A Review of Levelized cost of Electricity for Photovoltaic systems combining with their Environmental Impacts

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Abstract—There exist several Techno-economic analysis tools and financial indicators used to determine the financial worthwhile of different energy systems. These tools and 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 energy systems viability in a given region. The metric commonly used by these tools for the assessment of the economic worthwhile of these power generation technologies is the Levelized cost of Electricity (LCOE). The levelized cost is a constant cost per unit of generation which is computed to compare the cost of generation of one unit with other types of generating resources over a similar lifespan with similar operational profiles and system value. It is an economic assessment of the cost of energy generating system that includes all the life cycle costs. The life cycle costs that are included in almost all LCOE calculations are the capital costs, fuel costs, fixed and variable operations and maintenance costs, financing costs, and the assumed capacity factor. LCOE is a representation of the cost of electricity that would equalize the cash flows, that is, the inflows and the outflows which is usually normalized over a certain period of time and allows the IPPs to fully recover all the costs over a predetermined financial lifespan. It is mainly applied in many different evaluative purposes such as utility resource selection, dispatch decisions, electricity pricing, energy conservation programs, R&D incentives, subsidy determination and environmental planning. However there are certain aspects that are not covered by LCOE which includes damage from air pollution, energy security, transmission and distribution costs and the environmental impacts. This paper investigates the types of costs that are included in the techno-economic analysis of solar photo-voltaics incorporating their environmental impacts. The paper identifies a need to come up with an environmental decision making tool with renewable energy technologies as the traditional tools reviewed such as HOMER, SAM, INSEL,SOMES among others do not consider the environment in their analysis.

Keywords: Levelized cost of electricity, Environmental Impacts, Life cycle cost

I. INTRODUCTION

CURRENTLY, the biggest portion of the energy demand across the world is met by the fossil fuels such as coal, natural gas, crude oil etc. On the other hand, the demand for electricity is increasing each day which has caused rapid depletion of fossil fuels. Energy production from fossil fuels emits dangerous greenhouse gases that are harmful to the environment [1], [2]. The signing of the Kyoto protocol has seen many nations across the world cut down the usage of the fossil fuel related energy sources and have sort alternative sources of energy. This has further intensified the quest for more sustainable energy systems to reduce the high dependence on the fossil fuels. The only viable solution to this problem is the utilisation of renewable energy sources available especially in the rural areas which are far from the grid. It is estimated that more than 2 billion (about 44% of the world population) people across the world do not have access to grid electricity connection because of the high grid connection, dispersed population and the rugged terrain [3][4].

Global attention has majorly focused on the hostile impacts of the conventional energy sources to the environment. These include the emission of the greenhouse gases, oil spillage in rivers which may interfere with the aquatic life etc. On the other hand, the non-conventional sources of energy have always been regarded as clean and harmless to the environment. Abbasi et al [5], reports that in all public discussion held regarding pollution from conventional sources of energy, the advice is that everyone should adopt the renewable energy sources. But are non-conventional sources of energy as clean and harmless as 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 endeavour to promote them, their utilisation which stands at 15-20% has not fully penetrated the market due to several barriers [1][5][6]. These barriers include negative impacts RETs have on the environment, social world, high initial cost, and the technical barriers. The emissions include GHG emissions (shown in Table), impacts on natural biota, habitats and wildlife, ground water contamination, visual intrusion, water use and impacts, air quality, land use impacts and soil fertility [7]. In order to ensure sustainability of RETs the environmental inefficiencies must always be considered during their design to determine their economic viability in a particular area[7].

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 PV	98-167	0.2-0.34	0.18-0.30
CSP	26-38	0.13-0.27	0.06-0.13
Natural gas	430	-	0.5

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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

I. PREVIOUS WORK

A. Levelised cost of Electricity

The calculation of LCOE involves 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 [8] . 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) [9]. The life time cash flows are as defined below by Equation (1) and (2).

$$lifetimecashinflows = \sum_{t=1}^{T} E_t * COE_t / (1+r)^t \quad (1)$$

$$lifetimecashoutflow = \sum_{t=0}^{T} C_t / (1+r)^t \quad (2)$$

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).

