INSTITUTE FOR PROSPECTIVE TECHNOLOGICAL STUDIES
SEVILLE
W.T.C., Isla de la Cartuja, s/n,
E-41092 Sevilla

The environmental impact of photovoltaic technology

(Task 6- INTERSUDMED Project)

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Miquel A. Aguado-Monsonet

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1. Introduction

The increasing demand for electricity in Southern Mediterranean countries and their willingness to preserve their hydrocarbon resources clearly address the need to further develop the use of renewable energies for electricity production in this area. Fully aware of this, the European Union is aiming to promote initiatives to support the implementation of renewable energy technologies within the Mediterranean basin. In this respect, the APAS MEDENERGY project (1995-1996) elaborated an action plan for the development of renewable energies in those countries. Pre-feasibility studies of a set of renewable energy plants should provide strategic support for a major market deployment of renewable energy technologies in the Mediterranean basin and therefore assist regional development. National and local authorities, research, development and demonstration (RDD) institutions, manufacturers, utilities and users should participate in the subsequent project stages. In order to accomplish these objectives, the IPTS, together with other partners, has undertaken a JOULE project, named INTERSUDMED.

The project has been divided into several tasks. Each of these tasks has been co-ordinated by one of the partners. A close collaboration between Northern and Southern partners, especially regarding information and experience exchange, has played a key role during the project. The different tasks appear in the following table:

TASK	**DESCRIPTION**
1	Selection of appropriate sites and technologies given the local context
2	Analysis of the Southern Mediterranean institutional framework regarding electricity production
3	Basic engineering and techno-economic studies for renewable energy plants, including network integration.
4	Local industrial capabilities in each country for manufacturing plants, and technology transfer
5	Evaluation of the social and economic impacts
6	Evaluation of the environmental impact
7	Development of financial schemes

Table 1.-INTERSUDMED Tasks

The INTERSUDMED project is composed of thirteen renewable energy projects, with different renewable energy technologies. Five of them are photovoltaic projects and are distributed across the following countries: one in the south of Algeria, one in the North of Sinai (Egypt), one in the north of Morocco, one in the central region of Tunisia and another one in Palestine.

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.

In previous publications [1,2], the use of life cycle analysis has been reported, as well as the methodology applied to energy systems. These documents have created a research protocol that it is designed for use within the energy R&D-context: they provide a protocol for finding bottlenecks and opportunities for (new) energy technologies in the context of (energy) resource scarcity and environmental issues. For this, the protocol particularly stresses the improvement analysis part of the Life cycle assessment-methodology.

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.

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

2. Life Cycle Analysis (LCA) Methodology

Environmental costs arise from emissions at various stages in the construction, operation and decommissioning of power sources. In order to identify and quantify these environmental externalities, a full life-cycle assessment of energy systems has to be undertaken. The identification of the “upstream” and “downstream” activitites of energy systems allows a comparative evaluation of their environmental burdens, impacts and costs.

There are also a range of costs imposed on society which are associated with energy supply but which flow from decisions taken by governments for reasons which may not always be related directly to energy supply. These non-enviromental external costs include national security considerations (including security of supply and safety issues), natural resource management, liability limitations, employment and politico-economic instruments such as subsidies or tax concessions. It is extremely difficult in most cases to quantify these non-environmental costs and even more difficult to allocate these costs to specific technologies in terms of costs per unit output. Attempts have been made to quantify R&D expenditures, subsidies and tax concessions to specific energy technologies. However, although consensus of the appropriate treatment of these issues has not been reached yet, these costs do not appear to be negligible and are quite likely to increase over the years.

The emissions of pollutants can, at least in principle, be measured and a quite accurate technical assessment can be made by emissions from given power sources, and the means and costs of controlling them. These emissions disperse into the environment, and although this can be modelled quite well on a large scale, microclimatic effects can change the burden imposed on natural systems on smaller geographical scales.

Life cycle assessment generally is a tool used to compare two competitive activities or products. In the comparison of energy technologies the following impacts should be considered: a) Exhaustion of raw material, b) Energy needed, c) Global warming, d) Acidification and e) Waste

3. Application of LCA to photovoltaic technology

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 decomissioning 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.

