households

3. Enter the number of Industries

Figure 0.10: Load size Selection



Energy Required Per Household Kwh 10428.0500

Number of Household 100

Energy Required in Industry Kwh 100000.0000

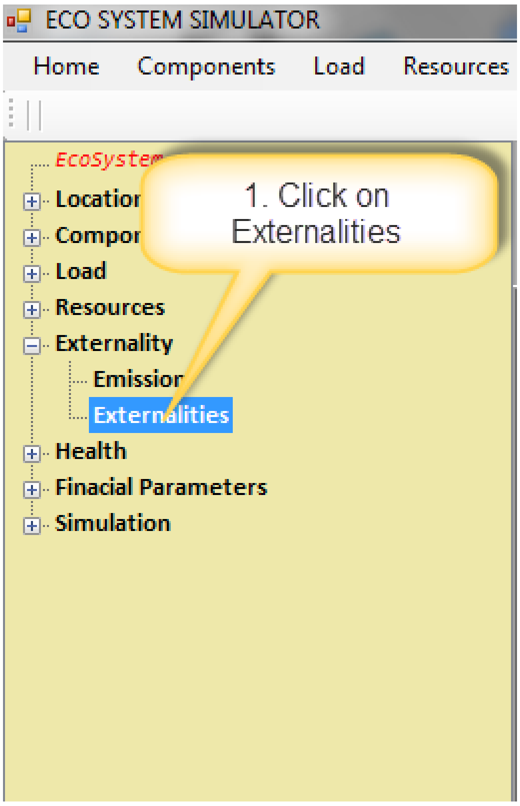
Number of

4. Click Command Set Parameters to set the load

Figure 0.11: Setting the Load parameters

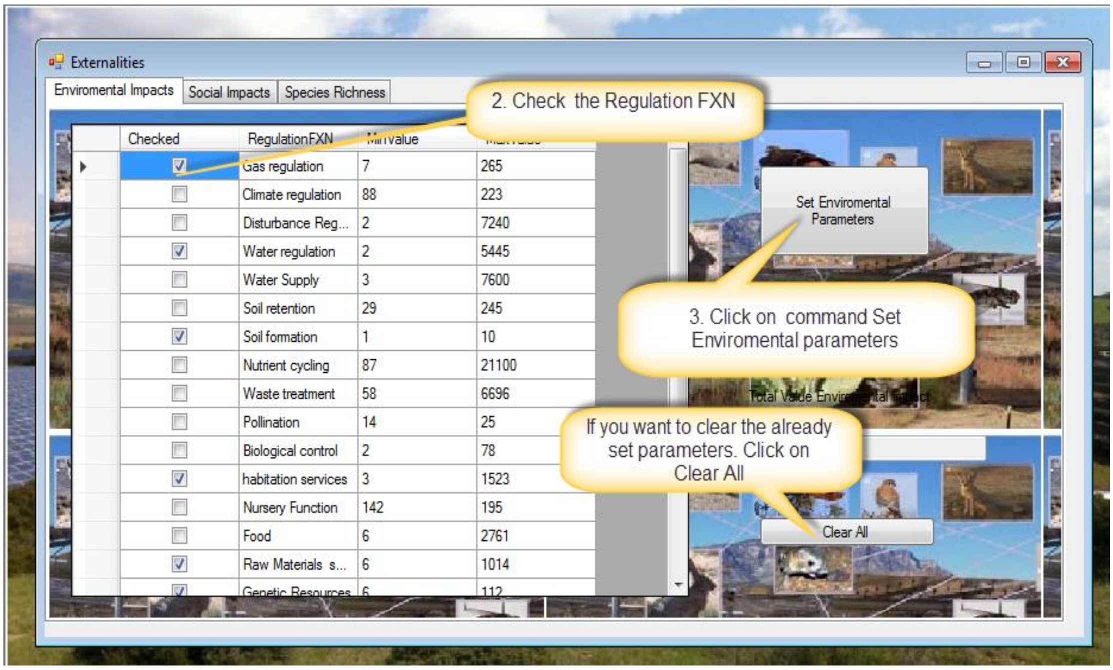
Externalities of Solar PV

The externalities of Solar PV considered in the SPECA modeling tool development are considered in this window as shown in Figure 0.12, Figure 0.13, Figure 0.14, Figure 0.15, Figure 0.16, and Figure 0.17.



1. Click on Externalities

Figure 0.12: Externalities of Solar PV



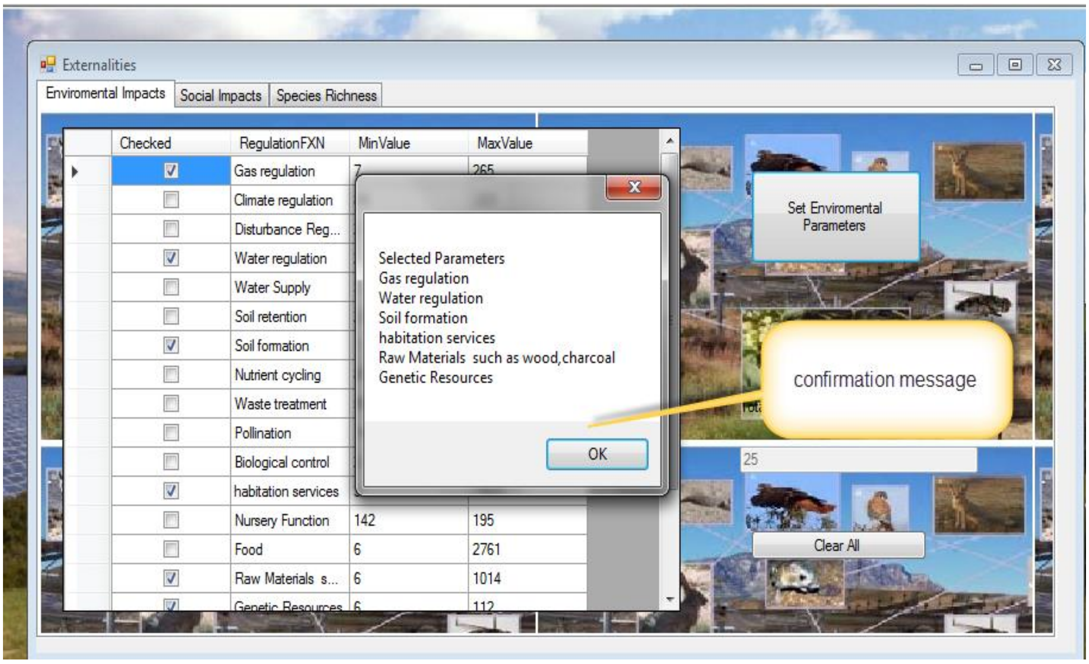
2. Check the Regulation FXN

	Checked	RegulationFXN	MinValue	MaxValue
▶	☑	Gas regulation	7	265
	☐	Climate regulation	88	223
	☐	Disturbance Reg...	2	7240
	☑	Water regulation	2	5445
	☐	Water Supply	3	7600
	☐	Soil retention	29	245
	☑	Soil formation	1	10
	☐	Nutrient cycling	87	21100
	☐	Waste treatment	58	6696
	☐	Pollination	14	25
	☐	Biological control	2	78
	☑	habitation services	3	1523
	☐	Nursery Function	142	195
	☐	Food	6	2761
	☑	Raw Materials s...	6	1014
	☑	Genetic Resources	6	112

