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Environmental Impacts of Photovoltaic

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Abstract- This paper is an overview of the impact of photovoltaic solar energy conversion on the environment. The paper presents development of photovoltaic cells, the need for environmental assessment of energy sources, methodology framework for the assessment and the normalization and valuation. The photovoltaic solar cell is reviewed in respect to hazard like pollution caused by the chemical components and cost incurred. The paper also presents the life-cycle analysis of solar cell.

Keywords: Silicon, Environment, Photovoltaic, Life-Cycle, Pollution

I. INTRODUCTION

The increasing demand for electricity in the world especially developed countries coupled with their willingness to preserve their hydrocarbon resources clearly addresses the need to further develop the use of renewable energies for electricity production [1].

But the outweighing effects of this energy system in the environment are much alarming especially in areas where this is dominant. The pollution it causes, both on terrestrial and aquatic system are pertinent problems that has to be tackled if solar energy is to be an efficient and preferable source of electricity generation in our society today.
Procedure for Paper Submission

II. DEVELOPMENT OF PHOTOVOLTAIC CELLS

Photovoltaic involves the conversion of sunlight into direct current (DC) electricity through the use of thin layers of materials known as semiconductors [1]. The physical processes involved in the conversion of sunlight into electricity include light adsorption, electron transport, and recombination mechanisms, which are determined by the electro-optical properties of the material.

The first practical photovoltaic cells were developed in 1954 at Bell Laboratories [2]. The first solar cells developed were made of silicon, and were used primarily by the space industry for vehicle and satellite power supplies, beginning in 1958 [2]. The material properties and abundance of silicon made it a desirable choice for the manufacturing of solar cells. Silicon (Si) is a fairly cheap and plentiful element, found, for example, as quartz in sand. The properties of silicon that make it suitable for solar cells are that it is an excellent electrical and chemical insulator, has high electrical resistivity, has a relatively low saturation current density, and can absorb a large portion of the solar spectrum. In 1997, 98 percent of photovoltaic modules produced were made of silicon amorphous silicon was first used for PV cells in1976. Development of thin film silicon cells began in the late 1970s.

Silicon-based concentrator cells were first used in space, but have recently been adapted for terrestrial applications. Thin-film cells, such as the cadmium telluride (CdTe) cell, were commercially produced in 2001, but the PV cell market is still dominated by silicon-based cells [3].

The application of this energy by means of PV conversion into electricity is now being developed at the growing scale and is very perspective for the future needs[4].

III. THE NEED FOR ENVIRONMENTAL ASSESSMENT OF ENERGY SOURCES

Energy systems are known as a major source of environmental pollution. Therefore, the selection of a particular energy system can influence the pollution output by reducing or increasing the extent of emissions dispersed into the environment. Criteria developed to choose from various energy technologies need to take into consideration not only technical but also socio-political aspects to ensure that the social and environmental costs and benefits of a chosen energy technology have been taken into account [1].

Emissions generated during the life-cycle of a given energy system are dispersed into the environment and impose a burden on living systems and items of value to human society, such as historic buildings. These burdens have an impact on the physical and biological environment as well as on human health, and thus these impacts impose significant costs on society. Costs imposed by pollution have in the past been treated as external to the energy economy and have not been incorporated into the total costs of energy production and distribution [1].

The main objective of this document is to describe the basis of performing analysis of the photovoltaic systems. A derived goal of this study is to gain experience in using the LCA-framework, and to evaluate the usefulness of these instruments in helping to find and analyze bottlenecks and opportunities in the energy technologies.

IV. LIFE CYCLE ANALYSIS (LCA) METHODOLOGY FRAMEWORK EXTERNAL COSTS

External costs are generally divided into environmental and non-environmental costs. Most of the external costs are grouped under the heading of components of external costs-the valuation of human health and life, acid deposition, greenhouse gases and global warming, to name but the most important ones. There is still a debate about non-environmental costs, about the importance of these costs, their magnitude and the extent to which they ought or out not be included in external cost calculation. However, if non-environmental costs are divided into the following four major types: aspect of security, natural resource management, employment and politico-economic instruments; then it is obvious that there are quite considerable societal costs involved and this indicates that non-environmental externalities should not be neglected when calculating the full cost of energy technologies.

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In order to quantify environmental externalities and link them to the internal costs to derive the total societal costs of these energy systems it is necessary to find a single nominator for all aspects. Monetization of environmental externalities is one of several valuation approaches that are aimed exactly at this: to express environmental costs in the same monetary unit as used for calculating internal costs of energy technologies.

