Universitat de Lleida

Life Cycle Assessment of novel Building Integrated Concentrating Photovoltaic systems through environmental and energy evaluations

Karim Ali Ibrahim Menoufi

Dipòsit Legal: L.309-2014
http://hdl.handle.net/10803/131056

ADVERTIMENT. L'accés als continguts d'aquesta tesi doctoral i la seva utilització ha de respectar els drets de la persona autora. Pot ser utilitzada per a consulta o estudi personal, així com en activitats o materials d'investigació i docència en els termes establerts a l'art. 32 del Text Refós de la Llei de Propietat Intel·lectual (RDL 1/1996). Per altres utilitzacions es requereix l'autorització prèvia i expressa de la persona autora. En qualsevol cas, en la utilització dels seus continguts caldrà indicar de forma clara el nom i cognoms de la persona autora i el títol de la tesi doctoral. No s'autoritza la seva reproducció o altres formes d'explotació efectuades amb finalitats de lucre ni la seva comunicació pública des d'un lloc aliè al servei TDX. Tampoc s'autoritza la presentació del seu contingut en una finestra o marc aliè a TDX (framing). Aquesta reserva de drets afecta tant als continguts de la tesi com als seus resums i índexs.

ADVERTENCIA. El acceso a los contenidos de esta tesis doctoral y su utilización debe respetar los derechos de la persona autora. Puede ser utilizada para consulta o estudio personal, así como en actividades o materiales de investigación y docencia en los términos establecidos en el art. 32 del Texto Refundido de la Ley de Propiedad Intelectual (RDL 1/1996). Para otros usos se requiere la autorización previa y expresa de la persona autora. En cualquier caso, en la utilización de sus contenidos se deberá indicar de forma clara el nombre y apellidos de la persona autora y el título de la tesis doctoral. No se autoriza su reproducción u otras formas de explotación efectuadas con fines lucrativos ni su comunicación pública desde un sitio ajeno al servicio TDR. Tampoco se autoriza la presentación de su contenido en una ventana o marco ajeno a TDR (framing). Esta reserva de derechos afecta tanto al contenido de la tesis como a sus resúmenes e índices.

WARNING. Access to the contents of this doctoral thesis and its use must respect the rights of the author. It can be used for reference or private study, as well as research and learning activities or materials in the terms established by the 32nd article of the Spanish Consolidated Copyright Act (RDL 1/1996). Express and previous authorization of the author is required for any other uses. In any case, when using its content, full name of the author and title of the thesis must be clearly indicated. Reproduction or other forms of for profit use or public communication from outside TDX service is not allowed. Presentation of its content in a window or frame external to TDX (framing) is not authorized either. These rights affect both the content of the thesis and its abstracts and indexes.

Universitat de Lleida
Departament de Medi Ambient i Ciències del sol

Life Cycle Assessment of novel Building Integrated Concentrating Photovoltaic systems through environmental and energy evaluations

PhD Thesis

Author:
Karim Ali Ibrahim Menoufi

Directors:
Dr. Daniel Chemisana
Dr. Joan Ignasi Rosell

Lleida (Spain)
January 2014

Acknowledgments (Part 1/2)

I would like to express my true and deep gratitude to the following persons who have made the completion of this PhD thesis possible:

I would like to thank Dr. Joan Ignasi Rosell, my thesis supervisor and research project manager, for the encouragement and support, and for encouraging me to start my PhD thesis in such interesting research project.

I would like to thank Dr. Daniel Chemisana, my thesis supervisor, for the continuous support, for the great scientific knowledge and experience, for the fruitful guidance, and for the true leadership.

In addition, I would especially like to thank both of my supervisors, Dr. Joan Ignasi Rosell, and Dr. Daniel Chemisana, for providing me with a healthy and comfortable working environment. I would like also to thank the rest of the group members for their assistance in various occasions and for helping making CREA a place to learn and excel: Dr. Chiara Lodi, Dr. Jerome Barrau, Dr. Chryssa Lamnatou, Dr. Bahy Saad, Jordi Cipriano, Jorge Olivera, Gerard Mor, Tamara Doz, José Lopez, and Meredith Davis.

I would like to thank Prof. Dr. Ali Menufi, my father, and Prof. Nadia Guda, my mother, for the support throughout the years, for all the sacrifices and assurance all the way, and for encouraging me to work and continue. I would especially like to thank them for always being there whenever I needed help.

I would like to thank the rest of my family members and friends (Dr. Samar Ali, Dr. AbdelHalim Menufi, Dr. Hazem El-Gamal, and many others), for their help and support in various occasions.

This work has been achieved at the Applied Energy Research Centre (CREA) of the University of Lleida (Lleida, Spain) within the Department of the Environment and Soil Sciences (Applied physics section). The work has been supported by the project ENE2010-18357 under Grant reference BES-2009-028293, funded by the Spanish Ministry of Science and Innovation (MICINN). A part of this work has been achieved at the Department of Environmental Sciences of Radboud University Nijmegen (The Netherlands) within a short stay research period of three months permitted from the 15th of June 2013 until the 15th of September 2013.

Acknowledgments (Part 2/2)

A mi querida madre, lo único valioso en mi vida. Que
Dios te bendiga y bendiga tu alma. A pesar de mi dolor
indescriptible y eterno, sé que la muerte no está
separándonos aparte, sé que todavía estamos juntos, y sé
que siempre vamos a estar juntos, querida madre.
Nadia Guda Mohamed Hassan el Dabae (10 de Febrero
1956 – 19 de Diciembre 2013)

To my beloved Mother, the only precious thing in my life.
God bless you and bless your soul. Inspite of my
indescribable and everlasting grief, I know that death is
not separating us apart, I know that we are still together,
and I know that we will always be together, my beloved
Mother.
Nadia Guda Mohamed Hassan el Dabae (10th of February
1956 – 19th of December 2013)

الى أمي الحبيبة الغالية، التي هي كل شيء غالي في حياتي، بارك الله لكي
وأسكنك فسيح جناته. بالرغم من حزني الأبدي و الذي من المستحيل وصفه
بمجرد كلمات، أعرف أن الموت لم يفرقنا، فنحن مازلنا سوياً، و سنبقى دائماً
سوياً، يا أمي الحبيبة الغالية.
نادية جودة محمد حسن الضبع (١٠ فبراير ١٩٥٦- ١٩ ديسمبر ٢٠١٣)

Abstract

Life Cycle Assessment (LCA) is a comprehensive tool for assessing the environmental impact of a product or an activity over its entire life cycle. The general aim of using LCA is to achieve sustainable systems and products through guiding the decision making process. In the regard of the renewable energy resources, the PV technology is considered as one of the cleanest energy resources, as it can be supplied for operation without environmental pollution. However, the PV technology is accompanied by impacts on the environment associated with the manufacturing processes. For this, conducting LCA studies for PV systems is an essential tool for measuring the sustainability level of a corresponding system. In this sense, and after conducting a theoretical analysis of the LCA studies of PV systems in literature within the context of energy generation, some gaps have been found. These gaps are briefly represented in the lack of variety of LCA indicators, where most of the studies are dependent on the Energy Payback Time as almost the sole environmental indicator, disregarding the use of environmental profile methods. In addition, another two gaps are observed concerning the lack of LCA studies highlighting the building integration from one side, and the use of the concentrating PV technology from another side. Hence, in this thesis, a novel contribution to the field of LCA studies of PV systems is presented. This is achieved through environmentally and energetically evaluating novel Building Integrated Concentrating Photovoltaic (BICPV) systems. The results are presented in terms of Life Cycle Impact Assessment methodologies (environmental profile), as well as the Energy Payback Time and the Energy Return Factor (Energy profile). The results, supported by sensitivity analyses and comparison to a conventional Building Integrated Photovoltaic (BIPV) system, show the significant environmental benefits that can be acquired through BICPV systems. Finally, recommendations for future work and improvements are discussed as well.

Resumen (Español)

El Análisis de Ciclo de Vida (LCA) es una herramienta integral para evaluar el impacto ambiental de un producto o una actividad a lo largo de todo su ciclo. El objetivo general de la utilización de LCA es lograr sistemas y productos sostenibles a través de la orientación del proceso de toma de decisiones. En la relación con los recursos de energía renovable, la tecnología fotovoltaica se considerada como una de las fuentes de energía más limpias, ya que se suministra sin ninguna contaminación. Sin embargo, la tecnología fotovoltaica se acompaña de los impactos sobre el medio ambiente asociados a los procesos de fabricación. Para ello, la realización de estudios de LCA para sistemas fotovoltaicos es una herramienta esencial para medir su nivel de sostenibilidad. En este sentido, y después de la realización de un análisis teórico de los estudios de LCA de los sistemas fotovoltaicos en la literatura en el contexto de la generación de energía, se han encontrado algunas lagunas. Algunas de estas lagunas se refieren: la falta de variedad de indicadores de LCA, donde la mayoría de los estudios dependen del tiempo de retorno energético, siendo este casi el único indicador medioambiental (no se tiene en cuenta el uso de los métodos de perfil medioambiental). Además, se observan otras dos brechas relativas a la falta de estudios de LCA destacando la integración en edificios de energía solar por un lado, y el uso de la tecnología fotovoltaica de concentración por otro. Por lo tanto, en esta tesis, se presenta una nueva aportación al campo de los estudios LCA de los sistemas fotovoltaicos integrados en edificios. Esto se logra a través de la evaluación medioambiental y energética de los sistemas de concentración fotovoltaica integrados en edificios (BICPV). Los resultados se presentan en términos de metodologías de evaluación del impacto del ciclo de vida (perfil medioambiental), así como el tiempo de amortización de la Energía y su Factor de Retorno (perfil de la Energía). Los resultados, con el apoyo de los análisis de sensibilidad y la comparación con un sistema convencional fotovoltaico para integración en edificios (BIPV), muestran beneficios ambientales significativos que pueden ser obtenidos a través de sistemas BICPV. Finalmente, se discuten las recomendaciones para trabajos y mejoras futuros.

Resum (Català)

L'Anàlisi de Cicle de Vida (LCA) és una eina integral per avaluar l'impacte ambiental d'un producte o una activitat al llarg de tot el seu cicle. L'objectiu general de la utilització de LCA és aconseguir sistemes i productes sostenibles a través de l'orientació del procés de presa de decisions. En la relació amb els recursos d'energia renovable, la tecnologia fotovoltaica es considerada com una de les fonts d'energia més netes, ja que es subministra sense cap contaminació. No obstant això, la tecnologia fotovoltaica s'acompanya dels impactes sobre el medi ambient associats als processos de fabricació. Per a això, la realització d'estudis de LCA per a sistemes fotovoltaics és una eina essencial per mesurar el seu nivell de sostenibilitat En aquest sentit, i després de la realització d' una anàlisi teòrica dels estudis publicats de LCA dels sistemes fotovoltaics, s'han trobat algunes llacunes. Aquestes llacunes es refereixen a la manca de varietat d'indicadors de LCA, on la majoria dels estudis depenen del temps de retorn energètic, sent aquest gairebé l'únic indicador (no es té en compte l'ús dels mètodes de perfil ambiental). A més, s'observen dues bretxes relatives a la manca d'estudis de LCA destacant la integració en edificis d'energia solar d'una banda, i l'ús de la tecnologia fotovoltaica de concentració per un altre. Per tant, en aquesta tesi, es presenta una nova aportació al camp dels estudis LCA dels sistemes fotovoltaics integrats en edificis. Això s'aconsegueix a través de l'avaluació ambiental i energètica dels sistemes de concentració fotovoltaica integrats en edificis (BICPV). Els resultats es presenten en termes de metodologies d'avaluació de l' impacte del cicle de vida (perfil mediambiental), així com el temps d'amortització de l'Energia i el Factor de Retorn (perfil energètic). Els resultats, amb el suport de les anàlisis de sensibilitat i la comparació amb un sistema convencional fotovoltaic per a integració en edificis (BIPV), mostren beneficis ambientals significatius que poden ser obtinguts a través de sistemes BICPV. A finalment, es discuteixen les recomanacions per a treballs i millores futures.

Nomenclature

LCA: Life Cycle Assessment

LCIA: Life Cycle Impact Assessment

LCI: Life Cycle Inventory

EI99: Eco-Indicator 99

UCTE: Union of Coordination of Transmission of Electricity

GHG: Green House Gas

GWP: Global Warming Potential

CED: Cumulative Energy Demand

EPT: Energy Payback time

ERF: Energy Return Factor

LT: Life Time

c-Si: Crystalline silicon

m-Si: Monocrystalline (Single crystalline) PV cells

p-Si: Multicrystalline (Poly crystalline) PV cells

a-Si: Amorphous silicon

mc-Si: microcrystalline silicon

µ-Si: nanocrystalline silicon

CdTe: Cadmium Telluride

CIGS: Copper Indium Gallium Selenide

CSP:Concentrating Solar Power

Pt: Points (Eco-points, endpoint indicators)

kWh: Kilo Watt Hour

PV: Photovoltaic

PV/T: Photovoltaic Thermal

CPV: Concentrating Photovoltaic

BICPV: Building Integrated Concentrating Photovoltaic

BICPV-F: Building Integrated Concentrating Photovoltaic-Façade

BICPV-H: Building Integrated Concentrating Photovoltaic- Shading

BIPV: Building Integrated Photovoltaic

Contents

Introduction

Resources of energy can be mainly classified into two sectors: non-renewable resources (which are depleting in time such as oil, coal, and gas), and renewable resources, which are dependent on natural resources, such as the sun, wind, tides and geothermal heat. In the first place, the human efforts were focused on the extraction of fossil fuels in order to supply the needed demand of energy. The excessive use of those traditional non-renewable fossil fuel resources have led to the generation of many environmental problems regarding various aspects. The conversion of fossil fuel into a suitable form of energy is a process that induces harmful emissions affecting different environmental areas. These effects are represented in, for example, acidification which affects the concentration of water compositions, respiratory effects and carcinogenesis that affects the human health, and the green house gases which contribute significantly to the climate change, etc. [1].

It is expected that the continuous extraction of fossil fuel resources may not be able to meet the increasing energy demands in the near future. Therefore, due to the increasing demand of energy, and because of those negative environmental impacts that results from relying heavily on fossil fuel resources, research trends and governmental policies and regulations are directed towards the use of renewable energy. This is changing the way how the energy will be utilized in the future. The trend nowadays is focused on the growth of cleaner and more sustainable energy practices, which makes the utilization of renewable energy resources a must in order to help resisting the environmental problems associated with fossil fuel resources.

Nowadays, renewable energies are playing an important role that is growing significantly in the worldwide energy markets affecting the social, industrial and economic development. Figure 1 shows the renewable energy share of global final energy consumption by the year 2009.

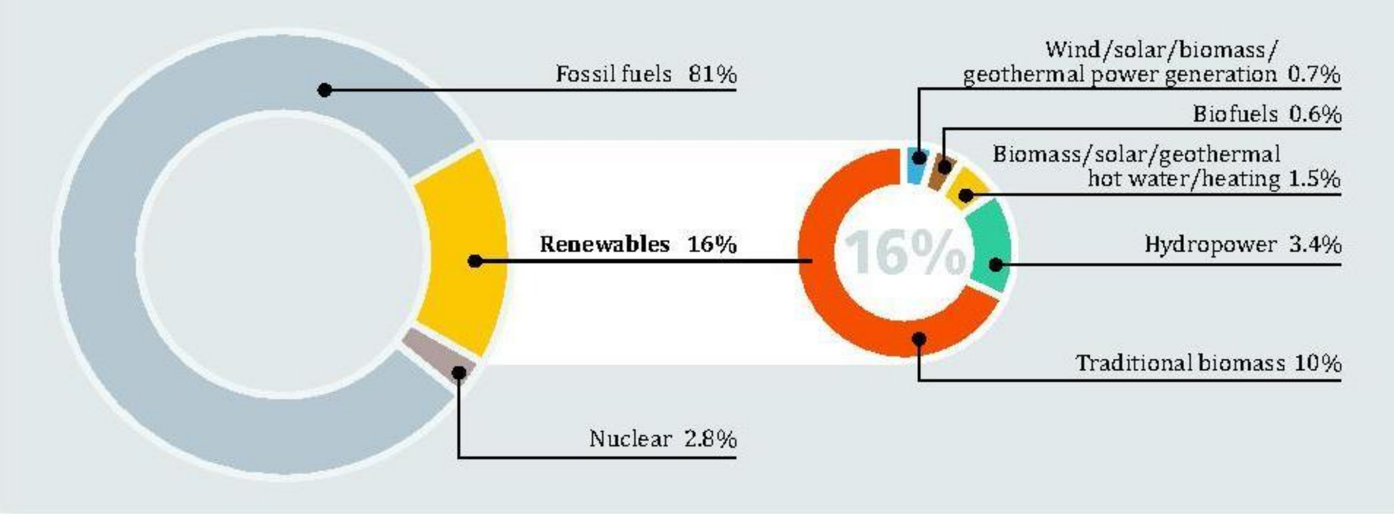

Figure 1. Renewable Energy Share of Global final energy consumption, 2009 [2]

A broad development of different methods and technologies are achieved everyday in order to improve and adapt the integration of these renewable technologies efficiently within the world energy network. The most significant types of those renewable resources are the PV systems, which have seen a significant growth during the last years.

However, renewable energy technologies may not be absolutely appropriate to all applications or locations, and may be associated with some environmental concerns. ([4], [5]). The PV technology, although regarded as sustainable energy resource, is accompanied by high rate of emissions and impact on the environment that results from its manufacturing. That is, the PV industry uses toxic and flammable substances which can involve occupational and environmental hazards. This is in addition to significant amounts of embodied energy invested within the PV fabrication processes.

In order to alleviate the environmental impacts and reduce the embodied energy of the PV technologies, novel systems have appeared aiming at increasing the efficiency of the PV systems, which in return improves the environmental and energy performances throughout the entire PV systems life cycle. An example of such novel systems are the concentrating technologies. Referring to its development, modelling and implementing, several research works are being conducted at the University of Lleida for these purposes ([6]-[10]). The concentrating technology aims at getting the maximum benefit of a PV system, through concentrating the solar radiation on smaller PV cell areas, using optical elements (lenses and reflectors). The use of this technology is expected to reduce the PV systems environmental impacts and embodied energy, as a large portion of the semiconductor material is replaced by lenses and reflectors that are mostly made of light weight materials. In addition, concentrating the solar energy on PV cells enhance the overall systems operational efficiency, which in return means more output energy, and better life cycle performance. However, it is necessary that the use of such technology to be assessed using a LCA approach, using environmental and energy evaluations, in order to compare and realize the significance of the shifting of burdens that may occur from one phase to another [11].

Thesis Objectives

The objectives of this thesis are summarized as follows:

- Conducting a critical analysis regarding the LCA studies of PV systems in literature. This mainly includes revealing the gaps and shortcoming of these studies, in terms of the types of systems considered, the general interest of this kind of studies during the last fifteen years, and the significance and sufficiency of the environmental and energy methods used.

- Presenting and evaluating two novel sustainable BICPV systems through Life Cycle Assessment. The analysis includes evaluating the environmental and energy profiles.

- Comparing the results of the two novel BICPV systems to those of a conventional BIPV system of the same power and aperture area and studied under the same conditions.

- Conducting sensitivity analyses of the corresponding BICPV systems in order to reveal the probable aspects to be improved within the systems assembly, integrating the Life Cycle Assessment within the design stages of further modified BICPV systems.

- Measuring the sustainability of the corresponding BICPV systems through using different LCA methods, highlighting the differences between the analyses results in that regard.

Thesis contents

The contents of this thesis are enclosed within five chapters as described below:

Chapter 1: This chapter presents an introduction to LCA. It serves as a guide for understanding the differences between LCA methods, and assist in choosing the suitable LCA tools for a corresponding application. This chapter is considered to be an update of a previous work achieved by the same author represented by a Master Thesis, cited in the bibliography as reference number [11].

Chapter 2: This chapter presents a general review about solar technologies. It focuses on defining and describing the available solar technologies through highlighting the materials used and the most widely used processes used within their fabrication. In addition, the latest efforts achieved for improving the efficiency of these technologies are presented. This knowledge serves as a technical background about solar systems and their potential life cycle stages, which is essential as a starting point for LCA study of a PV system.

Chapter 3: This chapter presents a critical analysis of the LCA studies of PV systems. This is a comprehensive study aiming at showing the latest studies of solar technologies and systems, mostly related to their application in energy generation, whether in power stations or buildings. The gaps found in the literature within the context of this analysis have been the principal motive for presenting and analyzing novel BICPV systems through LCA.

Chapter 4: This chapter presents two novel BICPV systems through LCA by using environmental and energy evaluations. The first system is nominated as BICPV-F referring to the installation of the reflectors as a vertical facade, while the second system is nominated as BICPV-S referring to the installation of the reflectors as a shading system. The results of the two systems are compared to those of a conventional BIPV system studied under the same conditions. Moreover, sensitivity analyses are presented, and a comparison between the uses of different LCIA methodologies is established.

Chapter 5: This chapter presents the conclusions of the study. Recommendations for future work are discussed as well.

Chapter 1

Life Cycle Assessment

1.1 Definition

Life Cycle Assessment (LCA) is defined as an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and material uses and releases to the environment, and to evaluate and implement opportunities to affect environmental improvements [12]. The assessment includes the entire life cycle of the product, process or activities, encompassing extracting and processing materials; manufacturing, transporting and distribution; use, reuse, maintenance; recycling and final disposal. Another definition for LCA exists in the ISO14040 standard, describing LCA as a technique for assessing the environmental aspects and potential impacts associated with a product by: compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study [13].

The term “life cycle” refers to the major activities in the course of the product life time, starting with the raw material extraction and manufacturing, including the use, maintenance, and ending with the final disposal. LCA evaluates all the stages of a product life cycle regarding their impact on the environment, where these stages are dependent on each other, which means that one operation leads to the next. In other words, besides helping in avoiding the shifting of burdens from one stage to another, LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle. That environmental impact is mainly related to two LCA aspects: The environmental profile, and the energy profile. Thus, LCA is a comprehensive tool that can help different applications to cope with the current energy and environmental performance needs.

1.2 The Purpose of using LCA

LCA can be used for several purposes, and each one may require a different level of details regarding the data collected. The data can be very detailed or simplified according to the system boundaries, the purpose, and the application that the LCA tool is used for [14].

1.2.1 Product development

In case of product development using LCA, it is considered as a design for environment process. In the design stage of a product, there are many options for the choice of materials and resources. Using LCA in a product development is critical because any decision concerning the materials and resources will affect the following life cycle stages of the product [15]. In this case, the use of LCA may need extensive data collection and can be time consuming. However, simplifying LCA in this case can be useful [16], such that, the analysis and the focus can be on the materials and resources that probably affect the environment significantly, and then seek alternative preliminary design solutions before proceeding in the development process. The focus on specific materials or resources can be dependent on the corresponding manufacturing process, or the quantity used, or other consideration regarding the boundaries and limitations of the corresponding study.

1.2.2 Product Improvement

Examining the possible improvement opportunities of an already made product can be easier regarding the data collection. When LCA is used as a product improvement tool, it is important only to focus on the materials and the resources that affect the product significantly. By this way, several products can be compared from an environmental point of view, where the impact of each product is evaluated and compared to another one of the same category. Alternative solutions for the materials or the resources that cause higher impact in each life cycle phase are then incorporated and gathered, and the whole solution is reassessed [17].