3. Click on command Set Enviromental parameters

If you want to clear the already set parameters. Click on Clear All

Figure 0.13: Selection of Ecosystems Goods and Services

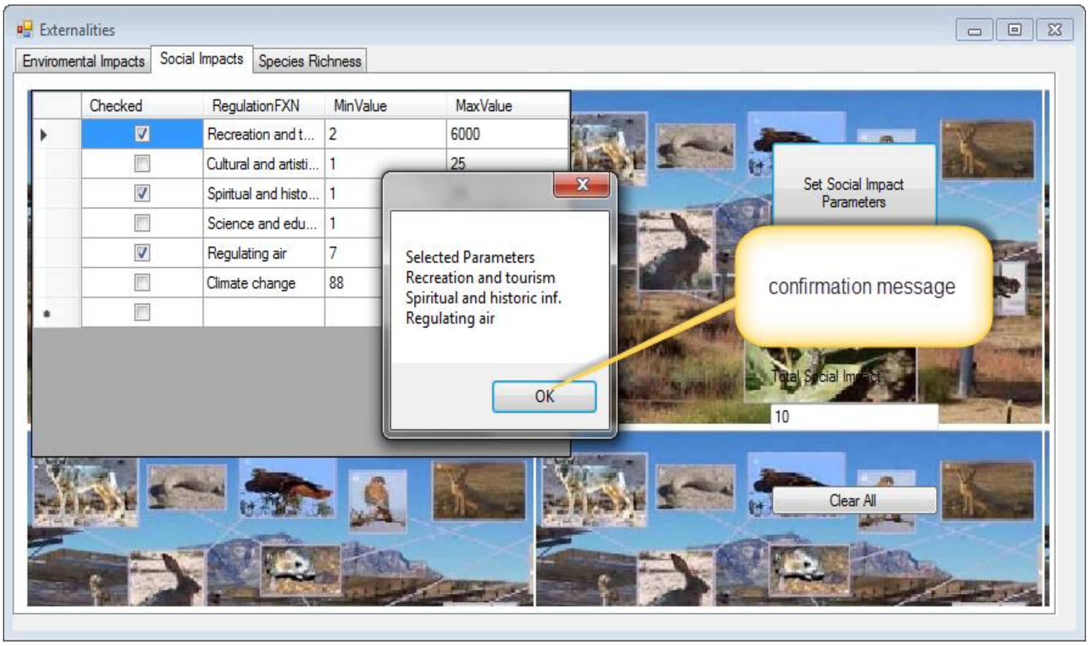


	Checked	RegulationFXN	MinValue	MaxValue
▸	☑	Gas regulation	7	265
	☐	Climate regulation		
	☐	Disturbance Reg...		
	☑	Water regulation		
	☐	Water Supply		
	☐	Soil retention		
	☑	Soil formation		
	☐	Nutrient cycling		
	☐	Waste treatment		
	☐	Pollination		
	☐	Biological control		
	☑	habitation services		
	☐	Nursery Function	142	195
	☐	Food	6	2761
	☑	Raw Materials s...	6	1014
	☑	Genetic Resources	6	112

Selected Parameters
Gas regulation
Water regulation
Soil formation
habitation services
Raw Materials such as wood,charcoal
Genetic Resources

OK

Figure 0.14: Aggregation of selected Ecosystem Goods and Services

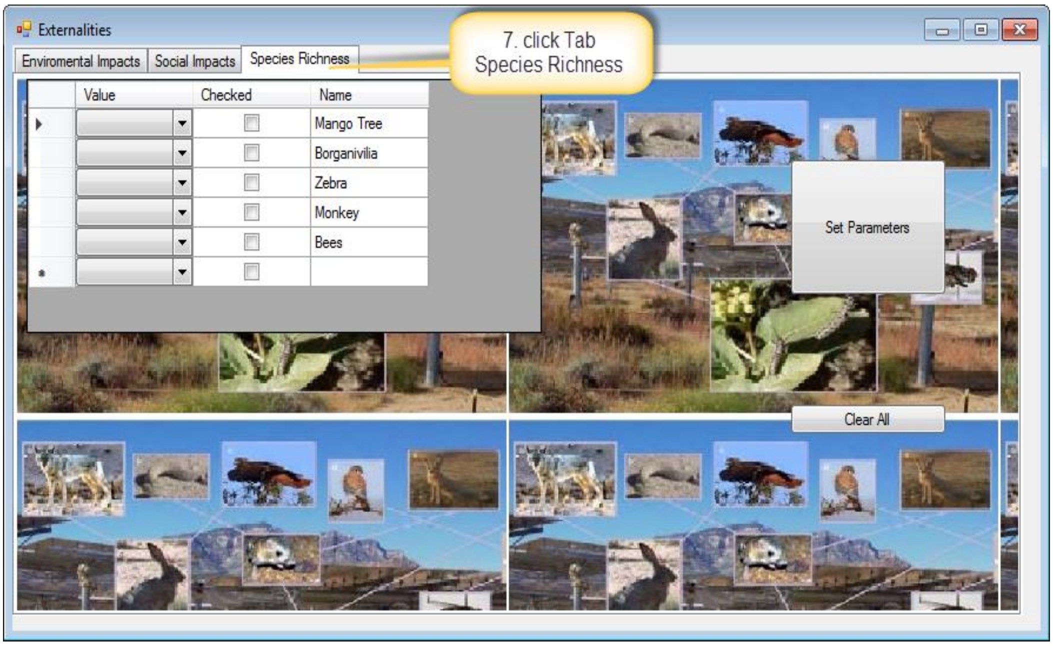


	Checked	RegulationFXN	MinValue	MaxValue
▸	☑	Recreation and t...	2	6000
	☐	Cultural and artisti...	1	25
	☑	Spiritual and histo...	1	
	☐	Science and edu...	1	
	☑	Regulating air	7	
	☐	Climate change	88	
*	☐			

Selected Parameters
Recreation and tourism
Spiritual and historic inf.
Regulating air

