Analysis of the Levelized cost of Electricity (LCOE) of Solar PV Systems considering their Environmental impacts on Biodiversity

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***Abstract*—Large scale solar photo voltaic plants are being developed and implemented at rapid rates and others are being set up to occupy large tracts of land running to millions of acres across the globe. The cascaded environmental impacts of such huge installations are not well addressed in both literature and in the famous techno-economic modelling tools such as HOMER, SAM, INSEL and TRNSYS. This study provides a full cost approach for determining the Levelized cost of Electricity (LCOE). The study incorporates all the costs incurred during generation and operation including the externality costs that have been traditionally omitted by other models. This has been aided by the use of a new software called the ECOS model developed by students of the Jomo Kenyatta University of Science and Technology. The study carries out sizing of Solar PV for Lodwar and the resultant metrics such as LCOE when externalities are included. The novel contribution of this paper is the incorporation of the environmental impacts of Solar PV which has not done by other software tools like HOMER.**

***Keywords*—ECOS Model, HOMER, Externalities, HRES**

I. Introduction

Solar Photovoltaic power is experiencing high growth having an installed capacity of 22GWp and growing at a rapid rate of about 40% annually [1]. 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 lead to wide scale land occupation and ecosystem damage. For instance, New Jersy has set a target of 22.5% renewable energy by 2021, New York has completed a 37MWp solar plant at Long Island, while Canadian Ontario has a complete solar Plant of about 80MWp [1][2].

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 energy payback time (EPBT) [3][4]. A small number of published work consider other impacts such as hazardous materials [5], land use and land use efficiency [6][7], wild animals habitat fragmentation [2][4][1]. It is further reported that the installation and operation phases of solar photovoltaic have received little scientific attention [1]. Most of these studies contains no quantitative information on the wider 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 [8]. However, this value does not account for the carbon dioxide where the solar photo-voltaic are mounted in forested regions where vegetation must be removed to pave way. Turney et al [1] reports that there is only one published report that collected raw data on the impacts of solar to the environment. Despite lack of enough studies addressing the wider impacts of Solar photovoltaic there is a significant need to address these impacts. This paper focuses on the impact identification and monetary valuation. Once the negative impacts of solar monetized, they are lumped up together LCOE equation using the ECOS modelling tool.

II. Installation, Operation and Characteristics of Solar Power

The development of solar photovoltaic is taking place in various with different ecosystems regions across the globe. The environmental impacts of solar are location specific [1]. In this section different biomes that characterize installations and operation of solar PV are described. The biomes included forested lands, desert shrub lands, deserts, grasslands and farmlands. The biodiversity in a given biome is measured by the species density per hectare which is associated with solar insolation and precipitation [9].

Forest lands receive precipitation of not less than 50cm per year, together with the absence of sustained drought and freezing [1]. Cloud cover in forested lands are known to reduce the direct solar insolation by factors of about 25-50% [1]. The average height of trees in the forested areas range from 5-100m whereas the rooting depths spans from 1-5m. The biomass density of tropical forests ranges from 100-500Mg C per hectare [10]. The forest cover are a source of goods and services such as floods control, source of wood and pulp, filtration of pollutants from rain water and air, habitat for wild animals and scenic and recreational values[10].

Grasslands receive an yearly average precipitation of about 30-50cm [11]. Droughts and freezing are experienced in glass lands which leads to low tree density. The biomass density is estimated at 10-50Mg C per Hectare with the majority of these biomass lying on the soil surface [11]. Biodiversity levels are about 25% less compared to forestlands. The grasslands provides the same services as forestlands, with the exception of wood and pulp, but they offer excellent grazing fields[11]. The precipitation received in desert shrub lands ranges from 5-30cm per year with lower cloud cover compared to forestlands and grass lands. The biomass density is also lower and stands at about 10-30Mg C per Hectare. The biodiversity level is almost the same as found in grasslands. They offer the same natural goods and services as grasslands with the exception of low floods mitigation and low grazing capacity.

