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Environmental Impacts of the Solar Photovoltaic Systems in the Context of Globalization

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ABSTRACT

Solar photovoltaics systems (PV) deliver substantial benefits to the environmental when compared with the conventional energy sources, hence supporting to the human activities ecological benefits with sustainable development. To maintain the quality of the environment at the same time, technological innovations are very much essential to cater the needs of more electrical power according to the demand, decreasing carbon emission by replacing the carbon releasing fossil fuels with the renewable energy. Installation of such facilities require lakhs acres of land globally and thus leads to number of various ecological issues. This paper presents the insight to various environmental issues. Some of the issues are with respect to land, health of human beings, animals, plant lives and environment are presented in this paper. In terms of numbers, the area of land required for a PV system is less or same per kWh power generated, when compared with a thermal power station. Deforestation for installation of solar PV systems is one of the major drawback as it leads to enormous environmental impacts. This paper analyses effects on the environment due to the usage of solar PV systems like, at the time of construction, installation and also at the time of destruction, sound and visual incursions, air, water and soil pollution, emission of greenhouse gases, effects on archaeological sites accidents to unskilled labor, and various socio-economic impacts. Subsequently, reduction in greenhouse effect, carbon footprints, global warming, ozone layer depletion, climate change and acid rains are some of the positive impacts during transition to green energy, i.e., usage of fuels from fossil fuels to solar energy at regional level, national level and global level. This paper outlines the pros and cons, positive and negative environmental impacts, by using solar PV systems to generate electrical power.

Keywords: environmental impacts, conventional sources of energy, non-conventional sources of energy, photovoltaic systems, life cycle assessment, life cycle inventory.

INTRODUCTION

Globally, the demand for electrical power is growing up exponentially due to rapid increase in population and urbanization. The conventional sources of energy are getting depleted at a faster rate to cater the needs of electrical power. To retain the conventional energy sources for the future generations to come, also due to environmental impacts like pollution, greenhouse gases emission, carbon footprints and more importantly due to the public fear over sustainability, ecology and efficiency, the non-conventional sources of energy has emerged as a major replacement around the world and among them, the solar energy has a better edge. Clean and safe supply of electrical energy is essential for our society's sustainable progress. There are various renewable energy sources like solar energy, wind energy, wind energy, tidal energy, geo thermal energy, ocean energy, bio energy, etc., The solar power plants also called as photovoltaic (PV) systems generate electrical power from solar energy and hence are used for generating electrical power. Globally, many state, local governmental administrations are making compulsory to have renewable portfolio to deliver some part of their power demand and the remaining power to be supplied from the utility grid. The electrical power generation from solar PV systems has a number of advantages, it also discussed in Viet Thang Tran et al. (2018), M. Vinay Kumar et al. (2022), Jhon Jairo Montano et al. (2022), like the best vital thing is that the solar energy is a renewable resource and it will never be ended, the solar energy is available free of cost and hence there is great reduction in running costs, the usage of solar energy reduces carbon footprint and this leads to reduction in global warming which causes the melting of glaciers, endangering of animals and erosion of shorelines. The usage of solar energy helps in conserving around 16500 gallons of water per year and also reduces the dependence on conventional sources of energy. The PV system does not require more maintenance as there is no wear and tear, the inverter needs to be replaced after a time span of 5–10 years. The usage of solar PV systems generates jobs by retaining the solar installers, solar panel manufacturers, etc., and which in turn improves the economy of the country, reduces in imports of oil for energy generation, the excess power generated from solar PV systems can be sold back to the utility grid which can be monitored by using net metering, the solar PV systems generate electric power during day time and it is stored in batteries which deliver back the power during the night times, the solar energy can be used to power buildings and homes, heat water, also can be used to power vehicles, the power generated from the solar PV systems is safer than conventional electric current, the government is promoting, encouraging for the usage of solar PV systems by giving tax incentives, rebate programs and federal grants hence helps in reducing initial cost of installation, trenching is not required. Though there are a number of advantages for using the solar PV systems, still it is porn to few disadvantages like, the installation cost is high, the payback period is too long, the PV system efficiency is low and its around 20–25%, the space required for installation of PV system is large, as the sun light is not available during night times, a battery bank is needed to store the generated electrical power during the day time, subjective to the geographical location the solar panels size may vary for generation of the same amount of electric power, there is no electric power generation during cloudy days, etc., All of them have been discussed by M. Vinay Kumar et al (2018), Amit Kumar Bhattacharjee et al. (2019)