Environmental impacts and the associated external costs can be grouped into four categories: negligible costs, small costs, significant costs and large costs. At each stage of the fuel cycle analysis an estimate of the physical magnitude of the environmental impacts can be given by using these four categories. Most notable among external costs are risks of damages to the environment and human health resulting from air pollutants emitted by fossil-fuel-fired generation and from the radiation risks of nuclear plant operations. Environmental costs of air pollutants in general are associated with large cost. The greenhouse effect, caused principally by CO_2 emissions from the burning of fossil fuels, and the resulting global warming are only just being assessed but are associated with large cost even if there are still considerable uncertainties about the order of magnitude of the effects and the costs involved.

A number of other environmental impacts, such as acid rain, risk to human health and life, and catastrophic events, will incur large costs as well. Impacts such as visual intrusion or operation accidents at the extraction stage or radiation risks may result in quite significant costs, whilst other environmental impacts such as noise or health and safety costs, whilst other environmental impacts such as noise or health and safety costs associated with materials inputs and construction can be expected to be small or even negligible, provided that care is taken in the design and operation of the industrial processes [5].

Detailed and reliable information and final figures for the environmental impacts will only become available when the valuation of these impacts has been undertaken.

V. FUEL CYCLES, ENVIRONMENTAL BURDENS AND IMPACTS

A detailed analysis of the fuel cycles of different energy systems is needed to determine the external costs incurred during the various stages of the fuel cycle process and hence to internalize these externalities into the full cost analysis of each of the energy technologies. This in turn facilitates a one-to-one comparison of different competing technologies on an even footing. Based on these data, informed policy actions/choices, either encouraging or limiting particular energy options, can be taken.

The analysis of the fuel cycles of energy systems covers all stages of the energy production process including extraction, preparation, transport, conversion, operation, distribution, utilization, waste processing and disposal. Each of these stages can impose environmental burdens such as, for example, acid deposition, and these burdens result in environmental impacts. Such as forest damage, which in turn pose considerable costs to society.

Some of the environmental burdens and impacts are well documented and can be identified and measured. In many other cases, however, such as global warming or loss of species, the burden/impact relationships are fraught with considerable uncertainties and non-linearity. These may result from scientific uncertainties. Unavailability of accurate data, spatial and temporal variability, or the fact that many impacts are the synergistic action between two or more burdens, e.g. the formation of ozone through the photochemical reactions between NO_x and hydrocarbons. Further work will be required to find appropriate methods of defining the burden/impact relationships which cannot be accurately measured so far[5].

VI. ENVIRONMENTAL COST OF PHOTOVOLTAICS

The application of the LCA methodology to the photovoltaic technology should consider all steps necessary for the production of the components of a photovoltaic system as well as the decommissioning of the system. For this reason, the first step to follow is to evaluate in each stage of the process a detailed inventory of the inputs and outputs of energy, materials and required capital equipment. In a second step, the evaluation of the potential hazards associated with each step of the process should be also evaluated for each component of the photovoltaic system. The following figure shows the life steps for a photovoltaic module.

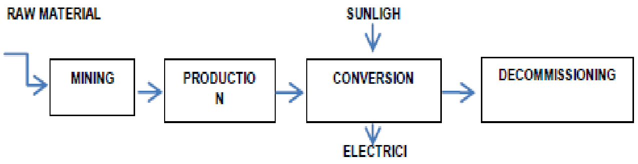

Figure 1: Life-cycle of Photovoltaic Panel [1]

The commercial standard PV module uses solar cells made from wafers of silicon. Usually 0.3 mm thick and 10cm x 10cm in area. Each of the steps shown in fig 1 has inputs of energy and materials requires capital equipment, and each also has potential hazards associated with it. The first step is a standard mining operation with associated records to the miners and inputs of diesel fuel and machinery. Metallurgical silicon is made in large quantities for the steel industry, with a small ongoing as input to the semiconductor industry. The major emission substantial energy input. the purification of the microelectronics industry and their monitoring and control is well established. The material's for construction of the complete PV system, other than the PV modules, are steel, aluminium. Copper, concrete and electronic equipment, with which are associated the standard industrial hazards.

The energy used in manufacturing the PV modules and the other components of the PV modules using silicon wafers has been measured at the photowatt plant by palz and Zibetta (1991) as 235kWh(e)/m^2 for 1990 technology as 1.5 MW per annum production rate. Thus for the 1990 crystalline silicon PV technology in small-scale production, the CO_2 emission is around 400.000 tonnes per giga watt-year of energy output. This compares with the CO_2 output from the most modern and efficient coal fired plant of 9 million tonnes per gigawatt-year (1991), mainly from the fuel production steps, but this estimate did not include the energy used for decommissioning and waste treatment and storage. The CO_2 emissions estimated for the various current PV cell technologies are shown in Table 2, along with an estimate of values which might be typical of 2020 PV technology. The thin-film polycrystalline materials have been studied by Hynes et al. (1991) and those data in Table 2 are taken from their work.