1.2.3 Marketing

In case of conducting an LCA for the purpose of environmental marketing, the most relevant type of this kind of marketing is called environmental labelling (Eco labelling) [18]. Environmental labelling is considered as a proof that a certain product is environmentally friendly. When a product coincides with the Eco labelling criteria, it is given an Eco label and can therefore be attractive for marketing purposes, such that, environmentally friendly products can be visible to the consumer. According to the EU Eco label regulation, LCA is required for the development of Eco label criteria. ([18]-[20]). Another type of marketing purposes similar to the Eco label scheme is the environmental product declaration (EPD). The general idea of EPD is to give a product a graphical presentation of a preset number of environmental impacts, for example, by using a bar diagram. This graphical presentation can therefore be interpreted easily by professional buyers and environmentally conscious consumers, but still may not be clear to general consumers ([18], [22]).

1.3 General LCA Framework

According to the ISO 14040 recommendations [13], a frame work is given in order to conduct an LCA process. These recommendations can be summarized in the following four main steps:

- Definition of goal and scope

- Inventory analysis
- Impact assessment
- Interpretation of results.

These steps are demonstrated as shown in Figure 2. The double arrows between the phases indicate the interactive and iterative nature of LCA.

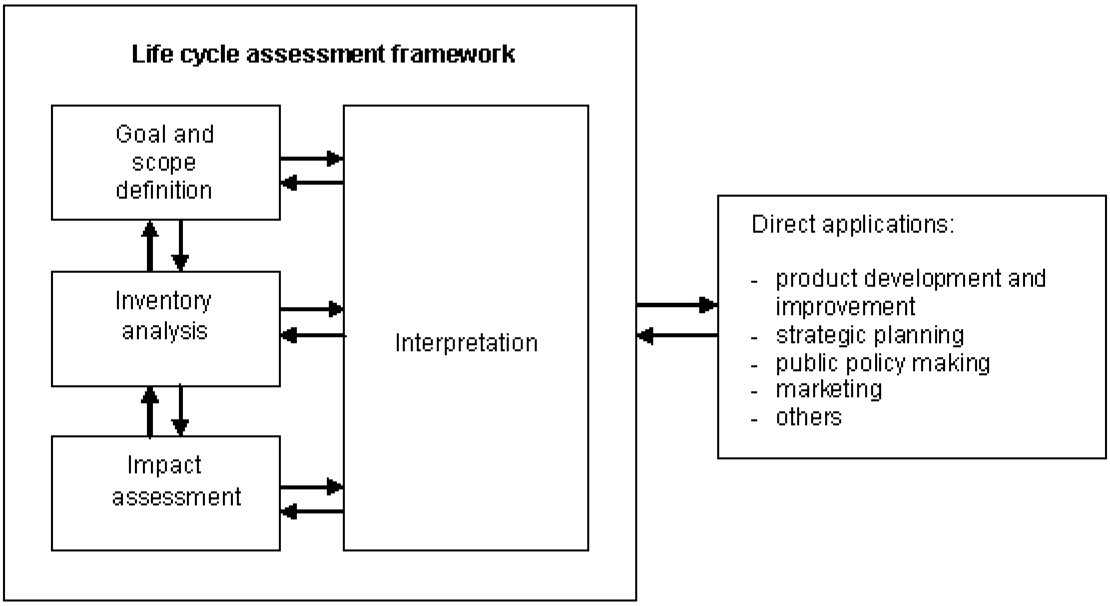

Figure 2. LCA frame work according to ISO 14040 standard [13]

For example, while performing the impact assessment, it may arise that certain information is ambiguous or missing, which means that the inventory analysis must be improved. Another example is that during the interpretation phase, the interpreted results may be unclear or insufficient to fulfill the application requirements, and this means that the goal and scope definition may need to be revised and modified [18]. These four phases (steps) that are required in order to conduct an LCA effectively are detailed in the ISO standard series ([13], [23]-[25]).

1.3.1 Goal and scope definition

Goal and scope definition is the first step in an LCA where the product to be assessed is defined, as well as the context of the assessment to be made. This step is essential in an

LCA process; it has a great influence on the impact assessment step as many parameters are identified, such as the time and resources needed, the purpose of the study, the intended application, the system boundaries, the assessment methodology, and the general assumptions and limitations. Therefore, definition of the goal and scope will guide the entire LCA process to ensure that the most relevant results are achieved [23]. However, due to the iterative nature of LCA, changes may occur during the study in defining the goal and scope.

1.3.2 Inventory analysis

The result of the inventory analysis step is a list containing the quantities of the materials and energy consumed throughout the different stages of the life cycle of a product (Life Cycle Inventory – LCI). Therefore, in the inventory analysis step, the related materials and energy flows of a product are explained in order to represent the product and its total inputs and outputs from and to the natural environment, respectively ([23], [26], [27]). The LCI analysis is dependent on the types and quantities of natural resources (water, energy, etc.), the materials used in the production of the product, the transportation methods, the way in which the product is used during its life time, and how the product is finally disposed of.

1.3.3 Impact assessment

This is the step where the LCI list that contains the corresponding materials and consumed energy quantities related to the studied product is interpreted and transformed into understandable impact indicators. These indicators express the severity of the contribution of the impact categories to the environmental load. These indicators are concluded through a series of steps recommended by the ISO standards 14042 [24], where some of these steps are obligatory and others are optional. The obligatory steps are: Definition and classification of impact categories, and characterization. The optional steps are normalization and weighting. The details of these steps are as follows:

1.3.3.1 Definition and classification of impact/damage categories

The impact/damage categories are defined and selected in order to describe the impacts caused by the emissions and the consumption of natural resources that are induced during the production, use, and disposal of the considered product.

1.3.3.2 Characterization

After the impact categories are selected and defined, the relative contribution of each input and output within the product system to the environmental load is assigned to these impact categories are converted into indicators that represent the corresponding potential impacts on the environment. This is done by multiplying the results of the inventory obtained in the classification phase by the characterization factors of each substance within each impact category. The characterization factors linearly express the contribution of a unit mass (1 kg) of an emission to the environment. As an example, the relative contributions of different gases to climate change are commonly aggregated and compared in terms of carbon dioxide equivalents using Global Warming Potentials (GWP) (A GWP_{500} of 100 implies that 1 kg of the substance has the same cumulative climate change effect as 100 kg of carbon dioxide during, in this case, a 500 year time period) [28]. The characterization factors are calculated using quantitative models based on scientific analysis of the relevant environmental processes.

1.3.3.3 Normalization

Normalization adds the benefits of placing the characterized impact indicator results in a broader context. It is expressed in a way that allows the impact indicators to be compared to each other, such that, the sum of each category indicator result is divided by a reference value. The normalization factors are usually chosen to represent the real or potential magnitude of the corresponding impact category for a geographic area and over a certain time span. An example for a reference value is the annual national USA contribution to climate change in terms of GWPs. Other attributes that could be taken into account when choosing the reference value are the total emissions or resource use for a given area on a per capita basis, the ratio of one alternative to another (i.e. The baseline) and the highest value among all options ([26], [28]).

1.3.3.4 Weighting

Weighting is the process of converting the results of the normalised indicators of the different impact categories into other values using numerical factors (weighting factors) based on subjective valuations, that is, these weighting factors are dependent on the incorporation of social, political and ethical factors. The weighting process consists of multiplying the weighting factors by the result of the normalization for each impact category. Weighting is often applied in the form of linear weighting factors.The weighting factors of each impact category represent its relative importance to the environment. These factors are subjective and can vary according to the geographic area based on socioeconomic criteria. For example, the impact category "water consumption" can have significant importance in countries suffering from drought, where its relative importance in countries with plentiful water supplies is lower. A difference between the normalization and weighting steps can be noticed, that is, normalisation provides a basis for comparing different types of environmental impact categories (all impacts get the same unit), while weighting assigns weights or relative values to the different impact categories based on their perceived importance or relevance [29]. Thus, although the weighting step is optional according to the ISO standards, its importance can be summarized in ([18], [24]):

- Expressing the relative preference of an organization or group of stakeholders based on policies, goals or aims, and personal or group opinions or beliefs.
- To ensure that the process is visible, documentable, and reportable, and to verify that the relative importance of the results is based on the state of knowledge about these issues.

Weighting can be regarded as both qualitative and quantitative step that is not necessarily based on natural science but often on political or ethical values ([18], [30]). Weighting methods have been developed by different institutions based on different principles; such as the proxy approach, monterisation, distance to target, and pannel approach ([18], [28]-[31]).

1.3.3.5 Interpretation of results

In this step, the impact assessment results are interpreted, and conclusions are established in order to guide the decision making process. The critical environmental issues are defined, and the significance of the relative contribution of a certain product components or processes to the environmental load is recognized. Depending on the need of the study, verification of results can be done through checking the data with respect to three perspectives ([25], [18], [27]) as follows:

- Completeness check: Ensure the completeness of the study, such that, check that the significant environmental issues previously identified represent the information from the different LCA phases adequately (inventory analysis and impact assessment) in accordance with the goal and scope defined.
- Sensitivity check: Check if the final results and the conclusions are affected by uncertainties in the data or the selected evaluation methods. The aim of the sensitivity check is to establish a required degree of confidence in the results of the study relative to its overall goal. This check is mostly used in order to test

the assumptions made during the study. The sensitivity check can be done by making a kind of “what if” scenario, where the value of different input parameters is changed systematically.

- Consistency check: Evaluating the consistency of the methods, procedures and treatment of data used throughout the study, and check their coherency with the objective and scope of the study. The items that can be subject to the consistency check are: data source, data accuracy, geographical representation, and system boundaries and assumptions.

1.4 LCA methods

The LCA methods can be mainly divided into two categories: The enviromental profile evaluation methods; and the energy profile evaluation methods.

1.4.1 Environmental profile evaluation methods (LCIA methodologies)

Many differences exist between LCIA methodologies [11], such as:

- The modeling approach (midpoint, endpoint, or combined midpoint-endpoint).
- The number of impact categories covered by each methodology (midpoints and endpoint categories).
- The characterization, normalization, and weighting factors.
- The substances covered by each methodology.
- The regional validity of the methodology, that is, a question may arise to specify if the methodology is developed based on the environmental background (Environmental profile) of a certain continent or a country.
- The temporal validity of the methodology, that is, this questions if the data used in the modeling are very old and does not suit the current environmental profile changes.

The methodologies that are used within the environmental analysis of this thesis are presented in details in Chapter 4. The most up to date existing LCIA methodologies are listed as follows:

- CML ([33], [34]).
- EDIP (Environmental Design of Industrial Products) ([35]-[38]).
- TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) ([39]-[44]).
- EI99 (Eco Indicator 99) ([45]-[52]).
- EPS (Environmental Priority Strategies in product design) ([54]-[59]).
- Eco scarcity ([60]-[63]).
- JEPIX (Japan Environmental Policy Priorities Index ([64]-[69]).
- Recipe ([70]-[74]).
- LIME ([75]-[81]).
- IMPACT 2002+ ([82]-[87]).
- LUCAS (LCIA method Used for a CAnadian-Specific context) ([88]-[91]).
- MEEup (Method for the Evaluation of Energy using Products) ([92]-[94]).
- BEES (Building for Environmental and Economic Sustainability) ([95]-[99]).
- Ecological Footprint ([100]- [103]).
- USEtox ([104], [105]).
- EDP (The Eco system Damage Potential) ([106], [107]).
- IPCC (Intergovernmental Panel on Climate Change) ([108]-[110]).

1.4.2 Energy profile evaluation methods

- CED (Cumulative Energy Demand) ([111]-[115]).
- Emergy Analysis ([116]-[119]).

2 Chapter 2

Solar technologies and systems: Materials used, manufacturing methods, and related processes

2.1 *Solar energy*

This utilization of solar energy can principally be divided into two types: passive solar design and active solar design. The passive solar design can be achieved through trapping the heat during winter months and prevent overheating through summer months. Such designs include using solar collectors for heat storage and natural illumination.

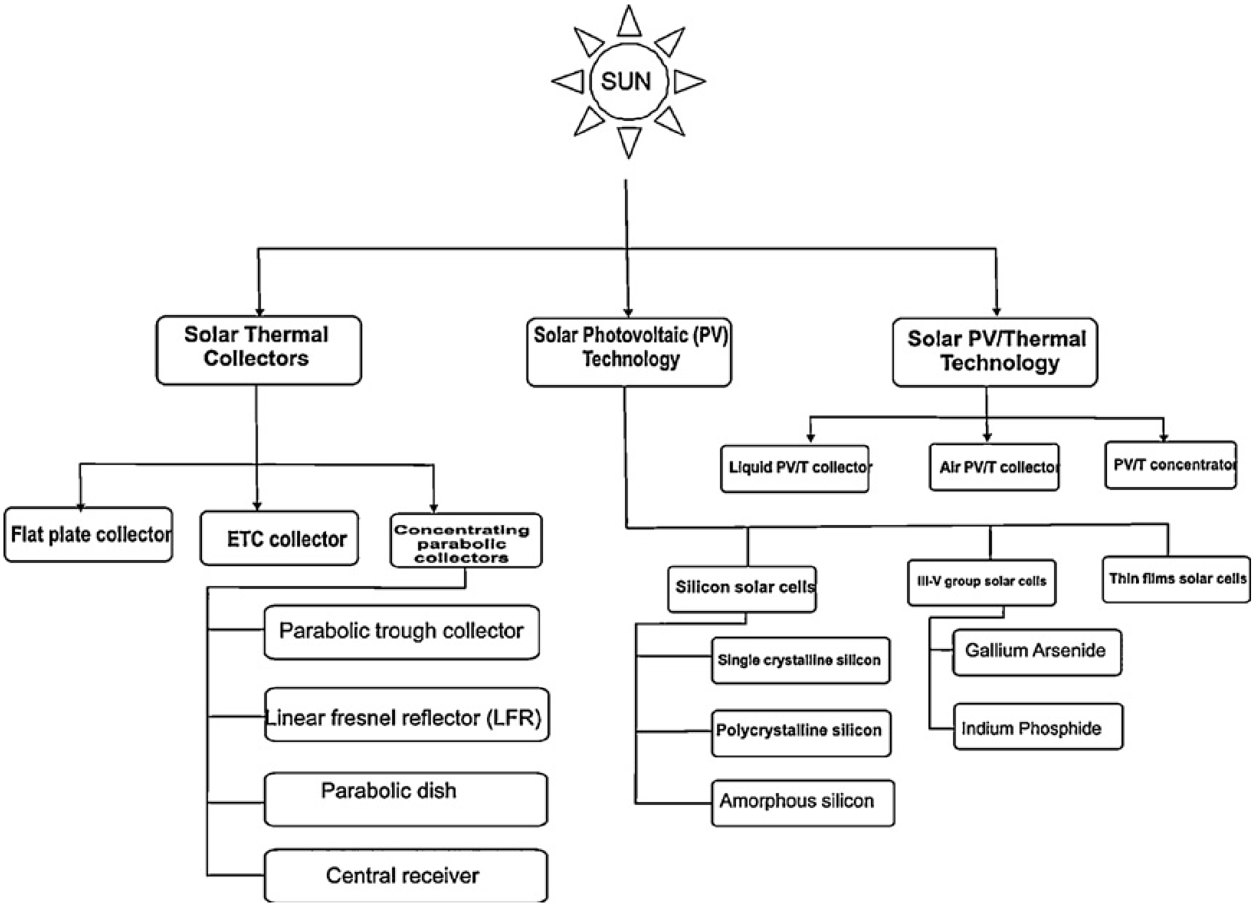

Figure 3. Classification of various solar design usages [121]

The active solar design can be represented in various methods, such as the distribution and extraction of the stored heat, and the conversion of solar energy into electricity through the photovoltaic technologies (Figure 3). The later type includes various novel technologies and schemes, PV systems, CPV systems, hybrid solar thermal photovoltaic systems (PV/T), novel materials used for PV cells, etc. as will be detailed in the following sections.

2.2 Solar technologies and systems

2.2.1 Silicon PV cells for low and medium solar concentration

As the standard form of PV cells is made of silicon, including those that are used in the low and medium solar concentration systems, a review about the silicon PV cells and the related technological processes is demonstrated in that regard.

The production of silicon PV cells starts with silicon crystals. It is present not in a pure form, but in chemical compounds with oxygen in the form of silicon dioxide as in quartz or sand. To extract silicon, the undesired oxygen has to be first separated out of the silicon dioxide. This is achieved by heating the silicon dioxide together with carbon powder, coke and charcoal in an electric arc furnace to a temperature of 1800°C to 1900°C. This produces carbon monoxide and what is known as metallurgical silicon, which is about 98 % pure, as there are common impurities found in silicon such as iron Aluminium, magnesium, and calcium. The purest grade of silicon used in semiconductor applications contains about one part per billion (ppb) of contamination. Purification of silicon involves different types of complex refining technologies such as chemical vapour deposition, isotopic enrichment, etc. One of the most widely used methods is the Siemens process. The Siemens process is described as follows: The two gases (Silicon and hydrogen) are blown into a reactor where thin rods of high purity silicon are located, heated to between 1000°C and 1200°C. Silicon from the trichlorsilane is deposited onto these rods. The silicon formed in this process is known as polycrystalline silicon. The rods grow in diameter to between 10cm and 15cm. These are broken up into pieces and used as a resource material for monocrystalline or multicrystalline PV cells processing. Those two processes require a considerable input of energy and are the major contributors to the energy content of silicon PV cells.

Nevertheless, in the Siemens process, the quality of the finished product is high, although at the expense of high energy consumption. There is another similar purification method called Vapour to Liquid Deposition method, where trichlorosilane together with hydrogen are injected into graphite tubing heated at 1500 °C, producing a silicon melt deposit. The deposition rate is faster than that of the traditional Siemens method, enabling higher efficiency silicon raw material. However, in this method it is more difficult to eliminate the impurities ([123], [125]).

Other purification processes are under investigation in order to further reduce the amount of input energy. For example, the free space reactor, or also known as the tube reactor, is similar to the Siemens reactor and provides an alternative to it. In this reactor, a hollow silicon cylinder has to be heated to 800 °C, where hot inert gas is injected through the porous wall and reactant gas (Hydrogen and Silane) is injected in the centre. However, it has a disadvantage, which is the diffuclty to regulate the melting process for generating of ingots and wafers. In addition, the silicon powder has to be modified to allow easy handling, transport, charging and melting. This step needs to be carried out carefully without further contamination of the silicon, neither metals nor carbon or oxygen ([127], [128]).

The fluidized bed reactor is another purification method; where tiny particles of silicon are introduced into the reactor. Trichlorsilane or Silane is blown into the reactor together with hydrogen. At 1000°C for trichlorsilane or 700°C for Silane, the silicon from these materials is deposited onto the particles, which become larger and larger until they become so heavy so that they fall to the bottom of the reactor and can be removed as silicon granulate. Fluidized bed reactors have excellent heat and mass transfer characteristics and can be utilized for Silane decomposition to overcome the energy waste problem in the Siemens process. The energy consumption is lower because the decomposition operates at a lower temperature and thus cooling devices are not required. In addition, fluidized beds have high throughput rate and operate continuously. The final product consists of small granules of high purity silicon that are easy to handle compared to powder produced by free space reactor. Several improvements that have been achieved to the fluidized bed reactor through different design schemes are discussed in literature ([127]-[131]).

Different simultaneous processes may be necessary for refining different impurities. However, the purity percentage of the yield of each individual process may be not suitable for the high purity level required for the PV cells fabrication. Some of these processes are: Evacuation (heating the metallurgical silicon under vacuum to remove some volatile elements), formation of volatile species (Impurities react to form volatile molecular species and further refining can be achieved), oxidation of impurities (Impurities in the metallurgical silicon can be oxidized to form other species and separated from the metallurgical silicon in a slag). Leaching with calcium based slags (leaching with acids) may remove some impurities as well. Slagging is another purification process, where impurities can be reacted to form a non-volatile species, so, it may be possible to incorporate the species or a combination of species to form a second phase, thereby isolating the impurities away from metallurgical silicon into this “slag” phase. This slag phase can either float on the surface of molten silicon or sink to the bottom of the crucible and be easily removed. Gas blowing is another method, where during refining of molten metallurgical silicon, gases can be purged through the melt. These gases can be of reactive nature to react with the impurity elements, or neutral to promote stirring of the melt [132]. A more advanced purification method, which is the isotopic enrichment of the silicon isotopes, has been studied. It is expected that the availability of these isotopes of Si in such a pure form will permit important progress in a variety of basic and applied research areas, and they could be useful in the reprocessing industry of PV cells [133]. Another advanced way has been recently proposed is the purification of silicon using electromagnetic separation, where the principal is based on pushing the impurities particles (less conductive) away from the molten silicon (well conductive) towards the boundary layer by means of Lorenz force under the effect of Electromagnetic field [134].

Different types of silicon solar cells can be produced, such as monocrystalline (m-Si), polycrystalline (p-Si) and ribbon. After the purification processes, the polysilicon has the desired level of chemical purity, where the impurity level should be at the one parts per billion (ppb) level or less. However, its structural quality is still deficient and not suitable for the required PV cell processing. The structural quality is improved using different methods depending on the required outcome ingot (Monocrystalline, polycrystalline or ribbon).

After this, the ingot is cut in wafers. Depending on the technique used on cutting the wafers, it may be necessary to remove the saw damaged layers on the wafers surfaces using etching. The damage removal etch is typically based on 20-30 wt. % aqueous solution of NaOH or KOH heated to 80-90 °C. After this process, the surface of the wafer is left shiny, and consequently, it can reflect more than 35% of the incident light. Therefore, antireflection coatings (usually titanium oxide) are applied in order to increase the amount of light coupled into the PV cell. Another method used to reduce the reflection is the light trapping. This is done by texturing the front wafer surface.

This texture consists of tiny pyramids that further reduce reflection losses, such that, the incident light striking the surface is reflected and refracted repeatedly by the pyramid surfaces. This allows light to penetrate the PV cell and be absorbed efficiently. Depending upon the process and manufacturer, different surface structures or textures are etched into the PV cell (e.g. inverted pyramids).

Following this, wafers are typically cleaned after texturing. Traditionally RCA cleaning that is originally developed for use in microelectronics is the most widespread cleaning method in PV cell processing. Cleaning is considered to be important for PV cell performance. The conventional RCA cleaning normally is done using mixtures of $NH_4OH/H_2O_2/H_2O$ and $HC1/ H_2O_2/H_2O$. Another trend is to replace the RCA with the IMEC cleaning. This cleaning procedure, consisting of a H_2SO_4/H_2O_2 step followed by a 1% diluted HF step, reveals a perfect removal of metallic particles.

After the cleaning step, the p-n junctions are formed by thermal diffusion. In the diffusion process, an electrically heated tube furnace with a quartz tube is used. Diffusion temperatures vary between 800◦C and 1200◦C. All high temperature steps require very clean conditions in order to avoid contaminants. Diffusion sources are phosphorus for the emitter junction (front surface) and boron for the back surface. The doping elements are introduced as liquid or gaseous compounds, e.g., phosphine (PH) or phosphorus oxychloride ($POCl_3$) for N doping, and boron bromide (BBr_3) for P doping.

