Available online www.ejaet.com

European Journal of Advances in Engineering and Technology, 2020, 7(12):26-31

Research Article ISSN: 2394 - 658X

# A Review of Mathematical Modelling of the Levelized cost of Electricity considering the Species Area Relationship (SAR)

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**ABSTRACT**

*Large scale hybrid "wind and solar photo voltaic" plants are being developed and implemented at a very high rate. The set-up of others occupies large tracts of land running to millions of acres across the globe. The cascaded environmental impacts of such huge installations have not been adequately addressed in both literature and in the famous techno-economic modelling tools such as HOMER, IHOGA, SAM, INSEL and TRNSYS. This study provides a full cost approach for developing a mathematical model that attaches the Levelized cost of Electricity (LCOE) of the renewables to the environmental impact including the species conservation. The study reviews and incorporates all the costs incurred during generation and operation including the externality costs that have been traditionally omitted by other models. The study appliers the species area relationship (SAR-Model) to include the externalities of Renewable Energy systems. The novel contribution of this paper is the review of the incorporation of the environmental impacts of renewable technologies in the cost modelling.*

**Key words:** ECOS Model, HOMER, IHOGA, SAM, Externalities, HRES, LCOE, LADA, ICID (international Commission of Irrigation and Drainage

## 1. INTRODUCTION

The cascaded environmental impacts of large-scale hybrid 'wind and solar photo voltaic' plants are being developed and implemented at rapid rates. 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. A full cost approach for determining the Levelized cost of Electricity (LCOE) is therefore necessary.

## 2. ENVIRONMENTAL IMPACT ASSESSMENT METHODS

No single method can meet all the necessary criteria but method selected mostly address the following: simple, manpower, time and budget constraints and flexibility. The commonly used methods for environmental impact assessment include; Baseline studies, The ICID Check-list, Matrices, Network diagrams, Overlays, Mathematical modelling, Expert advice, Economic techniques [1]. Renewable energy systems are considered as friendly to the environment highly expected to drive sustainable development. The accelerated development of renewables is targeted to reduce the dependence on fossil fuels, to contribute to reduction in greenhouse gas emissions and also provide social benefits through increasing access to clean energy (green energy). However, those benefits notwithstanding, even small-scale plants can cause some adverse environmental and social impacts [2].
The environmental and social effects, beneficial and adverse outcomes, need to be considered at all stages throughout a project cycle for following reasons: a) Ensure compliance with state regulations and funding agency on environmental impact assessment requirements for major projects, those projects taking place in protected or sensitive areas, or those judged likely to have significant environmental/social impacts [2]. b) Ensure compliance a variety of environmental protection regulations and quality standards governing: Including water quality, waste management, noise, and nature protection, which need to be respected by any development proposal. C) Ensuring that adverse environmental and social benefits are avoided and benefits optimized or enhanced: Aspects are fully considered at the project feasibility stage and are taken forward to design, implementation and evaluation stages [2]. d) Develop the regulatory framework necessary for determination of optimum energy generation cost optimization: Taking into consideration all social environmental

restorations [3]. e) Those adverse cases can be avoided or mitigated through project planning, design and implementation. Assessment can also often identify opportunities for enhancing the benefits of such projects.

Most countries, has in place regulatory framework designed to promote sustainable development and to avoid and control environmental damage. The frameworks are used to determine if the impacts are likely to be large, important and or significant. It is important to determine, the number of people who will be affected, the extent of the area affected, the intensity and duration of the impact, the amount of other environmental components which will be affected, the cumulative nature of the impact and the reversibility or non-reversibility of the impact [2]. The potential impacts assessment also includes impacts on, bio-physical related issues ,Protected areas and forests, water resources and water quality, Biological diversity, Air quality, Environmental quality, Natural and cultural heritage, Environmentally orientated cultural values, Land ownership and control, Employment and business opportunities, Community living Standards, Public Health including Direct or Indirect Impacts, Short-term or permanent, large or small; certain, likely or possible, and identification of mitigation measures [2]**.**

Assessment also includes the environmentalimpact of the project on the cultural heritage in relation to the following qualities: direct/indirect, spatial distribution, beneficial or adverse, short or long term, permanency (especially); spatial and temporal extent; degree of recovery of the affected environment; value ofthe affected environment; level of public concern; political repercussion [4].