The paper is presented in six sections. Section I provides the introduction of this paper. The mathematical modelling PV cell is presented in section II. The metrics for ecological effects is briefed in section III. The section IV describes the application of LCA to PV systems, the LCA guidelines for PV systems are presented in section V, while ecological effects from PV systems are deliberated in section VI. Finally, the conclusions of the paper are drawn in section VII.

MATHEMATICAL MODELLING OF PV SYSTEM

In India, the amount of solar radiation received from the sun on PV panel per unit area is assumed as 1700 kWh/m^2/year. The lifetime of a solar PV panel is assumed to be around 25 – 30 years and an efficiency of 15–20%. The general elements of a solar PV system are PV modules, DC-DC converter, DC-AC converter and a filter. A classic PV solar cell generates a voltage of 0.5V, which produces electricity of 0.7 W. The PV modules consists of PV cells which absorb the solar energy and generated DC power using photovoltaic effect, a DC-DC converter steps up the generated DC voltage to the required voltage level, a DC-AC converter converts the DC voltage to AC voltage and finally a filter removes the harmonics present in the output of the PV system. The mathematical modelling has been presented by Yousef Mahmoud et al. (2012), M. Vinay Kumar et al. (2017, 2018).

a) PV cell modeling – the basic element of a solar PV system is a PV solar cell. The PV cell generates a voltage of 0.5 V to 0.6 V and current generated is determined by the size of PV cell and it is around 28 mA to 35 mA per cm square. The PV panels are connected in series to get higher voltages and are connected in parallel to get higher currents. The PV cell be modelled with either single diode, double diode, triple diode models. The functioning diagram of a single diode model of a PV cell is depicted below in figure1. The load current is given as

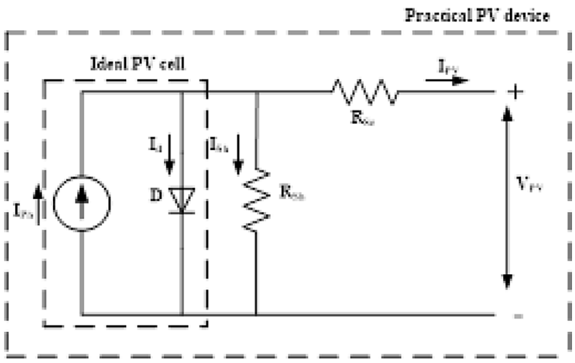

Figure 1. A single diode model of a PV cell

$$I_{PV} = I_{Ph} - I_o \left[exp\left(\frac{V_{PV}+I_{PV}R_{Se}}{aV_T}\right) - 1\right] - \left(\frac{V_{PV}+I_{PV}R_{Se}}{R_{Se}}\right) \quad (1)$$

where: l_{pv} – the load current, l_{ph} – the photon current, l_o – the reverse saturation current, V_{pv} – the voltage across the load, R_{se} – the series resistance, V_t – the thermal voltage.

The thermal voltage is given as

$$V_T = \frac{kT}{q} \quad (2)$$

where: k – the Boltzman's constant, q – the charge.

b) DC-DC converter modeling

c) The DC-DC converter steps up the generated DC voltage to the required voltage level, it controls the PV array output voltage. The DC-DC boost converter circuit diagram is shown in Figure 2.