OK

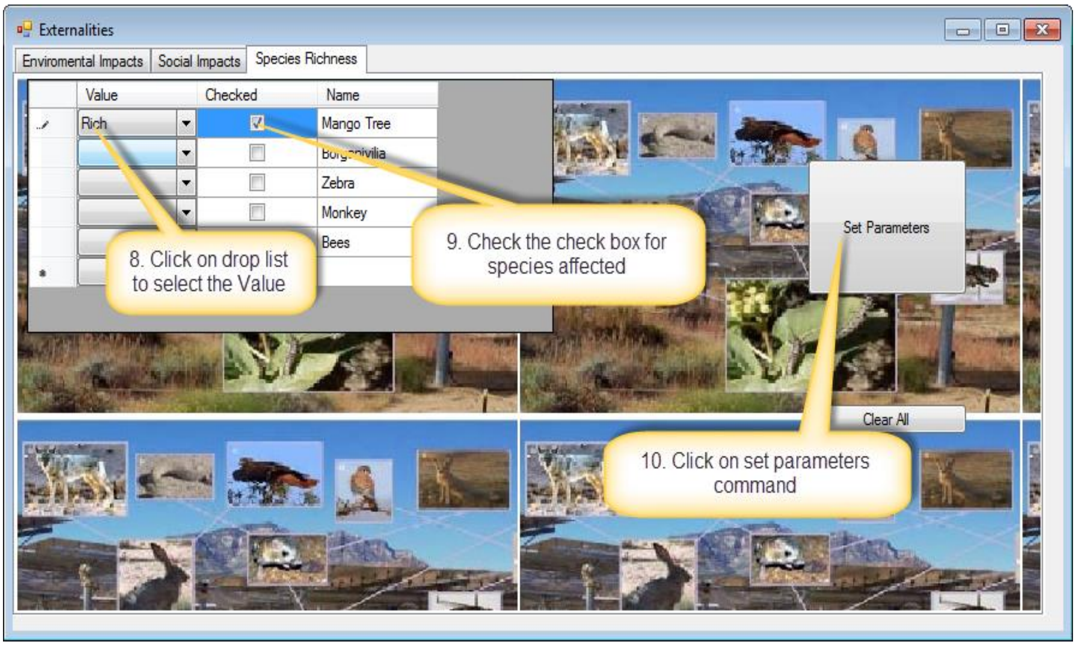
Figure 0.15: Social Impacts Selection



7. click Tab Species Richness

Value	Checked	Name
	☐	Mango Tree
	☐	Borganivilia
	☐	Zebra
	☐	Monkey
	☐	Bees
	☐	

Figure 0.16: Species Richness factor



Value	Checked	Name
Rich	☑	Mango Tree
	☐	Borganivilia
	☐	Zebra
	☐	Monkey
		Bees

8. Click on drop list to select the Value

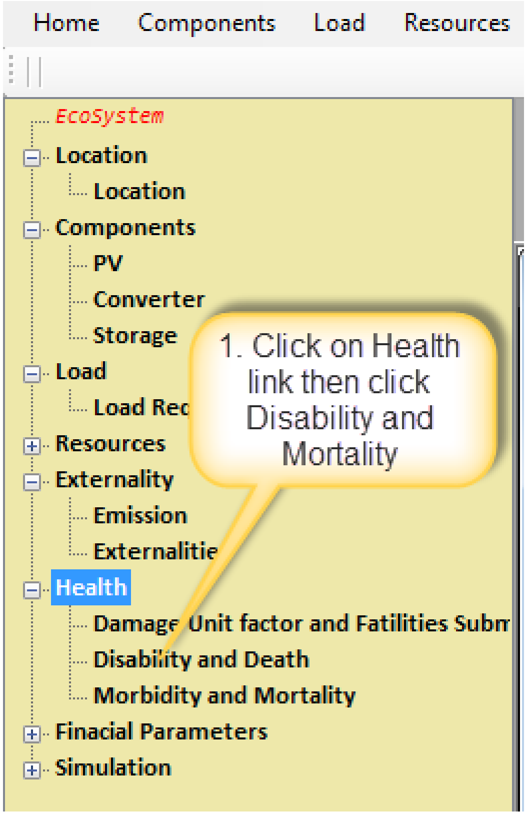
9. Check the check box for species affected

10. Click on set parameters command

Figure 0.17: Species Type and Species Richness

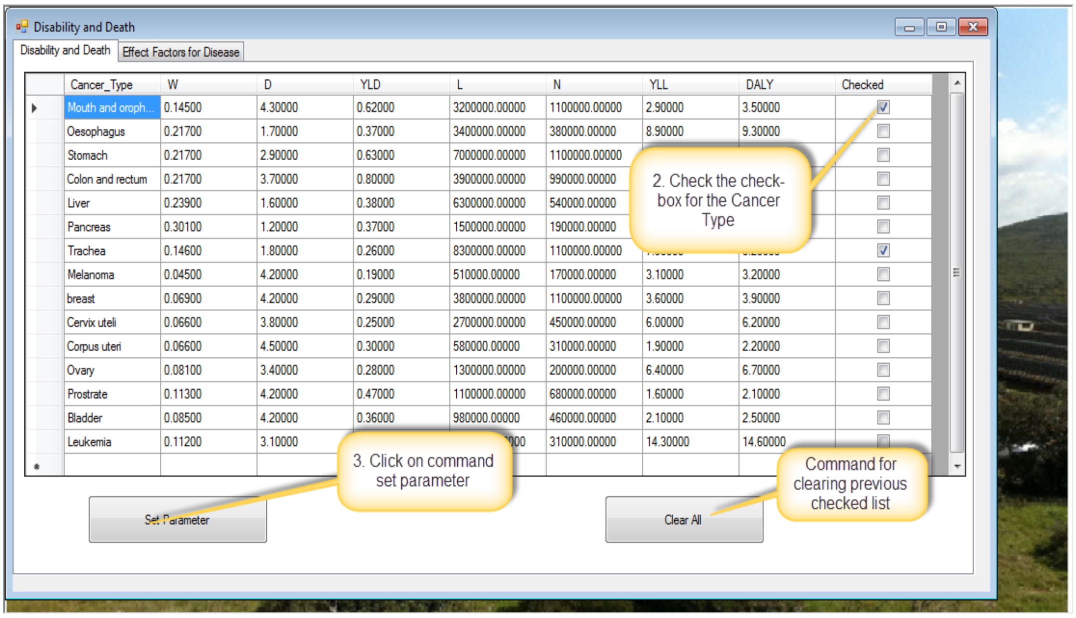
How to set Health impact parameters

The SPECA modeling tool classifies the disease burden caused by Solar PV installation according to disability and death occasioned during generation and construction as described in Figure 0.18 and Figure 0.19.



1. Click on Health link then click Disability and Mortality

Figure 0.18: Disability and Mortality selection Window



Cancer_Type	W	D	YLD	L	N	YLL	DALY	Checked
Mouth and oroph...	0.14500	4.30000	0.62000	3200000.00000	1100000.00000	2.90000	3.50000	☑
Oesophagus	0.21700	1.70000	0.37000	3400000.00000	380000.00000	8.90000	9.30000	☐
Stomach	0.21700	2.90000	0.63000	7000000.00000	1100000.00000	[illegible]	[illegible]	☐
Colon and rectum	0.21700	3.70000	0.80000	3900000.00000	990000.00000	[illegible]	[illegible]	☐
Liver	0.23900	1.60000	0.38000	6300000.00000	540000.00000	[illegible]	[illegible]	☐
Pancreas	0.30100	1.20000	0.37000	1500000.00000	190000.00000	[illegible]	[illegible]	☐
Trachea	0.14600	1.80000	0.26000	8300000.00000	1100000.00000	[illegible]	[illegible]	☑
Melanoma	0.04500	4.20000	0.19000	510000.00000	170000.00000	3.10000	3.20000	☐
breast	0.06900	4.20000	0.29000	3800000.00000	1100000.00000	3.60000	3.90000	☐
Cervix uteli	0.06600	3.80000	0.25000	2700000.00000	450000.00000	6.00000	6.20000	☐
Corpus uteri	0.06600	4.50000	0.30000	580000.00000	310000.00000	1.90000	2.20000	☐
Ovary	0.08100	3.40000	0.28000	1300000.00000	200000.00000	6.40000	6.70000	☐
Prostrate	0.11300	4.20000	0.47000	1100000.00000	680000.00000	1.60000	2.10000	☐
Bladder	0.08500	4.20000	0.36000	980000.00000	460000.00000	2.10000	2.50000	☐
Leukemia	0.11200	3.10000	[illegible]	[illegible]	310000.00000	14.30000	14.60000	☐