As shown in table 1, there are a number of technologies for PV cells other than those using wafers of silicon. Amorphous silicon cells are widely used in solar calculators, clocks, etc., but seem unlikely to be widely used for power modules. Thin multicrystalline films of silicon on ceramic substrates and thin polycrystalline films of copper indium diselenide (CIS) and of cadmium telluride (CdTe) are the three most promising technologies for efficient low-cost modules and all seem likely to be in commercial production within the next 2-4 years. An excellent review of the scientific, technical, economic and environmental issues associated with these three materials has been given by.

The environmental impacts of the thin-film silicon cell are similar to those of the wafer silicon cell, but reduced in magnitude because of the smaller volume of silicon used. The CIS cell has a potential hazard in the hydrogen selenide used in its manufacture. A report on CIS manufacture by moskowitz et al. (1990) has concluded that hydrogen selenide can be used safely provided that adequate safety precautions are adopted. There are proposals for the production of CIS which involve the use of solid selenium rather than hydrogen selenide (Badawi et al., 1991) which would largely obviate this hazard.

Table 1: Carbon dioxide emitted in the production of PV modules (in units of kilotonnes per gigawatt-year)

Cell material	Production scale	Efficiency (%)	Lifetime (years)	CO_2kt/(Gwyr)
Monocrystalline silicon	Small Large	12 16	20 30	400 150
Multicrystalline silicon	Small Large	10 15	20 30	400 100
Thin-film silicon	Small Large	10 15	20 30	130 50
Thin-film polycrystalline materials	Small Large	10 14	20 30	100 40
Future (2020) multi junctions	Large	30	30	24

For comparison, the most efficient coal plant emits 9 million tons of CO_2 per gigawatt-year, whilst as BwR nuclear plant emits 75 000 tons of CO_2 per gigawatt-year (plus an unknown amount for decommissioning and waste treatment).

Both CIS and CdTe cells have a window layer of cadmium sulphide, cadmium hazards arise in the refining stage, with emissions of cadmium oxide dust, emissions of cadmium during manufacture, or during a fire in which cadmium-containing PV modules were involved, and from possible leaching of cadmium from modules discarded at the end of their working life. In all of these cases, the control strategies are well established in industry, and the magnitude of the hazard is in proportion to the amount of cadmium present in the cells.

In CIS modules, the amount of cadmium used is about 0.04 g/m^2, equivalent to 400 g per MW_p of output. This tiny amount of material is easily controlled during manufacture, whilst cadmium evaporated from modules on a building which caught fire would pose a negligible hazard to anyone for enough from the fire to avoid being burnt to death. Careless disposal of large numbers of CIS modules in one location could post a hazard from leaching of cadmium and selenium into ground water. However, the rather scarce indium and regulations on the disposal of cadmium and selenium products would lead to recycling of the modules and reuse of the indium, cadmium and selenium.

The PV modules using CdTe cells would contain much more cadmium (about 5 g/m^2) than those using CIS cells, and the potential hazards are correspondingly higher. It is clearly beneficial to use a manufacturing process with a high utilization of cadmium feedstock, and the success of electrochemical deposition as a production technology gives the opportunity for such process.

It is interesting to note that the among of cadmium contained in the CdTe modules needed to generate energy of, say , I GWh over their lifetime is about equal to the cadmium emitted from the smoke-stack of a typical coal-fired station wilst generating the same 1 GWh of electrical energy. Very little of the cadmium in the PV modules would be lost into the environment to the PV plant is cleaner, even for cadmium emissions, than a coal-fired power station.

VII. CLASSIFICATION OF MAIN ENVIRONMENTAL ISSUES

After the inventory analysis, the classification of the five issues -exhaustion of raw materials, energy, global warming, acidification and solid waste- was carried out resulting in the environmental profile for the studied functional unit as shown in table 2

Table 2: Impact scores per functional unit for the main environmental issues of the two cases.

	Case 1	Case 2
Exhaustion Raw Materials	6.91	0.13
Energy	744	269
Global warming	47.3	13.8
Acidification	0.23	0.08
Solid waste	1.89	0.19

Plastic waste, after disassembly for incineration is not taken into account in solid waste; nor are the other environmental interventions due to the incineration of the plastics .

VIII. OTHER ENVIRONMENTAL ISSUES

The waste resulting from the extraction and production of makes it a significant contributory factor in aquatic ecotoxicity when leaking into soil takes place. The use of zinc in the support structure should therefore be avoided if possible.