B. Land use and land use Efficiency

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. On average utility scale solar energy has a land efficiency of 35W.m-2. Machinda et.al [10] in their study discussed CSTP as inefficient in terms of land usage in the sense that 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 and therefore the more the concentrators the high he intensity and hence the electrical energy. Mathematical expressions for relating the solar efficiency and land use factor are described by equations (3), (4) and (5) respectively [10].

$$\boldsymbol{Solarelectricityefficiency\ (SEE)} = \frac{\boldsymbol{AnnualNetpowergeneration}}{\boldsymbol{AnnualDNIonAperture}} \quad (3)$$

$$\boldsymbol{Landusefactor(LUF)} = \frac{\boldsymbol{Apertureareaofreflectors}}{\boldsymbol{totallandrequired}\ (\boldsymbol{m^2})} (4)$$

$$\boldsymbol{Landuseefficiency(LUE)} = \boldsymbol{SEE} * \boldsymbol{LUF}$$
(4)

In Spain for example, the 50MW, 7.5-hour parabolic trough CSTP plant known as Andasol 1 occupies a direct area of 510,120m2 and a total area of 200ha. The 64MW Nevada Solar 1 plant in Mojave Desert in California, USA occupies a total area 400 ha of land. Plans are also underway to install a 100MW CSTP plant in a site near Uppington, South Africa which receives an annual DNI of approximately 2995kWh/m2/year [11][10][12]. This plant will have an estimate of 4000-5000 heliostat mirrors, each heliostat occupying 140m2. This implies that the plant will occupy approximately 172 acres of land. According to a report [13], the monetary value of such cultivatable lands in South Africa is $667/ha/year, and 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 [14][15]. In the endeavour to promote solar PV, US has put aside 285,000 acres of public land for the solar projects. A summary of land use requirements for PV and CSTP projects in the United States is shown in Table 1 below.

Table 1 Area occupied visa vis Energy Generated

Technology	Direct Area		Total Area	
	Capacity-weighted average land use (acres/MW)	Generation weighted average 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

The land cover change as a result of occupation of land for a number of 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 concern over GHG emission. 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 in the US 97000ha of land have pending leases for the development of utility scale solar energy in which majority of this land is occupied by shrub-lands ecosystems. There are also some wetlands and glass lands that have been approved for the same purpose [16][17].

Hernandez et al. [18] report that there are over 20MW of utility scale solar power plants that are in operation, occupying 86000ha of agricultural and arid lands in California, USA. In California 28% of the utility scale solar energy systems are located on crop land and pastures and only 15% of the total installations are located in compatible areas [19]. Globally the monetary value of cropland and pastures is about $752/ha/yr while the total economic value of arid areas is $258/ha/yr[20]. Therefore, the total revenue lost as a result of installing a CSTP plant in a 86000 ha of crop land and arid areas would result in a lost value of $64.672 million and $22.118 respectively[19].

In the South West United States [21], large areas of public land are reported to be on 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 the fossil generated energy and also the concerns about emission of the GHG gases. The Deserts in South West which include Mojave and Sororan which are hosts to some potentially endangered species of animals and plants which are under stress already 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 CSTP plants and pollution effects from spills [21]. Globally the USSE installations and the land cover type are as shown in Table 2 below.

Table 2 Types of land cover Types and Installed Energy[21]

Land cover type	Name Plate capacity (MW)		Area, kM	
	PV	CSP	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

II. IMPACTS OF RETs

It is reported that the 10MW Solar 1 CSTP plant in Mojave Desert killed 70 birds for a period of 40 weeks which equates to a mortality rate of 1.9-2.2 birds per week [16]. The major cause of death of the birds (81%) was attributed to collision with the CSTP infrastructure while the rest (19%) died as a result of burning when the heliostats were oriented towards their eyes which impaired their visual ability. Additionally, there are changes in land surface temperatures as a result of their installations and thus killing some insects, birds, burrowing animals, and other sensitive plants which thrives in areas they are installed. Some of these plants have medicinal values [21].

The solar tower type of CSTP are seen to have the potential of concentrating light to high intensities that could impair the eyesight of wild animals and the 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 etc.) [5],[22],[16],[19]. The fragmentation of habitats of both animals and birds can lead to low turnover in revenues collected from tourism.

Large scale solar power at their inception are reported to be more hazardous emitting greenhouse gases and respective environmental degradation than does a nuclear plant and other fossil energy generating systems [5]. The green gas emissions are 40-55 grams per Kilo watt of generation capacity for the standard silicon panels and 25-32 grams for the thin mirrored solar panel types [23].

A. Cost of Electricity Generating Technologies

The Levelized cost of electricity (COE) from the different energy sources is as shown in Table 3 below.

Table 3 current and Expected LCOE [23]

Energy Source	Technology	Current cost (€c/kWh)	Expected future cost (2020)
Coal	Grid supply	3-5	Capital costs expected to go down due to technological evolution
Gas	Combined cycle	2-4	
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/m2	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

This metric relates the life cycle costs such as the capital cost, operations and maintenance costs and the replacement costs with the lifetime energy production[24].