2. Check the check-box for the Cancer Type

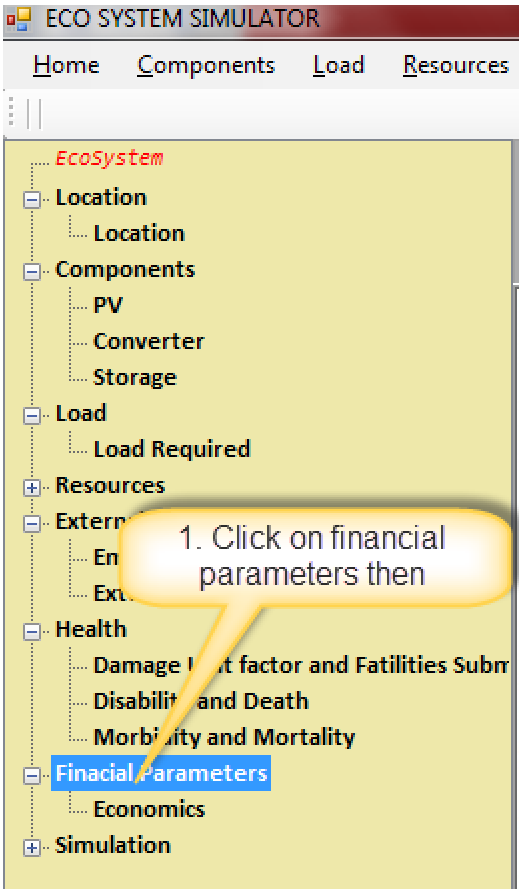
3. Click on command set parameter

Command for clearing previous checked list

Figure 0.19: Disease Burden Selection

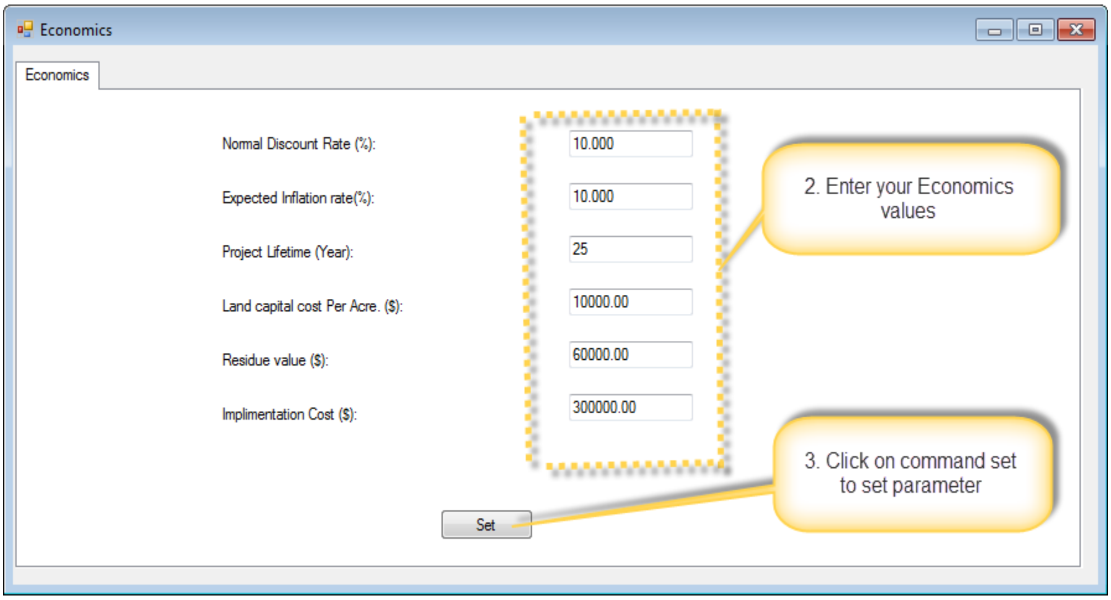
How to set Economic parameters

Economic metrics such as LECOE, LESCOE, and LCOE are determined based on economic and technical parameters. The economic parameters include the cost of land, interest, depreciation, discount rates, inflation rates, and equipment cost of equipments. Once enjoined with the technical parameters such as project lifetime, energy generated by the panels, and the area occupied yields the LECOE, LESCOE, and the LCOE as described by Figure 0.20 and Figure 0.21.



1. Click on financial parameters then

Figure 0.20: Economic parameters Selection Window



Normal Discount Rate (%): 10.000

Expected Inflation rate(%): 10.000

Project Lifetime (Year): 25

Land capital cost Per Acre. ($): 10000.00

Residue value ($): 60000.00

Implimentation Cost ($): 300000.00

2. Enter your Economics values

3. Click on command set to set parameter

Figure 0.21: Selecting the Economical Parameters

Simulator

After doing all the entries in the SPECA modeling tool, simulation can be prompted. This is done by clicking the simulation button on the simulation window, as shown in Figure 0.22. The results and analysis window appear that contain the outcome of the simulation.