True deserts have precipitations as low as 3cm per year with no biomass and biodiversity [1]. They include Sahara desert, Arabian Desert among others. Such environments are conducive for solar energy harvesting because they have low population density, wildlife and biomass.

Farmland are manmade [1] and can be built in replacement of forested areas, woodlands, shrub lands or deserts. The cloud cover in farmlands depends on the type of land cover type, it could be a desert, forest lands or shrub lands. Biodiversity is less compared to grasslands but the biomass level are almost the same [1].

Installation of solar photovoltaic requires the removal of trees and the root balls [1]. The PV panels are mounted on steel and Aluminum supports approximately 1m above the ground level on concrete footings. The level of the ground where mounting is done is kept below 5% by grading and periodical mowing is done to keep to prevent shading and this keeps the vegetation height below 1m. Herbicides are sometimes applied instead of mowing [12]. The balance of plant (BOP) that is, the plant auxiliaries systems such as inverters transformers cable channels access roads etc also occupy surmountable space and cascaded environmental impacts. Denholm et al [13] reports 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. The spatial density ranges from 5-8 acres of land per MWp. The water uptake for commercial solar thermal power requires estimated 500-1000 gallons per MWp [13]. The main contribution of this paper is the development and use of the ECOS model, a tool which is able to integrate the environmental impacts in the LCOE metric. In the following section the methodology on the use of ECOS model as a sizing and techno-economic tool is discussed.

III. METHODOLOGY

The methodology followed in this paper starts with the mathematical description of the ECOS model and the incorporation of the environmental impacts of solar energy in the cost modelling analysis. The ECOS software development involves the use of the lifecycle analysis methods and other life cycle cost of Solar PV such as initial cost, replacement cost, operations and maintenance cost and the salvage value. The key impact categories identified in the development of the ECOS software are land use, human health, wildlife and the Greenhouse gases (GHG) emissions. Each of the impact category is described in subsequent sections.

A. ECOS Model System Architecture

The ECOS modelling tool was developed to overcome the inability to include the environmental impacts of Solar PV in the determination of the system metrics. The traditional tools which includes HOMER, IHOGA, SAM uses the capital cost, operations and maintenance costs, residual value and life time energy generated to calculate the LCOE as shown by Equation 1-2 below.

$$LCOE = \frac{Total\ life\ cycle\ \cos ts}{Total\ life\ time\ energy\ production} \qquad (1)$$

$$LCOE = \left\{ \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \right\} \Big/ \left\{ \sum_{t=1}^{T} \frac{E_t}{(1+r)^t} \right\} \qquad (2)$$

LCOE represents the cost of electricity that would match the cash inflows and the cash outflows normalized over the lifespan of the plant. This important metric allows the independent power producers (IPPs) to fully recover all the costs of the plant over a predetermined period of time [14][15] . The LCOE of an energy generating unit is usually determined at the point where the sum of all the discounted revenues equalizes with the sum of all the discounted cost as described by equation (3).

$$\sum_{t=1}^{T} \frac{R_t}{(1+r)^t} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (3)$$

Unlike the modeling done by HOMER, the LCOE equation (4) adopted in the ECOS model has included the externalities $\sum_{i=k}^{k} EC$ (social, environmental and economic) of solar PV in the computation of LCOE and other metrics such as energy generated, cash flows among others.

$$LCOE = \frac{IC - \sum_{t=1}^{T} \frac{DEP+INT}{(1+DR)^n} TR + \sum_{t=1}^{T} \frac{LP}{(1+DR)^t} + \sum_{t=1}^{T} \frac{O\&M}{(1+DR)^t}(1-ROI) - \frac{RV}{(1+DR)^t} + \frac{\sum_{i=k}^{k} EC}{(1+DR)^t} + RC}{\frac{\sum_{n=1}^{N} S^t * (1-SDR)^t}{(1+DR)^t}} \qquad (4)$$

The ECOS model is developed using visual basic programming. A graphical user interface (GUI) provides user interactive platform. SQL has been used for database development. The system has the user interface and the database. The GUI 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 process flow diagram of the ECOS model is described by Fig 1 below. The database used is a relational database management system which is a Microsoft SQL server. The database stores the tabular files of DNI, cost of equipment's used for solar photovoltaic and their types, different environmental aspects of the different regions in Kenya, batteries, inverters etc.