The DC-DC boost converter operates in two modes i.e., mode-I, mode-II, in the first mode switch is closed and in the second mode the switch is opened. The figure 3 below depicts the second mode of operation of the DC-DC boost converter. When the switch is 'closed', the input voltage is equal to the inductor voltage.

$$V_L = V_{int} \quad (3)$$

The Figure 4 depicts the second mode of operation of the DC-DC boost converter. When the switch is 'opened'.

$$V_L = V_{int} - V_{out} \quad (4)$$

d) DC-AC converter modeling

The DC-DC boost converter output voltage is converted into controlled AC voltage using an inverter. The three phase inverter circuit is shown in Figure 5 below. The three phase voltages are given as:

$$V_{AN} = \frac{1}{3}(2V_{AB} + V_{BC}) \quad (5)$$

$$V_{BN} = \frac{1}{3}(2V_{BC} + V_{CA}) \quad (6)$$

$$V_{CN} = \frac{1}{3}(2V_{CA} + V_{AB}) \quad (7)$$

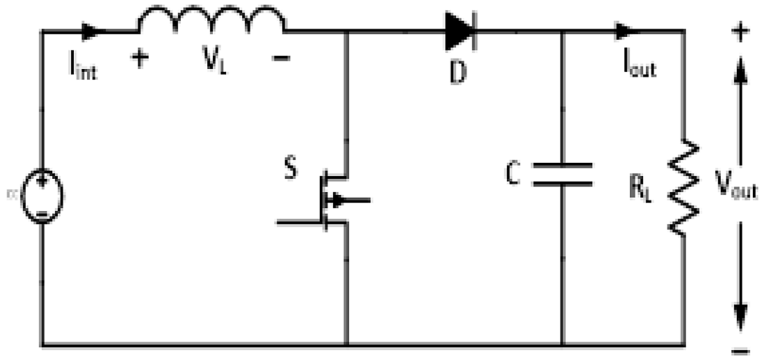

Figure 2. DC-DC boost converter

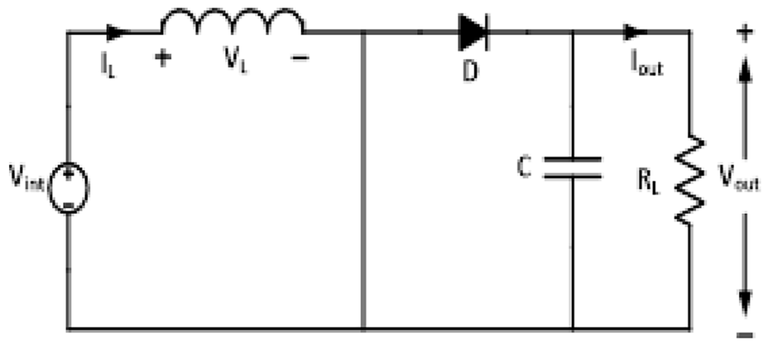

Figure 3. Mode-I operation of DC-DC boost converter

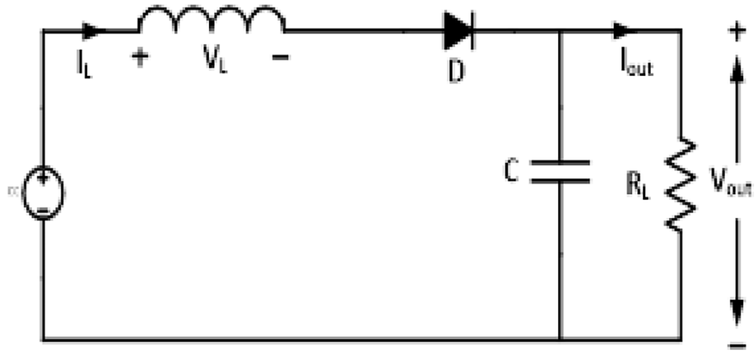

Figure 4. Mode-II operation of DC-DC boost converter

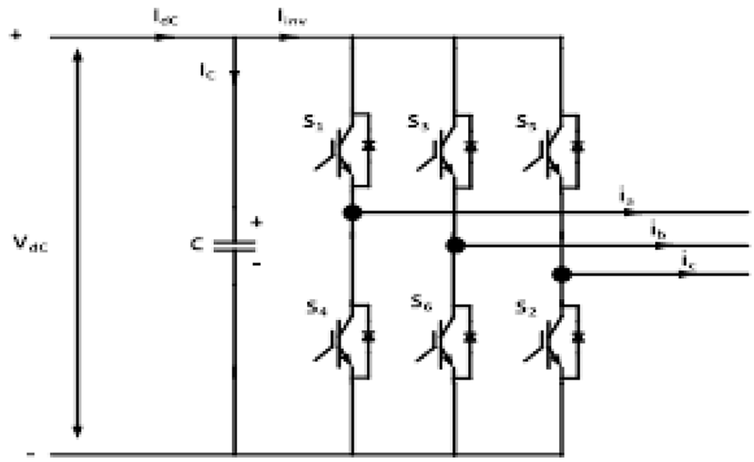

Figure 5. Three phase inverter circuit

METRICS FOR ECOLOGICAL EFFECTS

Electric power generation using solar energy has gone up by a record value of 179 TWh in 2021 achieving 20% growth when compared with 2020. It is the third largest growth in generation by renewable energy sources after wind energy and hydel energy. Also electric power generation using solar energy is the least cost for production by using solar PV system and its accounts for third largest 3.6% of electric power generation global. Various metrics with respect to ecological effect have been presented by Myeon-Gyu Jeong et al.(2015). This report was published (iera 2010-2030). The figure 6 below depicts solar PV power generation during 2010–2030.

The electrical power production from PV systems has gone up by a record of 179 TWh in the year 2021, it has been presented by Fthenakis V M et al. (2005). The PV systems account for a 3.6% of global electrical power production. In the year 2020, electrical power generation capacity of 48.2 GW by PV system were installed, as compared to 43.4 GW electrical power generation capacity by PV system in the year 2018 and 30.1 GW of electrical power generation capacity by PV system in the 2019. The top five countries having largest installed electrical power generation capacity by PV system are firstly, China claims the world's largest installed electrical power generation capacity by PV system as 205 GW in the year 2019, as per the IEA's Renewables 2020 report. Secondly, US has the world's second-largest installed electrical power generation capacity by PV system in the year 2019, thirdly Japan ranks third among countries with the largest electrical power generation capacity by PV system 63.2 GW in the year 2019, according to the IEA's data, fourth, Germany is the world's fourth-largest for solar electrical power generation capacity by PV system around 49.2 GW in 2019 and fifth, India has the world's fifth-largest installed electrical power generation capacity by PV system 38 GW in 2019, the data has been published (iera.2020). Various influences associated with the usage of PV systems are health of human being, their welfare, requirement of land, flora and fauna and their habitat, weather, geohydrological resources etc., A metric by name