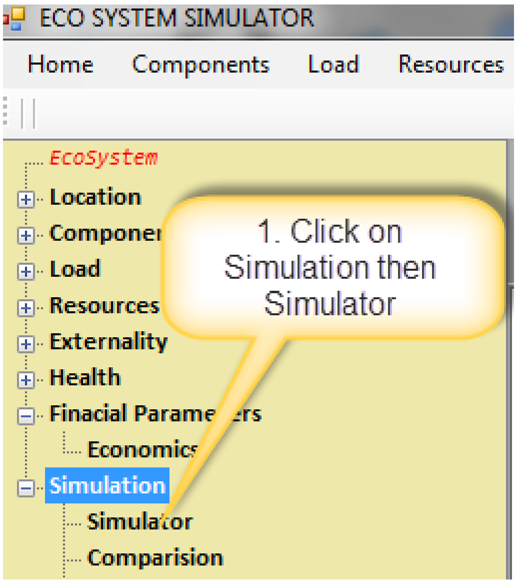
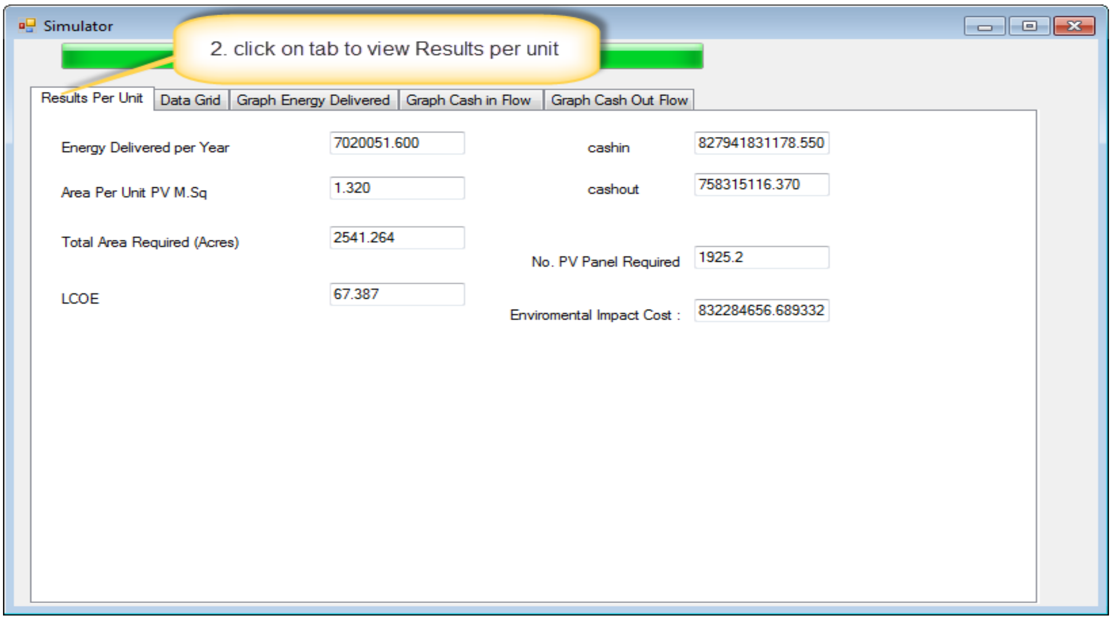


Figure 0.22: Simulator Window

The results window contains the metrics output, including the energy delivered, area occupied by a single panel, total area of land required, including the BOP, LCOE, cash inflow, cash outflow, and the total number of panels required. Also, in the same window, the energy data grid and the respective graphs of delivered energy, cash inflow, and cash outflow are shown in Figure 0.23.



2. click on tab to view Results per unit

Energy Delivered per Year: 7020051.600

Area Per Unit PV M.Sq: 1.320

Total Area Required (Acres): 2541.264

LCOE: 67.387

cashin: 827941831178.550

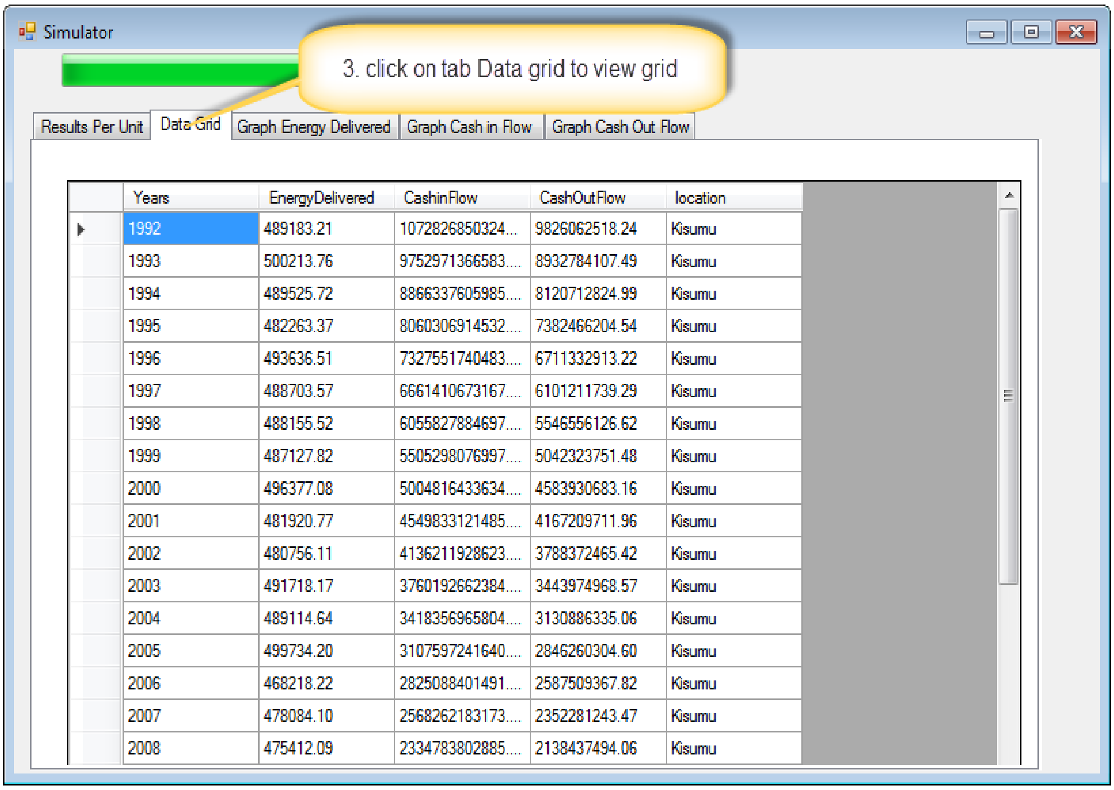
cashout: 758315116.370

No. PV Panel Required: 1925.2

Enviromental Impact Cost : 832284656.689332

Figure 0.23: Metrics Output

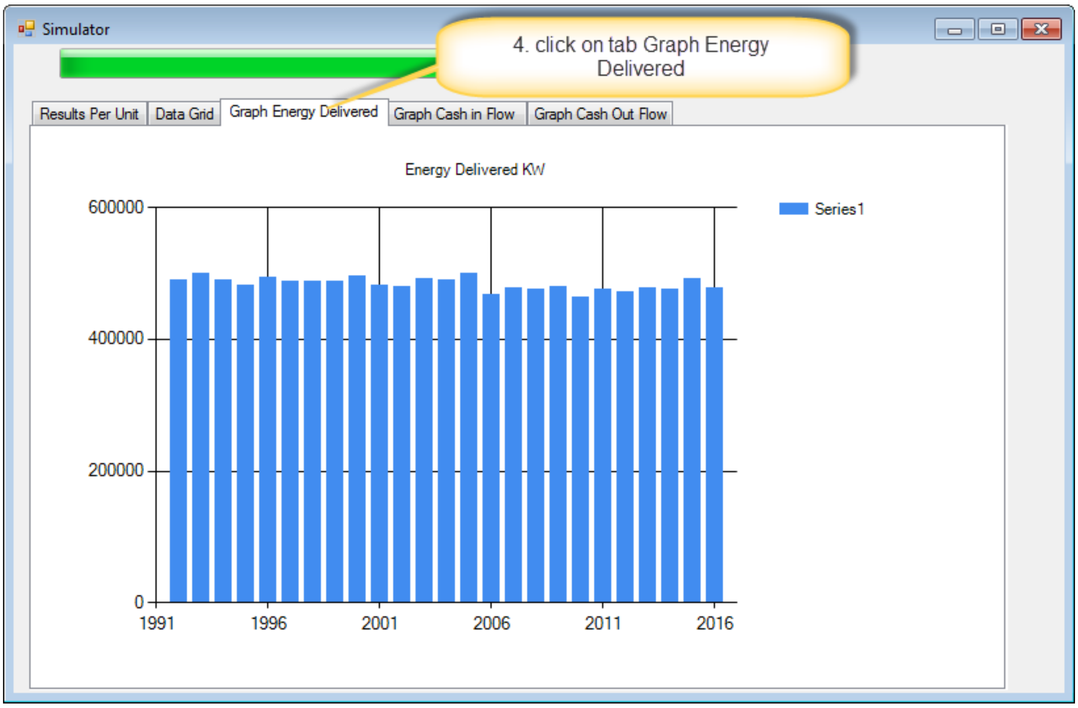
The data for the cash inflow and cash outflow, yearly energy generated, graph of cash inflow and cash outflow is shown in Figure 0.24, Figure 0.25, Figure 0.26, and Figure 0.27.