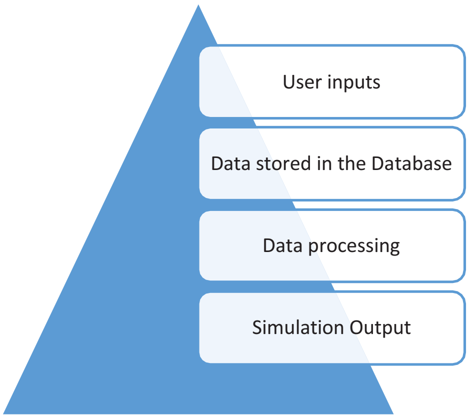

Fig 1: ECOS Model system Architecture

B. Land use

The land use intensity is a very important impact category as it is used as a proxy for other impacts. In the ECOS model land use is quantified by use of land area directly occupied by the panels which results to transformation of land use. The ECOS model defines the land occupation as the occupation of land for a number of years defined as the area occupied multiplied by the length of time the land is under occupation of the Solar PV. The measurement of land use metrics in this paper followed the work done by [1] and is shown by Equations (5-8) below.

$$ED / yr = P_{ac} * DNI_{site} / day * CF * 365\ days \quad (5)$$

$$P_{ac} = \frac{ED / yr}{DNI_{site} / day * CF * 365 days} \quad (6)$$

$$P_{dc} = \frac{P_{ac}}{Mismatch * dirt * invertereffciency} \quad (7)$$

$$Area\ occupied = \frac{P_{dc}}{DNI_{site} / year * collector\ efficiency} \quad (8)$$

A 30% balance of plant (BOP) was included in the area occupied which caters for the auxiliary systems such as access roads, storage facilities, offices etc.

C. Human Health

The health impacts of solar energy in this paper were modelled as the external effects of the different pollutants emitted. They represent the damage done to the human population. In order to calculate the external cost (XC) associated with the emissions of CO_2, SO_2, NO_x, PM, VOC and the other air pollutants, the quantities released per unit of electricity generated from USSE was determined. This was done using the damage cost ($/ton of pollutant emission) which is ascribed to the emissions and an emission factor EF , defined as the tonnage of the pollutant emitted per unit of energy generated from solar PV. The cost of per unit of electricity produced is determined using these factors and is incorporated directly into the LCOE equation above. The equation for calculating XC ($/kWh) of the pollutant emission is as shown by equation (9)[16].

$$XC = DC * EF \quad (9)$$

Where DC is the damage cost ($/ton of pollutant)

EF Emission factor Kg pollutant per kwh of energy produced

The externality cost is determined by assigning each of them a global warming potential (GWP) as shown in equation (10) below [16].

$$XC = DC_{co2} * GWP * EF \quad (10)$$

The damage cost and emission factor values used in this paper are as shown in Table 1 below.

Table 1: Damage and Emission factor values

Pollutant	EF (kg/Kwh)	Estimate damage ($)
CO_2	117	26.4
SO_2	0.00058	1869.77
NO_x	0.4	7919.03
PM	0.0066	4839.41
VOC	0.0021	5265.79

D. Morbidity and Mortality submodel

The health impacts of solar energy in this paper were modelled as the external effects of the different pollutants emitted. The work-related and non-work related accidents considered in this paper are for the non-Organization for Economic Corporation and Development countries where Kenya is classified into[17]. The per unit prices for treating persons suffering injuries or mortalities while working with USSE are based on the studies done by [18][19]. This sub-model consists of two variables viz. unit morbidity value and the unit mortality value. The per unit morbidity value (UV_{mod} $/person) is estimated using Equation (11) below.