In order to integrate the PV cell into electricity circuits, metallic grids (contacts) are printed using screen printing on the boron and phosphorus doped zones and the PV cell is thus finished. The grids make it easier to collect the electricity without resistance losses and are commonly applied with screen printing methods. Each individual line in the metallic grid has a width of around 0.01 to 0.02 mm. Two collector contact lines (bus bars) of around 1.5mm to 2.5mm thick run across the thin contact fingers. These bus bars are later connected to the back contacts of the next cell in the string via a thin soldered copper strip. The contact fingers and bus bars are sintered by firing at 800°C to 900°C and forced through the anti-reflective coating beneath them. Silver paste is used for the front surface, and aluminium paste is used for the back contacts.

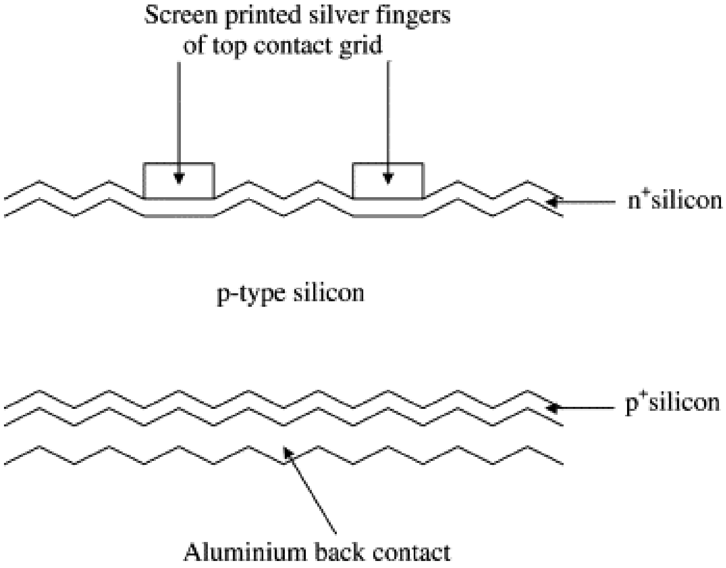

Figure 4. A schematic cross-sectional view of a silicon PV cell with screen-printed grid contacts [135]

Using screen printing process is associated with some issues that affect the cell efficiency, such as high shading losses, the high resistivity of the screen printed silver grids compared to pure silver, a high contact resistance between the grid and silicon and poor aspect ratio. Thus, another method is developed (Buried contacts) where silicon dioxide is formed on the silicon surface using thermal oxidation to passivate the silicon surface. Then, laser scribing is used to define the contact area. In this case, the contacts are buried within the device to minimise shading losses and contact resistance. The contact metals (nickel, copper and then silver) are deposited using electroless methods (Figure 4 and Figure 5) [135].

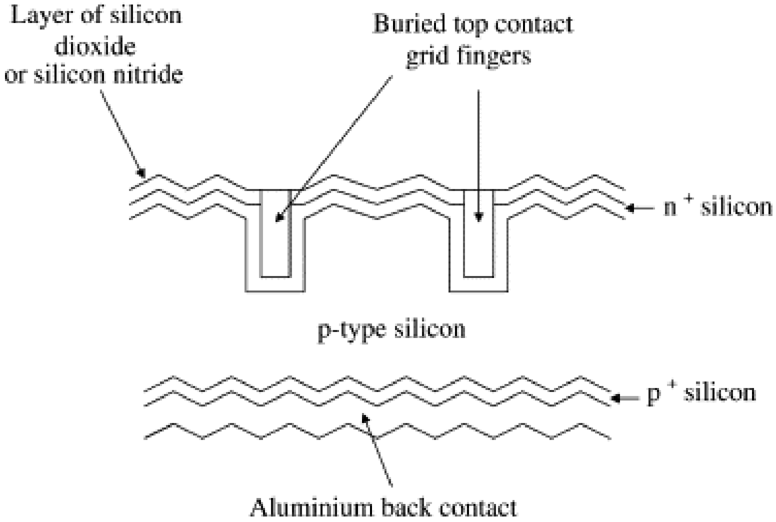

Figure 5. A schematic cross-sectional view of a buried-contact silicon PV cell [135]

Another development to solve the screen printing efficiency issues is the Passivated Emitter Rear Locally diffused (PERL) cell. In this process, a layer of silicon dioxide is formed at the back surface of the silicon and then contact made by diffusing the aluminium into the silicon via small windows opened in the oxide layer to produce localised p^+ regions. The oxide layer not only passivates the back surface, but reflects light back into the device as well. In combination with the texturing of the surfaces, this process enhances light trapping within the device, increasing the cell efficiency and permitting thinner slices of silicon to be used.

The cells are then interconnected and soldered within a PV module with tinned copper ribbons, and then laminated and framed through being encapsulated in a sandwich that is formed of a sheet of tempered glass, an embedding polymer that surrounds the PV cells, and a back sealing plastic layer.

Further details about the various manufacturing aspects and considerations of PV cells can be found in literature ([124], [136]). The previous processes are generally applied within the production of the required silicon PV type (Mono crystalline, polycrystalline and ribbon). They are considered to be as generic steps that can be adapted in the manufacturing of silicon PV cells in general, which mostly yields the metallurgical silicon. Then, differences in the PV cells manufacturing are found depending on their type, as will be shown in the following subsections ([137]-[145]).

2.2.1.1 Monocrystalline silicon PV cells

In order to produce the monocrystalline silicon, the Czochralski process is used. In this process, the polysilicon is melted at around 1420 °C and is allowed to solidify very slowly around a rotating crystalline seed. This crystalline seed is dipped into the melt silicon and slowly drawn upwards. In this way, a cylindrical single crystalline ingot is obtained of up to 25 cm diameter and of 100 cm or more in length. These cylindrical mono-crystals are cut to form semi-round or square bars, which are further cut into wafers. However, the results of the Czochralski process contain residual impurities such as oxygen. Therefore, in order to refine the product to be suitable for further processing, magnetic confinement is used to reduce the amount of oxygen.

Another method with less oxygen contamination is used as well, which is the float zone method. In this method, a rod of solid highly purified polycrystalline silicon is melted by induction heating and a single crystal is pulled from this molten zone. This method is of high purity, as it has a very low oxygen contamination which cannot be avoided with the Czochralski method because of the quartz crucible, but it is more expensive than Czochralski method which limits its use to be mostly for R&D activities rather than manufacturing ([146], [147]).

2.2.1.2 Multicrystalline silicon PV cells

Multicrystalline PV cells are made from cast block square (ingots) of silicon that are produced through controlled heating and cooling. The cast block cools evenly in one direction. The purpose of this directed solidification is to allow columnar crystal growth and form large numbers of the largest possible homogeneous silicon crystals, with grain sizes from a few millimetres to several centimetres; and consequently, adjacent wafers can be fabricated out of the ingots showing nearly identical defect structures (grain boundaries and dislocations). After this, these ingots are cut into wafers approximately 0.3mm thick using a wire saw, as in case of monocrystalline silicon.

Two different fabrication technologies for multicrystalline silicon are used: the Bridgman process and the block-casting process [122]. The main difference between both methods is that in case of the Bridgeman process, only one crucible is used in melting and crystallisation, whereas two crucibles are used for the melting and crystallisation in the block casting method. However, there is an advantage of the block cast method over the Bridgeman one, that is, in the Bridgman technique, shorter crystallisation and cooling times can be realised by employing a more variable heater system.

In both processes, the crucibles used for silicon crystallization growth are made of quartz and coated with a Si_3N_4. The Si_3N_4 coating acts as an anti-sticking layer in order to prevent the adhesion of the silicon ingot to the quartz crucible walls during the volume expansion that occurs during the crystallisation of the silicon material; as this expansion may lead to the destruction of both the silicon ingot and the crucible. The advantage of the multicrystalline silicon over the monocrystalline one is that the ingots can be easily processed into square PV cells in contrast with the monocrystalline ones that usually have round shapes. However, the crucibles used during the multicrystalline silicon introduce impurities which further contribute to lower cell efficiency. But on the other hand, it is much easier to assemble multicrystalline wafers into modules with nearly complete utilization of the module area. Thus, the lower efficiency of cast material tends to be reduced at the module level ([122], [148]).

2.2.1.3 Ribbon- pulled silicon PV cells

The most common industrial approaches of converting the polysilicon into PV cells in industry rely on the growth of monocrystalline silicon in the Czochralski process or the casting of multicrystalline silicon in the Bridgman process that is subsequently followed by cutting into wafers through a sawing process using wire saws. These processes have high capital and operating costs, that’s why they are carried out in small scale batch equipment. In addition, material losses exceed 50% due to the sawing process. Thus, one of the major challenges for the silicon solar cell efficient production is to solve the consequences of the wafering problem through achieving wafering systems that does not need significant energy requirements and that result in a few amounts of waste. Besides, the final product has to meet the same efficiency requirements of the PV cells produced by the Czochralski or Bridgman process.

Different methods have been proposed to reduce the effect of the wafering problem, one of which is the ribbon pulled silicon technology that uses different techniques. Among these techniques that are mostly utilized in the industry are : the Edge-Defined Film-Fed Growth (EFG), Dendritic web growth, string ribbon processes (STR), the ribbon growth on substrate (RGS), and silicon film ([149]-[151]).

In the Edge-Defined Film-Fed Growth (EFG) technique, an octagonal shaped graphite die is dipped into the silicon melt and pulled out (capillary action). This creates octagonal tubes up to that are then wafers are cut from the eight sides to produce the required wafers for the cell production.

In the dendritic web growth process, two dendrites are dipped into supercooled silicon melt and then withdrawn quickly. The withdrawal process results in a thin sheet of silicon trapped between the two dendrites, and it quickly solidifies. The dendritic web growth method has evolved into the ‘‘string ribbon method’’ where two graphite strings are used rather than the dendrites, as this makes process control much easier.

Unlike the vertical growth methods mentioned, other methods have emerged that are characterized by horizontal growth technique and a higher wafer production speed. Among these methods is the Ribbon Growth on Substrate (RGS) method. Generally, the ribbon pulled methods are gaining wide acceptance as they are more energy efficient due to the elimination of the energy consuming complete wafering process; besides, the future development of the RGS method is especially important, as it can produced silicon ribbons at high speeds. In this growth technique, the silicon melt and die are located close to the top surface of a substrate. The substrate may be graphite or ceramic. The substrate extracts the crystallisation heat from the liquid silicon in the casting frame causing the crystal growth of a silicon ribbon in contact with the substrate. The silicon crystallizes in a direction perpendicular to the direction of the moving substrates. In this way the crystallization speed is decoupled from the pulling speed. Then, after the crystal growth is stopped, the silicon ribbon can be removed.

Another method, which is quite similar to the RGS and widely investigated nowadays, is the silicon thin film PV technique. A difference between the two techniques can be noticed, that is, in case of RGS method, the silicon ribbon is detached from the substrate after the crystallization is completed, while in case of the silicon thin film method, the substrate becomes an active part of the silicon ribbon. Further details about the thin film technology using silicon and other materials will be discussed in the following section.

However, resultant ribbon cells generally have lower efficiencies (higher percentage of defect density, high reflective surfaces, impurity content, etc) than those made from the cast silicon (multicrystalline). Therefore, the cast silicon method is preferred by many manufacturers. However, some quality enhancements during the ribbon cell processing are adapted in order to be able to compete with the multicrystalline cells. Some of these enhancements are represented in texturing and passivation techniques such as rapid thermal processing, electrical discharge machining, metal assisted texturing, photolithography, plasma-enhanced chemical vapour deposition (PECVD), and microwave-induced remote hydrogen plasma (MIRHP) passivation ([152]-[154]).

2.2.1.4 Thin film PV cells

Using PV thin film technologies help reducing the embodied energy of a PV system. Besides, the thin film technology is characterized by its flexibility and light weight which make it easily integrated into buildings; there are even some types that are semi transparent, which make it possible to make PV windows. In the thin film approach (Figure 6), thin layers of semiconductor material are deposited onto a supporting substrate, or superstrate, such as a large sheet of glass. Typically, less than a micron thickness of semiconductor material is required, 100-1000 times less than the thickness of silicon wafer.

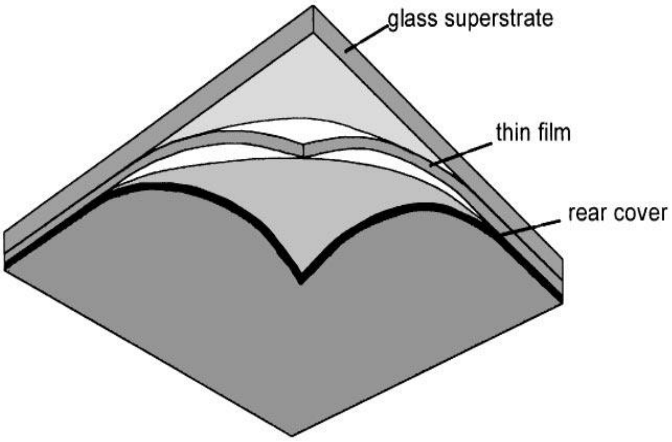

Figure 6. An illustration of the thin film concept [155]´

As mentioned previously, silicon is one of the few semiconductors that are inexpensive and widely abundant in the earth's crust. This makes it a suitable candidate material to be used to make solar cells from wafers on a large scale. However, in the thin film form, due to the reduced material requirements, other types of material semiconductors rather than silicon can be used. In addition, as semiconductors can be formed from compounds and alloys involving multiple elements, there is essentially a wide variety of materials to choose from [155]. In general, a thin film PV cell consists of a substrate a Transparent Conductive Oxide (TCO) layer, window layer, absorber layer and a metal contact layer. The various interfaces between these layers affect the overall performance of the device in some aspect, as the materials included has different physical and chemical properties, such as different crystal structure, microstructure, lattice constant, expansion coefficient, etc. Thus, the interfaces can cause stresses, defect and chemical and physical changes that have a direct effect on the solar cell performance. Referring to the substrate part, a thin film solar cell is configured in either substrate or a superstrate structure. For superstrate configuration, the substrate is transparent and the contact is made by a conducting oxide coating on the substrate. For the substrate configuration, the substrate is metal or metallic coating on a glass/polymer substrate which also acts as the contact. It is required to be mechanically stable, matching thermal expansion coefficient with deposited layers and inert during the device fabrication. Electrically conductive substrate enables the fabrication of front and rear side conduction cells, whereas insulating substrate enables fabrication of monolithically interconnected cells for modules. Deposition involving high temperature processes, depending on the deposition technique used. However, a low temperature process enables the usage of less expensive and flexible substrate, and the reduction of the energy consumption during manufacturing as well. Actually, the substrate devices are the most widely used, as they reported higher efficiencies values. Substrates materials are various, metallic and non metallic, depending on each application ([156], [157]).

As mentioned previously, light trapping is an important feature that improves the PV cells efficiency. This feature is important as well in case of thin film PV cells. In case of thin films, this is achieved by using Transparent Conductive Oxide (TCO) layer. Actually, TCO layers in the thin films PV cells represents the front electrode and a part of the back side electrode, which is normally made of an opaque metal coating. Thus, TCO has to be characterized by a high optical transparency and electrical conductivity. TCO can be made up of different materials, such as fluorine-doped tin oxide (SnO2:F, or FTO), doped zinc oxide (e.g. ZnO:Al) and indium tin oxide (ITO). Studies have shown that only ZnO-based TCOs can withstand the processing conditions, and are also stable up to 800 ºK. Therefore, ZnO-based materials are being increasingly used in thin film PV cell technologies. By controlling the microstructure, textured single and double layer TCOs can be deposited ([158], [159]).

For the window layer, its primary function is to form a junction with the absorber layer while allowing a maximum amount of light to the junction region and absorber layer; no photocurrent generation occurs in the window layer. The window layer has to be characterized by high optical throughput with minimal resistive loss. The material of the window layer varies according to the manufactured cell, different materials exist such as Cadmium sulphide (Cds), Zinc oxide (Zno), etc.

The absorber of a thin film PV cell is the essential part within the device. Actually, thin film PV cells are classified according to the materials used in manufacturing the absorber layer. Different materials are used to manufacture the absorber, such as: amorphous silicon (a-Si), microcrystalline silicon (mc-Si), Cadmium telluride (CdTe), copper indium diselenide, organic thin films, etc.

The different materials layers used in the thin film PV cell fabrication are usually manufactured with different deposition methods; each method can be further divided into various techniques, depending on the requirements of the production. The most widely used are physical vapour deposition (PVD) and chemical vapour deposition (CVD). They are the most common methods for transferring material atom by atom from one or more sources to the growth surface of a film being deposited onto a substrate. Vapour deposition describes any process where a solid immersed in a vapour becomes larger in mass due to transference of material from the vapour onto the solid surface. The deposition is normally carried out in a vacuum chamber to enable control of the vapour composition. If the vapour is created by physical means without a chemical reaction, the process is classified as PVD; if the material deposited is the product of a chemical reaction, the process is classified as CVD. Many variations of these basic vapour deposition methods have been developed in order to balance advantages and disadvantages of various strategies based on the requirements of the film purity, structural quality, the rate of growth, temperature constraints and other factors. In case of thin film PV cells, CVD methods are the most widely used; they are used in the production of polycrystalline silicon as well, as mentioned in the previous section. The CVD techniques are various, such as low pressure CVD, atmospheric pressure CVD, hot wire CVD and plasma enhanced CVD (also known as PECVD), and assisted CVD. Actually, the most widely used CVD technique is the PECVD one, as it allows for deposition at low temperatures (between 300 ºC and 600 ºC), which is beneficial in reducing the energy consumption and allows the usage of a wider variety of substrates materials. Besides, the PECVD process helps in reducing the process complexity and preventing lifetime degradation. It is characterized also by high deposition rate, in-situ chamber cleaning, and good control over film quality. Further modifications are done as well on the PECVD, such as very high frequency (VHF) PECVD, pulsed PECVD, remote enhances PECVD, laser enhances PECVD, etc. in order to achieve better cell efficiency and other specific objectives ([160]-[162]).

As mentioned previously, the thin film solar cell types are mainly classified according to the material used in manufacturing the absorber. More details about those materials are discussed as follows:

Amorphous silicon (a-Si) is widely accepted as a thin film PV cell material as it is abundant and non-toxic; and it does not requires high processing temperatures which is useful in using various types of substrates of flexible and low cost ones. In addition, the PV cell thickness requirement is small, 1–2 µm, due to the inherent high absorption coefficient compared with crystalline silicon. Thin films of amorphous silicon are produced using various deposition methods; they are mostly manufactured using the PECVD process of gases containing silane (SiH4) or using hot wire CVD technique as well. Silane is actually an alloy of silicon and hydrogen (5–20 % hydrogen). The hydrogen plays the important role in passivating the solar cell and thus reducing the density of the defects leading to the creation of a thin film PV cell of amorphous silicon a-Si:H with a band gap of 1.75 eV. However, the conventional p-n junction configuration for a-Si:H based PV cells suffers from various inherent limitations due to the presence of a large number of defect states, even after hydrogen passivation. The doping of a-Si:H further increases this concentration, which reduces the average lifetime of the free carriers as a result of high recombination probabilities and lower diffusion lengths, which affect conducting the electricity efficiently. Thus, PV cells in the p-n configuration do not work and are not considered suitable. Hence, the basic structure of an a-Si:H PV cell configuration is a “p–i–n” junction, shown in Figure 7, where an intrinsic layer of a-Si:H is sandwiched between the p and n doped layers of a-Si:H or its alloys. These p and n layers build up the electric field across the i-layer. This electric field drives the electrons and holes photo-generated in the i-layer in opposite directions, so that the i-layer essentially acts as the absorber layer in a-Si:H PV cells. Generally, a-Si:H PV cells on glass are available in the superstrate configuration starting with a transparent conducting oxide (TCO) window, then having p–i–n layers grown on it, followed by another TCO layer and a metallic back reflector layer. Thus, the design of the cells optimizes the collection of current by having very thin n-layers and p-layers, with an intrinsic intermediate layer with enough thickness to absorb almost all the incident light, giving a p-i-n structure. However, a common problem regarding the amorphous silicon is that the physical properties of the i-layer degrade under illumination, because Si-H bonds are destroyed under visible light, and the efficiency degrades under illumination to about than 5-6% of stabilized efficiency because of a phenomenon known as the Staebler-Wronski effect, although the actual efficiency of the cell can be more than 12%. This effect can be reduced by careful control of the deposition process, decreasing the thickness of i-layer, and using multiple junctions.

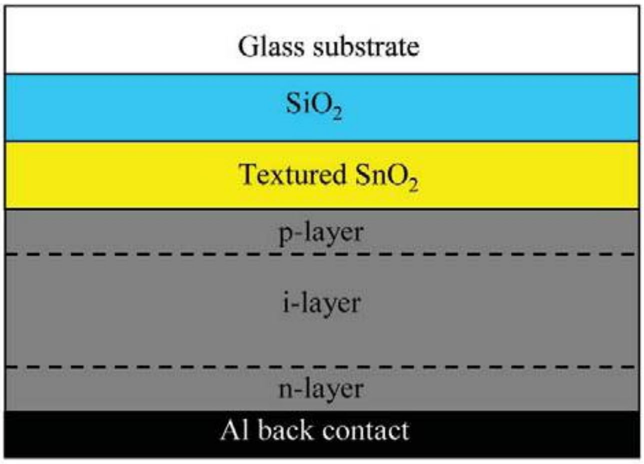

Figure 7. cross sectional view of a single junction a-Si:H cell [165]

When the gases used for the deposition of amorphous silicon are diluted in hydrogen, the microstructure of the deposit becomes different. In particular, for highly diluted gases, the deposit consists of regions of crystalline silicon immersed in an amorphous matrix. This two phase material is known as microcrystalline silicon (µ-Si) or ¨nanocrystalline silicon¨. The physical properties of the material resemble those of crystalline/multicrystalline silicon rather than amorphous silicon, especially with regard to stability under intense illumination. The structure of films can be controlled by the silane-to-hydrogen ratio in the process gas mixture. The amorphous-to-microcrystalline transition occurs in a very narrow range of silane-to-hydrogen ratio (approximately 6% silane) in the process gas mixture and depends also on the surface morphology of the substrate. Initially, microcrystalline silicon PV cells were being fabricated using the very-high-frequency (VHF) PECVD method. This has been yielding microcrystalline silicon solar cells with improved efficiency stability against light degradation compared to a-Si:H. The highest reported initial efficiency that has been achieved by using the combination PECVD and HWCVD techniques has been around 10%. A key challenge in developing the microcrystalline PV cells is the development of deposition techniques capable of providing higher rates without degrading the power conversion efficiency. Another rapidly progressing thin film PV cell technology is the thin film polycrystalline silicon (p-Si) PV cells. Despite the lower light absorption coefficient of the thin film P-Si, approach, it has the benefits of improved light trapping technologies. In contrast to a-Si:H solar cells, poly-Si devices feature the p–n junction structure of conventional Si cells based on bulk Si wafers. Generally, producing thin film poly-Si is based on amorphous silicon technology. One approach is using the PECVD technique, where the silicon is deposited in amorphous form on a glass substrate and then is crystallised by heating for prolonged periods at intermediate temperatures. A plasma hydrogenation process is carried out within the manufacturing in order to reduce the defect density. The best efficiency obtained for the thin film p-Si is around 10%. It is noted that, in contrast to other thin film technologies, TCO layers are eliminated from the fabrication process owing to the improved electrical properties of poly-Si, which substantially reduces the production cost. In addition, the poly-Si technology possesses several other important features making it particularly attractive for mass production of PV modules, including a simple solar cell structure and an expected excellent long term stability of the modules. Thus, the thin film p-Si PV cells are an emerging technology that aims at combining the advantages of crystalline Si and thin film technologies ([165]-[170]).