3. click on tab Data grid to view grid

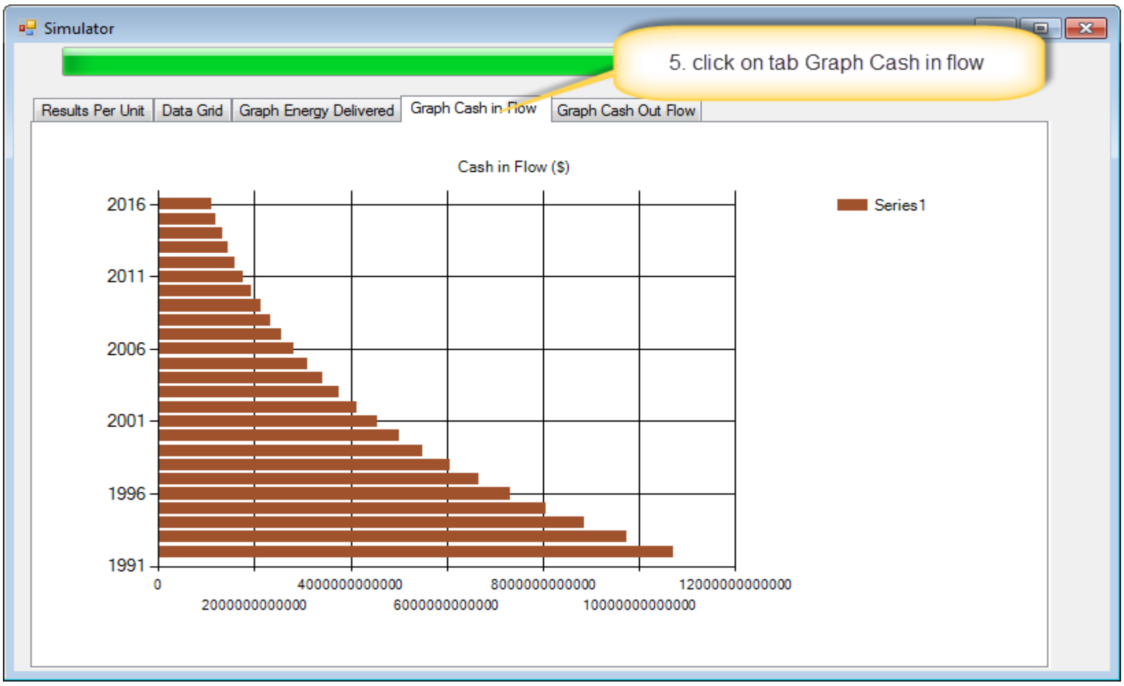
Years	EnergyDelivered	CashinFlow	CashOutFlow	location
1992	489183.21	1072826850324...	9826062518.24	Kisumu
1993	500213.76	9752971366583....	8932784107.49	Kisumu
1994	489525.72	8866337605985....	8120712824.99	Kisumu
1995	482263.37	8060306914532....	7382466204.54	Kisumu
1996	493636.51	7327551740483....	6711332913.22	Kisumu
1997	488703.57	6661410673167....	6101211739.29	Kisumu
1998	488155.52	6055827884697....	5546556126.62	Kisumu
1999	487127.82	5505298076997....	5042323751.48	Kisumu
2000	496377.08	5004816433634....	4583930683.16	Kisumu
2001	481920.77	4549833121485....	4167209711.96	Kisumu
2002	480756.11	4136211928623....	3788372465.42	Kisumu
2003	491718.17	3760192662384....	3443974968.57	Kisumu
2004	489114.64	3418356965804....	3130886335.06	Kisumu
2005	499734.20	3107597241640....	2846260304.60	Kisumu
2006	468218.22	2825088401491....	2587509367.82	Kisumu
2007	478084.10	2568262183173....	2352281243.47	Kisumu
2008	475412.09	2334783802885....	2138437494.06	Kisumu

Figure 0.24: Cash inflow and Cash Outflow



4. click on tab Graph Energy Delivered

Figure 0.25: Energy Output



5. click on tab Graph Cash in flow

Figure 0.26: Graph of Cash inflow

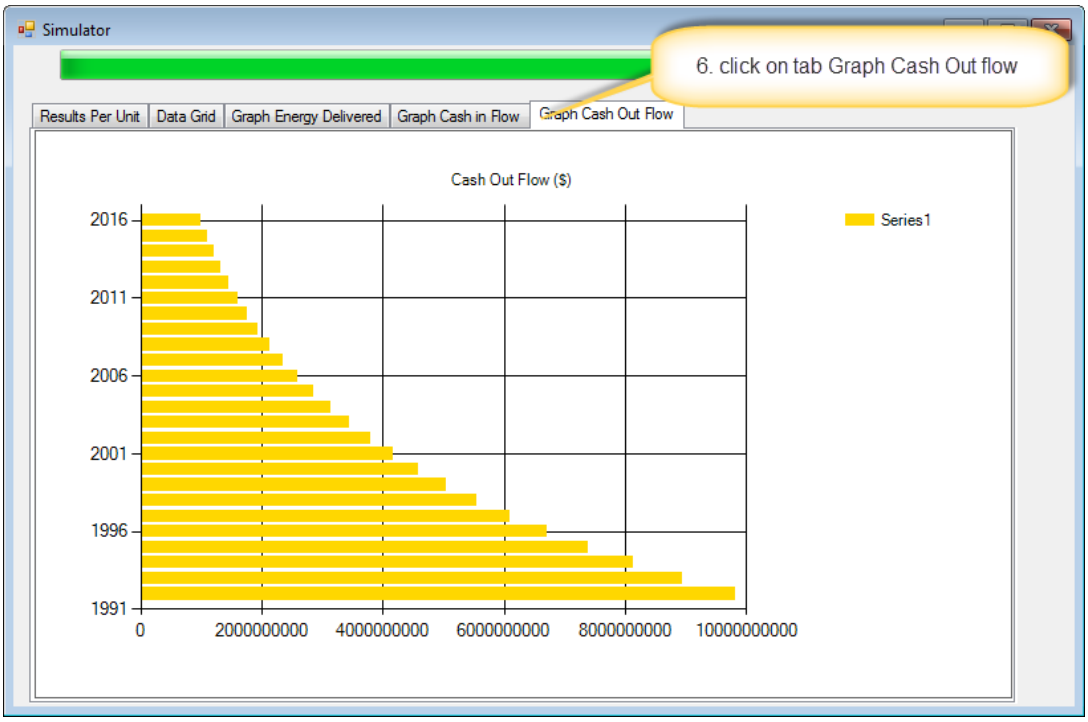
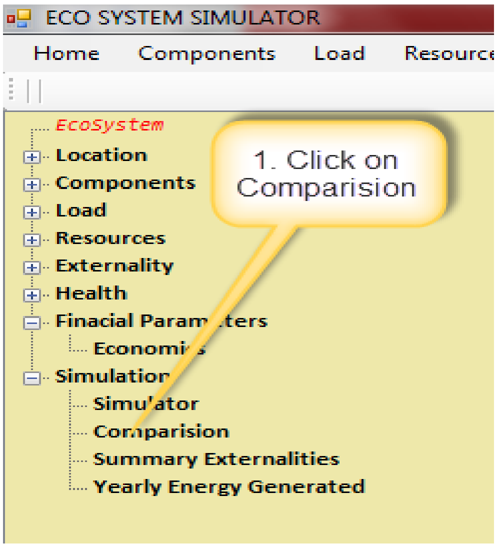