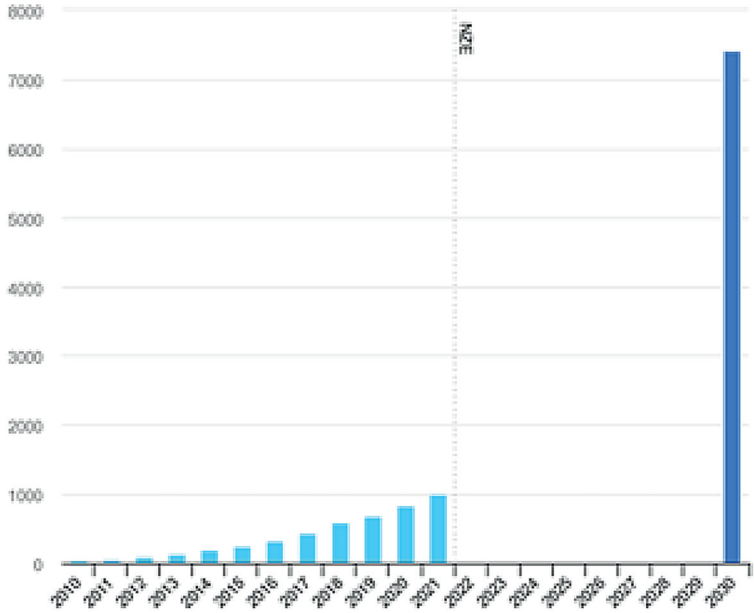

Figure 6. Solar PV power generation during 2010–2030

life cycle assessment (LCA), for ecological impacts by the usage of PV systems has been presented in literature by and mostly discusses about energy payback time, greenhouse gas emissions, emission of dangerous materials, effects on wild animals, water, huge requirement of land etc., The U.S. Department of the Interior's Bureau of Land Management (BLM) and U.S. Department of Energy (DOE) conjointly prepare a solar energy programmatic environmental impact statement (Solar PEIS). The BLM and DOE evaluates the weather changes, land requirement due to installation of large PV systems. They also mention various policies and strategies for sponsoring financially. The application of renewable energy source like solar energy for electricity generation reduces pollution, carbon products, greenhouse gases emission and at the same time has many ill effects too and it is discussed in literature by Ilke Celik et al. (2018).

The usage of renewable energy sources like solar energy, wind energy, hydel energy, tidal energy reduces carbon foot prints, greenhouse gases enormously. The life cycle of renewable technologies is explained with help of the figure 7 depicted below. The life cycle of renewable technologies explains staring from the acquisition of raw materials, production of materials and equipment's, operation and system assembly and finally finishes with their dumping. The above stated life cycle of renewable technologies require the effort from all the economic sectors namely machine-building, metallurgical, agricultural etc., Also, the usage of energy from fossil sources, leads to the emission of hazardous substances into the environment. The related data was discussed by Ying Huang et al. (2015), Sachin Angadi et al. (2021). The life cycle assessment of solar PV systems is shown in figure 8 below. LCA is used in calculating the emissions, facilitating the measures for reduction in emissions. Though, ideally it is not suited for assessment on a large scale, it is highly suitable for small-scale analysis. The results of LCA are very important as the results, assessment help in protecting the planet from a number of ecological effects like

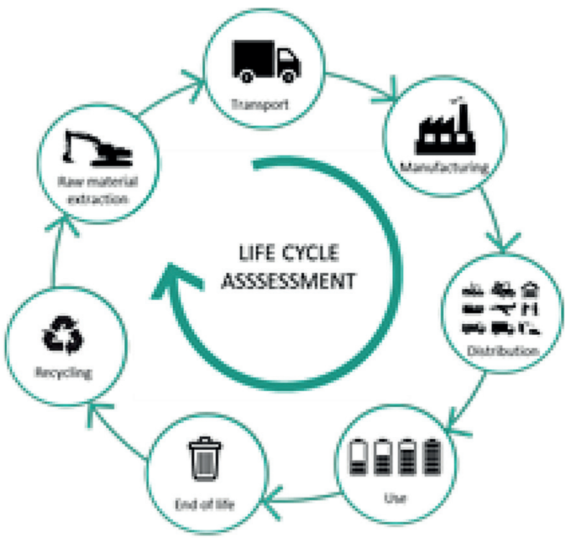

Figure 7. Life cycle of renewable technologies

increase in rainfall due to floods, more chances of draught, melting of glaciers due to increase in temperature, greenhouse gases emission (CO_2, NO_2, CH_4, etc.), also more importantly the manufacture, transport, use, disposal, etc. The analysis and research scheme for LCA is depicted in Fgure 9 below. The LCA comprises of the four stages, they are described as follows, firstly goal and scope, secondly inventory analysis thirdly impact assessment and finally interpretation. The inventory analysis results are mentioned as life cycle inventory (LCI). The LCA can be applied to any service or product, but the results get affected by assumptions, accuracy, data availability and objects. At the time of LCA, its limitations must be taken into account and from the results the assumptions will be made.

APPLICATION OF LCA TO PV SYSTEM

The procedures of LCA applied to PV systems are discussed as it leads to the evaluation and its effectiveness depends upon the operator as it is finally related to electric power generation. The LCA is done on PV systems as a whole. The LCA for the PV systems will be evaluated before its installation, as it delivers two advantages, firstly optimization of PV system during which various parameters like greenhouse gases emission, the incurred will be deliberated and secondly comparing various electrical energy production technologies. This application of LCA to PV systems have been presented in literature by Sorin Orboiu et al. (2020), Ziyi Wang et al. (2022).