When the nature and scale of potential impacts are understood, ways of minimizing or eliminating negative impacts are then considered which may include technology or design changes, or the introduction of protection measures on design [2].

Economic or Cost-benefit analysis is used to express impacts in monetary terms based on net present value calculations using direct and indirect evaluation techniques; Multi-criteria analysis (weights) achieving consensus on the significance of impacts [4].

Undertaking a Decision analysis (trees) reveal value judgements which underpin decisions and allowing for the identification of the full consequences of a given course of action; Goals achievement matrices relating community goals to the impact of a development proposal generate agreement on the environmental aspects and their significance, Impact mitigation and monitoring. Assembly of the result of an EIA in an Environmental Impact Statement (EIS) relates all the positive and negative effects of a particular project on the environment [4]. Environmental Impact Assessment (EIA) it is carried out on the following tasks: Establish the suitability of the site for the set-up of the Power Plant, proved a concise description of the national environmental legislative and regulatory framework, baseline information, and any other relevant information related to the project, give a description of the technology, procedures and processes to be used, in the implementation of the project, provide a description of materials to be used in the construction and implementation of the project, the products, by-products and waste to be generated by the project, describe the potential effect to the environment, conduct specialized baseline surveys on air, water, soil and noise pollution in the project area.Line [5] carry out the assessment of ground and surface water sources for the proposed power plant, give a full description of environmental effects of the project including the social and cultural effects and the anticipated direct, indirect, cumulative, irreversible, short-term and long-term effects, make a recommendation of specific environmentally sound and affordable wastewater management system, provide alternative technologies and processes available with reasons for preferring the chosen technology and processes., analysis of alternatives including project site, design and technologies, develop an Environmental and Social Management Plan (ESMP) with recommendations of proposing the measures for eliminating, minimizing or mitigating adverse impacts on the environment, including the cost, timeframe and responsibility to implement the measures. Develop an action plan for the prevention and management of the foreseeable accidents, hazardous activities in the course of project construction and operation and decommissioning processes, with Proposal of measures to prevent health hazards and to ensure safety in the working environment for the workforce and the community [5].

The land degradation assessment (LADA) study found that of land degradation (Soil degradation) include and not limited to; (i) Decline in the productive capacity of soil resources due to adverse changes in their biological, chemical, physical and hydrological properties, (ii) Soil erosion, compaction, loss of fertility, changes in soil pH or soil structure. (iii) Water degradation - Decline in the quantity and quality of both surface groundwater resources,including; aridification, drying up of water sources, salinity build up and water pollution.(iv) Vegetation degradation :Decline in the quantity and quality of vegetation including; trees, grasses, shrubs and woody biomass (e.g. through deforestation, overgrazing, fires, cultivation, charcoal burning) [6]. (v) Biodiversity degradation: Decline in the natural genetic resources, loss of species, and ecosystems (including loss of crop plant genetic resources), lowering of habitat quality and reduction in habitats for associated species – both floral and faunal (terrestrial and aquatic). (vi) Chemical degradation– Negative changes in chemical properties of soil, water and ecosystems including; pollution of land and/or water, the environment, soil fertility decline, salinity build-up and/or alkalization, (vii) Physical Degradation - Loss of natural or aesthetic physical conditions of the land e.g. from quarrying, mining, scarification and unplanned developments. (viii) Climate deterioration– Adverse changes in the micro and/or macro climatic conditions that increase vulnerability of crops, livestock, wildlife, biodiversity, ecosystems and human livelihoods. (ix) Land conversion - Decline in the total area of land used, or with potential to be used for crop, livestock and/or forestry e.g. through urbanization, unplanned settlements, cultivation or mining [6].