Figure 0.27: Graph of Cash outflow

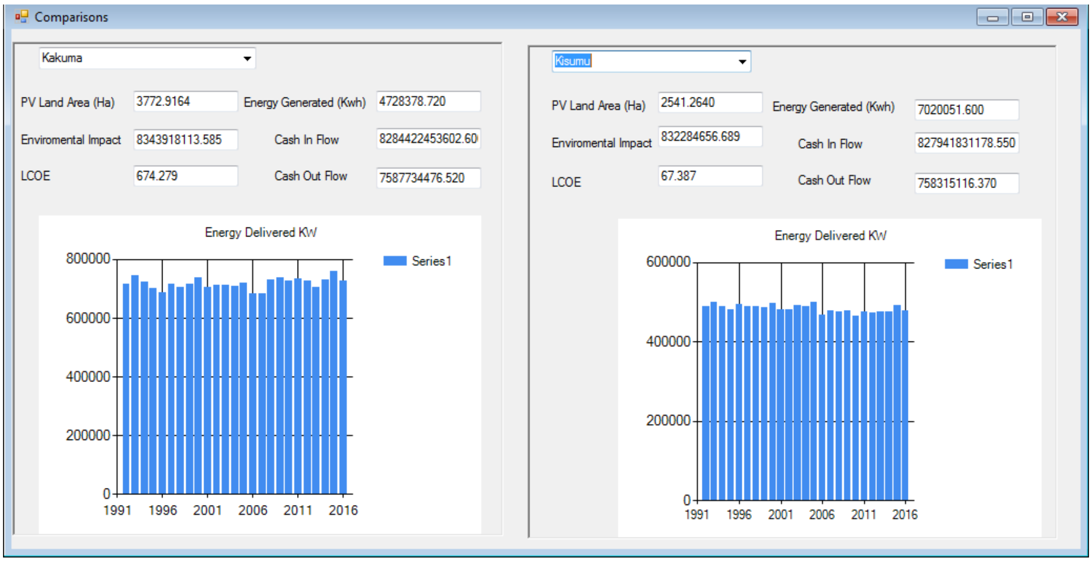
Comparison

The SPECA modeling tool can compare metric outputs of different regions with different irradiation levels and geographical regions. The comparison windows are as shown in Figure 0.28 and Figure 0.29, respectively.



1. Click on Comparision

Figure 0.28: Comparison Window



Kakuma

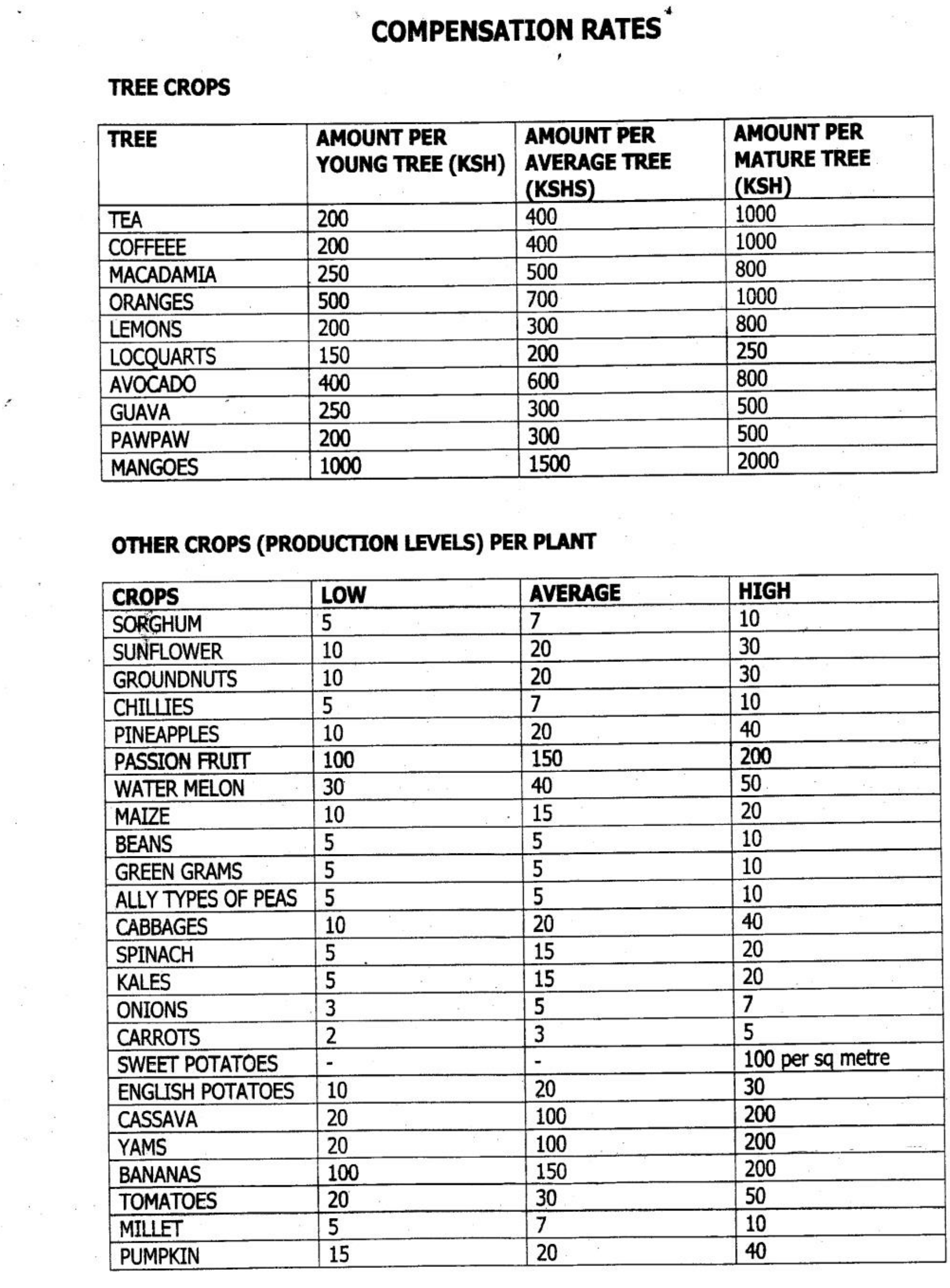
PV Land Area (Ha) 3772.9164
Energy Generated (Kwh) 4728378.720
Enviromental Impact 8343918113.585
Cash In Flow 8284422453602.60
LCOE 674.279
Cash Out Flow 7587734476.520