$$UV_{mod}(t) = UV_{mod}(1804) + \Delta UV_{mod}(t) \quad (11)$$

Where $\Delta UV_{mod}(t)$ is the discounted change in morbidity value. The unit mortality values (UV_{mot} ,$/person) in this paper were obtained from [17] and are described by Equation (12) below

$$UV_{mot}(t) = UV_{mot}(17413) + \Delta UV_{mot}(t) \quad (12)$$

Table 2: Morbidity and mortality values

Parameter	Unit	Value
Unit mortality value	$/person	17413
Unit Morbidity	$/person	1804
Fatalities per million tons of ncrete	Persons/million tons	0.159
Fatalities per million tons of el	Persons/million tons	2.0158923
Fatalities per million tons of estone	Persons/million tons	0.2906977
Fatalities per MWh	Persons /MWh	2.6E-7
Injuries per MWh	Persons /MWh	1.0E-7

The unit mortality value and the unit morbidity values shown in table derive their costs from three phases that is during the construction of the USSE, operation phase and the decommissioning phase. The parameters used for the fatalities/mortality and morbidity in Table 2 below.

E. Ecosystems goods and services submodel

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 in this paper were adopted from Groot et al [20] and are divided into four different ecosystems services i.e provisioning services, regulating services, habitat services and the cultural services. Each of the four is also divided into different subcategories as shown in Table 3 below.

Table 3: Valuation of Ecosystem Goods and Services

Ecosystem Goods and services	Valuation ($)/ha
Regulating functions of ecosystems	
1 Regulating air	7-265
2 Climate change	88-268
3Disturbing ecosystems goods and services	2-7240
4 Water uptake and usage	2-5445
5 water supply	3-7600
6 Soil erosion	29-245
7Soil maturity and formation	1-10
8 soil nutrients recycling	87-21,100
9 plants pollination	14-25
10. Biological control	2-78
Habitat provision	
11 habitation services	3-1523
12 Nursery function	142-195
Bleeding and production services	6-2761
13 food	6-1014
14Raw materials such as wood, charcoal	6-1014
15Genetics	6-112
16medicinal value	6-112

The monetary value of the ecosystem service value for each of the region is estimated by Equation (13) below.

$$ESV = \sum A_k * VC_k \qquad (13)$$

Where ESV = ecosystem service value estimate

A_k = Area in hectares

VC_k = value coefficient of ecosystem ($/ha/year)

The different values of VC_k used as proxies for the different biomes. They are obtained from the Ecosystem service value database (EVSD).

IV. SIMULATION SETUP FOR THE ECOS MODEL

The HRES is designed considering solar PV and batteries with 2 hours of autonomy. The financial parameters used for the design are described by Table 4 below.

Table 4: ECOS Model Economic Inputs

Component	% Amount
Discount rate	7.5%
Expected inflation rate	7%
Project lifespan	25 years
land cost/acre (for ECOS model)	Area dependent variable
Residual value (ECOS model)	4.5% of CAPEX

It should be noted that some aspects like the land cost, environmental cost, social cost are treated as sunk cost in HOMER because they are not included in the user inputs nor are they displayed in the simulation results and analysis. The LCOE equation in most models includes the anticipated residual value after decommissioning the plant [14][15], which has not been included in the traditional tools architecture.

V. CRITERION OF SIZING SOLAR PV USING ECOS MODEL

The economic criteria used in the sizing of the solar PV depends on the load demand. In this paper the load demand of a typical village in Turkana district was estimated as shown in Table () below which was used as an input to the ECOS model to determine the number of solar panels required and the batteries. Solar PV system includes different components that should be selected according to the system type, site location and applications. The major components for solar PV system are the PV module, inverter and the battery bank.