A study of the Introduction of the solar pump system at Turkana -Lodwar Water and Sanitation Company (LOWASCO) which was proposed to serves domestic water users in the area and also livestock famers the county. The water service providers in urban area in the County operate water sources mainly boreholes with diesel Engine driven motor pump and hand pump. It is notes that solar power pumping system needs high initial investment, needs limited operation cost, and it is almost maintenance free. On the other hand, a diesel generator's power pumping system requires continuous funding for expenses for fuel consumption and maintenance. Total O&M costs of solar power pumping system are much lower than that of pumps with Genset giving it a big economical advantage. Water fee collection maintained at the same tariff though government –user agreement, which will result in producing surplus of funds. It is therefore expected that water service provider can have enough operations fund for sustainable use of the pumping system. And the excess of such operation fund can be diverted as a special financial source for the routine maintenance and repair cost in the pastoralists" communiqués as the "preparedness" described above [7].

Solar power pumping system needs vast initial investment, but no operation cost is required and almost maintenance free, while the existing pumping system requires continuous expense for power supply from KPLC and fuel consumption of stand-by diesel generators during brownout period. Total O&M costs of solar power pumping system are much lower than that of existing pumps. The solar system has big economical advantage to reduce operation cost. On the other hand, water fee collection will be continued at the same tariff of the present agreement, which will result in producing surplus of fund. It is therefore expected that water service provider can have enough operation fund for sustainable use of the pumping system. And an excess of such operation fund can be diverted to a special financial source for the routine maintenance and repair cost in the pastoralists' communiqués as the "preparedness" [7].

The Lake Turkana Wind Power project though being one of the largest private investment, itsbenefit to Kenya cannotbe underscored. The project injected about 300MW of reliable, low cost wind energy to the national grid that is equivalent to over 20% of the current installed electricity generating capacity the largest in Kenya and Africa the power is delivered though the 365KW turbines each with a capacity to generate 850kW. The wind farm site is located in Marsabit District in northern Kenya, approximately 50km north of South Horr Township and 8km east of Lake Turkana. The 'Project' comprise a wind farm, associated overhead electric grid collection system and a high voltage substation. The Project also provided funds for the rehabilitation of the existing road networks from Laisamis to the wind farm site, of more than 200km, and other access road network. A high voltage substation connect the wind power to the Kenyan national grid through an associated Transmission Line. It provide more Kenyans unlimited access to electrical power at a lower cost. It is a zero-emission project that will contribute in enhancing the energy needs of Kenya, enhancing energy diversification and saving 16 million tons of $CO_2$ emission compared to a fossil fuel-fired power plant. This Wind power project created a 300 MW wind farm [8]. The project also create a great link of Great Rift Valley region to the rest of the country through improved infrastructure(road network) linking the wind farm, fiber-optic cable and electrification [8]. With the presence of some 180,000 refugees (40% of the population of Turkana West), the programme and activities proposed for the county aim to boost the County's efforts to achieve its own human development objectives, as well as those of Kenya as a nation, and the global SDGs. The project is expected to help to provide a key opportunity for the development of Turkana [9]. Other energy benefits include the installation of a solar hybrid fuel- solar energy system in Kalobeyei 'Super' Health Centre that utilize solar energy to provide power on a 24/7 basis, with an aim to cut costs and therefore provide better and a more efficient provision of health services for Kalobeyei residents. The system enhances the provision of vital health support to refugee and host communities:[10] 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 [11-12], which has not been included in the traditional tools architecture.

- *Quantitative methodologies offered by NEEDS Integrates three well established methods into a new single framework to be widely applied by researchers and policy analysts.(New Energy Externalities Developments for Sustainability - NEEDS - Future Energy Program - Research Programs - Research - Fondazione Eni Enrico Mattei (FEEM), n.d.) These are:*
- *ExternE :calculates the external costs associated to the supply of electricity and heat based on the most relevant for both current and future technological options*
- *Life Cycle Analysis (LCA): This calculates energy, environment, material and economic resources used by the most relevant power supply options what is referred to as "cradle to grave";*
- *The Integrated MARKAL, EFOM System (TIMES) :Generates technology rich partial equilibrium solutions for the long term development of energy and environment systems.(New Energy Externalities Developments for Sustainability - NEEDS - Future Energy Program - Research Programs - Research - Fondazione Eni Enrico Mattei (FEEM), n.d.)*