Kisumu

PV Land Area (Ha) 2541.2640
Energy Generated (Kwh) 7020051.600
Enviromental Impact 832284656.689
Cash In Flow 827941831178.550
LCOE 67.387
Cash Out Flow 758315116.370

Figure 0.29: Regional Comparison

Appendix III: Ministry of Agriculture (MoA) Compensation Rates



COMPENSATION RATES

TREE CROPS

TREE	AMOUNT PER YOUNG TREE (KSH)	AMOUNT PER AVERAGE TREE (KSHS)	AMOUNT PER MATURE TREE (KSH)
TEA	200	400	1000
COFFEEE	200	400	1000
MACADAMIA	250	500	800
ORANGES	500	700	1000
LEMONS	200	300	800
LOCQUARTS	150	200	250
AVOCADO	400	600	800
GUAVA	250	300	500
PAWPAW	200	300	500
MANGOES	1000	1500	2000

OTHER CROPS (PRODUCTION LEVELS) PER PLANT

CROPS	LOW	AVERAGE	HIGH
SORGHUM	5	7	10
SUNFLOWER	10	20	30
GROUNDNUTS	10	20	30
CHILLIES	5	7	10
PINEAPPLES	10	20	40
PASSION FRUIT	100	150	200
WATER MELON	30	40	50
MAIZE	10	15	20
BEANS	5	5	10
GREEN GRAMS	5	5	10
ALLY TYPES OF PEAS	5	5	10
CABBAGES	10	20	40
SPINACH	5	15	20
KALES	5	15	20
ONIONS	3	5	7
CARROTS	2	3	5
SWEET POTATOES	-	-	100 per sq metre
ENGLISH POTATOES	10	20	30
CASSAVA	20	100	200
YAMS	20	100	200
BANANAS	100	150	200
TOMATOES	20	30	50
MILLET	5	7	10
PUMPKIN	15	20	40

Ministry of Forestry and Wildlife (MoFW)

Tree Species	Clear fells (Kshs)	Thinning (Kshs)
Grevillea		
Logs than 200mm	2114	1733
Logs of diameter (240mm-319mm)	2461	2018
Logs of diameter (320mm-399mm)	2840	2329
Logs of diameter (400mm-479mm)	3555	2915
Logs of diameter (480mm-559mm)	3978	3262
Logs of diameter 560mm and over	4311	3535
Juniperus Procera (Cedar)		
Logs than 200mm	5043	4136
Logs of diameter (240mm-319mm)	5870	4813
Logs of diameter (320mm-399mm)	6775	5556
Logs of diameter (400mm-479mm)	8482	6955
Logs of diameter (480mm-559mm)	9491	7782
Logs of diameter 560mm and over	10284	8433
Vitex keniasis (Meru oak)		
Logs than 200mm	3020	2476
Logs of diameter (240mm-319mm)	3515	2882
Logs of diameter (320mm-399mm)	4057	3327
Logs of diameter (400mm-479mm)	5079	4165
Logs of diameter (480mm-559mm)	5683	4660
Logs of diameter 560mm and over	6158	5050
Cypress		
Logs than 200mm	2375	1972
Logs of diameter (240mm-319mm)	2375	1972
Logs of diameter (320mm-399mm)	2398	1991
Logs of diameter (400mm-479mm)	2421	2010
Logs of diameter (480mm-559mm)	2444	2029
Logs of diameter 560mm and over	2468	2069

Botanical name	**Common name**	**Common usage**	**Kshs**
Afzelia Quanzensis	Mbambakofi	Carving/floor	5150

Albizzia gummifera	mukurwe	Timber/veneer	3260
Aningeria Altissima	Mukangu	Timber/plywood	2378
Bosquiea phoberos	Mbarakaya	furniture	3264
Chlorophora	Mvule	Furniture	5149
Cordia spp	Muringa	Furniture	4458
Combretum schumani	Munguruwe	Carving floor	3266
Brachylaena Huilensis	Muhugu	Carving floor	4458
Croton macrostachys	Mungoma	plywood	2173
Dombeya goezetini	Mukeu	Joinery	3266
Ficus spp	Satin wood	plywood	2673
Dombeya Goetzenii	Mukeu	Joinery	3266
Euphorbia spp	Euphorbia	plywood	2673
Juniperus procera	Cedar	Floor/furniture	5940
Hagenia abyssinica	Rosewood	Joinery	5149
Manilkara butugi	kydilani	Timber	3266
Maesopsis eminii	mutere	joinery	3266
Funtumia africana	mutondo	timber	2673
Nesogordia	mnovi	timber	3266
Acacia	kanunga	Carving	4000
Vitex doniana	mfundu	timber	3266
casuarina	mvinje	timber	1600

Other forest products

Produce	Units	Price (Kshs)
Bamboo	Per piece	55
withies	Per piece	10
Firewood	Per cubic metre	1200
Cut stone	Annual (20m*20m)	30,000
Culvert	Per piece	3500
Limestone	Per metric tonne	190
Crushed stone	Per metric tonne	200
Soil	Per metric tonne	300
Honey	Annually	10,000

Publications

Chowdhury, S., & Kibaara, S. K. (2016). Review of economic modelling for quantifying the environmental impacts of renewable energy sources. *IEEE PES PowerAfrica Conference, PowerAfrica 2016*, 280–284. https://doi.org/10.1109/PowerAfrica.2016.7556617

Journal, E., Kibaara, S., Murage, D. K., Musau, P., & Saulo, M. J. (2019). *The Challenges and Capabilities of the Existing Techno-economic Modelling Tools for Renewable Energy Utilization*. *6*(5), 57–64.

Kibaara, S., Murage, D. K., Musau, P., & Karweru, M. (2020). Analysis of the Levelized Cost of Electricity (LCOE) of Solar PV Systems Considering their Environmental Impacts on Biodiversity. *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020, August*. https://doi.org/10.1109/PowerAfrica49420.2020.9219929

Kibaara, S., Murage, D. K., Musau, P., & Saulo, M. J. (2019). Development and Implementation of the ECOS Modelling Tool for Utility Scale Solar Energy. *European Journal Of Operational Research*, *6*(5), 23–33.

Kibaara, S., Murage, D. K., Musau, P., & Saulo, M. J. (2020). Comparative analysis of the implementation of solar PV systems using the ECOS model and HOMER Software: A kenyan scenario. *6th IEEE International Energy Conference, ENERGYCon 2020, April,* 350–355. https://doi.org/10.1109/ENERGYCon48941.2020.9236543