A. Sizing of a standalone PV system

For convenience and accurate sizing of a PV system, the specific area, Direct Normal Irradiance (DNI) data and the anticipated load are defined. The size of the PV system, total number of PV panels and the number of batteries are then calculated. As such several factors considered are the amount of energy (kWh) that can be generated by the solar PV to meet the load demand, the Ah of the batteries required and the area occupied. There are several sizing techniques used previously in literature such as intuitive, numerical, analytical, commercial computer tools, artificial intelligence and the hybrid methods[21]. The numerical technique has been used in this paper for sizing the PV system because of its known accuracy and ability to easily use the linear functions unlike other tools [21].The energy delivered by a PV is given by equation (14)

$$P_{ac} = P_{dc,STC} * \eta \ (5) \qquad (14)$$

where

P_{ac} =actual ac power delivered

$P_{dc,STC}$ =rated dc power output under standard test conditions

η =conversion efficiency which accounts for inverter efficiency, dirt, PV collectors efficiency and mismatch factor.

B. Steps followed in Sizing the PV Array

The insolation data (kWh/m^2) for the different sites used in the ECOS model are obtained from the NASA websites. The worst month (month with the lowest solar irradiance) of the year is used for design. As shown by Equation (15) identification of a PV module and using its rated current IR together with its columb efficiency of about 0.9 and a derating factor (DR) of 0.9 and the Direct Normal Irradiance (DNI) of the design month , the Ah/day produced by each solar PV string is determined.

$$Ah / day - string = DNI\,(kWh / m^2) * I_R * DR \qquad (15)$$

The number of parallel strings is given by equation (16) below

$$Strings in\ parallel = \frac{designmonth\ load\ (Ah / day)}{Ah / day\ per\ module\ in\ designmonth} \qquad (16)$$

The number of PV modules in series is determined by equation (17) below

$$modules in\ series = \frac{systemvoltage(V)}{No\min al\ module\ voltage(V)} \qquad (17)$$

C. Determination of collector Area

The size of area occupied and the number of PV cells varies according to type, as each has different parameters.

Amount of energy delivered by a cell PV is described by Equations (18) and (19) below

$$T_{cell} = T_{ambient} + \left(\frac{NOCT - T_{av}}{0.8}\right)..* DNI_{STC} \quad (18)$$

Where

DNI_{STC} =insolation under standard test conditions (kWh/m^2),

$NOCT$ =Nominal Operating Cell Temperature, T_{av}=average maximum daily temperature,

$$P_{dc} = PV_{rating}[1 - P_l](T_{cell} - T_{ov}) \quad (19)$$

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

Including the dirt, mismatch and inverter efficiencies will result in an estimated ac rated power of the solar photo voltaic (P_{ac}) shown by Equation (20).

$$P_{ac} = P_{dc} * mismatch * dirt * inverter\eta \quad (20)$$

The collector area is governed by the yearly energy yield and the yearly energy demand as described by Equations (21)-(24) below.

$$ED / yr = P_{ac} * DNI_{site} / day * CF * 365\ days \quad (21)$$

$$P_{ac} = \frac{ED / yr}{DNI_{site} / day * CF * 365 days} \quad (22)$$

$$P_{dc} = \frac{P_{ac}}{Mismatch * dirt * inverterefficiency} \quad (23)$$

$$Area\,occupied = \frac{P_{dc}}{DNI_{site} / year * collector\ efficiency} \quad (24)$$

D. Battery Storage

The battery storage capacity is determined by Equation (25) below.

$$batterystoragecapacity = \frac{Ah / day * days\ of \quad autonomy}{MDOM * DR} \quad (30)$$

Where

$MDOM$ =maximum depth of discharge

DR =% discharge rate

VI. RESULTS AND ANALYSIS

In this section the simulation results obtained from ECOS model and HOMER software for Turkana District are discussed and compared. The two software calculates the output based on the procedure mentioned in the methodology and the results of each software are described in the following sections. The ECOS model displayed results of yearly energy generated from 1992-2016 as shown in the diagram below. The energy delivered varies according to the DNI estimated at 1800kWh/m^2/yr. Fig 2 shows the yearly energy generated during the lifespan of the plant. The random variability of the solar resource leads to the uneven energy production in the different years. The area required for installation to meet the electricity demand was estimated to be 5130 acres of land that required about 4008 solar photovoltaic panels and 394 batteries.