Indices for evaluation of LCA

The indices for LCA evaluation are fixed depending upon the purpose of work. Now PV systems produce electricity, hence the index will be energy payback time (EPT), it has to be estimated. The EPT states the total number of years the PV system has to operate to regain the consumption of its initial energy incurred in the creation during its life period during the energy production of the same system. The EPT is given as:

$$\mathrm{EPT(Years)} = \frac{\mathrm{ELPC}}{\mathrm{EPPA}} \quad (8)$$

where: EPLC – Electric power used by PV system during the life cycle (kWh),
EPPA – Electric power produced annualy (kWh).

Figure 8. Life cycle assessment of solar PV systems

To know the effect of global warming due to PV systems, its CO_2 emission rate needs to be calculated, this rate is compared with different energy generation technologies. The CO_2 emission rate is given as:

$$CO_2 \text{ emission rate} = \frac{\mathrm{CO2ED}}{\mathrm{EPGA} * \mathrm{LT}} \quad (9)$$

where: CO_2ED – CO_2 emitted during its life (gCO_2),
EPGA – electric power generated annually (kWh/Yr),
LT – life time.

Lesser the carbon emission rate, better would be the environment, lesser temperature. The energy return on investment (EROI) is defined as the ratio of the working energy returned during operation of the system to all the required energy to make this energy working.

$$\mathrm{EROI} = \frac{\text{Life time}}{\mathrm{EPT}} \quad (10)$$

Boundaries for LCA of a PV system

The usual boundaries for LCA of a PV system is shown in Figure 10 starting from the initial stage of mining to the final stage of disposal. The boundaries specify the services and the products related of each stage. The direct factors and the indirect factors should be considered, for example, for a suitable PV system, depending upon the type of PV cells the operation efficiency varies. The final disposal phase for the PV systems completely depend upon the type of the PV cells.

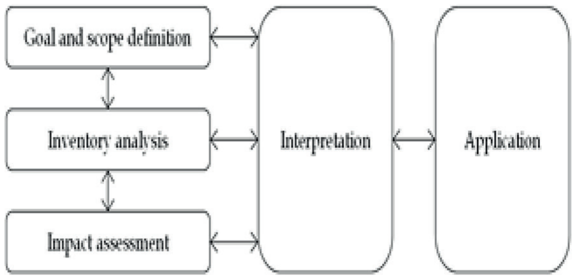

Figure 9. Scheme of life cycle assessment

Inventory investigation

The analysis of inventory is executed to estimate the quantities of materials produced or consumed that would influence the environment during life cycle of the object. It comprises of identifying various steps to be followed in the life cycle and quantitatively estimating them, then recognizing all materials that influence the environment. The data of the object is calculated. Nevertheless, it is challenging to gather all the data related to the processes. During performing the LCA study, the applicable boundaries, various assumptions for calculation and the data quality have to be clearly understood.

Impact valuation

Impact valuation comprises of three procedures; characterization, weighting and classification. During characterization procedure, the impact category indicators are produced by calculating quantity of material with factors of characterization. The input energy is found out in terms of calorific value or electricity. With the help of global warming potential, the greenhouse gas emissions are found out in terms of CO_2 equivalents. The inventory analysis is used to calculate the input data & output data. The impact category indicator would be obtained by calculating CO_2 equivalent values and the results representing the requirement of the energy. Weighting procedure is not specified in the international standardization as it is deliberated challenging to form a single display for the depletion potential of ozone and the global warming potential of different areas. Weighting has two methods namely, environmental category weighting by estimation and damage evaluation method.

In classification procedure, the materials influencing environment are categorized in terms of their influence. For example, global warming is caused by CO_2 and will be categorized as global warming producer, acid rain is caused by sulfur oxide (SO_x) and will be categorized as acid rain producer, both of them affect the public health and so on. Based on inventory analysis, the impact potential is calculated. The quantity of energy consumed is classified and calculated based on energy payback time during research. Emissions are classified and calculated into appropriate category depending upon research on CO_2 emission rates.

