Proceedings of the 2022 Sustainable Research and Innovation Conference
JKUAT Main Campus, Kenya
5 - 6 October, 2022

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

S Kibaara and D.K Murage

Abstract - Throughout the growth of the energy industry in the world, photovoltaics have received a trajectory of growth. This has witnessed many plants being installed to augment the existing grid or as alternatives to those living away 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 paper 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.

Keywords— Externalities, LCOE, USSE, ECOS Model, LECOE.

I. INTRODUCTION

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 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 [2]-[3]. Global attention has focused on the negative impacts of conventional energy sources on the environment [3]-[4]. These include the emission of greenhouse gases and oil spillage in rivers, which may interfere with aquatic life and habitat fragmentation [3].

On the other hand, non-conventional sources have always been regarded as clean and harmless to the environment [4]. In all public discussions held regarding pollution from conventional sources of Energy, the advice is that everyone should adopt renewable energy sources [5]. 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, their utilization is low, standing at 15-20%, therefore not fully penetrating the market due to several barriers [1]-[5]-[6]. 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[1]-[5]-[6]-[7]-[8]. The market prices of Energy generated from fossil fuels are lower than the prices of Energy generated from renewable energy technologies such as solar, wind, and biofuels [9][10].

II. LEVELIZED COST OF ELECTRICITY

The Levelized cost of electricity (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 (inflows and outflows) [11]. The lifetime cash flows are as defined by Equation (1).

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

Where CO, Ct, T, t, and r are initial cost, capital cost, total lifespan, number of years, and interest rate.

LCOE is 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 paper, 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),

S Kibaara Department of Electrical Engineering, phone: +254720443813; e-mail: kariukisamuel2004@gmail.com.
DK Murage, Department of Electrical Engineering, JKUAT (e-mail: dkinyua. jkuat.ac.ke).

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 [12][13]. It is reported that the actual cost of electricity production from either renewable energy technologies or conventional sources of Energy must take into consideration the external costs incurred while generating energy [9].

III. METHODOLOGY

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. 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.

The Solar-PV based Power and Environmental Cost Assessment (SPECA) 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 energy generated, pay back time, NPV, Net present value, Levelized cost of electricity, Levelised Externality Cost of Energy (LECOE) and Levelised Total Cost of Energy (LTCOE). LTCOE is an estimate of the total amount of money paid if the environmental impacts are taken into consideration. In this paper the modelling tool called SPECA is implemented using visual programming which is coupled with a GUI to provide an interactive user platform and friendliness. SQL is used for database development. The SPECA model architecture is as shown on Fig 1.

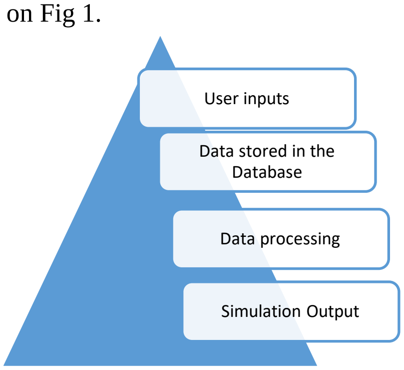

Fig 1: SPECA Model System Architecture

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.

IV. SPECA MODEL

A. Life Cycle Costs

The techno-economic indicators which are 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 constituents of the 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 are shown in Table 2.

The SPECA modeling tool estimates the total electricity generation cost 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 cost and the O&M costs, which individually constitute 88.1 % and 11.7%. In comparison, the replacement cost accounts for 0.2% for Lodwar. The capital cost, O&M costs and the replacement costs in Gatarakwa are 87.8%,12.1% and 0.4%.

Table 2. 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 LTCOE, LECOE and LCOE computations over the 25 years lifespan of the solar PV was arrived by discounting all the life cycle costs to present values. A discount rate of 5% was used in this paper.

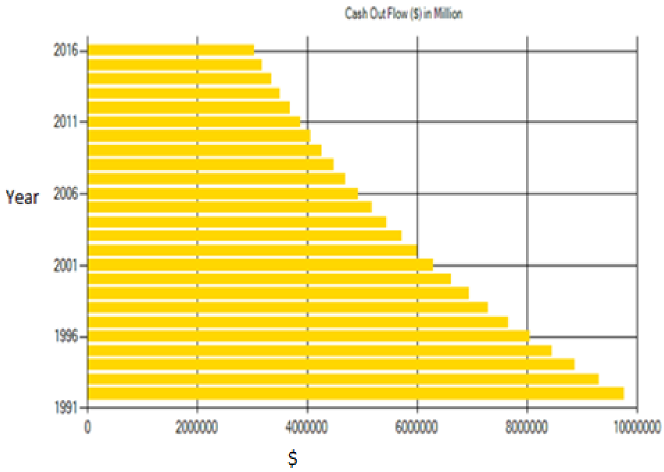

Fig 3. Cash outflow for Lodwar

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 and hence reducing the net income earned from the sale of Energy.

The SPECA modeling tool computes the NPV, which examines the cash inflows and cash outflows as shown in Fig 3. The cash inflow indicates the amount of revenue generated as a result of selling Energy while the cash outflow is the cumulated yearly expenditure over the lifespan of the plant.

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 the following section.