## 3. MONITORY EVALUATION PROCEDURE OF THE ENVIRONMENTAL IMPACT OF THE RENEWABLE ENERGY TECHNOLOGIES

*Cost-effectiveness analysis for species conservation*

*Specific forms for C' ( ) and S'( ):*

$C' = \sum c_i A_i$, *where* $c_i$ *= cost (per km2) of habitat protection in ecoregion i.*

*S' = ∑Si, sum of species conserved in ecoregion i (each ecoregion has unique set of species)*
*Si = bi Ai z , species-area function for ecoregion i(Plummer, n.d.)*
*Species-area function relates habitat area to number of species extant in that area*

- *Long known to be an empirical relation, works particularly well for islands and species of terrestrial flora and fauna*
- *S' = bAz most common functional form, with z = 0.2 – 0.4*
- *This relation has been applied to global extinctions by considering species endemic to particular areas and projecting species extinctions as a result of habitat loss in those areas.*
- *Hoekstra et al. (2007) have also used the species-area function in examining cost-effectiveness of conservation (and I steal data from their paper)(Plummer, n.d.)*

*Additive separability of S'( ) and C'( ) makes algebraic solutions possible for Ai*, Wi * (share of ecoregion i in total area of habitat protection), and ei * (share of ecoregion i habitat protection expenditures in total conservation budget): where θi = bi / ci and γ = 1/(1-z)*
*θi => "Priorities" for relative habitat protection shares ?*
*Lagrange multiplier, λ, has simple but important interpretation:*
*λ = "shadow value" of conservation budget in conserving species*
*Legacy conservation areas: Current protected areas is treated as a set of minimum habitat area constraints:*
*{Ai 0} => Ai ≥ Ai 0*
*Geographic limits on habitat protection: Limits on available habitat is treated as a set of maximum habitat area constraints:*
*{Ai max} => Ai ≤ Ai max*
*Add either or both to Lagrangian and maximize subject to full set of constraints*

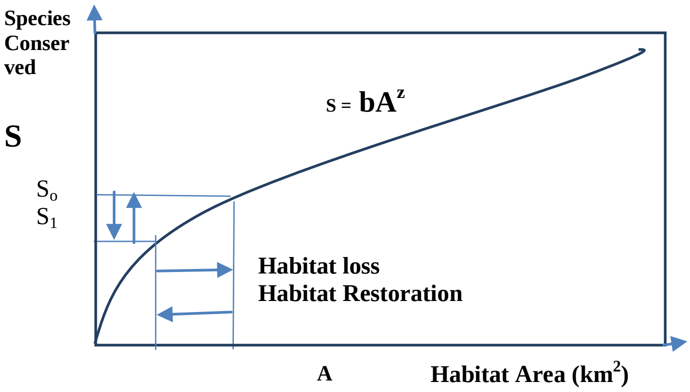


Fig. 1 Species-area curve showing habitat loss and restoration [13]

*Cost-effectiveness and conservation priorities – are there simple rules of thumb to guide conservation?*
*Legacy conservation and conservation priorities – how does the existence of such areas change priorities?*
*"Representative" conservation: The Nature Conservancy has set the most ambitious goal in the organization's history: to work with others to ensure, by 2015, the effective conservation of places that represent at least 10 percent of every major habitat type on Earth*
*Habitat protection v. habitat restoration(Plummer, n.d.)*
*The LCOE equation (4) adopted in the ECOS model included the externalities*

$$\sum_{i=k}^{k} EC$$

Is enhanced to include species area conservation cost C' x S' where
C' = ∑ci. Ai and S' = ∑Si

Incorporating a full cost, Levelized approach on externalities has a large impact on the LCOE and the relative attractiveness of electricity generation options that results in clean and efficient generation technologies that are the most attractive when all options are examined [14].
When the nature and scale of potential impacts are understood, ways of minimizing or eliminating are then considered which may include technology or design changes, or the introduction of protection measures on design [2].