2.2.2 Hybrid solar thermal PV collectors (PV/T)

PV thermal collector (PV/T) is a module in which the PV is not only producing electricity but also serves as a thermal absorber. In this way, both heat and power are produced simultaneously. Since the demand for solar heat and solar electricity are often supplementary, it seems to be a logical idea to develop a device that can comply with both demands. Normally, as mentioned in the previous sections, PV cells utilize a fraction of the incident solar radiation to produce electricity and the reminder is turned mainly into waste heat in the cells, which cause the temperature of the PV cells to rise, and consequently, the efficiency is decreased. The photovoltaic/thermal (PV/T) technology recovers part of this waste heat and uses it for practical applications. Besides, applying simultaneous cooling of the PV module maintains electrical efficiency at satisfactory level and thus the PV/T collector offers a better way of utilizing solar energy with higher overall efficiency. In other words, PV modules are coupled to heat extraction devices, in which water or air is heated and at the same time the PV module temperature can be reduced to keep electrical efficiency at sufficient levels. Different types of PV/thermal collector are being used, such as, PVT/air, PVT/water and PV/T concentrated collector ([121], [221], [222]).

2.2.2.1 *Flat plate PV/T collectors*

Flat plate PV/T collectors look very similar to the flat plate thermal collectors explained previously; the only significant difference is that a PV panel which is attached on the top of the metallic absorber plate (Figure 8).

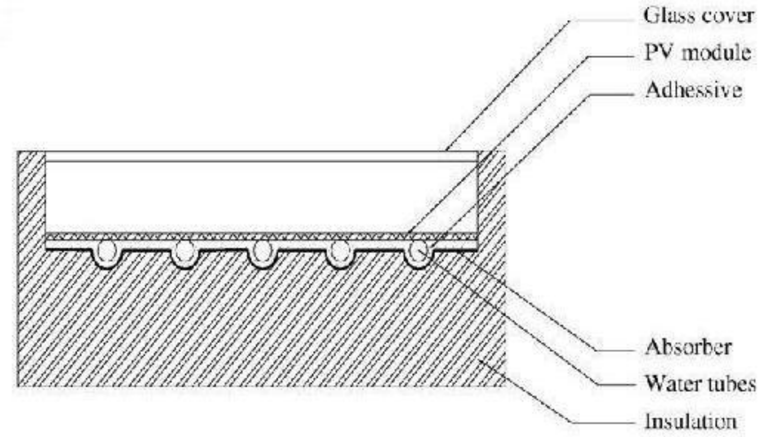

Figure 8. Flat plate PV/T collectors [121]

There are two types of Flat plate PV/T collectors that can be distinguished: Liquid PV/T collector and air PV/T collector. Liquid PV/thermal collectors are used to heat up the water and simultaneously produce electricity for various domestic and industrial applications. The domestic water heater generally uses flat plate collectors in parallel connection and run automatically with the thermo-siphon action, whereas the industrial water heating system uses a number of flat plate collectors that are connected in series. It uses a PV driven water pump to maintain a flow of water inside the collectors. A schematic diagram of a PV/T water collector is shown in Figure 9 [223].

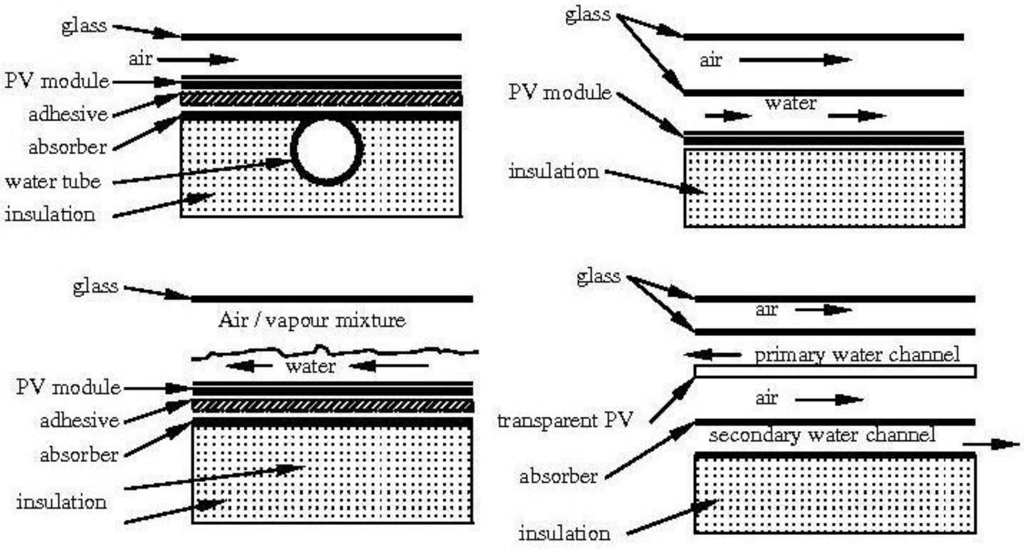

Figure 9. Types of water PV/T collectors [223]

PV/T air collector is similar to that of the water one. Air and water both are being used as heat transfer fluids in practical PV/T solar collectors, yielding PVT/air and PVT/water heating systems respectively. PVT/water systems are more efficient than those of PVT/air systems, due to the high thermo-physical properties of water as compared to air. However, PVT/air systems are utilized in many practical applications due to lower construction requirements and operating cost [121].

2.2.2.2 PV/T concentrator

PV systems can operate at higher temperatures than those of the flat plate collectors. Collecting the rejected heat from a PV system constitutes the PV/thermal (PV/T) system, providing both electricity and heat at medium temperatures. The use of PV/T in combination with concentrating systems and CPV cells has a significant potential to increase the power production from a given photovoltaic cell area. The current research is going towards developing PV/T collector for more electricity as well as heat generation [121].Various designs exists regarding PV/T systems, depending on the requirements the corresponding applications. Studies focusing on the testing, simulation and enhancement of the systems can be found in literature as well ([224]-[228]).

Concentrating Photovoltaic (CPV) is a different technology that aims at increasing the energy output of PV cells. This can be achieved by using mirrors or lenses to concentrate the incoming solar radiation onto the PV cells. In other words, a part of the PV cell area is replaced with optical materials. This allows for a reduction in the cell area required for producing a given amount of power, which consequently, reduce the embodied energy and the environmental impact of the system.

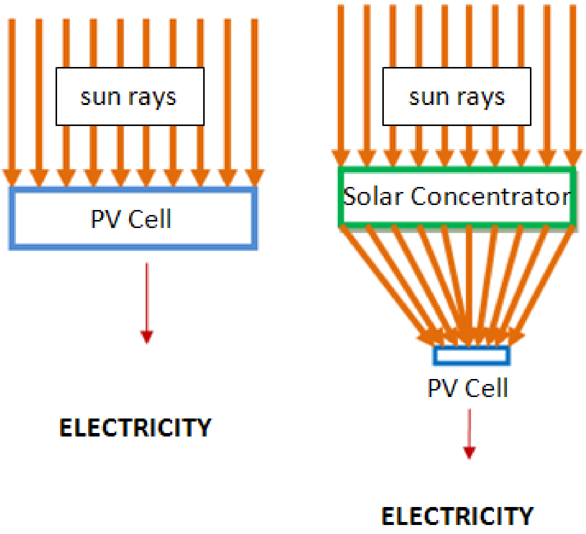

Figure 10. Generating electricity from the sun, with and without concentrator [175]

This approach also provides the opportunity to use higher performance PV cells that would be expensive without concentration [174] (Figure 10). The material used to fabricate the concentrator varies depending on the usage. For solar thermal plants, most of the concentrators are made from mirrors, while for the BIPV system, the concentrator is either made of glass or transparent plastic [175]. The CPV optical systems are often composed of a primary concentrator with a secondary optical element; these secondary elements are usually joined to the PV cells and are employed to improve the concentration factor and the angular acceptance [176]. However, despite of the benefits of CPV systems, they still have some drawbacks, for example, at high concentration levels, as a result of light concentration, heat generated in PV cells increases resulting in an increase in the cell temperature if proper cooling schemes are not applied. The increased cell temperature reduces the cell performance, and could also be harmful for the module in long term; as the high module temperature reduces the operating life of PV cells by degrading cell encapsulation and PV cell contacts faster. For this, usually the cooling of the cells is achieved by putting a heat dissipater metal sheet with or without fins at the rear side of a concentrator PV module. Therefore, the PV cells are needed to be cooled down to ensure that its performance is optimum [177]. Another disadvantage is that a mechanical system tracking the sun is needed in order capture the maximum amount of radiation, as the concentrators normally capture only the direct solar radiation.

Concentrators are divided into different classes according to various features. Mainly, concentrators can be divided into four groups depending on the optical means used to concentrate the light: The reflector type, the refractor type, the hybrid type and the luminescent type. In the reflector type, the sun rays are reflected to the PV cell upon hitting the concentrators (Examples: Parabolic Trough, Parabolic Dish, CPC Trough, and Hyperboloid Concentrator). In the refractive type, the sun rays are refracted to the PV cell (Example: Fresnel Lens Concentrator). In the hybrid type, the sun rays can experience both reflection and refraction before hitting to the PV cell. In the luminescent type, the photons will experience total internal reflection and guided to the PV cell. Each of those types will be discussed in the following subsections.

Another classification that can be done for the CPV systems is according to the concentration ratio of the solar radiation incident onto the cell. This ratio indicates the number of times that the solar light is concentrated and it is usually known as ‘Suns’. The definition of these concentration levels (suns) is done taking into account the relation between the optical device aperture area and the PV cell area, that it is known as geometric concentration ratio. According to that description, three different CPV systems can be defined as follows [120]:

- Low concentration PV: It refers to those systems that concentrate the light between 1 and 40 times (1–40×), so the low concentration PV systems have a concentration factor between 1 and 40 suns.
- Medium concentration PV: These are the systems that concentrate the sunlight between 40 and 300 times (40–300×)
- High concentration PV: The concentration level of these systems varies between 300 and 2000 suns (300–2000×). These systems are the one with more power installed of the CPV technology.

Monocrystalline silicon PV cells represent a very efficient candidate for low concentration ratios. In reference to high concentration ratios, it is found that III–V multijunction PV cells are more efficient than any other PV cell technology. It is also considered as the PV technology with the highest efficiency growing rate, such that, its efficiency reached more than 40 % under the standard concentrator terrestrial spectrum. ([178], [179]).

One of the drawbacks of a CPV system is that it captures only direct solar radiation, which invokes the need for mechanical tracking system. Tracking systems can be either one-axis or two-axis tracking system [180].

2.2.2.2.1 Parabolic trough concentrators

Parabolic trough collectors are made by bending a sheet of reflective material, usually silvered acrylic, into a parabolic shape. A black metal tube, encased in a glass tube that helps in reducing heat losses by convection, is placed along the focal line of the receiver. The metal tube’s surface is often covered with a selective coating that features high solar absorbance and low thermal emittance. The glass tube itself is typically coated with antireflective coating to enhance transmissivity. A vacuum can be applied in the space between the glass and the metal pipes to further minimize heat loss and thus boost the system’s efficiency (Figure 11 and Figure 12) ([181], [182]). When the parabola is pointed toward the sun, parallel rays incident on the reflector are reflected onto the receiver tube. The concentrated radiation that hits the receiver tube heats the fluid that circulates within. Usually the fluid inside is oil that is then passed through a heat exchanger to produce high temperature steam. This powers a turbine, which in turn drives an electrical generator. Thus, in this way, the solar radiation is transformed into

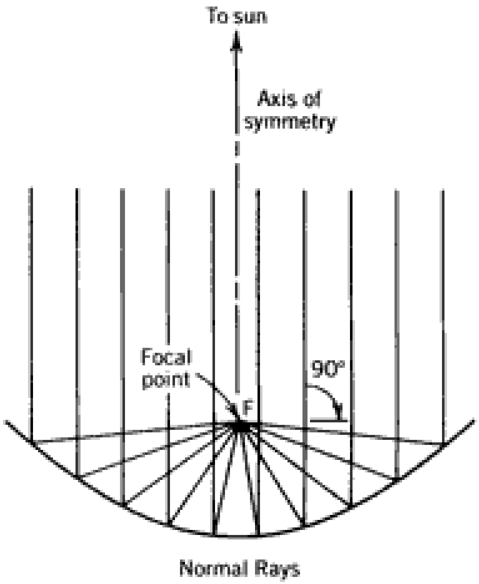

Figure 11. The sun rays are focused at the focal point of the parabola [175]

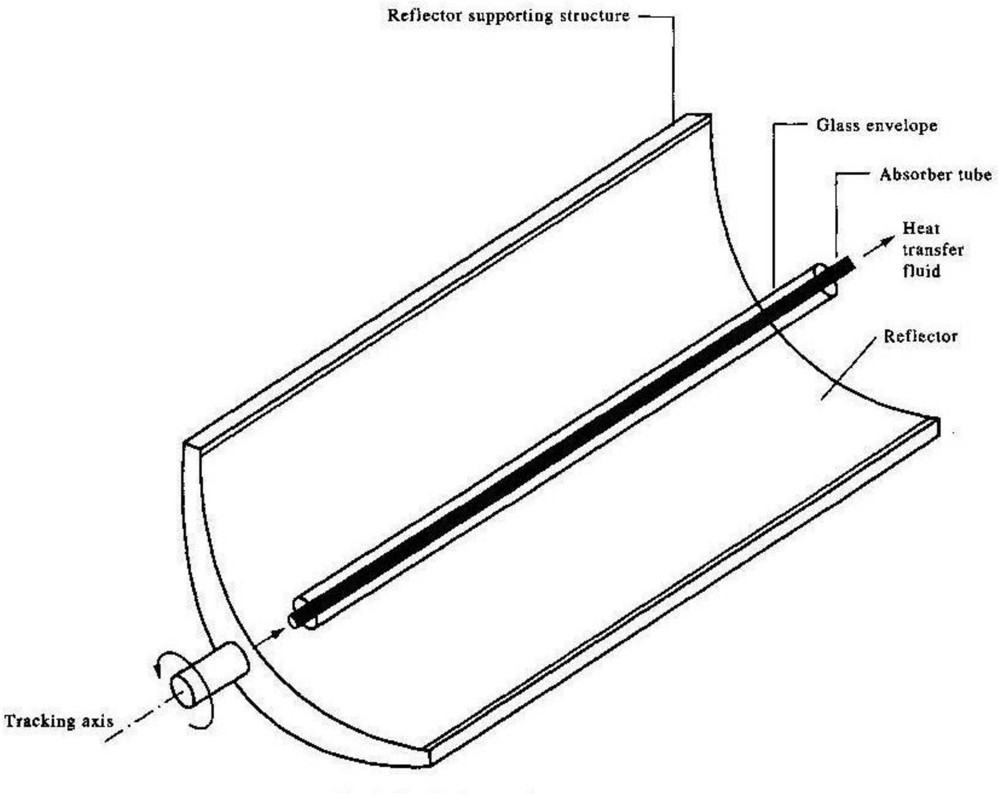

Figure 12. Parabolic trough concentrator [182]

useful heat through concentration using parabolic trough concentrator. This kind of concentrators is usually installed using single-axis tracking mechanism to follow the sun's trajectory, thus focusing the solar energy onto a linear receiver at the focal axis. Such concentrator can concentrate direct sunlight to generate working temperatures up to 400 ºC and achieve concentration ratios in the range of 30-100 suns ([174], [183]).

Parabolic trough concentrator's fields usually follow a north-south alignment with careful consideration given to the distance between collector rows, as this distance will determine the amount of land and piping used and, therefore, this will affect the embodied energy of the system. Moreober, it will also affect fluid transport and optical shadowing losses which in turn affect the efficiencies of the system. The collector efficiency reported for this type of concentrators ranges from 40% to 60% [184]. Parabolic concentrators are more highly developed for solar thermal applications in which high temperature is desired and flux uniformity is not a big issue, as with PV receivers. Nevertheless, some researches aim at improving the associated non uniform illumination at the cells, such as using micro structured reflector surfaces [185]. Other research works are interested in experimenting new configurations with the aim of improving the overall collector efficiency; an example is designing a variable-focus-parabolic trough reflector in which the focal length varies as a function of the vertical displacement of the incidence point relative to the horizontal centreline of the receiver [186]. A review about parabolic-trough collectors that have been built and marketed, as well as the prototypes currently under development can be found in [187].

2.2.2.2.2 Compound Parabolic Concentrators (CPC)

A CPC collector is composed of two truncated parabolic reflectors; neither one keeps its vertex point but both rims must be tilted toward the Sun. Figure 13 shows the geometric relationship between the two parabola segments for the construction of a CPC. Figure 14 shows the trajectory of the incident rays inside the CPC. The two parabolas are symmetrical with respect to reflection through the axis of the CPC and the angle in between them is defined as the acceptance angle. In a parabola, light rays must always be parallel to the parabola’s axis; otherwise, it is out of focus.

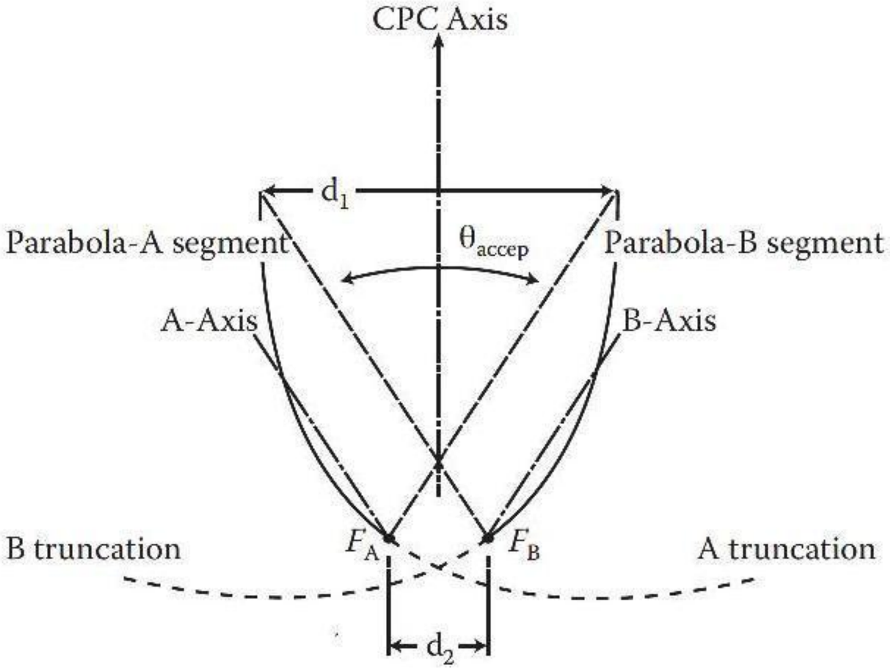

Figure 13. Cross section of a CPC concentrator [175]

Compound parabolic concentrators can be manufactured either as one unit with one opening and one receiver or as a panel. When constructed as a panel, the collector looks like a flat-plate collector, as shown in Figure 15 ([175], [183]). Compound parabolic concentrators have the capability of reflecting all of the incident radiation to the absorber, as they can accept incoming radiation over a relatively wide range of angles. By using multiple internal reflections, any radiation entering the aperture within the

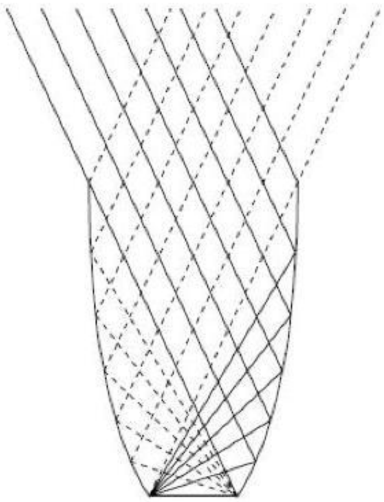

Figure 14. Trajectory of the incident rays inside the CPC [175]

collector acceptance angle finds its way to the absorber surface located at the bottom of. the collector. There are two basic types of CPC collectors: symmetric and asymmetric.

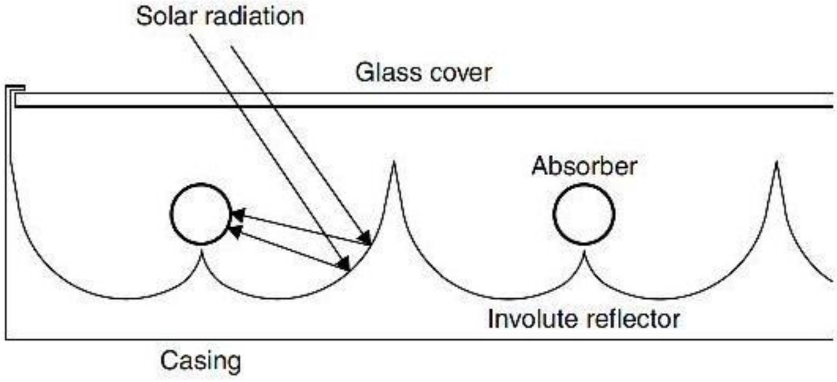

Figure 15. A schematic diagram of CPC panel [183]

CPCs usually employ two main types of absorbers: the fin type with a pipe, and tubular absorbers. The fin type can be flat, bifacial, or wedge, for the symmetric type, and can be single channel or multichannel.

As a method to get higher concentration values, and due to the impractically large size of a conventional CPC for concentration ratios above 10 suns, an alternative approach is to use a lens in front of the concentrator's aperture entrance. These are then referred to as primary and secondary concentrators, respectively. To reduce the size and weight of the lens, a Fresnel lens, either linear or circular, is usually selected. The advantage of refractive materials, such as Polymethyl Methacrylate (PMMA) which is often used to make Fresnel lenses, is that they are generally cheaper and have a longer lifespan than reflective materials used to make mirrors. Other materials can be used as well such as aluminium or glass. Furthermore, if a material is chosen has some flexibility, a less rigid frame is required to withstand wind loads without risk of fracture. More details about the Fresnel lenses will be discussed later in the following sections ([188], [189]).

Another approach that aims at enhancing the concentration is to fill the CPC with dielectric materials. Refraction in a dielectric-field concentrator enables greater concentration to be achieved with stationary systems, while maintaining a wide acceptance angle. Besides, the majority of reflections occur within the angle of total internal reflection, and thus reflection losses are minimised. However, the use of the conventional CPC keep the system size minimized ([190], [191]).

2.2.2.2.3 V-trough concentrators

These systems, similar to the CPC in design, mostly use two lateral mirrors adjacent to the PV modules [124]. Sun tracking can be avoided or it can be reduced to only seasonal tracking. However, for higher concentration levels, sun tracking system would be necessary. V-trough concentrators are composed of aluminium sheet bended to obtain the desired V-trough structure, in addition to an anodized reflector layer of high reflectivity mounted on walls of the V-trough [192]. Compared to CPCs, V-trough concentrators are much easier to be constructed, the distribution of solar intensity on the base of V-trough is more uniform, and the unused heat is more easily dissipated through side walls of V-trough [193].