Understanding

The LCA results depend upon inventory analysis and the research boundaries and it is related to the operation methods during the interpretation. For LCA, the data will be taken from the referred information and the estimates. Therefore, it can be concluded that the results get effected significantly due to the estimated data and if necessary sensitivity analysis will be carried out.

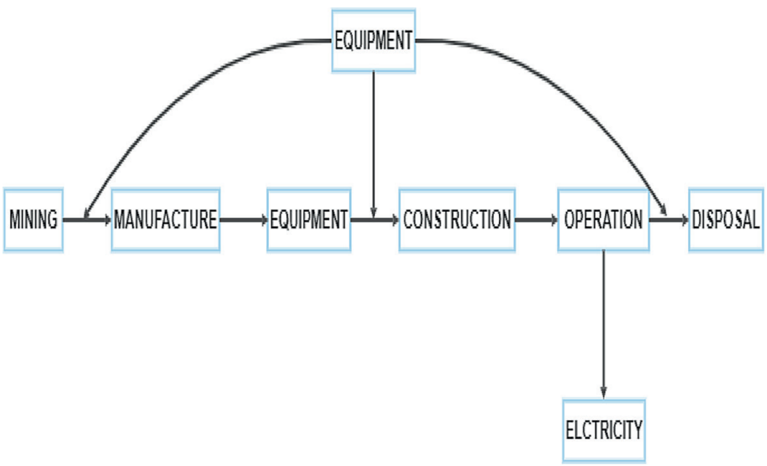

Figure 10. The Boundaries for LCA of a PV system

LCA GUIDELINES FOR PV SYSTEMS

In recent times, the International Energy Agency Photovoltaic Power System Programme (IEA PVPS), Task 12, Subtask 20, has published, guidelines of LCA for PV systems by name methodology guidelines on life cycle assessment of photovoltaic electricity. The data in the mentioned guidelines consists lot of data and information which would be useful for the operators of LCA of PV systems for its evaluation. The guidelines for assessing PV systems is hereby briefed in this section and has been discussed (iea-pvps.org 2020).

Life period of a PV system

It is difficult to express the life period of a PV system, as the PV systems are still in the developing phase of its technology improvement and operation.

Though, many research scholars have put forward the life span of PV systems. The guidelines present the results of papers contributing to the lifetimes. The Table 1 below reflecting the data from IEA/PVPS Task12 is shown below.

Degrading

Generally, PV systems, mainly PV modules of thin film type deteriorate year after year, Most PV modules degrade year by year to an extent that is still an active topic of research, especially for thin-film PV systems. However, 0.5% per year seems to be a typical number for crystalline silicon PV modules. Accordingly, the guidelines set the degradation rate for flat-plate PV modules. Mature module technologies are considered to maintain 80% of their initial efficiency at the end of the 30-year lifetime under the assumption of linear degradation during this time.

Irradiation data

The angle of tilt of PV modules and the place of installation decides the quantity of irradiation. Irradiation is defined as the radiant energy received on a surface per unit of area, it is also defined as the equivalently irradiance on a surface integrated over time of the irradiation. Pyranometers are radiometers used for measuring the irradiance on a plane surface.

ECOLOGICAL EFFECTS FROM PV SYSTEM

PV systems do not produce sound, noise, chemicals or gases during its functioning. It can be used in city areas creating a picturesque area without having poles or wires hanging all over. These effects were discussed in literature by Aiman Abd Elkader Tawfiq et al. (2021), Gangjin Ye et al. (2020). The effect of PV systems on various natural parameters are as follows:

a) ejections of pollutants – in the course of usual operation of the PV systems, it does not emit any solid, liquid or gaseous pollutants. But, in case of a fire accident of the PV systems, the PV modules generate toxic substances or chemical pollutants that will be released into the atmosphere. These hazardous byproducts released at the time of accidents may lead to various health issues due to contamination of air, water and soil, would lead to ill effects on plants, animals and human lives.
b) air pollution – in terms of LCA, the system environmental performance is greatly influenced by how energy-efficiently it is manufactured, particularly with regard to the generation of power. In comparison to those involved in production, the emissions related to the transit of the modules are minimal. Around 1% of manufacturing associated emissions constitute of transport emissions. For poly- and mono-crystalline modules, the expected discharges are 5.049–5.524 kg SO_2/kW_p, 2.757–3.845 kg CO_2/kW_p and 4.507–5.273 NO_x/kW_p. In the urban environment, the architecture of integrated buildings, i.e., for the building portico, PV modules can be laid in place of mirrors. Hence power can also be generated. In rural areas,