The cascaded impacts on land as a result of this land occupation includes diseases like Cancer which results from emission of some hazardous gases such as particulate matter , lead, VOC among others. The ECOS model estimated the NPC including the externalities (environmental and health costs) to a tune of \$2.07 billion for a period of 25 years The environmental cost included were the cost of land and the various function of land in this particular region as was described in Table 3.

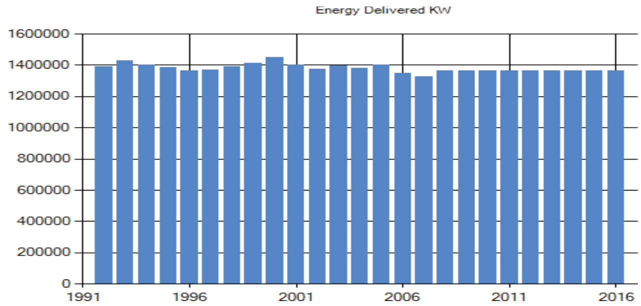

Fig 2: Yearly Energy Generated

The ECOS determines the cost of a disease using two functions described above, that is, unit morbidity value and unit mortality values. The cash inflow and cash outflow for the whole period is shown in Fig 3 and Fig 4. The cash flow is highest at the beginning of the project and minimum near the end of the lifespan.ECOS model further determines the LCOE to be about \$3.81. As discussed earlier LCOE is a function of the Life cycle costs (LCC) and the energy generated. The ECOS model is among the first tools to accommodate the external costs of energy generation which in this case are the environmental costs and the health costs.

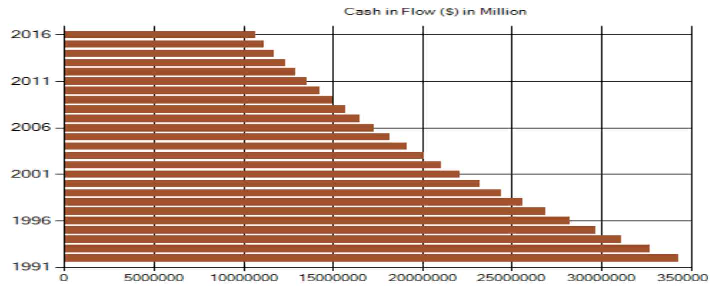

Fig 3: ECOS Model Cash Inflow

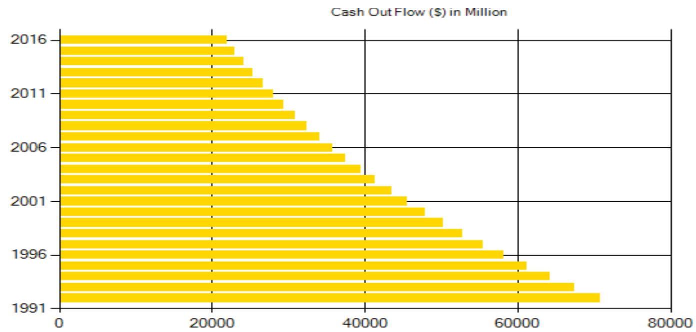

Fig 4:ECOS Model Cash outflow

VII. CONCLUSIONS AND RECOMMENDATIONS

In this paper the ECOS modelling tool has been used to size solar photovoltaic system for Turkana District. The ECOS model calculates the LCOE based on the full cost life cycle costing over the entire life of the plant. The result shows a levelized cost of electricity of about 10.57 USD cents and 7396 acres of land occupied inclusive of the balance of plant. The results further indicates a total of 5778 PV modules and 213 batteries. The environmental costs amounts to about 573 Million USD. If no externalities are considered the LCOE is about 8% lower which indicates that the incorporation of the environmental impacts tends to increase the overall cost of energy. The highest contribution of the added cost (externality cost) comes from the land use occupancy. Research and development should be geared towards improving the ECOS model software to accommodate more than one energy resource type to enhance hybridization of renewable energy systems.

REFERENCES

[1] D. Turney and V. Fthenakis, "BNL-96353-2011-JA Environmental impacts from the installation and operation of large-scale solar power plants," *Renew. Sustain. Energy Rev.*, vol. 15, no. 6, pp. 3261–3270, 2013.