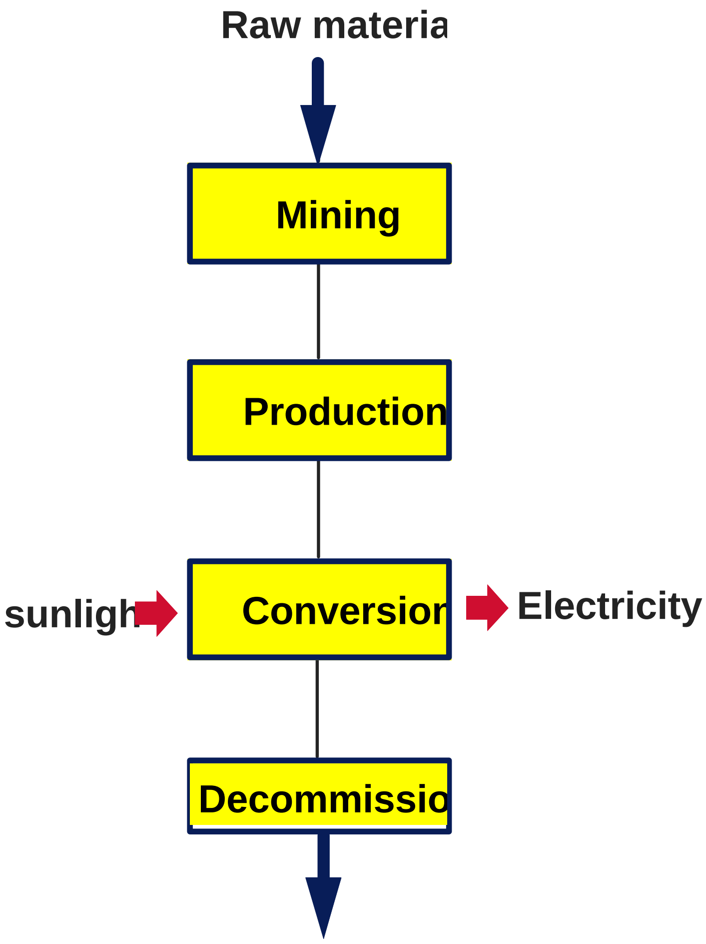

Figure 1.- Life cycle of the photovoltaic panels

Of course the evaluation of the inventory and the analysis of the hazards of each step should be made for each component of a photovoltaic system. Each step of the process has inputs of energy and materials and requires capital equipment, and each also has potential hazards associated with it.

A photovoltaic system consists of the following set of components: photovoltaic panels, batteries (if they exist) and electric and electronic equipment (battery regulator, cabling, controller and inverter (if it exists)).

3.1 Photovoltaic panels (including structure)

In this exercise on the evaluation of the impacts of the renewable energy projects, a commercial standard photovoltaic modules has been considered that uses solar cells made from wafers of silicon, usually 0.3 mm thick and 10 cm x 10 cm in size. The environmental impact of thin film silicon cells is similar to that of the wafer silicon cell, but reduced in magnitude because of the smaller volume of silicon used.

The first step is a stardard mining operation with associated hazards to the miners and inputs of diesel fuel and machinery.

Metallurgical grade silicon is made in large quantities for the steel industry, with a small fraction going as input to the semiconductor industry. Its major emission is silica dust which can cause lung disease, and there is a substantial energy input.

The purification of silicon can involve hazardous materials such as silane, whilst the doping of the silicon involves toxic chemicals such as diborane and phosphine, although only in small quantities diluted in inert gas. These materials are used in the microelectronics industry and their monitoring and control is well established. The materials for construction of the structure of the PV system, other than the PV modules, are steel, aluminium and concrete which are associated with the standard industrial hazards.

The energy used in manufacturing the PV modules and the other components of the PV system is derived from the fuel mix of energy system and is therefore associated with emissions of greenhouse gases and acidic gases. The energy content of PV modules using silicon wafers has been measured as 235 $kWh_{el}.m^{-2}$ for 1990 technology at 1.5 MWp per annum production rate [3]. The electrical production during the lifetime of the PV modules is around 1,500 $kWh_{el}.m^{-2}$. In this case, the CO_2 emission is around 400,000 Tonnes per GWyr of energy output. This compares with the CO_2 output from the most modern and efficient coal-fired plant of 9 million tonnes per GWyr. Boiling water reactors have been estimated to emit around 75,000 Tones of CO_2 per Gwyr, 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.