In Table 3 above, the different LCOE of both renewable and non-renewable energy sources is shown and their forecasted future LCOE.

1) Environmental Impacts of Non-Renewable Energy Technologies

In the beginning the world utilized energy from conventional sources such as oil, coal, and the natural gas. These sources of energy posed a lot of negative impacts to the environment and human beings at large. These sources has limited reserves coupled with their uneven geographical distribution[25]. Therefore their continuous usage leads to depletion. Nuclear energy generation has less GHG emissions compared to oil and gas. According to [26] nuclear energy has reduced the emission of CO2 by approximately 2.5 billion tonnes per year. The non-renewable energy sources pose great danger to the environment because of their emissions which include carbon dioxide, carbon monoxide, sulphur dioxide, nitrogen oxides, particulate matter, heavy metals such as mercury together with the radioactive nuclides such as uranium and thorium. These pollutants are as shown in Table 4 below.

Table 4: Estimated Emission [26]

Fuel Type	Fuel Consumption(t)	Emission type	Amount in Tonnes
Crude oil	1,400,000	CO2	5,000,000
		SO2	40,000
		NOX	25000
		Particles	25000
coal	2,000,000	CO2	6,000,000
		SO2	120,000
		NOX	25000
		Particles	300,000
Natural gas	1000000	CO2	3000000
		SO2	20
		NOX	13000
Nuclear	30	Uranium	28.8
		Plutonium	0.3
		Fission products	0.9

These pollutants emissions has impacts on the human health and the biodiversity which includes damage to nervous system, lungs, breathing problems bronchitis, sperm cells impairment, cardiovascular and kidney effects among others. Impacts to biodiversity includes damage to crops and forests, water contamination, marine life etc. [25].

B. Monetization/valuation of Ecosystems goods and services

The valuation of ecosystems goods and services usually take into account three main attributes i.e ecological valuation, socio-cultural valuation and the economic valuation [27].

In the energy markets all across the world, 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. These market prices however do not take into account the true 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 includes damage to human health and the ecosystems [28].The monetary evaluation of the impact of externalities carries a huge 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 modelling of electricity generating units, renewable electricity generation is comparable in cost to the fossil fuels [29].

Monetization of the externalities of electric generating units is important because it provides clear and understandable comparisons of the direct costs and the environmental costs. If these costs of energy planning are not expressed in the common units the comparisons become very confusing making comparisons between the trades-offs between the economic factors and environmental costs less comprehensible. The other reason for monetization of externalities is that it allows for consistent treatment and evaluation of environmental issues in a very consistent manner which many other methods do not [30]. The following section discusses the different methods of weighing the externalities.

C. Biodiversity/externality valuation instruments

The process of encapsulating the wide range of benefits ecosystems contributes to the world inform of monetary and non -monetary terms is generally referred as biodiversity valuation [31]. Biodiversity valuation is a key pillar when integrating the environmental impacts in the cost modelling of RETs.

There are four main approaches of externality valuation namely contingent valuation, hedonic price method, travel cost method and the restoration cost approach. 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 due to the fact that people have problems understanding some questions and therefore giving a wrong impression [32].

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 method is mostly applied in noise and aesthetic effects.

Thus, according to hedonic price approach an increase in noise pollution will see reduction of property values. Hedonic approach has limited applicability in diversity valuation [32].

Travel cost approach is mainly used for recreational impacts valuation. The method assumes that the costs incurred by the locals in travelling to the park, entrance fees paid etc are an indication of WTP for the recreational facilities in the expense of the environment. 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 [32].

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 the value of replacing an ecosystem or its services is the value of that particular ecosystem and its services [32].

D. Conclusions and recommendations

In this paper it has been identified that the popular economic valuation instruments for energy such as LCOE, initial rate of return (IRR), Net present value (NPV) among others use the capital cost, operation and maintenance cost, replacement cost and the residual value to determine the financial worthwhile of a project. Tools have been developed across the world in which some of these economic valuation instruments are embedded. It has been found that these tools do not put emphasis on the conceivable environmental, social and health impacts. In the decision making in citing and generation of electricity from solar energy or wind, the resources are important (wind speed and direct normal irradiance) but the externalities as well should be put into consideration. The externalities/ impacts if included in modelling guides investors of renewable energy on where to locate the said plants. If externalities are incorporated during design and modelling of energy technologies there will be a drastic reduction of human/energy wildlife conflict. This paper suggests the development of an economic modelling tool that fully incorporates the environmental goods and services in the LCOE metric development.

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