Table 1. List of lifetimes of PV system components

PV Modules	30 Years for mature module technology
Inverters	15 years for small plants or residential PV systems, 30 years with 10% part replacement every 10 years for large plants.
Structure	30 years for rooftop - and facade-mounted units, 30 to 60 years for ground-mounted installations on metal supports.
Cabling	30 Years

where electrification is not up to full extent, this way of alternate power generation is very much useful. In terms of economy, it is highly economical to install self-owned PV generator when compared to government laying long transmission and the distribution lines.

c) land use – the effect of land use on the environment depends upon various features like how much land area PV systems covers, the landscape topography, biodiversity and the distance from sensitive environment. The landscape gets modified during the construction of PV system. Also the cultivable land has to be sacrificed for the construction of PV system. This finally leads to reduction in production of all the cultivated food items.

d) visual impacts – the invasion to eyes depends upon the type PV system and its scheme. If the PV system is near to the zone of natural beauty, the visual effect would be meaningfully high. The use of PV modules as covering material for the building is gaining more attention for the clients of the architectural professionals. When the building portico is integrated with PV modules, the visual impact on the eye would be more scenic when compared with the old buildings. With development in different types of PV modules for the porticos, they give a beautiful look in addition to it they perform their applied functions such as heating, current generation, shading, etc., Different electrical schemes, with PV modules in the rural areas help in providing electrical power at the consumer premises.

e) noise interruption – during the construction, installation of the PV systems there will be some noise generated. Moreover, there will be generation of employment in the course of the construction stage and operational stage. The manufacturing company should produce the PV systems that can be easily recyclable. This would further encourage more usage of PV systems.

f) exhaustion of natural resources – prior to usage of renewable energy sources, fossil fuels were used for all purposes. Due to the natural resources getting depleted, the renewable energy sources are replacing the natural resources. Particularly the mono-crystalline PV modules and the poly crystalline PV modules generate electrical power at high efficiency. The thin film PV modules have better efficiency. The quantity of Cd discharged during production of CdTe conforming to 0.01 g/GWh is 0.001% Cd. Along with production of Zn, Cd will be produced and can be used for beneficial purpose or be released into the environment.

g) waste administration – during stand-alone mode of operation of PV systems, though it covers lesser percentage of the total PV generation, the batteries being used should be handled carefully as they may result in causing various health issues. The LCA of the batteries being used in this mode of operation specifies that the batteries are responsible for the various environmental effects due to heavy metal contact and the life span of the batteries being small. Moreover, a large quantity of energy and raw resources are required for the production of the batteries. Also a recycling arrangement can improve this condition.

CONCLUSIONS

The solar PV systems offer a number of advantages when compared with traditional sources of energy. The solar energy is never exhausting, the SPVS do not produce any gaseous byproducts during their operation, the solar energy is safe and clean energy. The SPVS can be operated in standalone mode, hence does not require laying of long transmission lines to the hilly areas, remote places thus facilitating the ecological balance safeguarding the picturesque landscape. The solar system can be used for water heating, space heating in addition to electric power generation.

Still there are few ill effects due to the usage of SPVS's, like air pollution, land use, visual impacts, noise interruption, generation of waste during production of PV panels, requirement of batteries for storing the energy generated during day time, as electric power can't be produced during the night time due to non-availability of sun light, no power generation during cloudy days, the efficiency of the SPVS being very low around 25–27%, the SPVS can't be afforded financially by ordinary person unless the price is subsidized by the government, various ecological factors like partial shading conditions, water droplets, the accumulation of dust, birds droppings, reduce the efficiency of the SPSVs significantly, etc.

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