Cell Material	Production Scale	Efficiency (%)	CO_2 output (kTonnes/GWyr)
Crystalline-Si	Small	12	400
	Large	16	150
Multicrystalline-Si	Small	10	400
	Large	15	100
Thin film Si	Small	10	130
	Large	15	50
Thin film polycrystalline materials	Small	10	100
	Large	14	40

Table 2.- CO2 emissions of photovoltaic technology

Table 3 represents the calculation of the emissions for a PV home application [4].

	Emissions kg per kWp	Emissions g per MWh produced
SO_2	1.9	104
NO_x	1.8	99
Particles	0.11	6.1
CO_2	971,000	53,300
CH_4	1.6	88
N_2O	0.0031	0.2

Table 3.- Emissions from the PV life cycle

The next table represents a comparison between the different environmental impacts for the different types of photovoltaic modules.

Material	Production	Operation	Disposal
Si	Silica dust Silanes Diborane Phosphene Solvents		
$CuInSe_2$	H_2Se	Cd	Cd

	CdO Cd dust Selenium solvents	Se (In a fire)	Se (If not recycled)
CdTe	CdO Cd dust Tellurium solvents	Cd Te (In a fire)	Cd Te (If not recycled)

Table 4.- Comparison of the hazardous emissions from different photovoltaic module compounds

The decommissioning of silicon photovoltaic modules does not cause any environmental problem. It can be considered as construction waste. This is not the case when other types of substance are used to manufacture the photovoltaic cells, such as in the case of the $CuInSe_2$(CIS) and CdTe modules. The disposal of CdTe modules should be controlled more strictly than CIS modules and recycling the materials is more important both for environmental reasons and for the value of the Cd and Te.

In next table shows a summary of the main environmental impacts identified in the life of a silicon module. In this table the impacts have been quantified from high environmental impact to low environmental impact. Places where the impact has not been quantified means that no environmental impact has been detected.

	Mining	Technology production	Conversion	Decommissioning
Exhaustion of raw material		Medium		
Energy needed	Medium	High		Low
Global warming	Medium	High		Low
Waste	Medium	Low		Medium

Land use	High	Low	Low	

Table 5.- Environmental impacts detected in the life of a silicon photovoltaic module

3.2 Batteries

The evaluation of the environmental impacts of the production and decommissioning of the batteries depends on the type of batteries used. The type of battery most used in the INTERSUDMED projects has been the lead-acid battery. This type of battery is the most common in developing countries and they are less expensive than PV batteries. The manufacture of batteries involves heavy metals. PV batteries use cadmium, a very toxic chemical, and that should be recycled. The most appropiate use of the exhausted batteries is to reuse the lead contained in or recycle them. The next table shows the main environmental impacts detected during the life of the battery.

	Mining	Technology production	Conversion	Decommissioning
Exhaustion of raw material		Medium		
Energy needed	Medium	Medium		Low
Global warming	Low	Medium		Low
Waste	Medium	High		High
Land use	Low	Low		Medium (if it is not recycled)

Table 6.- Environmental impacts detected during the life of the batteries

3.3 Electric and electronic equipment

The materials for construction of the electric and electronic equipment in a PV system are steel, aluminium, copper, and regular electronic equipment, which are associated with the standard industrial hazards.

	Mining	Technology production	Conversion	Decommissioning

Exhaustion of raw material		Medium		
Energy needed	Medium	Medium		Low
Global warming	Medium	Medium		Low
Waste	Medium	Medium		Medium
Land use	Low	Low		Low

Table 7.- Environmental impacts due to electric and electronic equipment

3.4 Example of application of LCA to a photovoltaic system

3.4.1 Definition of the functional unit

In case I we study a system of 30 m^2 of amorphous silicon (a-Si) modules which are connected to the grid directly. The modules comprise a-Si cells and have a conversion efficiency of 10%. Integration into the roof is done with aluminium profiles.

In case 2 we study a system of 30 m^2 a-Si cell modules integrated in the roof with plastic tiles. The modules have an efficiency of 15% and connection to the grid is more or less centralized: 25 systems share an inverter which is connected to the grid.

