Economic, Environmental, Health and Social Impacts of Utility Scale Solar Energy Generation: A Review

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***Abstract*—**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. Therefore their continuous usage leads to depletion. Nuclear energy generation has less GHG emissions compared to oil and gas. 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 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. Environmental externalities/impacts are defined as benefits or costs generated as a by-product of an economic activity, that do not accrue to the parties involved in the activity. They are the benefits or costs that usually manifest themselves through changes in the physical-biological environments. In electricity pricing externalities refers to the costs associated with the fuel cycle that are not incorporated in the electric utility cost structure. The major contribution of this research work is to bring to realization the environmental, social and the health impacts of utility solar energy technologies and how these impacts can be monetized. This paper further reviews methods that has been used in the quantification of these impacts.

Keywords: Electricity Pricing, Renewable Energy, Externalities, Biodiversity.

I. INTRODUCTION

In the world today, it is reported that 40% of the global population rely on the traditional use of biomass for meeting their energy needs. It is projected that by the year 2030 (date of the proposed goal of the universal access to clean energy services), about 1.2 billion people will still lack access to electricity [1][2]. Approximately 80% of these people without access to clean energy sources live in the rural areas of sub Saharan Africa, India and other Asian developing countries [3]. In South Eastern Asia for example, the level of electrification in the rural areas is about 51%, while the level of electrification in the urban areas is 90%[3]. In the Sub Saharan Africa (SAA), the overall electricity connection stands at about 23% with the urban and rural area figures standing at 51% and 8% respectively. In the Sahelian countries energy access remains low despite the abundance of high wind speeds and high solar irradiance [4]. Senegal has the lowest energy consumption per capita (0.19) despite being located in a region with a very high isolation of about 2kWh/m^2 and high wind speeds. In Senegal 60% of the urban population are connected to the utility grid while only 15% enjoy the utility connection in the rural areas [4]. As depicted in Figure 2.1, the deployment of renewable energy is potentially one of the solutions which is capable of alleviating the energy poverty index that is continuously being experienced by about two billion people across the world. Majority of these people lives in rugged terrain areas and are sparsely populated making the utility grid connection impractical because of the high costs that will be incurred in reaching such areas [4]. These renewable energy sources of energy include solar, wind, biomass, hydro etc. These energy sources are clean, inexhaustible, and are environmentally friendly. However, it should be noted that the weather dependent renewable energy alternatives such as wind and solar are intermittent and volatile in nature therefore not able to match the time distribution of the load demand. Intermittent refers to the unavailability of the wind or solar for longer or extended periods of time while volatility refers to the smaller and hourly fluctuations of the wind or solar within their intermittent characteristics. As such neither a wind standalone nor a solar system can provide continuous power supply due to the above reasons. This short coming not only affects the systems energy performance but it also affects the batteries life. This is because in most of the times the batteries state of charge is not maintained and therefore the loads drain the battery completely. The stochastic nature of each of the resources, either sun or wind, can be partially or wholly overcome by integrating these two resources together using the strengths of one resource to overcome the weakness of the other [5]. The independent use of a standalone wind, solar or diesel results in over sizing which makes the system very costly, inefficient and unreliable [6][7]. The hybrid combination therefore provides a good base to improve the system reliability and efficiency. Wies et al. [3], reports that a PV-diesel system is economical because it provides a reduction in the operation and maintenance costs and the amount of GHG gasses emitted to the atmosphere. Research and marketing is ongoing to prove the various combinations of

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wind turbine generator solar photovoltaic generator, diesel generator with or without rechargeable batteries are the most ecological sound solutions to the energy situation in the rural areas Dennie et al [8].This will help overcome this challenge of provision of clean energy to the rural population and save the depleting fossil fuels and emissions of the greenhouse gases (GHG) such as carbon dioxide, Oxides of Nitrate and sulphur dioxide. Therefore, harnessing of sustainable renewable energy technologies is inevitable [6].Sustainable renewable energy sources are cost effective, reliable, and use the locally available resources to generate electricity. Increase usage of renewable energy systems for electricity generation leads to a decreased external energy dependence from the grid, decrease in transmission and transformation losses etc.