Silane and phosphine, used in the module production process, are both inflammable gases and phosphine is also highly toxic. Classification factors are not yet derived, so the impact of possible interventions when leakage occurs, compared to other hazardous gasses in this case, cannot be calculated. These gases should be a point of concern. In theory these gases should not escape, but in case of an accident, emissions can take place. Risks and impacts involved in accidental emissions are only discussed to a limited extend in the LCA protocol and are not incorporated in this study.

IX. NORMALIZATION AND VALUATION

In addition to this analysis, normalization may be carried out in order to put the results of the classification into perspective and to identify of the bottlenecks and opportunities of roof-integrated PV-systems. The classification of the cases can be normalized in relation to the classification of the total environmental interventions in the country where the LCA analysis is made.

The results of the normalization have been reached using data from the Netherlands and give an indication of the relative contribution of the technology to the impact categories of the Netherlands within a case. It should be noted that the interventions of the cases partly take place outside the Netherlands, but the interventions of the Netherlands activities are restricted to those which take place in the Netherlands. Results are given in the table [3].

Table 3.Normalized impacts of the two cases

Normalization	Case 1	Case 2
Energy	1.0	1.0
Exhaustion of Raw Materials	0.32	0.017
Global Warming	1.2	0.95
Acidification	1.2	1.2
Solid Waste	0.89	0.25

The figures for all issues are of the same order of magnitude, except for exhaustion of raw materials which contributes less in case 2. Therefore we can conclude that if we want the environmental profile to be improved, all issues need attention. Since the contribution to environmental issues is mainly caused by the module production and the production of the support structure, the search for improvements should be focused on these processes. Furthermore it has already been shown that increases in efficiency and in the lifetime of the system have a positive effect on the environmental profile.

The module production is one of the parts of the life-cycle that makes a significant contribution to the environmental issues. From detailed analyses we have found that the cumulative energy requirement and emissions of the materials used in this process contribute up to 20% to the environmental issues. The production of capital goods for module production contributes up to 30% and the module production process itself up to 50%. Therefore, a substantial reduction in the energy requirement in this life cycle can only be achieved if the production process, as well as the capital goods and the material used can be improved.

The second important process block is the support structure. In case I aluminum is the main contributor (about 75%) to the environmental profile of the support structure and in case 2 it represents 85%. The environmental profile can be improved by a reduction in the use of these main materials. In case I zinc is used which results in a significant contribution to the exhaustion of raw materials and to the solid waste. The use of zinc should therefore be avoided as much as possible. From detailed analysis of the support structure of case 2, it can be concluded that compared to the recycling of the plastics, the incineration causes a reduction in the energy use of about 30%. It also causes a doubling of the global warming potential and of the acidification potential. Compared to dumping, incineration of plastics used in the support structure is favourable from an energy and waste point of view, but not from a global warming and acidification point of view.

If closed-loop recycling is applied and no or little processing is needed, the contribution to the environmental profile is reduced by as much as the regular material is replaced by the closed-loop recycled material. If all materials in the support structure can be re-used for another lifetime of the PV-system, the environmental profile of the support structure is reduced to 50%.

At first sight closed-loop recycling is preferred to the incineration option. However, further research is necessary on the quality of the material after decommissioning of the system: is it suitable for re-use? And, if processing is necessary, what is the environmental profile of the closed-loop recycling of the materials?

Analyzing the other parts of the life-cycle, it can be concluded that the choice of shared power conditioning in case 2 above individual inverters in case I is a choice for a decrease in interventions. Because in case 2 less materials need to be transported, is seems obvious that the contribution to the environmental issues in case 2 is reduced.

Transportation and the power conditioning and cabling are of minor importance to the environmental profile. Even if the materials and the system parts are transported across long distances overseas, the contribution will be about the same.

X. CONCLUSION

Photovoltaic systems are almost entirely benign in operation, and potential environmental hazards occur at the production and disposal stage. Silicon is a very stable material and its release into the environment poses no hazard in the production of silicon cells the hazards are similar to those encountered in the microelectronics industry, and monitoring and control procedures are well established for even the largest production rates envisaged. For PV modules based on CiS or CdTe cells. There are potential hazards from the use of hydrogen selenide and cadmium. It is clear from this review, however, that there are well established methods of monitoring, control and alleviation which can reduce these hazards to within international safety limits for all stages of production, operation to disposal. All production processes require an input of energy, and this energy is derived from the standard fuel mix of the nation in which production takes place the production of PV systems has associated with I, therefore, emissions of greenhouse and acidic gases. In the present state of the PV industry, with small-scale production and technologies some way from industry, with small-scale production and technologies some way from maturity, these emissions are much less than those from fossil fuels but exceed those from the operation and fuelling of large nuclear reactions. As the new thin-film PV technologies come into production later into this decade, and the scale of production increases, the energy input to PV systems will decrease considerably, with consequent reduction in carbon dioxide emissions to levels below that of other electricity generating technologies**.**

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