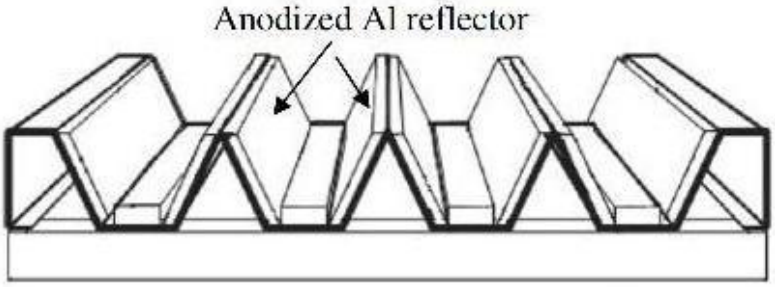

Figure 16. Aluminum sheet bended to obtain the desired V-trough structure [192]

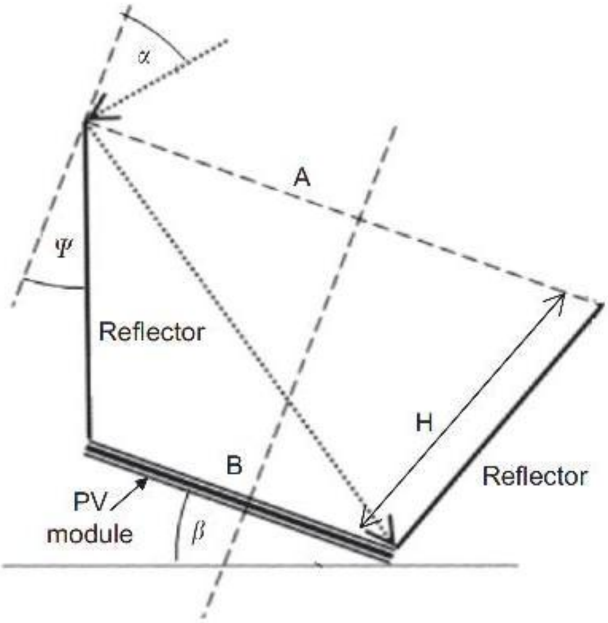

Figure 17. V-trough and its design parameters: ά is the acceptance angle, γ is trough angle, A is collector aperture width, B is receiver base width and H is the slant height of reflector) [192]

The higher the desired concentration, the greater the relative advantage of the CPC over the V-trough. The upper limit of concentration for a practical V-trough is about 3 (as a nontracking collector with daily tilt adjustments). With summer/winter adjustments only, the V-trough is limited to Concentration values below 2, and for a completely fixed collector a V-trough gives almost no concentration. As for absorber shapes, the V-trough is limited to flat one-sided absorbers.

A similar concentrator, the hyperboloid one, is shown in Figure 18. It consists of two hyperbolic Sections. The sun rays entering the concentrator from AA’ will be reflected and focused to the exit aperture BB. The advantage of this concentrator is that it is very compact, since only truncated version of the concentrator needs to be used. Because of this factor, it is mainly used as a secondary concentrator.

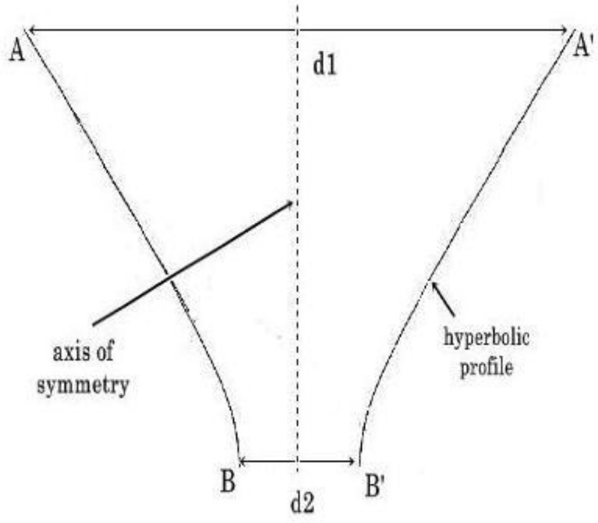

Figure 18. Hyperboloid concentrator [175]

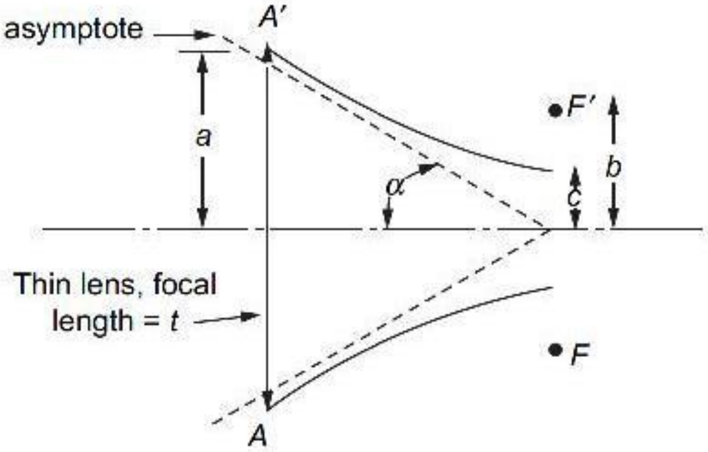

Figure 19. Hyperboloid concentrator with a lens at the entrance [194]

However, in most applications, it requires the usage of lenses at the entrance diameter AA’ in order for the concentrator to work effectively, as shown above in Figure 19.

2.2.2.2.4 *Fresnel lenses and reflectors*

The use of Fresnel lenses in solar concentration reduce the amount of material required compared to a conventional spherical lens through breaking the lens into a set of concentric annular sections.

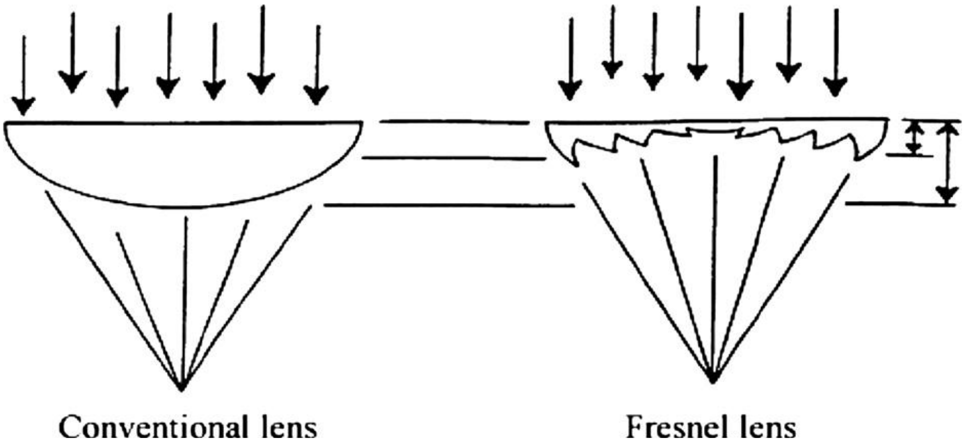

Figure 20. Conventional lens and Fresnel lens [195]

The volume is greatly reduced while the optical properties of a normal lens are almost kept. The more sections created, the better the optical approximation. A high-quality linear Fresnel lens should have more than 1,000 sections per centimeter. The flatness results in great savings in material. However, in order to maintain the refracted image focused on a receiver that is fixed with respect to the lens, the Fresnel collector or any other lens system requires at least one single-axis tracking system to keep the incident light rays normal to the lens aperture [175]. Fresnel lenses may be made either point-focus, in which case they have circular symmetry about their axis, or linear focus, in which the lens has a constant cross section along a transverse axis. Such lenses focus the light into a line. Point-focus lenses usually use one cell behind each lens, whereas line-focus lenses have a linear array of cells. The material of choice for the lens is usually Acrylic plastic (Polymethyl Methacrylate - PMMA), which molds well and has shown good resistance to weather conditions. Nevertheless, there remain some long term durability concerns for PMMA, and therefore, there are attempts to make the lens from glass, or to mold the lens material to the underside of a glass substrate, have been made. So far, these ideas have remained in the laboratory.

For the Fresenel reflectors, there is a trend that they replace the parabolic mirrors, as the linear Fresnel reflectors consist of flat or slightly curved mirrors that can be arrayed in long rows and aligned so that they focus the solar radiation. Actually, concentrated solar power production using linear Fresnel reflectors is quite similar to the parabolic trough collector scheme; the two share common principles in both arrangement and operation. The concentrated radiation can be focused onto a receiver, with the aid of a small secondary reflector. A heat transfer fluid circulates through the receiver, collecting and transporting thermal energy to power production and storage units. Radiation can be focused as well onto a receiver that is mounted on a tower (usually 10–15 m tall). This is considered as an advantage, as the receiver in this case is a separate unit, and does not need to be supported by tracking device (Figure 21) [196].

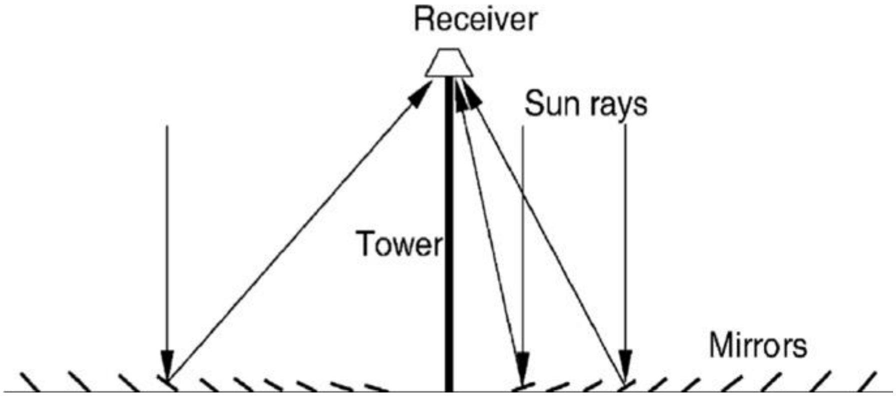

Figure 21. Linear Fresnel reflector [196]

A significant challenge with linear Fresnel lenses systems is light blocking between adjacent reflectors. Solving this issue requires either increasing the spacing between mirrors, which takes up more land, or increasing the receiver tower height, which increments the cost. So, alternatively, a relatively new design known as the Compact

Linear Fresnel Reflector can be used, where two receivers can be used with interleaving mirrors as shown in Figure 22.

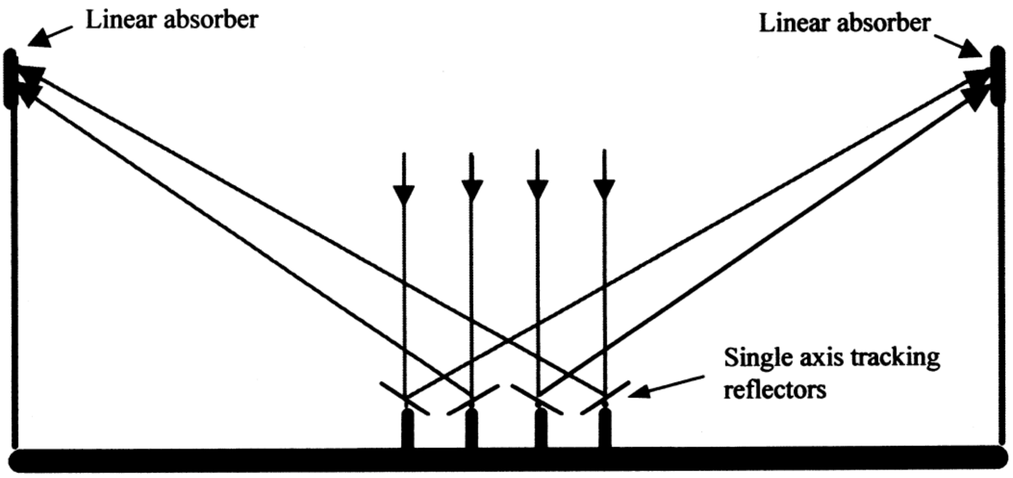

Figure 22. Schematic diagram showing interleaving of mirrors without shading between mirrors [197]

The use of multiple receivers allows a more compact reflector distribution. This avoids shading and allows the utilization of more solar flux. However, the high number of segmented mirrors means that a more complex control system is required to operate the large number of drives. Some studies found in literature are demonstrating the use of compact liner Fresnel reflectors on large scales [197].

Generally, Fresnel lenses and reflectors have been incorporated into solar thermal energy systems. Beside the solar radiation concentration, the use of a Fresnel lens can be adopted in other applications, such as the interior illumination of buildings. Secondary optical elements are often used with the Fresnel lenses. The objective of using a secondary optical element is to increase concentration, or alternatively to increase acceptance angle [10]. They are applicable with either reflective or refractive systems; however, they are most often used with point focus Fresnel lenses in which concentration ratios are in the range of 200 to 1000 are typical. V-troughs and refractive compound parabolic concentrators are common types of secondary elements. An extensive review about Fresnel lenses and reflectors can be found in [6] and [195], where several aspects regarding the development and recent designs are discussed.

2.2.2.2.5 Dielectric Total Internal Reflection Concentrator

The Dielectric Total Internal Reflection Concentrator (DTIRC) has the capability to achieve concentrations close to the theoretical maximum limits. There are two ways to produce the DTIRC: the maximum concentration method and phase conserving method. Although both methods can be used to create similar structure, the former technique offers slightly higher concentration and therefore is more suitable for solar energy application.

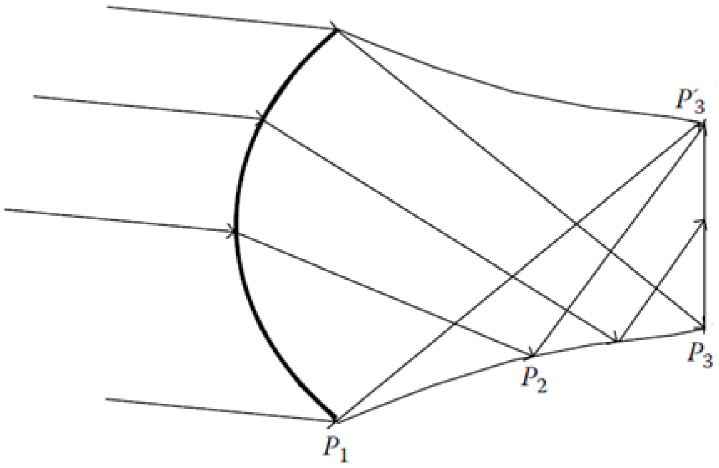

Figure 23. Dielectric total internal reflection concentrator [198]

DTIRC consists of three parts: a curved front surface, a totally internally reflecting side profile and an exit aperture (Figure 23). When the rays hit the front curved surface, they are refracted and directed to the side profile. Upon hitting the sidewall, they are totally internally reflected to the exit aperture. The front aperture can be a hemisphere, but different designs such as parabola and eclipse have been developed recently.

The DTIRC is often compared to the dielectric CPC. The advantage of a DTIRC over a CPC is that it offers higher gain and smaller sizes. As the front surface arc angle increases, the total height of a DTIRC shrinks dramatically. This is useful in producing a more compact concentrator design. An increase in the front surface curvature will also change the side profile from convex to concave. DTIRC can be applied in various forms. For example, in some studies as in [198], it has been used with BIPV systems, and has been integrated to be used in space applications as well [199].

2.2.2.2.6 Fluorescent solar concentrators

The fluorescent solar concentrator consists of a transparent polymer plate containing fluorescent particles. PV cells are connected to one or more sides of the polymer plate (Figure 24). The fluorescent particles absorb radiation and emit light with a longer wavelength. Most of the emitted light is totally reflected internally and therefore trapped and guided to the sides of the concentrator, where the PV cells convert it into electricity [200]. Unlike standard solar concentrators, the fluorescent concentrator is able to concentrate both direct and diffuse light, which means that tracking the sun is not required. This further enhances potential cost reductions and making them excellent candidates for BIPV systems. This makes the use of PV technology more efficient in cloudier climates as well.

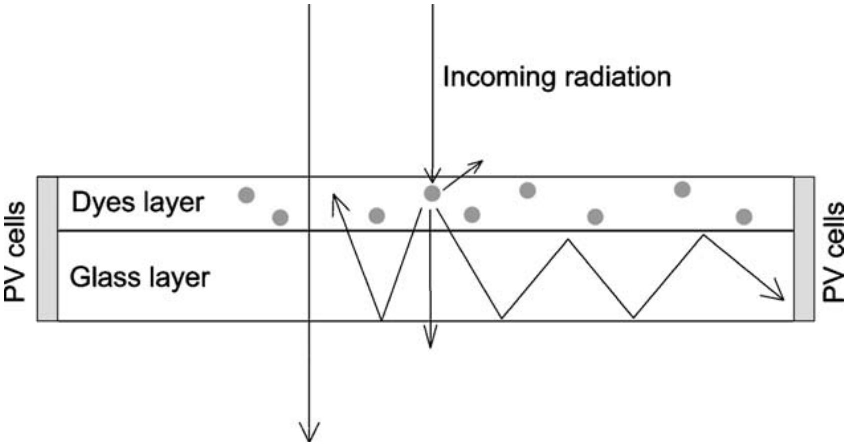

Figure 24. Fluorescent concentrators technology [6]

Normally, fluorescent concentrators use organic dyes as luminescent materials. Although many efforts have been done in order to improve its technical properties, there are still further improvements to be made. Some of these technical problems are non-unity fluorescence quantum yield, reabsorption losses, incomplete utilization of the solar spectrum, and escape cone losses, which can be found in details in [201]. Within this context, other materials have emerged, such as such as semiconductor quantum dots, rare earth materials, and semiconducting polymers. The most significant of which are the semiconductor quantum dots, where many researches are interested in the development and improving the performance of fluorescent concentrators through replacing the luminescent organic dyes by the semiconductor quantum dots. The unique advantage of the quantum dots is their absorption threshold that can be tuned by the choice of the dot diameter ([202]-[206]). Materials such as photonic layers and liquid crystals have also been utilized to reduce losses within the devices. Moreover, some hybrid designs combining between organic and inorganic materials have been recommended in order to get benefit of the advantages of both organic and inorganic materials.

Other studies can be found concerned with improving the performance through designing a stack of fluorescent collectors with different dyes (photonic structure). The stack configuration allows for ‘‘recycling’’ of emitted photons that are lost in one collector, but can be absorbed in another one. This photonic structure acts as a band stop reflection filter, such that, it allows light in the absorption range of the dyes to enter the collector, but reflects light in the emission range. Therefore a larger amount of light is trapped in the collector and guided to the solar cells at the edges [207].

Application of fluorescent concentrators is extended to include interior lighting of buildings. This application is important, as it helps avoiding the complicated wiring needed for providing day lighting illumination using light pipes and optical fibres [208]. Moreover, further research is being conduced in order to fully utilize the fluorescent concentrators technology, including various design and material aspects that are examined using thermodynamic and ray trace modelling techniques, in addition to experimental results ([209]-[212]).

2.2.2.2.7 Holographic concentrators

Holographic optical elements (diffraction gratings) are diffractive structures that are constructed holographically by the interference of two beams of light. Typically one beam resembles the ‘‘playback’’ beam that illuminates the holographic optical elements in the final system. The second beam corresponds to the ‘‘image’’ beam that is supposed to exit the holographic optical element upon its playback. These images are projected on a recording medium. Holographic optical elements can be approximated as holograms of point sources or collimated beams of light, such that, light from one source is imaged onto the other. Optical elements such as lenses, beam splitters, diffraction gratings and filters can be generated by holographic imaging. They have the advantage of simple design, small size, light weight and are easily reproducible by embossing polymer materials. They are wavelength selective and have high diffraction efficiency ([213], [214]). A single element hologram focuses light to the side and also spectrally splits it. The output appears as a thin concentrated line, focused perpendicular to the hologram and displaced to the side [215]. Two types can be identified for holographic concentrators: Reflective and transmitive. The holograms can be multiplexed to diffract various wavelength bands in different directions. Unwanted spectral bands can be directed away from the PV devices and improve the overall efficiency of the PV system [216].

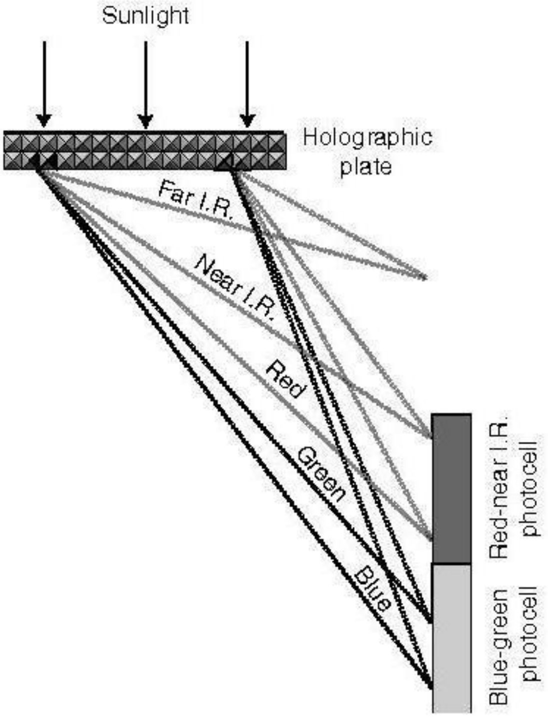

Figure 25. An illustration for the holographic concentration principle [214]

By multiplexing holographic gratings one over the other or stacking several holographic lenses side by side, the daily movement of sun can be tracked which ensures complete elimination of tracking parts. However, on multiplexing, diffraction efficiency falls. Hence, the number of holographic lenses that can be multiplexed is limited. If a single lens has large acceptance angle with reasonably good diffraction efficiency, then less number of multiplexed holographic lenses can track the daily movement of sun ([217], [218]).

A fair amount of work on the subject of the fabrication of holographic recording mediums where some recording medium elements are being developed, such as zone plates, lenses, shear elements, double and multiple shear lenses, achromats, mirrors, beam splitters, gratings, birefringent elements, multi-function elements, etc. The frontline recording materials for the fabrication of holographic optical elements have been the conventional silver halide emulsions. Materials such as dichromated gelatin, photo-resist and photo-polymers, etc., have also been employed in the fabrication of the holographic optical elements. Dichromated gelatine appears to be the best for recording holograms among the commercial gelatine material family, as it has the highest refractive index modulation capacity [219]. Regarding the spectrum splitting feature, some research work is being conduced using various methods, such as cascaded cells, multiband semiconductors and filtered cells [214]. Other works can be found interested in simulation and modelling of the implementation of such novel technology [220].

2.3 Solar technologies and buildings

The idea of building integration is implementing the use of PV devices to replace conventional building materials in parts of the building envelopes, such as the roofs, skylights, or facades. They can be incorporated into the construction of new buildings and in the retrofitting of old buildings as well. Two principal classifications can be defined for building integrated systems: BIPV (Building Integrated Photovoltaics) and BAPV (Building Added Photovoltacis) [229].

BIPV systems are considered as a functional part of the building structure, or in another words, they are architecturally integrated into the building’s design. This category includes designs that replace the conventional roofing materials, such as shingles, tiles, slate and metal roofing. Besides, BIPV can be used for façade integration as well, such as the case of curtain walls, awnings, windows and skylights.