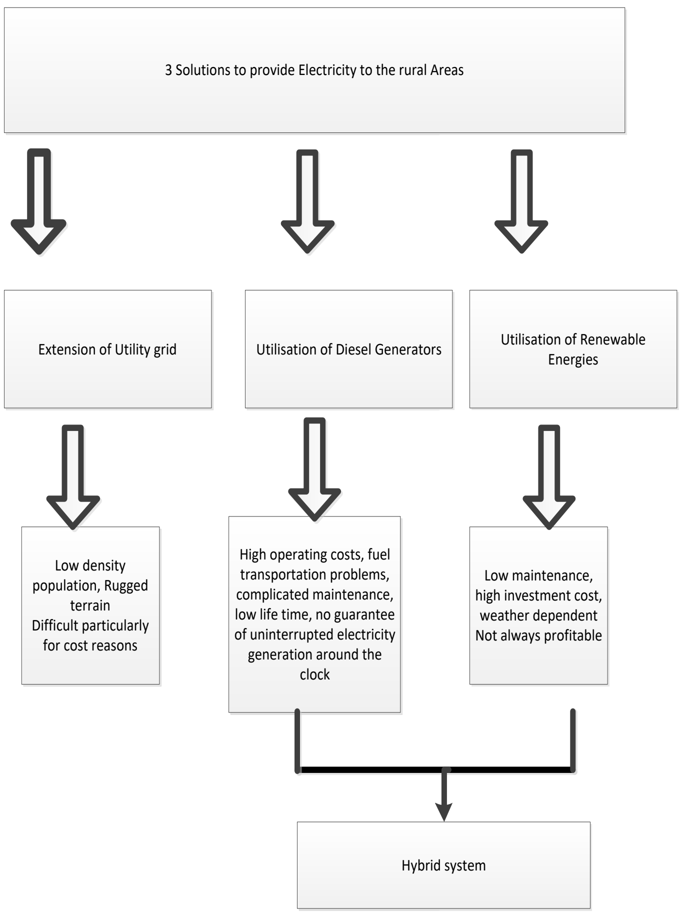

Figure 1: Solutions for Rural Electrification [7]

Although renewable energy sources are perceived to be clean and economically viable they are yet to realise their full potential because of some barriers such as environmental externalities which have impeded their penetration especially in the African continent. In fact, it is reported that 95% of the commercial energy production across the world still comes from fossil fuels or the nuclear energy[9]. This research work will evaluate the environmental impacts as an impeding barrier towards the success of RETs in the African continent by developing a versatile economic model that incorporates these externalities into the calculation of the LCOE and other parameters important in determination of the viability of RETs. The following section discusses the environmental impacts of solar PV and CSTP.

Contribution: The major contribution of this paper is for the first time a review of the environmental, social and health impacts of USSE and how these impacts can be monetized and included in the economic modelling.

II. ENVIRONMENTAL IMPACTS OF RENEWABLE ENERGY TECHNOLOGIES

The inhibition towards the full realization of RETs includes cost effectiveness, technical barriers, market-related barriers and their negative socio-economic and environmental impacts. Some barriers are specific to a certain renewable energy technology while others depend on the location. The implementation of large scale solar or wind energy as an environmental friendly alternative to fossil fuels sources of energy may actually increase the environmental degradation on a regional scale with a lot of negative effects on animals and plants. This research work is confined only to the environmental impacts of wind and solar energy technologies.

A. Solar Energy Including PV and CSP

Matured and emerging solar energy technologies such as photovoltaic (PV) systems and concentrated solar thermal power (CSTP) uses sun's radiation in generating electricity [6][10].

The two main solar energy technologies differ in the fact that PV converts solar energy directly into electricity while CSTP uses the thermal effect of solar irradiation to generate steam which is used to run a turbo-alternator to generate electricity. A CSTP plant employs reflective mirrors to focus solar irradiation on an absorber carrying a heat transfer fluid [6]. The heat transfer fluid undergoes a Rankine cycle in which water is vaporized at high pressure to run the turbine which is connected to an electrical power generator. There are basically four types of CSTPs technologies: parabolic trough collectors (PTC), linear Fresnel collectors (LFC), Solar Towers (heliostat field collectors) and parabolic dish reflectors (PDR).

Parabolic trough shown by Figure 2 CSTP plant is the most proven of all the CSTP technologies because of the nine large commercial scale solar power plants, which has been operating in California Mojave Desert since 1984. They represent a total of 354MW of installed capacity [11] Parabolic trough collectors trap the sun along the East-West direction during the day. The reflected solar radiation is absorbed by absorbers which carry a heat transfer fluid which is used to evaporate water for steam production. The steam is used to run a turbine which is coupled to a generator for electricity production [11].