The functional unit is expressed per 1000 kWh produced by the defined systems.

3.4.2 Inventory Analysis

In the inventory analysis the process tree was divided into the following process blocks: raw materials (extraction and processing), module production, support structure, power conditioning, cabling, transportation, installation and decommissioning. Data on the distinct processes was gathered from literature and in-house experience. The amount of data available in the diverse sources differs from material to material and from process to process. For some materials quite complete data sets are available. However, when we compare part processes from one data set with other data sources, the emissions may vary a lot. The reason for this may be found in the variation of processes from one country to another.

For other materials and processes, only information on the energy requirements is available. Because of these drawbacks the resulting figures and the conclusions made should be handled with care.

3.4.3 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 7.

	case I	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**

Table 8.- Impact scores per functional unit for the main environmental issues of the two cases. 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

Because the impact scores for case 2 are lower than those for case I, we can conclude that case 2 is an improvement of case 1. This improvement is partly caused by the increase in the lifetime of the system, partly by the increase of the conversion efficiency of the modules and partly by a reduction in material use and energy requirements and the use of alternative materials.

Calculation of the relative contribution of the distinct processes to the environmental issues shows that the module production and the production of the support structure cause the biggest environmental interventions in the life cycle of roof-integrated PV systems.

3.4.4 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 (Engelenburg and Alsema (1993)). Classification factors are not yet derived, so the impact of possible interventions when leakage occurs, compared to other hazardous gasses in this case, can not 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.

3.4.5 Normalization and Valuation

In addition to this analysis, a 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 next table.

Normalization	case I	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**

Table 9.- Normalized impacts of the two cases

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 said 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 contribute 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 aluminium 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 prefered to the incineration option. However, further research is necessary on the quality of the material after decommisioning 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.

4. Conclusions

Because the environmental performance of PV-systems is greatly improved by increased efficiency and longer lifetimes, both should be stimulated for the modules as well as the total system.

For roof-integrated PV-systems, module production and production of the support structure are the largest contributors to the environmental issues and are almost equally important from an environmental point of view. If batteries are used their recycling should be considered.

Environmental interventions in the module production process can be reduced by about 30% through increasing production scale and optimizing the production process, simultaneously resulting in material and energy requirement reduction. Little supplemental energy conservation policy may be necessary to achieve this outcome. Assumptions were made in the two cases about the recycling of the modules: 80% of the modules in case I and 95% of the modules in case 2.

- Research should be carried out as to how recycling of 80% to 95% of the modules can be achieved. The energy requirement of the module production process as well as the capital goods and the materials used in the module production process (glass, EVA) are about the same size. To achieve further reductions of environmental interventions:
- the production of glass and EVA should be improved. If possible, the use of these materials should be reduced or alternatives, both in material and in module construction, should be studied and environmentally evaluated;
- the uncertainty in the value of the gross energy requirement of the capital goods needs to be reduced to gain more insight into the importance of the capital goods. If the actual GER is the same size as the value assumed in this study, possibilities of reducing of the energy requirement for capital goods in the module production should be looked into;
- possibilities of reducing of the energy requirement of the production process should be looked into.
- In the module production process hazardous gases are used. The environmental impacts of these hazardous gases that may be released when calamities happen, were not studied in this report. The handling of hazardous gases in the module production should be a point of attention, especially where large scale production is concerned.

The assumptions of the amounts of material used in the support structures and the methods of waste treatment greatly influence on the decision. To gain more certainty, more knowledge about possible material reductions and recycling must be gathered.

- reduction of material use in the support structure should be pursued. In particular the use of zinc should be avoided if possible.
- Detailed analyses of the recycling processes of the materials in question can give more information about the advantages and disadvantages of recycling.
- Because availability, completeness and quality of the data on materials and processes is far from ideal, future research for LCA-studies should include the development of a database with data from both national and international (material) processes.
- In addition to the classification, a normalization step is also carried out to attain a better insight in the results of the inventory analysis. It is advisable to incorporate the normalization step into the protocol as part of an impact assessment which also includes the classification.
- Environmental impacts of calamities are not calculated within the scope of this LCA. Only little attention is paid to the evaluation of risks and impacts of calamities in the protocol, but deserves more attention.

5. Literature

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