BAPV systems are considered as an add-on to the building, not directly related to the structure’s functional aspects. They rely on a superstructure that supports conventional framed modules, such as standoff and rack-mounted arrays, which are considered to be the two subcategories for BAPV systems. This superstructure is typically attached to the roof through a series of brackets or bases that are mechanically fastened to a structure segment of the roof system. BAPV arrays can also be installed over the original roof without any mechanical connection. In these cases, the array must be ballasted or designed to remain in place when subjected to wind or other loads that would cause the array to slide, move or overturn.

Most of the building integrated applications are currently based on crystalline silicon technology. Because most PV companies are active in the field of conventional crystalline silicon panels, many of them have made the step towards the building integrated applications. Thin film technologies make up a lower share of that market. Most of the products using thin film technology are those that can make optimal use of the benefits of thin film, namely their ability to be made flexible and their good performance under diffused light conditions. The products using thin film technology are mainly the flexible ones, such as flexible laminates or the flexible PV shingles and the ones that can be installed under non-optimal inclination conditions, such as semi-transparent modules that are used in façades and skylights. Most of these products are based on silicon thin film. The other technologies, such as CIGS, CdTe, etc. make up only a very small part of the current BIPV market [230].

Comprehensive reviews about different BIPV technologies and products can be found in [230]. Other researches can be found examining the opportunities for better maintenance and construction methods for replacing old PV modules easily rather than focusing on prolonging their lifetime [229]. Enhancing the performance of building integrated systems through experimental works and simulation can be found in literature as well [231]. Other related hybrid PV technologies that can be integrated in buildings can be found in literature as well, such as Building Integrated Thermal photovoltaic (BIPVT) [232] and Building integrated concentrating photovoltaic (BICPV) [6].

2.4 Summary

Silicon is the most widely used and abundant material for manufacturing of PV cells. For low and medium concentration applications, many types of PV cells are available today such as monocrystalline, multicrystalline, thin film, etc. The main advantage of monocrystalline cells is their high efficiency, but the disadvantage of these cells is that complicated processes of higher energy are required for their production. Thin films have relatively lower efficiency. However, they consume less quantities of materials, and are characterized by their flexibility and variety of materials used in manufacturing rather than monocrystalline and multicrystalline silicon.

Several PV systems exist and tailored according to the need of each application. In reference to the systems efficiency, some works in literature are found to be interested in examining the efficiency and the conditions that affect the performance of different PV cells. In that sense, the most well known and up to date efficiency values of PV cells are demonstrated in [233] where the technical characteristics of the cells and the corresponding testing can be found in detail. Nevertheless, more tests under different conditions are to be carried out. In addition, the values given for efficiencies differ from manufacturer or research institute to another. Each application needs different conditions to be fulfilled regarding the amount of energy to be supplied, the ambient conditions and many other factors. Thus, the whole PV system efficiency is highly dependent on variable factors.

Regarding the systems types, it has been demonstrated that PV/T systems have shown reliability and efficiency in cooling the PV cells and consequently enhancing the efficiency, and at the same time using the waste heat for other purposes. Additionally, the whole system efficiency of a PV/T system is usually higher than the case of using PV cells only, especially when the PV/T system is used with the concentrators.

Building integrated systems varies greatly depending upon climate, built environment, industry structure, government polices, local product offerings, consumer demand, existing industrial capabilities, the forms of tariff arrangement for grid-connected PV power generation, and many other variable factors. The building integrated products can be categorized in different ways. Some products are classified and being widely used such as foils, tiles, modules and PV cell glazing products. The modules can normally be used with various kinds of roofing material. The PV cell glazing products can be integrated into facade, roof or windows, and provide various esthetical solutions. A summary of the most up to date existing and most utilized BIPV products can be found in [230] . However, it should be taken into account that some products hold a variety of properties, thus making them more difficult to categorize.

It has been clarified that the purpose of both BIPV and BAPV is to generate electricity. The differences between them are that BIPV systems level of integration is so high that the PV arrays can act as building envelopes, such as curtain walls, awnings, windows and skylights. The advantages of the BIPV form are that they are architecturally clean and attractive and offset the cost of some building components, such as roofing, facade or glazing. However, the BIPV comprises more complicated structures and difficult mounting and maintenance procedures than the BAPV. In addition, BAPV simply make PV components to overlap with the envelopes; their structures are simple to mount and maintain, and even without PV modules, these types of buildings can function normally. However, sometimes these two classifications cannot be clearly defined in practice. From the above definitions, the main difference between BIPV and BAPV can be summarized in the extent of tightness in the integration of the PV systems into buildings. In addition, various types of different BIPV systems can be configured depending on the application employed, such as Building Integrated PV/T system (BIPVT), Building Integrated concentrating Photovoltaics (BICPV), etc.

3 Chapter 3

LCA of solar technologies and systems: A critical analysis

3.1 Solar technologies and the environment

3.1.1 Operation

The electricity generated from PV systems contributes significantly to the protection of the environment. In industrial countries, each kWh that is generated by PV plants avoids significant amounts of emissions, depending on the energy mix in each country [234]. Although semiconductor materials are imbedded within the PV modules, the operation of PV systems does not produce any emissions, as the related toxic compounds within the semiconductor materials cannot cause any adverse health effects unless they enter the human body in harmful doses. The only pathways by which people might be exposed to PV compounds from a finished module are by accidentally ingesting flakes or dust particles, or inhaling dust and fumes. The PV material layers are stable and solid, and are encapsulated between thick layers of glass or plastic. Unless the module is ground to a fine dust, dust particles cannot be generated. Therefore, it is very unlikely for any vapours or dust to be generated during normal use of PV modules [235].

3.1.2 Manufacturing

The PV industry uses a variety of chemicals during manufacturing, where some of which are toxic to human health and the environment. In addition, the production of PV cells involves the use of a number of gases including silane, arsine, phosphine, hydrogen sulphide, cadmium and selenium. Detailed information about the toxicity factors and standards can be found in [234], where a comprehensive review is given about the emissions induced from the PV industry, based on a survey covering several manufactures, comprising different PV cell types and production volumes. Due to the toxic and explosive nature of these gases, the possible dangers to health might be both physical (explosions) and biological (inhalation of gases). The magnitude of potential effects will vary based on the materials toxicological properties, the intensity, frequency, and duration of human exposure [236]. The most likely routes for environmental release of trace elements are from accidental spills during the manufacturing process. Because of the higher risks of worker exposure, extensive work has been conducted on methods to reduce the hazards to manufacturing plant workers. However, this type of accidental release may present health risks to both workers and the general public as well. Typically, accidental releases of toxic gases can be caused by either human error or equipment failure. The mishandling of pressurized gas containers, inadequate purging of gas manifolds, and the cross-threading of valves on gas containers are common human errors that can lead to gas leaks. However, several prevention and control options exist to prevent or minimize leaks. The existence of these prevention and safety systems to detect leaks and the fact that releases are unlikely to occur outside of occupied work space greatly reduces the human health risks associated with the use of these toxic gases within the PV industry [237]. Another possible risk related to module manufacturing is accidental fires on rooftops or combustion of spent modules in a municipal solid waste incinerator that could theoretically release fumes or vapours into the atmosphere. The inhalation of these fumes or vapours by nearby populations could affect human health. The nearby populations are of primary concern because the concentrations of chemicals in the air decline rapidly as distance from the source increases. The types of chemicals released by a fire vary depending upon the type of PV module installed [238]. Regarding the impact on the environment and other living organisms, exposure to these chemicals can lead to a variety of impacts, including impaired reproduction, decreased pulmonary activity, increased mortality, and reduced growth. The severity of any effects will vary depending upon the amount and type of chemical being released. For example, ammonia, arsenic, and heavy metals are the only PV chemicals with established aquatic life criteria. Based on the criteria, cadmium appears to be the chemical most toxic to aquatic organisms [234].

From another perspective and in reference to the default associated environmental impact of PV manufacturing, the significance those emissions vary from one type to another, and from one fabricating step to another. For example, during the wafer production process, the crystalline ingots are subsequently cut into thin wafers, which results in a significant amount of waste. Besides, during sawing, a large amount of slurry is produced, which contains polyethylene glycol, silicon carbide, iron and silicon. Slurry recycling is gaining interest for environmental and economic reasons. Some improvements are being done in this step in order to reduce waste, such as using diamond wire saw, laser cutting systems, or ribbon growth. Furthermore, some chemicals are actually used during other manufacturing steps of PV modules. For example, during the crystalline silicon manufacturing, several etching steps are necessary: removal of sawing damage, texturisation to reduce the reflection (can be combined with saw damage removal) and phosphorus silicate glass removal. Alkaline solutions like KOH or NaOH are used for texturing mono-crystalline silicon PV cells. Industry is using this also for multicrystalline silicon, but less effectively, because of the different grain orientations. Research is now focused on wet acidic texturing with HF/HNO_3 solutions, as dry etching has the drawback of using gases with high GWP, like perfluoro compounds (PFCs) and sulphur hexafluoride (SF_6). The GWP of SF_6 for example is a factor 22200 larger than that of CO_2. Although these dry etching gases do not present a health hazard, the chemicals produced in the process may be toxic and/or polluting (SiF_4, HF) and need treatment. In the long term, the substitution of these high

GWP gases by low GWP ones is desirable. Dopant gases like $POCl_3$ and B_2H_3 and the gases SiH_4 and NH_3 used in the chemical vapour deposition process to make the Si_3N_4 anti-reflection coating, also pose a health risk. Lead (Pb), which is the toxic compound, exists in the tin lead solders used to interconnect the PV cells. Nowadays some alternatives are being produced, containing 96.5% tin and 3.5% silver, but this requires a higher working temperature. Other ways of encapsulation are being developed, avoiding the need for solders, where PV cells are connected by electrically conducting glues. In addition, several companies are involved in the development of lead free pastes ([239], [240]).

Thin film technologies, although presenting a significant potential for reducing energy, material and costs, have some environmental aspects that should be taken into consideration. The SiH_4 used in bulk quantities in amorphous silicon facilities may pose hazards to the surrounding community if adequate separation zones do not exist. In addition, hydrogen used in amorphous silicon manufacturing, is also flammable and explosive. Toxic doping-gases (e.g., AsH_3, PH_3, GeH_4) are used as well, but they are implemented in quantities that are too small to pose any significant hazards to public health or the environment. Nevertheless, at SiH_4 concentrations equal to or greater than 4.5%, the mixtures have been found metastable and ignited after a certain delay [235]. In CdTe manufacturing, the main concerns are associated with the toxicity of the feedstock materials (e.g., CdTe, CdS, $CdCl_2$). The occupational health hazards presented by Cd and Te compounds in various processing steps vary as a function of the compound specific toxicity, its physical state, and the mode of exposure. However, some researches concluded that the environmental risks from CdTe PV are minimal. The estimated atmospheric emissions of 0.02 g of Cd per GWh of electricity produced during all the phases of the modules life cycle are considered to be extremely low. In addition, the large scale use of CdTe PV modules does not present any risks to health and the environment as well, and recycling the modules at the end of their useful life completely resolves any environmental concerns ([241]-[244]). In case of CIS PV cells, the main processes include the co-evaporation of Cu, In, Se and selenization of Cu and In layers in H_2Se atmosphere. The toxicity of Cu, In and Se is considered mild, but hydrogen selenide is highly toxic. In addition, the presence of hydrogen selenide in some CIS fabrication processes requires engineering and administrative controls to safeguard workers and the public against exposure to this highly toxic gas exercised when working with this material, and several layers of control must be implemented to prevent exposure of the employees [245].

MOCVD is today’s most common process for fabricating mulitjunction III/V PV cells (GAs); but it employs the highly toxic hydride gases, such as arsine and phosphine, as feedstocks. Processes where such compounds are used or produced in the form of fine fumes or particles present larger hazards to health. Similarly, those involving volatile or soluble Cd compounds (e.g., $CdCl_2$) also must be more closely scrutinized

Actually, the most significant amount of emissions and impact on the environment comes from the associated intensive energy processes that are mostly dependent on fossil fuels. In this regard, research is ongoing to reduce energy consumed during manufacturing, as well as reducing the quantities of toxic materials employed during fabrication. This can be done through various techniques applied on various processes; for example, improving the deposition processes in the final PV cell layers. Another example is the development of a new texturization process based on a uniform, isotropic and slow removal of silicon, for multicrystalline silicon PV cells [246]. Other efforts can be found focused on developing a silane-free PECVD silicon carbon nitride passivation and antireflection coating for high efficiency silicon PV cells ([247], [248]). Some researches have studied the fabrication of Eco-friendly mini-modules made of n-type Aluminium rear emitter PV cells, where the PV cells are boron free which guarantees more stable efficiencies when exposed to sunlight. Moreover, a lead free conductive film has been used for bonding the interconnection tabs between PV cells [249]. Regarding the environmental improvements of thin film technology, one-step fabrication of the CIGS absorber layer without excess Se supply during/after deposition or post-selenization treatments has been reported [250]. Copper Zinc Tin Sulphide (CZTS) is a novel thin film technology that is considered as a replacement for CdTe PV cells in order to avoid the environmental concerns of Cadmium and the limited supply of Te. Such material is considered to be non-toxic, abundant and inexpensive. The deposition methods and the performance of such novel technology are discussed else where ([251]-[253]). Like the thin film materials, nanostructured PV cells are another technology type that is being developed with the aim of reducing the consumption of PV materials and embodied energy. Although environmental improvement has been claimed for the application of nanostructured PV cells, such as dye-sensitized and organic ones, their manufacturing still includes relatively high inputs of energy and scarce natural resources during the production of nanoparticles; in addition to a relatively low efficiency and poor recyclability compared with the multicrystalline silicon PV cells ([254]-[256]). This invokes the need to focus more environmental research on nanostructured PV cells. Within this context, some research trends are progressing in this field; an example is a recent study showing the fabrication of an efficient single layer organic PV cell based on plain buckminsterfulerence (C_{60}), which is expected to open the opportunity for a new environment-friendly energy source [257].

3.1.3 Decommissioning

The PV modules can be decommissioned at the end of their useful life, 20 to 30 years after their initial installation. Decommissioning of PV modules might be associated with some environmental concerns. For example, in case of decommissioning thin film PV modules, the principal concern is associated with the presence of Cd in CdTe and CdS PV thin films, and the presence of lead (Pb) in multicrystalline silicon modules (in case they contain Pb-based solder). If these modules end in a municipal waste incinerator, the heavy metals will gasify and a fraction of which will be released in the atmosphere. If the modules end in municipal landfills, then the potential for the heavy metals to leach out in the soil and surface water exists [235]. However, on the other hand, the results of some works within this context concludes that the on going growth of CdTe PV is unlikely to produce a significant increase in the overall Cd emissions to the environment; principally thanks to the expected stringent control of the related Cd containing waste flows, as well as the intrinsically lower leach ability and toxicity of CdTe than other Cd compounds [258].

The ultimate solution to the PV waste and end-of-life management appears to be in recycling of the PV modules, as it has been claimed that it offers better environmental benefits ([259], [260]). In addition, recent studies shows that recycling, based on current collection/recycling infrastructure and on emerging recycling technologies, is technologically and economically feasible. In general, a sustainable recycling of PV thin film modules is gaining importance due to the considerable growth of the PV market and the scarcity of the resources for semiconductor materials. An example for recycling is reclaiming metals from used PV panels in metal smelting/refining facilities which use the glass as a fluxing agent and recover most of the metals by incorporating them in their product streams [261].

Furthermore, several research works can be found interested in the advancement of environmentally friendly disposal and recycling of PV modules. An experimental work reports a new procedure for the recovery of resources from waste PV modules, where the metal impurities are removed by applying a chemical etching solution on the surface of the PV cell. This investigation shows that a high yield of up to 86 % of pure silicon with purity of 99.999% could be obtained [262]. Another experimental work is found discussing the validation of a technology for the chemical recycling of crystalline silicon PV cells. It presents a chemical method for recycling spent or damaged modules and cells, and the results of its experimental validation. In those experiments, the recycling of PV cells consists of two main steps: the thermal or chemical separation of cells, and their refinement. During this process, the antireflection, metal coating, and p–n junction layers are removed in order to recover the silicon base, ready for its next use. Thus, the silicon wafers have been used for producing new silicon PV cells. In addition, although the new cells have no SiNx antireflective coating, they have very good efficiency values within the range of 13–15% [263].

Another study is found focusing on the development of two strategies for thin film PV recycling [264]. One strategy is based on wet mechanical processing for broken modules, and the other consists of combined thermal and mechanical methods for end-of-life modules. The feasibility of the processing steps has been demonstrated in laboratory scale as well as in semi technical scale using the example of CdTe and CIS modules. The investigation of the environmental impacts of both recycling strategies indicates that the strategy, which includes wet mechanical separation, has better advantages in comparison to the thermal treatment or disposal on landfills; an important one of which is that in the wet mechanical processing almost no or a small amount of chemicals are used.

Other studies show that the recycling of silicon can lead to the production of other new products, where new de-Metallization process of broken silicon PV cells and silicon PV cell production waste has been developed. In such process, the treatment of crystalline silicon PV cells or rather broken cells with a solution of aluminium chloride leads to polyaluminium-chloride which is very useful for waste water treatment or for the paper making process [265].

In reference to the wastes produced during the manufacturing of PV cells, it has been shown that recycling the significant amount of solar grade silicon that is lost into sawing slurry during the wafering processes can be beneficial. In that research, potential approach and routes for recycling and reuse of silicon wafer sawing slurry are explored. Various techniques have been used including distillation, heavy liquid separation, acid leaching and high temperature processing. In those processes, solar grade silicon could be separated and recovered depending on the impurity level, or converted into an alloying metal like copper, or technical ceramic products [266].

3.2 LCA studies of solar technologies and systems

From the above discussion, it is clearly shown that the main motive of conducting LCA of solar technologies and systems is evaluating the impact on the environment, especially during the manufacturing phase, which is responsible for inducing harmful emissions and includes various energy intensive processes. For this, a huge range of studies can be found in literature, comprising different types of systems configurations (roof mounted, ground mounted, building integrated, etc.) and different types of PV cells (c-Si, m-Si, thin film, etc.). In this chapter, a review about the LCA studies of solar technologies and systems is presented. Then, a critical analysis is conducted, showing the specifications of such studies. In addition, further classifications will be detailed in the discussion section.

During conducting this critical analysis, a filtering criterion has been adopted as follows:

- The studies before the year 1997 have been considered to be outdated.
- The studies taken into consideration in this analysis are those during the last fifteen years (Starting from the year 1997 until the year 2012).
- The articles that were published in scientific journals have been considered. The conferences papers, abstracts, reports, and other communications have been excluded.
- The review is emphasized in presenting the LCA studies of PV, PV/T, and concentrating technologies implemented as power supplying systems, whether for large scale power generation (power plants), or for smaller scales for buildings (grid connected, stand-alone, etc.). Hence, all these items are gathered in this chapter under the generic terminology ¨LCA of solar technologies and systems¨.

The state of the art and the corresponding critical analysis results are presented in the following subsections.

3.2.1 LCA of photovoltaic technologies and systems

Keoleian and Lewis (1997) [267] presents a study higlighting the LCA of the United Solar UPM-880 amorphous silicon PV module based on average insolation in Detroit, Boulder and Phoenix. In this study, the total PV life cycle, encompassing material production, manufacturing and assembly, use and end-of-life management, is investigated. Three metrics- EPT, electricity production efficiency and life cycle conversion efficiency – are used for PV modules with and without the BOS (Balance Of System) components. A minimum condition for assessing the sustainability of electricity generating systems is proposed and discussed. The results indicate that the aluminium frame is responsible for a significant fraction of the energy invested in the UPM-880 module.

Tahara et al. (1997) [268] examines the CO_2 emissions from the construction of various power plants. The LCI is calculated by "NIRE-LCA", which is a LCA software developed at the National Institute for Resources and Environment using a bottom up approach. CO_2 payback times of renewable energy electric power plants (hydroelectric, OTEC and PV) are calculated vs. conventional fossil fuel-fired power plants (coal, oil and LNG). The evaluated CO_2 payback times are found to be much shorter than the typical operational lifetimes of the respective renewable energy electric power plants.

In Dones and Frischknecht (1998) [269], the methodology used and results obtained for grid-connected PV plants in recent Swiss LCA studies on current and future energy systems are presented. Crystalline silicon technologies (c-Si, m-Si and a-Si PV) utilized in present and future panels are analysed for Swiss conditions. GHG emissions from present and future electricity systems are compared. It is found that although the high electricity requirements for manufacturing cause most of the environmental burdens associated with current PV, the environmental performance of PV systems is likely to improve substantially in the future due to the increasing efficiency of production processes and cells, and the reduced energy needs for manufacturing.

Alsema (1998) [270] compares and reviews a number of energy analysis studies for thin film PV modules (5 studies on a-Si modules and 2 studies on CdTe modules). It is concluded that significant differences are found, and many of these differences could be explained by the choice of materials for the module encapsulation. For categories with large observed differences like indirect process energy and capital equipment energy, additional analyses are performed. The EPT is found below 2 years for a grid connected module under 1700 kWh/m^2/yr irradiation. Nevertheless, it is found that an aluminium frame may add up to 0.6 years to the module EPT. Finally, it is concluded that an EPT below 1 year seems feasible in the near future.

Nieuwlaar and Alsema (1998) [271] present an expert workshop that was held in Utrecht (The Netherlands) which addressed issues and approaches regarding the environmental aspects of PV power systems, including EPT, CO_2 mitigation potential, environmental life cycle assessment and health and safety assessment and control. Various issues of environmental importance were identified during the workshop and recommendations were made for further work to ensure that PV power systems will indeed fulfil the promise of environmental sustainability. In that workshop, it was concluded that the use of PV as a replacement for fossil fuel based electricity generation has significant environmental benefits and there are no significant bottlenecks that cannot be overcome.

In Kato et al. (1998) [272], a LCA of a residential PV power system is studied, where three kinds of silicon-based PV modules are considered: c-Si, m-Si silicon and a-Si. For the c-Si PV module, it is assumed that off-grade silicon from semiconductor industries is used with existing production technologies. On the other hand, new technologies and the growth of production scale are presumed with respect to the m-Si and a-Si PV modules. The results show that c-Si PV modules have a shorter EPT than their expected lifetime and lower CO_2 emissions than the average CO_2 emissions calculated from the recent energy mix in Japan. Furthermore, it is concluded that the m-Si and the a-Si PV modules with later future technologies can give much reduction in EPT and CO_2 emissions. In addition, it is expected that reducing the glass use and planning a frameless design of the PV module might be an effective mean to further decrease the EPT and CO_2 emissions.

Watt et al. (1998) [272] addresses the air emissions of grid supply versus grid-connected and off-grid PV power generation in the context of rural household energy supply in Australia. Emissions of CO_2, SO_2 and NO_x are calculated for three life cycle stages: manufacture, use and disposal. Sensitivities to materials and data inputs, as well as to component efficiencies, lifetimes and sizing are discussed. For each supply option; the demand management options, including insulation and appliance choice, and the substitution of solar heating or bottled gas for electricity, are considered. The results show that the best option in all cases is a grid-connected PV system used to supply an energy efficient household with a mix of solar, gas and electric appliances.