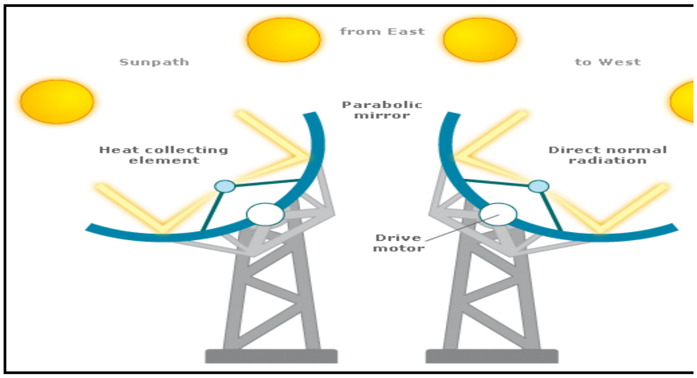

Figure 2: Parabolic Troughs [6]

The solar tower Solar (heliostat field collectors) uses several mirrors called heliostats for tracking the solar radiation on a central receiver. The sun is tracked on two axes following the azimuth and elevation angles. A HTF which passes to the receiver is heated and used to generate steam [12]. The heliostats are about 120m^2 in area. They are usually curved and the mirrors reflect the sun rays to a central receiver. The receiver on the tower is designed to reduce the radiation and the convectional losses. The steam in the turbine expands and produces mechanical power and electricity. The cold tank molten salts are kept at a temperature of 45°C above their melting point (240°C). A single 100MW plant with 12 hours of storage requires 1000 acres of desert land to supply electricity to 50,000 homes [11][13] Generally, they use 10 to-15 acres per MWe generated. The internal cross-section of the power tower is shown in Figure 3.

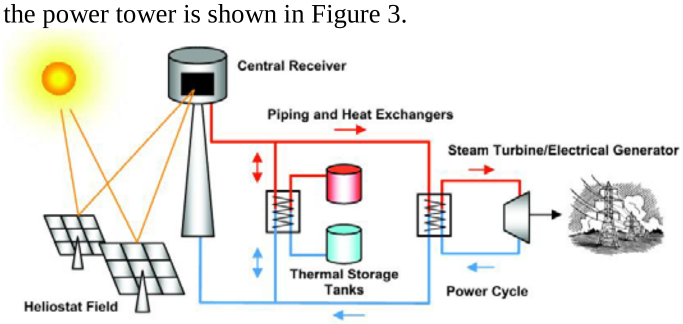

Figure 3: Scheme of CSTP Plant with Power Tower [12]

Linear Fresnel reflectors track the sun using one axis. The shape of a linear Fresnel resembles the parabolic trough. They consist of thin mirrors which focus the solar energy on a fixed absorber pipes carrying a heat transfer fluid as shown in Figure 4. It uses flat mirrors which are easy to make [13].

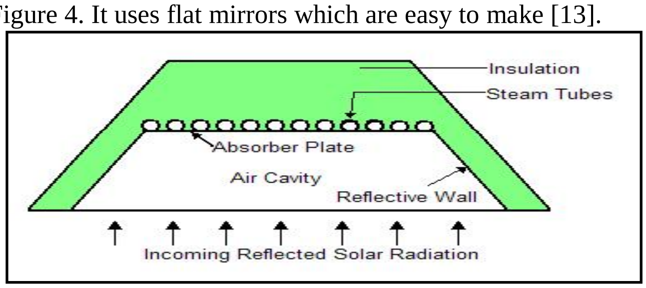

Figure 4: Linear Fresnel Showing Concentration of sun rays to heat HTF[14]

The flat mirrors used in Linear Fresnel have a capability of concentrating the solar irradiance 30 times its normal intensity. The concentrated solar energy is absorbed by the heat transfer fluid which undergoes a heat exchanging process to generate steam to power a steam turbine generator. The reflectors are located at the base and reflect the sun rays on a linear axis similar to the parabolic trough[14].

A parabolic dish CSTP plant concentrates solar irradiation to a single point using a point focus system. The solar irradiation is concentrated on the concentrator along two axes. A reflective glass or a metalized glass reflects the incident ray to a small region called the focus. A Stirling engine shown in Figure 5 is directly mounted at the base of the parabolic dish. The Stirling engine converts the concentrated heat into mechanical energy by compressing a HTF (for this case it is a gas) and then expanding it through a turbine to produce work. There are no means of storage for this plant which makes it less popular as compared to the parabolic trough. It requires continuous changing or adjustment of its position to maintain focus [14].There is no doubt that in terms of emissions, solar power is a clean source of energy and is environment-friendly compared to conventional sources. However large-scale deployment of solar PV and CSTP plants does have negative environmental implications which has created strong barriers in further dissemination of these systems [1][15][16][17].