## 4. COST OF ELECTRICITY GENERATING TECHNOLOGIES

In determining the cost of generating electricity, the metric most used is the Levelized Cost of Electricity (LCOE). LCOE is referred to as a constant level of revenue that is required to be achieved each year to recover all the expenses of a power generating plant [15]. It incorporates all the costs incurred in the daily running of the plant including operation and maintenance costs, fuel cost and capital cost. LCOE is the most convenient measure of the economic competitiveness of different electricity generating technologies. It's a metric of measure that indicates the price at which electricity must be sold to breakeven [16]. LCOE represents the per-kilowatt hour cost of building and operating a generating plant for its entire lifespan. In economic terms LCOE is the representative of the price of electricity that would equalize the life time cash flows (inflows and outflows) [17]. The lifetime cash flows are as defined below by Equation (1.1) and (1.2).

$$lifetimecashin\text{f } lows = \sum_{t=1}^{T} E_t * COE_t / (1+r)^t \quad lifetimecashoutflow = \sum_{t=0}^{T} C_t / (1+r)^t$$

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).

Levelized Cost of Energy Cost (LCOE) is one of the famous indicators that can be used for economic analysis of an energy system. LCOE is calculated as(Abdelaziz Mohamed & Eltamaly, 2018):

$$LCOE = \frac{TPV \ x \ CRF}{LAE}$$

Where $TPV$ is the total present cost of the entire system, $LAE$ is the annual load demand and $CRF$ is the capital recovery factor.

$CRF$ and $TPV$ can be determined by Abdelaziz Mohamed & Eltamaly [18] :

$$CRF = \frac{r(1+r)^T}{(1+r)^T - 1}$$

$$TPV = IC + OMC + RC + FC - PSV$$

r is the net interest rate and T is the system lifetime in years, normally assumed to be 25 years.

IC is the initial capital cost of the power system (supply, installation/construction, testing and commissioning). OMC is the present value of operation and Maintenance cost of the Energy system over its lifetime (salaries, insurances, inspections, all maintenance activities, etc). OMC can be assumed to be a fixed cost per capacity of each component of the energy system [18]. The total OMC cost can be determined using the following equations [18]:

$$OMC = OMC_o \frac{(1+i)}{(r-i)} (1 - \frac{(1+i)^T}{(1+r)} \qquad for \ r \neq i$$

Or $OMC = OMC_o \ x \ T \qquad for \ r = i$ (1.7)

Where $OMC_o$is the operation and maintenance cost a the first year of the project.

RC is the present value of replacement cost of components in the energy system that will be carried out throughout the lifetime of the energy system and is calculated as follows(Abdelaziz Mohamed & Eltamaly, 2018):

$$RC = \sum_{j=1}^{N_{rep}} C_{RC} \ x \ C_U \frac{(1+i)^{T*j/(N_{rep}+1)}}{(1+r)}$$

Where $i$ is the inflation rate of the replacement units which is around 5.7% in Kenya (Central Bank of Kenya). $C_{RC}$ is the capacity of the replacement units, which is in kW for the energy system, $C_U$ is the cost of the replacement units in Ksh/kW; $N_{rep}$ is the number of replacement unit over the lifetime, T of the power system components.

PSV is the present value of scrap

Calculation of PSV can be finalized as:

$$PSV = \sum_{j=1}^{N_{rep}} SV \quad \frac{(1+i)^{T*j/(N_{rep}+1)}}{(1+r)}$$

## 5. CONCLUSIONS

The analysis indicates that there is a wide range of technoeconomic tools in use. The tools differ significantly in terms of the regions they analyse, the technologies they consider, and the objectives they fulfil and there is no single computer tool that can meet all the requirements in an energy system but each tool is only able to meet a specific objective for a specific energy scenario. Additionally, the economic capabilities of these tools as analysed are limited since no single tool has the capabilities of incorporating environmental impacts to LCOE metric development.

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