In Alsema (2000) [274], the energy requirements for the production of PV modules and BOS components are analyzed in order to evaluate the EPT and the CO_2 emissions of grid-connected PV systems. Both crystalline silicon and thin film module technologies are investigated. The results show that the EPT is found between 2.5-3 years for roof-top installations and 3-4 years for multi-megawatt, ground-mounted systems. The specific CO_2 emission of the rooftop systems is calculated as 50-60 g/kWh at the moment of the study, and values of 20-30 g/kWh is expected to be achieved later. It is concluded that in the longer term, grid-connected PV systems can contribute significantly to the mitigation of CO_2 emissions.

In Alsema and Nieuwlaar (2000) [275], the energy balance of PV energy systems is analysed in order to evaluate the EPT and the CO_2 emissions of grid-connected PV systems. The energy requirements for production of PV modules based on crystalline silicon and thin film technologies are discussed, as well as for the manufacturing of other system components. The EPT is found to be 2.5-3 years for roof-top installations and almost 4 years for multi-megawatt, ground-mounted systems. Prospects for improvement of the energy balance of PV systems re discussed and it is found that for future PV technology (in 2020) the EPT may be less than 1.5 year for roof-top systems and less than 2 year for ground-mounted systems. The specific CO_2 emission of the roof-top systems is calculated as 50-60 g/kWh now and possibly around 20 g/kWh later in the future. It is concluded that in the longer term, grid-connected PV systems will have a significant potential for CO_2 mitigation.

Knapp and Jester (2001) [276] conducts an empirical investigation of as-manufactured PV modules, evaluating both established and emerging products. It is concluded that crystalline silicon modules achieve an EPT of 3 to 4 years, and the EPT for thin film CIS modules is between 9 and 12 years (8% production capacity), and in full production is around 2 years. In addition, it is concluded that over their lifetime, these solar panels generate 7 to 14 times the energy required to produce them. Energy content findings for the major materials and process steps are presented as well.

In Kato et al. (2001) [277], the EPT and the CO_2 emissions of a residential rooftop PV system using the CdS/CdTe PV modules are estimated. The EPT is found within the range of 1.7-1.1 years, which is much shorter than the lifetime of the PV system and similar to that of a-Si PV modules. The life-cycle CO_2 emissions are found between 14-9 g-C/kWh, which is less than that of electricity generated by utility companies. Furthermore, the study recommends further evaluating the environmental aspects for CdS/CdTe PV modules, since the CdS/CdTe PV modules uses toxic materials, and thus, additional energy might be required for processing toxic waste. The importance of decommissioning and recycling end-of-life CdS/CdTe PV modules is discussed as well.

Greijer et al. (2001) [278] perform a LCA study of a nano-crystalline dye sensitized solar cell system (ncDSC). Six different weighing methods are used to rank and select the significant environmental aspects to study further. The most significant environmental aspects according to the weighing methods are the emission of SO_2 and CO_2. However, CO_2 emission is selected as the environmental indicator depending on the growing attention on the global warming effect. In an environmental comparison of electricity generation from a ncDSC system and a natural gas/combined cycle power plant, the gas power plant results in 450 g CO_2/kWh and the ncDSC system in between 19–47 g CO_2/kWh. Moreover, it is concluded that the most significant component contributing to the environmental impact over the life cycle of the ncDSC system is the process energy for producing the PV module; secondly comes the glass substrate, frame and junction box. It is concluded that the main improvement from an environmental point of view of that technology would be an increase in the conversion efficiency from solar radiation to electricity generation and still use low energy demanding production technologies. It is recommended as well that the amount of material in the PV system should be minimised, and designed in a manner to maximise recycling.

Meijer el al. (2003) carry out an environmental comparison between the production and use phase of a tandem (InGaP on mc-Si) module, a thin-film InGaP cell module and a mc-Si module. The evaluation of the InGaP systems is made for a very limited industrial production scale. Assuming a fourfold reuse of the GaAs substrates in the production of the thin-film InGaP (half) modules, the environmental impacts of the tandem module and of the thin-film InGaP module are estimated as 50 and 80% higher than the environmental impact of the mc-Si module, respectively. The EPT of the tandem module, the thin-film InGaP module and the mc-Si module are estimated as 5.3, 6.3 and 3.5 years, respectively. Several ways are suggested to improve the life-cycle environmental performance of thin-film InGaP cells, including improved materials efficiency in production, reuse of the GaAs wafer and higher energy efficiency of the metal organic chemical vapour deposition process. The study remarks that it is worthwhile to continue the development of such thin-film systems.

Ito el al. (2003) [280] estimate the EPT, life-cycle CO_2 emission rate, and generation cost for a 100MW very large-scale PV power generation system. This system is designed assuming that it will be installed in the Gobi desert, one of the major deserts in the world. As a result of the estimation: 1.7 year of EPT and 12 g C/kWh of CO2 emission rate are found. These results show that the installation of such system in the

Gobi desert would be very promising for the global energy and environmental issues. The article points out to opportunities for future studies, where the same system could be analyzed in other desert locations.

Gurzenich and Wagner (2004) [281] examine three grid-connected PV systems (sc-Si, pc-Si and a-Si based) regarding their CED and cumulative emissions. The production of these systems was chosen to take place in seven European countries: Germany, France, Spain, Italy, Netherlands, Austria and Sweden. Due to the fact that electricity demand play a major role in production of PV modules and that power generation differs throughout these countries, it is found that CED varies from about 23.200 to 65.200 MJ/kWp. The cumulative emissions are found to lie between about 900 and 4000 kg CO_2/kWp, 1.9 and 5.5 kg NO_x/kWp, and 2.4 and 4.8 kg SO_2/kWp.

In Krauter and Ruther (2004) [282], the effective CO_2 reductions are derived for Brazil and Germany considering possible interchange scenarios for production and operation of the PV systems taking into account the CO_2 intensity of the corresponding local electricity grids. In the case of Brazil, off-grid applications and the substitution of diesel generating sets by PV systems were examined. It is concluded that CO_2 reduction may reach 26,805 kg/kWp in that case. It is remarked that the compositions of the local grids and their CO_2 intensity at the time of PV grid injection have to be taken into account during performing these calculations; as well as possible changes of the generation fuel mix in the future. It is recommended that advanced technologies such as thin films have to be considered in future studies.

Jungbluth (2005) [283] conducts a LCA study for PV power plants in the new Eco-Invent database at the time of the study. Twelve different, grid-connected PV systems are studied for the situation in Switzerland in the year 2000. They are manufactured as panels or laminates, from c-Si or m-Si, installed on facades, slanted or flat roofs, and have 3 kWp capacity. Country-specific electricity mixes are considered in the life cycle inventory (LCI) in order to reflect the market situation at that time. A new approach for the allocation procedure in the inventory of silicon purification is discussed in detail. The LCI for PV electricity shows that each production stage is important for certain elementary flows. The LCIA shows that there are important environmental impacts not directly related to the energy use (e.g., process emissions of NO_x from wafer etching). A future scenario (until 2010) is conducted, where it helps to assess the relative influence of technology improvements for some processes. Finally, it is remarked that the very detailed Eco-Invent database forms a good basis for similar studies in other European countries or for other types of PV cells.

Hondo (2005) [284] presents the results of life cycle GHG emissions from power generation systems. Nine different types of power generation systems are examined: coal-fired, oil-fired, LNG-fired, LNG-combined cycle, nuclear, hydropower, geothermal, wind power and solar PV per kWh of electricity generated is estimated for the systems using a combined method of process analysis and input–output analysis. First, average power generation systems reflecting the status in Japan are examined as base cases. Second, the impacts of emerging and future nuclear, wind power and PV technologies are analyzed. Finally, uncertainties associated with some assumptions are examined to help clarify interpretation of the results. Recommendations are presented for further analysis to evaluate those power generation technologies from other environmental as well as economic and safety aspects.

Tsoutsos et al. (2005) [285] present an overview of environmental impact assessment of PV systems. The potential environmental intrusions are assessed in order to improve them with new technological innovations and good practices in the future power systems. The analysis provides the potential burdens to the environment, which are included during the construction, the installation and the demolition phases, as well as-especially in the case of the central PV technologies- noise and visual intrusion, GHG emissions, water and soil pollution, energy consumption, labour accidents, impact on archaeological sites or on sensitive ecosystems, negative and positive socio-economic effects. It is concluded that PV systems presents tremendous environmental benefits when compared to the conventional energy sources.

In Kannan et al. (2006) [286], a LCA is performed for a distributed 2.7 kWp grid-connected c-Si PV system operating in Singapore. The principal finding of the study reveals that GHG emission from electricity generation from the PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant. However, the cost of electricity is about five to seven times higher than that from the oil or gas fired power plant. The environmental uncertainties of the solar PV system are also critically reviewed and presented.

In Fthenakis and Alsema (2006) [287], a LCA study of PV is performed using recent (2004–early 2005) manufacturing data, from twelve European and US PV companies. The study establishes an update of the EPT and GHG emissions and external environmental costs of commercial PV technologies. It is found that the estimates of external costs are about 70% lower than those in recent high-impact publications which are derived from the old data. Furthermore, it is found that for average South European solar irradiation (1700 kWh/m^2-yr) the EPT for complete installed PV systems ranges from 1 years to 2.7 years depending on the module technology. The corresponding GHG emissions range from 21 g CO_2-eq./kWh to 45 g CO_2-eq./kWh for South Europe and 27–59 g CO_2-eq./kWh for Southern Germany conditions (1300 kWh/m^2-yr). It is concluded that these emissions are 60 to 85% lower than the GHG emission estimates shown in the latest ExternE report to the European Commission.

In Tripanagnostopoulos et al. (2006) [288], an energetic and environmental assessment for the PV and PV/T systems installed at the Univetrsity of Patra (Greece) is performed by the University of Rome ‘La Sapienza’. The principal outcome of the study is that, among other different system configuration, the glazed type PV/T systems present optimum performance regarding energy, cost and LCA results. This is determined through calculating the EPT, CO_2 payback time, and cost payback time for different systems.

In Koroneos et al. (2006a) [289], a LCA is performed on the system of production of m-Si PV systems. Two environmental indicators are used: the EPT and the electricity production efficiency. Furthermore, it is assumed that the PV system is used in a small island economy, with the hypothesis of a total replacement of the existing conventional power diesel unit. Such comparison between the two power systems shows the benefits of an extended use of PV systems over the conventional diesel powered ones. According to the obtained results, the study highlights the PV systems great potential in producing electricity using limited resources during the several steps of their life cycle. In addition, it is advised that technological improvements need to be done in the manufacture of BOS components, which consume during their life cycle almost equal amounts of energy as the PV modules. In a complementary study, Koroneos et al. (2006b) [290] conduct a complete identification and quantification of air emissions, water effluents, and other life-cycle outputs is performed using the Eco-Indicator 95 methodology. The analysis shows that large scale PV systems have many advantages in comparison with a conventional power system (e.g. diesel power station) in electricity production, where burdens are released from the PV systems only during their manufacturing processes. The study recommends that technological improvements need to be done in the manufacture of BOS components which consume during their life cycle almost equal amounts of energy as the PV modules.

In Nawaz and Tiwari (2006) [291], the EPT and CO_2 emissions of PV system (A 1.2 kWp PV system of SIEMENS for mud house at IIT, Delhi) are analyzed. The embodied energy for production of PV module based on c-Si, as well as the manufacturing of other system components are computed at macro and micro levels assuming irradiation of 800–1200W/m^2 in different climatic zones in India for inclined surface. It is found that the embodied energy at micro level is significantly higher than the embodied energy at macro level. It is found that the EPT is within the range of 7-26 years, and the net CO_2 save is between 0.24–0.77 kg/kWh. The effect of insolation, overall efficiency, and the Life Time of PV system on the EPT and CO_2 emissions is studied with and without the BOS. The CO_2 mitigation potential, the importance, and the role of PV system for sustainable developments are highlighted.

In Agustin and Lopez (2006) [292], an economic and environmental evaluation is carried out on grid connected PV installations in Zaragoza (Spain). The Net Present Value and the Pay-Back Period were used to determine the profitability of a PV installation. Furthermore, the environmental benefits of the corresponding PV systems are evaluated through calculating the EPT, the emissions avoided and the externality costs. Finally, the possible effects of the application of the Kyoto Protocol are studied.

In Mason et al. (2006) [293], a LCA of the BOS components of a 3.5 MWp m-Si PV installation at Tucson Electric Power's (TEP) Springerville, AZ field PV plant is conducted. The estimate of the life-cycle energy requirements embodied in the BOS is found 71% less than those of an older central plant. The corresponding life-cycle GHG emissions are found as 29 $kgCO_2eq/m^2$. The EPT of the BOS is found as 0.21 years for the actual location of this plant, and 0.37 years for average US insolation/temperature conditions. The study considers that this is a great improvement for the EPT of about 1.3 years estimated for an older central plant. Furthermore, the results are verified with data from different databases and further tested with sensitivity and data uncertainty analyses.

Raugei et al. (2007) [294] conduct a LCA study of CdTe and CIS PV modules. The analysis makes use of an in-house developed impact assessment method named SUMMA (‘‘sustainability multi-method multiscale Assessment), where the authors employs a selection of methods that offer complementary points of view on the impact assessment, namely: material flow accounting, embodied energy analysis, emergy synthesis and CML 2 baseline 2000. A comparative study framework is also provided, where the electricity produced by the corresponding thin film systems is compared with the electricity produced by m-Si systems and the average European electricity mix. The results show a favourable environmental impact indicator of thin films, especially the CdTe systems.

Mohr et al. (2007) [295] present an environmental comparison of the production under average European circumstances and use in The Netherlands of modules based on two kinds of III–V PV cells: a thin-film GaAs cell and a tandem (GaInP/GaAs) cell. Furthermore, a comparison of these modules with m-Si modules is also presented. Such evaluation of both of the III–V systems is made for a limited industrial production scale of 0.1MWp per year, compared to a scale of about 10MWp per year for the m-Si system. The results indicate that the overall environmental impact of the production of the III–V modules is larger than the impact of the m-Si modules production. It is also found that for the III–V systems, the metal-organic vapour phase epitaxy (MOVPE) process is the main contributor to the primary energy consumption. The EPT of the thin-film GaAs and GaInP/GaAs modules are found as 5 and 4.6 years, respectively. For the m-Si module, an EPT of 4.2 years is estimated. Moreover, the study presents an uncertainty analysis, where the results for the III–V modules are found with an uncertainty up to 40%. It is concluded that the highly comparable results for the III–V systems and the m-Si system indicate that, from an environmental point of view, there are chances for further development of both III–V systems.

Pacca et al. (2007) [296] assess the environmental performance and the corresponding effect of the modelling parameters of two PV electricity generation technologies: the PVL136 thin film laminates and the KC120 m-Si modules. Three metrics are selected for such assessment: The NER, EPT, and the CO_2 emissions. The results reveal that some of the parameters affect the final analytical results: The level of solar radiation, the position of the modules, the modules manufacturing energy intensity and its corresponding fuel mix, and the solar radiation conversion efficiency of the modules. Within this context, a sensitivity analysis is presented, clarifying the effects of those parameters on the final results. For the baseline scenario, the EPT for the PVL136 and KC120 are 3.2 and 7.5 years, respectively. When expected future conversion efficiencies are tested, the EPT becomes 1.6 and 5.7 years for the PVL136 and the KC120, respectively. Based on the USA fuel mix, the CO_2 emissions for the PVL136 and the KC120 are 34.3 and 72.4 g of CO_2/kW h, respectively. It is recommended that the most effective way to improve the modules environmental performance is to reduce the energy input in the manufacturing phase of the modules, provided that other parameters remain constant. Consequently, the use of PV as an electricity source during PV manufacturing is also assessed, where the NER is considered an indicator for the performance of this scheme. The results show that the NER based on a PV system can be 3.7 times higher than the NER based on electricity supplied by the traditional grid mix, and that the CO_2 emissions can be reduced by 80%.

In Fthenakis and Kim (2007) [297], the GHG emissions, mainly CO_2, CH_4, N_2O, and chlorofluorocarbons of commercial technologies for solar electric and nuclear power generation are evaluated. The evaluation is done based on data from twelve PV companies, and reviews of nuclear fuel life cycles in the United States, Europe, and Japan. It is concluded that the lifetime GHG emissions from solar and nuclear fuel cycles in the USA are comparable under the production conditions at that time and average solar irradiation as follows: 22–49 gCO_2-eq. /kWh (average US), 17–39 g CO_2-eq./kWh (south west) for solar electric, and 16–55 g CO_2-eq./kWh for nuclear energy.

Those results are found different from previous GHG estimates which varies widely, from 40 to 180 CO_2-eq./kWh for PV, and 3.5–100 CO_2-eq./kWh for nuclear power. Nevertheless, it is remarked that several factors may significantly change this picture within the following 5 years, and that there are still unanswered questions about the nuclear fuel cycle that warrant further analyses.

Srinivasan (2007) [298] analyzes the impact of global trends on the Indian PV industry. The author believes that consolidation in the Indian industry simultaneously with exploiting its comparative advantage of flexible and low cost production techniques would help it stand on its own feet beyond the protectionist subsidy era. In addition, service provision and financing are likely to represent significant revenue opportunities while dwindling margins on module manufacture would expedite formation of vertically integrated energy service delivery chains.

Richard and watt (2007) [299] argue that the EPT time concept is obsolete, misleading and contributes in believing that ‘That PV does not payback the energy used to create it’. Thus, it is suggested using a new norm for the PV community which is the energy yield ratio (EYR). Within this context, EYR values for three different PV systems (m-Si module, 2 kW rooftop grid-connected systems, and a solar home system) are estimated and found between 4.8–13.9, which is many times the energy inputs required to fabricate the system. It is remarked that the EYR indicator is more ¨elegant¨ than the EPT since it incorporates the system life time. In addition, an energy system with an EYR of greater than unity is immediately recognisable as being able to generate more energy over its lifetime than was required to fabricate it, while a system with an EYR of less than unity can be regarded as environmentally unsustainable.

Fthenakis et al. (2008) [300] analyze the life cycle GHG emissions, criteria pollutant emissions, and heavy metal emissions from four types of major commercial PV systems: m-Si, c-Si, ribbon silicon, and thin-film CdTe based on PV production data of 2004–2006. Life-cycle emissions are determined by employing average electricity mixtures in Europe and the United States during the materials and module production for each PV system. It is found that thin film CdTe PV emits the least amount of harmful air emissions. This is attributed to the fact that it requires the least amount of energy during the module production. However, the differences in the emissions between different PV technologies are very small in comparison to the emissions from conventional energy technologies that PV could displace. Moreover, the effect of PV breeder is investigated. In general, it is concluded that all PV technologies generate far less life-cycle air emissions per GWh than conventional fossil-fuel based electricity generation technologies. In other words, at least 89% of air emissions associated with electricity generation could be prevented if electricity from PVs displaces electricity from the grid.

Ito et al. (2008) [301] present comparisons between five types of 100MW Very Large-Scale PV Power Generation Systems, from economic and environmental view points. The system considers using typical PV modules of m-Si, high efficiency m-Si, a-Si, CdTe, and CIS. The generation cost, EPT, and CO_2 emission rates are evaluated. It is found that the EPT is within the range of 1.5–2.5 years and the CO_2 emission rate is within the range of 9–16 gC/kWh. Moreover, it is concluded that using a m-Si PV module is convenient for cold deserts, while using thin film PV modules is suitable for hot deserts.

Stoppato (2008) [302] presents the results of a LCA study of the electric generation by means of PV panels. It considers mass and energy flows over the whole production process starting from silica extraction to the final panel assembling, considering the most advanced and consolidate technologies for m-Si panel production. Some considerations about the production cycle are reported; the most critical phases are found to be the transformation of metallic silicon into solar silicon and the panel assembling. Moreover, the EPT and the potential for CO_2 mitigation are evaluated, considering different geographic locations of the PV plant, with different values of solar radiation, latitude, altitude and national energetic mix for electricity production.

Celik et al. (2008) [303] present the optimal sizing and LCA of a residential PV system. The system consists of PV modules as the main power producer, lead–acid batteries as the medium of electricity storage, and other devices such as an inverter. The system's performance simulations are carried out with typical yearly solar radiation and ambient temperature data from five different sites in Turkey. The system performance is analysed as a function of various parameters such as energy production and cost. It is shown that those parameters change substantially for different system configurations and locations. It is found that, with the conservative European average electricity mix, the EPT is 6.2 years and CO_2 pay back time is 4.6 years for the presented system.

Mohr et al. (2009) [304] show, for ten impact categories, the environmental consequences of replacing fossil electricity with solar electricity into the life cycle of two types of PV modules: a thin-film GaInP/GaAs tandem module and a m-Si module. The environmental impacts are assessed for Western European circumstances. A shift in ranking of several environmental impacts of the modules is found when PV electricity is used instead of fossil electricity. Moreover, it is observed that the use of PV electricity instead of fossil electricity significantly reduces the environmental burdens of the GaInP/GaAs and the m-Si module. However, the reductions in toxicity impact scores are found to be smaller or negligible when fossil electricity is replaced by PV electricity. Thus, the study recommends giving specific attention to the processes which dominantly contribute to these impact categories. It is concluded that the results of a comparative LCA can thus be dependent of the electricity mix used in the life cycles of the assessed products.

In Garcia-Valverde et al. (2009) [305], a LCA of a 4.2 kWp stand alone PV system at the University of Murcia (south east of Spain) is presented. The EPT is found as 9.08 years, and the specific CO_2 emissions are calculated as 131 g/kWh. Furthermore, the system is compared with other supply options (diesel generator and Spanish grid), where the results show lower impacts in both cases. In addition, the results show the CO_2 emission reduction potential of PV systems in southern European countries, and point out the critical environmental issues in these systems.

In Perpinan et al. (2009) [306], a review of existing studies about LCA of PV systems is carried out. The data from this review are completed with a study conducted by the same authors in order to calculate the EPT of double and horizontal axis tracking and fixed systems. The results show that the EPT ranges from 2 to 5 years. When comparing tracking and fixed systems, it is highlighted that the great importance of the PV generator makes advisable to dedicate more energy to some components of the system in order to increase the productivity and to obtain a higher performance of the component with the highest energy requirement. Both double axis and horizontal axis trackers follow this way, requiring more energy in metallic structure, foundations and wiring, but this higher contribution is widely compensated by the improved productivity of the system.

Raugei and Frankl (2009) [307] present the state of the art of the PV energy sector, and describe three alternative scenarios for the future in terms of costs, market penetration and environmental performance. According to these scenarios, it is concluded that if economic incentives are supported long enough into the next ten to twenty years, the PV industry is likely to play a significant role in the future energy mix, while at the same time contributing in the reduction of the environmental impact of electricity supply.

In Kaldellis et al (2009a) [308], an optimum sizing methodology is developed, based on the criterion of minimum embodied energy. Various energy autonomous stand-alone PV-lead-acid battery systems are examined and two different cases are investigated: a high solar potential area and a medium solar potential area. It is found that the optimum CdTe based systems yield the minimum EPT (15 years), and the other PV systems yield less than 20 years. Finally, the principal finding in the study shows the fact that, in all cases examined, the contribution of the battery component exceeds 27% of the life cycle system energy requirements, reflecting the difference between grid-connected and stand-alone configurations. Similar to the same criteria used in that study, Kaldellis et al (2009b) [309] develop an optimum sizing methodology for stand-alone PV-battery systems in order to obtain configurations of minimum energy content. However, in this study, the proposed methodology is applied to three representative islands across the Greek territory. The results obtained are found favourable compared to the commonly used diesel electric generator solution.