[2] V. M. Fthenakis, M. Fuhrmann, J. Heiser, A. Lanzirotti, J. Fitts, and W. Wang, "Emmisions and Encapsulation of Cadmium in CDTe PV Modules during Fires," no. January, 2005.

[3] V. M. Fthenakis, H. C. Kim, and E. Alsema, "Emissions from photovoltaic life cycles," no. January, 2008.

[4] J. E. Mason, V. M. Fthenakis, T. Hansen, and H. C. Kim, "Energy Pay-Back and Life Cycle CO 2 Emissions of the BOS in an Optimized," 2005.

[5] T. Tsoutsos, N. Frantzeskaki, and V. Gekas, "Environmental impacts from the solar energy technologies," *Energy Policy*, vol. 33, no. 3, pp. 289–296, 2005.

[6] P. Denholm, M. Hand, M. Jackson, and S. Ong, "Land Use Requirements of Modern Wind Power Plants in the United States," *Natl. Renew. Energy Lab.*, vol. Technical, no. August, p. 46, 2009.

[7] V. Fthenakis and H. Chul, "Land use and electricity generation: A life-cycle analysis," vol. 13, pp. 1465–1474, 2009.

[8] E. A. Alsema, M. De Wild-scholten, and I. Researcher, "The real environmental impacts of crystalline silicon PV modules: an analysis based on up-to-date manufacturers data," no. January, 2005.

[9] B. A. Hawkins *et al.*, "Energy, water, and broad-scale geographic patterns of species richness," *Ecology*, vol. 84, no. 12, pp. 3105–3117, 2003.

[10] P. Crow, "The Influence of Soils and Species on Tree Root Depth," *For. Comm. Inf. Note*, pp. 1–8, 2005.

[11] X. Zhou, M. Talley, and Y. Luo, "Biomass, litter, and soil respiration along a precipitation gradient in southern Great Plains, USA," *Ecosystems*, vol. 12, no. 8, pp. 1369–1380, 2009.

[12] T. Tsoutsos, N. Frantzeskaki, and V. Gekas, "Environmental impacts from the solar energy technologies," vol. 33, pp. 289–296, 2005.

[13] P. Denholm and R. M. Margolis, "Impacts of Array Configuration on Land-Use Requirements for Large-Scale Photovoltaic Deployment in the United States Preprint," no. May, 2008.

[14] M. El-Shimy, *Economics of Variable Renewable Sources for Electric Power Production*. 2017.

[15] C. (United S. E. I. A. Namovicz, "Assessing the economic value of new utility-scale renewable generation projects," no. July, pp. 1–15, 2013.

[16] I. F. Roth and L. L. Ambs, "Incorporating externalities into a full cost approach to electric power generation life-cycle costing," *Energy*, vol. 29, no. 12-15 SPEC. ISS., pp. 2125–2144, 2004.

[17] N. P. J. N. B. Nkambule;, "Externality costs of the coal-fuel cycle: The case of Kusile Power Station," vol. 113, no. 9, pp. 1–9, 2017.

[18] T. Development and U. Kingdom, "New Elements for the Assessment of External Costs from Energy Technologies," no. September, 2004.

[19] P. Preiss and V. Klotz, "NEEDS - New Energy Externalities Developments for Sustainability," vol. 6, no. 9, pp. 1–95, 2008.

[20] R. S. De Groot, M. A. Wilson, and R. M. J. Boumans, "A TYPOLOGY FOR THE CLASSIFICATION , DESCRIPTION AND VALUATION OF ECOSYSTEM FUNCTIONS , GOODS AND SERVICES Figure 1 : Framework for Integrated Assessment and Valuation of Ecosystem Functions , Goods and Services," no. May, pp. 1–20, 2002.

[21] T. Khatib, I. A. Ibrahim, and A. Mohamed, "A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system," *ENERGY Convers. Manag.*, vol. 120, pp. 430–448, 2016.