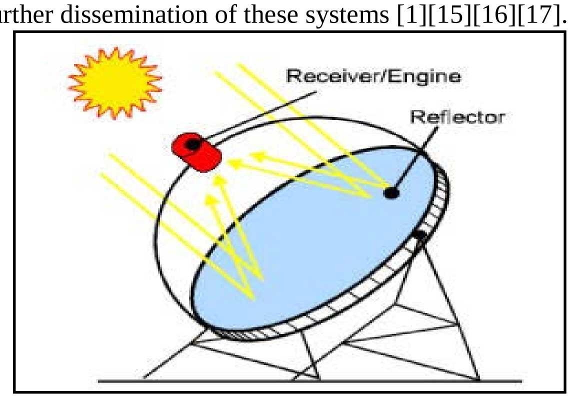

Figure 5: Parabolic Dish [14]

The following section discusses the negative impacts of solar energy on land and wildlife with emphasis on loss of revenue.

III. Environmental Problems Related to Utility Scale Solar Energy

1) Impacts on Land and Ecosystems

CSTP and solar PV need large tracks of land for installation and no reclamation can be done until the plant is decommissioned. The term land use has three meanings [18]. First, it means the physical nature of land being that will be affected by the installation of the project. The physical nature refers to the condition of the ground and the earth surface. The second meaning is a quantitative one and means the total area of land occupied by the installation. The third meaning refers to the alternative use of this land apart from solar installation. The impacts of solar plants on land depends on the topography of the landscape, area covered, type of land e.g.(cropland, forests etc.), distance from the areas of archaeological sites, types of sensitive ecosystems in that land and the biodiversity[19]. The size of land occupied by solar power plants also depends on the technology, topography of the site and the intensity of the solar resource availability. There are two ways to quantify the area impacted by solar energy technologies. The first is the total area which corresponds to all land enclosed by the site boundary which is characterized by fencing. The second one is the area directly occupied by access roads, solar arrays, substations, service buildings and other infrastructure. The direct impact area is contained within the total area boundaries [20].

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 [21] 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 (2.1), (2.2) and (2.3) respectively [21].

$$\textbf{Solar electricity efficiency } (SEE) = \frac{\text{Annual Net power generation}}{\text{Annual DNI on Aperture}} \quad \textbf{(2-1)}$$

$$\textbf{Land use factor}(LUF) = \frac{\text{Aperture area of reflectors}}{\text{total land required } (m^2)} \quad \textbf{(2-2)}$$

$$\textbf{Land use efficiency } (LUE) = SEE * LUF \quad \textbf{(2-3)}$$

In Spain for example, the 50MW, 7.5-hour parabolic trough CSTP plant known as Andasol 1 occupies a direct area of $510{,}120m^2$ 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 $2995kWh/m^2$/year [5][21][11]. This plant will have an estimate of 4000-5000 heliostat mirrors, each heliostat occupying $140m^2$. This implies that the plant will occupy approximately 172 acres of land. According to a report [12], 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 [19][22]. In the endeavor 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.

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 [6][23].

Hernandez et al. [24] 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 [25]. 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[9]. 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[25].

In the South West United States [26], 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.

Table 1:Summary of Land Use Requirements for PV and CSTP in the United States [20]

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,<20 MW)	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

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.

Table 2: USSE installations and Land cover type [25]

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

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 [26]. Globally the USSE installations and the land cover type are as shown in Table 2 above.

II) *Impacts on wild life and Human Health*

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 [6]. 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 [26].

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.) [1][16][6][25]. 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 [1]. 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 [27].

IV. Conclusions and Recommendations

Renewable energy technologies, although almost free have not been able to realize their full potential. As depicted in the studies above only 15-20% of their exploitation have been realized. The low exploitation can be attributed to their environmental impacts, social and health. It is observed that the solar energy technologies such as CSTP and CPV occupy huge tracks of land which could otherwise be utilized for other income generating technologies. Some of this plants are installed in places which are archaeological sites, forests, farmlands, deserts and other land use types. Some of these land use types are habitats of endangered species of animals, birds and plants. In this review it is realized that although a lot of research has been geared towards ending the human-wildlife conflict, this will not end until we have mechanisms that are able to include the willingness to pay or willingness to accept the aforesaid impacts in the cost modelling. Research and development should therefore be geared towards the development of a techno economic tool that is able include the environmental goods and services in the full realization of the Levelized cost of electricity (LCOE)

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