B. *Externalities of USSE*

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

The fatalities and morbidity values are the indicators of the number of deaths and injuries that will happen during the USSE life cycle. SPECA model estimates about 24 deaths likely to happen to the personnel working in the USSE sites and by 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 area of land 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. Accordingly, the species per Sqm are the number of species occurring in a given land use type per square meter and PDF denotes the number of species that are likely to be lost or displaced when USSE are installed. SPECA modelling tool calculates the total number of species likely to be in a given land use type, the displacement when USSE are installed and the number of species that remains after installation and running of the USSE.

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 paper 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.

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) as compared to 1565kWh/m^2/yr for Gatarakwa. The increased solar insolation in Lodwar of about 1800kWh/m^2/yr translates to a fewer number of panels to meet the demand. Externalities in Gatarakwa are slightly higher owing to the fact the value of biodiversity in Gatarakwa differs significantly from that in Lodwar. Land in Gatarakwa has major economic activities such as grazing, maize farming and tree planting. SPECA modelling tool classifies this region as ‘high rich’. 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.

V. Conclusions

The SPECA modeling tool has revealed that there is always a cost borne by the society of Energy from solar PV. The LCOE of solar PV in Lodwar is determined to be 95.3 % of the actual value while LECOE forms about 4.7%. LECOE originates from 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 De Groot et al. [16], where they are converted to proxies of land use per hectare. The main outcomes of this research show that while investment in Solar PV technologies 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.

VI. References

[1] J. P. Painuly, "Barriers to renewable eneryg penetration; a framework for analysis," *Renew. Energy*, vol. 24, no. 1, pp. 73–89, 2001, doi: https://doi.org/10.1016/S0960-1481(00)00186-5.

[2] S. Simon, "Sustainability Indicators," *Management*, vol. 2, no. February, pp. 1–10, 2003, doi: 10.1680/ensu.156.3.135.36967.

[3] P. A. Owusu and S. Asumadu-Sarkodie, "A review of renewable energy sources, sustainability issues and climate change mitigation," *Cogent Eng.*, vol. 3, no. 1, pp. 1–14, 2016, doi: 10.1080/23311916.2016.1167990.

[4] S. Chowdhury and S. K. Kibaara, "Review of economic modelling for quantifying the environmental impacts of renewable energy sources," *IEEE PES PowerAfrica Conf. PowerAfrica 2016*, pp. 280–284, 2016, doi: 10.1109/PowerAfrica.2016.7556617.

[5] S. A. Abbasi and N. Abbasi, "The likely adverse environmental impacts of renewable energy sources," *Appl. Energy*, vol. 65, no. 1–4, pp. 121–144, 2000, doi: 10.1016/S0306-2619(99)00077-X.

[6] R. Madlener and S. Stagl, "Sustainability-guided promotion of renewable electricity generation," *Ecol. Econ.*, vol. 53, no. 2, pp. 147–167, 2005, doi: 10.1016/j.ecolecon.2004.12.016.

[7] R. Laleman, J. Albrecht, and J. Dewulf, "Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation," vol. 15, pp. 267–281, 2011, doi: 10.1016/j.rser.2010.09.025.

[8] M. Bo and S. Brod, "Environment impact of a concentrated solar power plant," no. March, 2019, doi: 10.31803/tg-20180911085644.

[9] M. El-Shimy, "Economics of Variable Renewable Sources for Electric Power Production," in *Lambert Academic Publishing / Omniscriptum Gmbh & Company Kg*, 2017, p. 566.

[10] R. E. N. Members, *Renewables 2020 global status report 2020*. 2020.

[11] M. Said, M. EL-Shimy, and M. A. Abdelraheem, "Photovoltaics energy: Improved modeling and analysis of the levelized cost of energy (LCOE) and grid parity - Egypt case study," *Sustain. Energy Technol. Assessments*, vol. 9, pp. 37–48, 2015, doi: 10.1016/j.seta.2014.11.003.

[12] R. Sen and S. C. Bhattacharyya, "Off-grid electricity generation with renewable energy technologies inIndia: An application of HOMER," *Renew. Energy*, vol. 62, pp. 388–398, 2014, doi: 10.1016/j.renene.2013.07.028.

[13] C. D. Barley and C. B. Winn, "Optimal dispatch strategy in remote hybrid power systems," *Sol. Energy*, vol. 58, no. 4–6, pp. 165–179, 1996, doi: 10.1016/S0038-092X(96)00087-4.

[14] A. A. Rentizelas, A. I. Tolis, and I. P. Tatsiopoulos, "Investment planning in electricity production under CO2price uncertainty," *Int. J. Prod. Econ.*, vol. 140, no. 2, pp. 622–629, 2012, doi: 10.1016/j.ijpe.2010.11.002.

[15] L. M. Miller and D. W. Keith, "Observation-based solar and wind power capacity factors and power densities," *Environ. Res. Lett.*, vol. 13, no. 10, pp. 1–20, 2018, doi: 10.1088/1748-9326/aae102.

[16] R. S. De Groot, M. A. Wilson, and R. M. J. Boumans, "Framework for Integrated Assessment and Valuation of Ecosystem Functions , Goods and Services," no. May, pp. 1–20, 2002.