Chamsilpa et al. (2010) [310] investigate the environmental impacts of a PV power plant over its entire life cycle. The first PV power plant in Thailand with a capacity of 500 kWp is taken as a model for assessment and two types of the PV modules (m-Si and thin film a-Si). Three phases are taken into consideration: module manufacturing, transportation from manufacturer to the power plant, and the operation of the power plant. The environmental impact results of the PV power plant are compared to fossil fuel power plants (coal-fired, diesel-fired, gas turbine and combined cycle). The analysis is conducted by a methodology developed at Mie University (Japan), and applied in Japan and Thailand: Numerical Environmental Total Standard methodology (NETS). It is found that the highest value of environmental impact for the PV power plant occurs at the PV module manufacturing phase, where the major environmental impacts are natural resource depletion, fossil fuel depletion, and air pollution. Beside, it is concluded that the CO_2 emissions from the PV power plant are found to be much lower than those of the fossil fuel power plants.

Azzopardi and Mutale (2010) [311] focus on the environmental aspect of future PV systems. A hybrid quantum dot based PV cells developed within a project between the University of Manchester and Imperial College London is studied, based on a very small laboratory scale production. The aim of this project is to develop affordable PV cells with efficiencies up to 10% for micro-generation applications. Some environmental indicators are evaluated: NER, EPT, and CO_2 emissions per unit generated, where they are found lower than commercially available PV modules.

Ito et al. (2010) [312] present the LCA of a very large scale PV systems installed in desert area using six types of PV modules: c-Si, m-Si, a-Si/c-Si, a-Si/µ-Si, CdTe, and

CIS PV modules. Different environmental indicators are estimated: energy requirement, EPT, and CO_2 emissions rate. Concerning the energy requirement, it is found that the CIS represents the lowest value, and largest energy requirement comes from the m-Si. The EPT of the CIS system is approximately 1.8 years, and c-Si silicon is 2.5 years. The others are found approximately as 2–2.3 years. The CO_2 emissions rate is estimated as 43– 54 g-CO_2/kW h, where the m-Si, a-Si/c-Si, and CIS shows lower CO_2 emissions rate.

Sherwani et al. (2010) [313] present a review of LCA of PV based electricity generation systems. Mass and energy flow over the complete production process starting from silica extraction to the final panel assembling are considered considering various module types: a-Si, c-Si, and m-Si. In addition, the most advanced and consolidate technologies for the PV panel productions are studied. It is concluded that further development in efficiency of PV cells, amount of material used in the PV cell system and designing the system for maximum use of recycled material will reduce the energy requirement and GHG emissions.

Der Meulen and Alsema (2010) [314] investigate the environmental impact of the production of PV modules made from thin-film silicon. It is considered to be the first study to specifically investigate the effect of Fluor gas (F-gas) usage on the environmental profile of thin-film silicon PV modules. This is because the much larger global warming potential of F-gases (17200–22800 times that of CO_2) may lead to higher environmental burdens. The focus in this study is on novel micromorph applications of nc-Si materials into current a-Si devices. Two nc-Si specific details concerning the environmental performance are identified when comparing to a-Si modules: First, in how far the extra (and thicker) silicon layers affects upstream material requirements and energy use, and second, in how far depositing an extra silicon layer may increase emissions of GHG as additional emissions of F-gases are associated to this step. The overall conclusion show that the switch to the new micromorph technology will result in a 60–85% increase in GHG emissions (per generated kWh solar electricity) in case of NF_3 based clean processing, and 15–100% when SF_6 is used. Besides, it is concluded that F-gas usage has a substantial environmental impact on both module types, in particular the micromorph one. Furthermore, it is remarked that the micromorph module efficiencies need to be improved in order to compensate for the increased environmental impacts.

Kaldellis et al (2010) [315] determine the optimum size of a corresponding PV system, comprising m-Si PV modules and lead-acid batteries, based on the criterion of minimum embodied energy. For this purpose, a representative case study is examined considering the energy demand needs of a typical remote consumer on the Island of Rhodes (Greece). According to the results obtained, the autonomous energy character of the system is reflected by the comparatively higher EPT in comparison with the corresponding grid-connected option. Nevertheless, the configurations analyzed clearly constitute sustainable energy solutions. Finally, a sensitivity analysis is carried out, based on the variation of the input energy content data.

Zhai and Williams (2010) [316] advance the LCA of PV systems by expanding the boundary of the included processes using hybrid LCA and accounting for the technology driven dynamics of embodied energy and carbon emissions. It is remarked that some processes that are excluded in process sum LCA, such as transportation, affects the results significantly. It is concluded that extending LCA from the process-sum to hybrid analysis makes a significant difference. Furthermore, dynamics are characterized through a retrospective analysis and future outlook for PV manufacturing from 2001 to 2011. It is remarked also that there is technological progress in realizing reductions in embodied energy and environmental impacts as well as lower module prices.

Ramos et al. (2010) [317] compare the CO_2 emissions coming from supplying an electrochemical reactor by those coming from the conventional grid and from PV modules under Spanish frame conditions. It is concluded that the novel process of PV solar electrochemical oxidation would be a preferred environmental option due to the lower CO_2 emissions under present and future scenarios. It is recommended to explore not only the possibilities of this technology, but also other electrochemical technologies that can be supplied directly by electricity in order to have a better sustainability performance.

Valverd et al. (2010) [318] presents a LCA study of the laboratory production of a typical bulk heterojunction organic PV cell and compares this result with those obtained for the industrial production of other PV technologies. Moreover, a detailed material inventory from raw materials to final PV module is presented, allowing the identification of the potential bottlenecks in a future supply chain for a large industrial output. The results are shown using three parameters: the EPT (2-4 years), ERF (7.49-3.75), and CO_2 emissions (109.84-54.92 geq.-CO2/kWh). It is concluded that that there are plenty of chances for improvement of organic PV cells if the fabrication procedure is optimized and scaled up to an industrial process.

In Fthenakis and Kim (2011) [319], a description of material and energy flows in four commercial PV technologies is presented: c-Si, m-Si, ribbon-silicon, and CdTe. The same life cycle approach is applied to the BOS that supports flat, fixed PV modules during operation. Besides, the life cycle environmental metrics for a concentrating PV system with a tracker is considered as well. Furthermore, select life cycle risk indicators for PV, i.e., fatalities, injure, and maximum consequences are evaluated in a comparative context with other electricity-generation pathways. Thus, this article reviews the rapidly evolving life cycle performances of PV technologies and underlines the importance of timely updating and reporting the changes.

In Bravi et al. (2011) [320], the results of a LCA study of a novel grid-connected PV micromorph system are presented and compared to other thin film and traditional crystalline silicon PV technologies. The analysis is based on production data given to the authors directly from the PRAMAC Swiss Company and it is consistent with the recommendations provided by the ISO norms and updates. The gross energy requirement, GHG emissions and EPT are calculated. A comparative framework is also provided, wherein results obtained for the case study are compared with data from literature previously obtained for the best commercially available competing PV technologies. It is concluded that there is a significant decrease in gross energy requirement, in GHG emissions and also a shorter EPT for the micromorph technology.

Sengul and Theis (2011) [321] present the results of a LCA of a proposed nano-PV, quantum dot (QD) PV module. The LCA is confined to the stages of raw materials acquisition, manufacturing, and use. The impacts of QD PV are compared with other types of PV modules and energy resources, both renewable and non-renewable.

Comparative assessment with other types of energy sources includes coal, oil, lignite, natural gas, diesel, nuclear, wind, and hydropower. The results indicate that while QD PV modules have shorter EPT, lower GWP, SO_x and NO_x emissions than other types of PV modules. On the other hand, they have higher heavy metal emissions, underscoring the need for further investigation from a life cycle perspective. However, it is concluded that QDPV modules are better in all impact categories assessed than carbon-based energy sources, but still they have longer energy EPT than wind and hydropower, and higher GWP as well.

Chel and Tewari (2011) [322] present experimental outdoor performance of a 2.32 kWp stand-alone PV system in New Delhi (India) for four weather types in each month such as clear, hazy, partially cloudy/foggy and fully cloudy/foggy weather conditions respectively. Considering such conditions, the energy production factor and the EPT of such system are also presented and compared to another previously installed BIPV system.

In Laleman et al. (2011) [323], a broad environmental evaluation of residential PV systems for regions with a rather low solar irradiation of 900–1000 kWh/m^2/year, which is a typical value for Northern Europe and Canada, is presented. Based on the Eco-invent database, six LCIA methodologies are considered for six different PV-technologies: EI99 with its three perspectives (Hierarchist, Egalitarian and Individualistic), next to CED, GWP and EPT. For regions with low solar irradiation, it is found the EPT is less than 5 years. The GWP of PV electricity is found about 10 times lower than that of electricity from a coal fired plant, but 4 times higher when compared to a nuclear power plant or a wind farm. Moreover, it is found that the results from the EI99 methodology do not correlate at all with the findings based on EPT and GWP. Regarding the EI99 methodology, the results from the Individualist perspective are found strongly influenced by the weighting of the different environmental aspects, which is considered to be misleading. Thus, it is recommended that in order to obtain a well balanced environmental assessment of energy technologies, a carefully evaluated combination of various impact assessment methodologies is needed.

In Bayod-Rujula et al. (2011) [324], a LCA of two grid-connected PV plants (with and without solar tracking) in different geographic locations is presented. Different environmental indicators are used, such as the IPCC 2007, CED, and EI99. It is concluded that the use of just one environmental indicator can lead to inaccurate conclusions, because depending on the product and the manufacturing processes involved, the damage to the environment occurs differently. Each environmental indicator focuses the attention in different impact categories, as for example GWP, primary energy consumption or damage to the health.

Zhong et al. (2011) [325] compare the environmental impacts of a m-Si PV module and a wind turbine. The study models landfill disposal and recycling scenarios of the decommissioned PV module and wind turbine, and compare their impacts to those of the other stages in the life cycles. It is found that the wind turbine has smaller environmental impacts in almost all of the categories assessed. It is concluded that with the wind turbine recycling scenario, when large quantities of waste are recycled, the potential savings can be quite large, while with the PV module, small quantities of recycled waste mean that the benefits of recycling are not fully reaped.

In Reich et al. (2011) [326], the direct and indirect emissions associated with PV electricity generation are evaluated, focussing on GHG emissions related to crystalline silicon PV module production. Electricity supply technologies used in the entire PV production chain are found to be most influential. Emissions associated with only the electricity-input in the production of PV vary as much as 0–200 gCO$_{2\text{-}}$eq/kWh electricity generated by PV. This wide range of results is because of specific supply technologies one may assume to provide the electricity-input in PV production, i.e., whether coal-, gas-, wind-, or PV-power facilities. The heat input in the entire PV production chain, for which mainly the combustion of natural gas is assumed, adds another 16 gCO$_2$-eq/kWh. The GHG emissions directly attributed to crystalline silicon PV technology alone constitute only 1–2 gCO$_2$-eq/kWh. The difference in scale indicates the relevance of reporting indirect emissions due to energy input in PV production separately from direct emissions particular to PV technology. Furthermore, it is also demonstrated the utilization of direct and indirect shares of emissions for the calculation of GHG emissions in simplified world electricity and PV market development scenarios.

In Held and llg (2011) [327], the update of LCA results demonstrates that considerable improvements are reached in the environmental profile of CdTe PV power and EPT over the last four years. Depending on the location of installation in Europe, the corresponding GHG emissions of PV power for ground mounted power plants are found between 19 and 30 gCO$_2$-eq/kWh and between 0.7 and 1.1 years in terms of EPT. Furthermore, the environmental impacts due to an already applied recycling procedure of CdTe modules and its relative contribution to the CdTe PV life cycle are investigated.

Ito et al. (2011) [328] identify a suitable type of mega-PV system from an environmental viewpoint. The authors have evaluated six types of twenty different PV modules with actual equipment data and output: m-Si, a-Si/m-Si, mc-Si, a-Si, mc-Si/a-Si and CIS. The boundaries of LCA are from the mining stage to that of waste management. The results show an energy requirement ranging from 19 to 48 GJ/kW and an EPT of between 1.4 and 3.8 years. CO_2 emissions are from 1.3 to 2.7 t-CO_2/kW, and CO_2 emission rates ranges from 31 to 67 g-CO_2/kWh. The m-Si and CIS types show good results due to their relatively higher efficiencies and lower energy requirements. The m-Si PV module do not show good results, and this is attributed to their higher energy requirement, and not having high efficiency. It is recommended that data from a longer period should be collected to obtain long term irradiation figures and clarify degradation, as the operation data used covered only one year.

Turney and Fthenakis (2011) [329] discuss the environmental issues related to the installation and operation phases of large scale PV power plants. In this study, 32 impacts from these phases are identified and appraised, under the themes of land use intensity, human health and wellbeing, plant and animal life, geo-hydrological resources, and climate change. These appraisals assume that electricity generated by new PV power facilities will displace electricity from traditional U.S. generation technologies. It is found that 22 of the considered 32 impacts to be beneficial. Of the remaining 10 impacts, 4 are neutral, and 6 require further research before they can be appraised. None of the impacts are negative relative to traditional power generation. The impacts are ranked in terms of priority, and it is found that all the high priority impacts are beneficial. In quantitative terms, large scale solar power plants occupy the same or less land per kWh than coal power plant life cycles. It is concluded that removal of forests to make space for PV power causes CO_2 emissions as high as 36 g CO_2 /kW h, which is a significant contribution to the life cycle CO_2 emissions of solar power, but is still low compared to CO_2 emissions from coal-based electricity that are about 1100 gCO_2eq/ kWh. Thus, it is remarked that PV power plants located in true deserts, and other locations where solar insolation is intense and wildlife is absent, have the most beneficial environmental impact.

Kim and Fthenakis (2011) [330] investigate the life cycle energy implications of a-Si PV designs using a nc-Si bottom layer in the context of a comparative, prospective life-cycle analysis framework. Three R&D options using nc-Si bottom layer are evaluated and compared to the current triple-junction a-Si design, i.e., a-Si/a-SiGe/a-SiGe. The life cycle energy demand to deposit nc-Si is estimated from parametric analyses of film thickness, deposition rate, precursor gas usage, and power for generating gas plasma. It is found that the extended deposition time and increased gas usages associated with the relatively high thickness of nc-Si lead to a larger primary energy demand for the nc-Si bottom layer designs, than the current triple-junction a-Si. It is found that assuming 8% of conversion efficiency, the EPT of those R&D designs will be 0.7–0.9 years, close to that of currently commercial triple-junction a-Si design, 0.8 years. Future scenario analyses show that if nc-Si film is deposited at a higher rate (i.e., 2–3 nm/s), and at the same time the conversion efficiency reaches 10%, the EPT could drop by 30%. The study recommends keeping a timely update of this analysis if these new technologies dominate.

Gottesfeld and Cherry (2011) [331] estimate the environmental lead emissions in China and India for new PV installations, which rely heavily on lead-acid batteries for storage.

It is found that the average loss rates are 12 kg (China) and 8.5 kg (India) of lead lost per kw year of installed PV capacity in these countries. In addition, it is concluded that the planned systems added in China and India will be responsible for 386 and 2030 kt of environmental lead loss respectively over their lifespan, which is equal to 1/3 of the global lead production in 2009. It is recommended that investments in environmental controls in lead smelting, battery manufacturing, and recycling industries along with improvements in battery take-back policies should complement deployment of PV systems to mitigate negative impacts of lead pollution.

D. Zhang et al. (2012) [332] carry out a detailed study to quantify the co-benefit from the replacement of traditional coal-fired power by the large-scale PV power comprised of m-Si cells in China. The avoided emission by the substitution of PV power for coal-fired power per kilowatt-hour in China was found as CO_2 equivalent 9.597E-01 kg, SO_2 2.740E- 04 kg, NOx 6.247E-04 kg and TSP 1.020E-04 kg. The co-benefit of PV power is estimated as 0.167 yuan/kWh. From sensitivity analysis, it is found that the estimation of the damage cost, especially for CO_2, plays a decisive role in co-benefit estimation.

J. Zhang et al. (2012) [333] discuss the environmental impact assessment of three main stages in crystalline silicon PV system lifecycle: manufacture, use and disposal. The manufacture stage focuses on pollutant generation and discharge coefficient measurement of four productive processes in the crystalline silicon cell industry chain. During the use stage, the climate and environment impact assessment of large-scale PV plant is discussed. The disposal stage introduced the technology development and environment evaluation of PV system recycling and safety disposal. It is concluded that by identifying the environmental sensitivity factors and key points of pollution prevention, the environmental impact analysis and assessment for PV system in the whole lifecycle can promote the technical progress of clean production for PV industry, recycling and safety disposal of PV system in China.

Raugei et al. (2012) [334] show that there is largely a misconception fostered by the use of outdated data and, often a lack of consistency among calculation methods regarding the Energy Return On Investment (EROI) of conventional thermal electricity from fossil fuels, which is conceived being much higher than those of PVs. A thorough review is presented of the methodology, discussing methodological variations and presenting updated EROI values for a range of modern PV systems, in comparison to conventional fossil-fuel based electricity life-cycles.

Beylot et al. (2012) [335] characterize the environmental performances of large scale ground-mounted PV installations. Four scenarios are compared, considering fixed mounting structures with primary aluminium supports, or wood supports and mobile structures with single-axis trackers, or dual-axis trackers. LCI are based on manufacturers data combined with additional calculations and assumptions. Fixed-mounting installations with primary aluminium supports show the largest environmental impact potential with respect to human health, climate change and energy consumption. The climate change impact potential is found between 37.5 and 53.5 gCO_2-eq/kWh depending on the scenario, assuming m-Si modules. Moreover, it is found that mobile PV installations with dual-axis trackers show the largest impact potential on ecosystem quality, with more than a factor 2 of difference with other considered installations. It is recommended that a multi-criteria perspective with respect to environmental indicators and installations key design parameters should be undertaken with a view to optimizing PV large-scale installations environmental performances in a near future.

Kim et al. (2012) [336] present the process and the results of harmonization and screenings of GHG emissions during the life cycle of commercial thin-film PV technologies: a-Si, CdTe, and CIGS. 109 studies are reviewed, and the estimates of GHG emissions are harmonized by aligning the assumptions, parameters, and system boundaries. Other criteria we applied as well, including completeness of reporting, validity of analysis methods, and modern relevance of the PV system studied. In addition, it is examined whether the product is a commercial one, whether the production line still exists, and whether the study's core data are original or secondary. It is concluded that these screenings produced five studies as the best representations of the carbon footprint of modern thin-film PV technologies. These are harmonized through alignment of efficiency, irradiation, performance ratio, balance of system, and lifetime. The resulting estimates for carbon footprints are found as 20, 14, and 26 gCO_2-eq/kWh, respectively, for a-Si, CdTe, and CIGS, for ground-mount application under south-western United States (US-SW) irradiation of 2400 kWh/m^2/yr, a performance ratio of 0.8, and a lifetime of 30 years. Moreover, it is found that harmonization for the rooftop PV systems with a performance ratio of 0.75 and the same irradiation resulted in carbon footprint estimates of 21, 14, and 27 g CO_2-eq/kWh, respectively, for the three technologies. It is concluded that this screening and harmonization rectifies previous incomplete or outdated assessments and clarifies variations in carbon footprints across studies and amongst thin-film technologies.

Traverso et al. (2012) [337] carry out the first implementation of sustainability assessment of the assembly step of PV modules production through Life Cycle Sustainability Assessment (LCSA) and the development of the Life Cycle Sustainability Dashboard (LCSD). It is concluded that the LCSA and LCSD methodologies represent an applicable framework as a tool for supporting decision-making processes which consider sustainable production and consumption. However, there are still challenges for a meaningful application, particularly the questions of the selection of social LCA indicators and how to weigh sets for the LCSD.

In Brown et al. (2012) [338], a common framework of foreground and background categories, consistent with both LCA and Emergy Synthesis, is identified and discussed. A revised operational definition of the Emergy Yield Ratio is introduced, in light of the proposed categorization scheme, for consistent application to technological processes. Two case studies, CdTe PV and oil-fired thermal electricity production are investigated and compared. The Unit Emergy Value (UEV) of electricity generated by the thermal plant is calculated to be 5.69E5 seJ/J with services and 5.11E5 seJ/J without services. The UEV for electricity generated by the PV system is found as 1.45E5 seJ/J with services, and 7.93E4 seJ/J without services. The computed Emergy Yiled Ratio values including services are 6.8 for thermal electricity and 2.2 for PV electricity.

In Ozturk et al. (2012) [339], an energy and exergy analysis of a Flat-Plate collector, a PV system and a PV/T collector is carried out. It is observed that instantaneous energy, daily energy and exergy efficiency of the Flate-Plate collector, the PV system and the PV/T collector vary between 53-61%, 19-30%, 23-37% and 56-74%, 11-15%, 21-34% and 2-7%, 6-22% and 8-16%, respectively. In addition, the energy and CO_2 payback time of these configurations are calculated, and are found to vary between 2, 12, 3.8 and 1.6, 3.6 and 1.8 years, respectively. Such study analysis show that a considerable amount of electrical and thermal energy is generated by the PV/T collector and the sustainability of the system is improved. It is concluded that the use of the PV/T collector has better features, especially when both electricity and heat are required for domestic applications.

Desdri et al. (2012a) [340] present a work that aims at evaluating the environmental impact of a ground-mounted 1778.48 kWp PV plant located in Marsciano (Perugia, Italy). The results of the analysis are demonstrated through different environmental indicators: EI99 methodology, EPT, EROI, CO_2 emissions and GWP. Finally, the environmental impact of PV plant is compared to that of some traditional energy production systems. The results show that the PV plant has an EPT of 4.17 years and an EROI value of 4.83. It is concluded that the use of PV technology presents important environmental benefits in comparison with traditional energy production systems. In addition, it is found that the assembly stage has the main environmental impact, followed by the disposal stage and the maintenance. The environmental damage caused during the operational phase is found to be very low and it is exclusively due to land occupation. In another LCA study, Desideri et al. (2012b) [341] present a comparative analysis of the environmental impact derived from the processes of electricity generation during the whole life cycle of two hypothetical power plants located on the same site, for which a preliminary design is made: a solar thermal power plant with parabolic trough collectors, and a PV plant with a single-axis tracking system. The environmental impact of the two power plants is evaluated using the EI99 methodology. In addition, the results of the analysis of the environmental impact are used to calculate other parameters associated to the power plants: EPT, CO_2 emissions, and GWP100. It is concluded that those values are lower than those of the PV technology.

Peng et al. (2012) [342] examine the sustainability and environmental performance of PV based electricity generation systems by conducting a thorough review of the LCA studies of five common PV systems (sc-Si, m-Si, a-Si, CdTe and CIS). The results show that, among the five common PV systems, the CdTe PV system presents the best environmental performance in terms of EPT and GHG emission rate due to its low life-cycle energy requirement and relatively high conversion efficiency. Meanwhile, the sc-Si system demonstrates the worst of these results because of its high energy intensity during the PV cells production processes. The EPT and GHG emission rate of thin film PV systems are found within the range of 0.75–3.5 years and 10.5–50 gCO_2-eq./kW h, respectively. In general, the EPT of sc-SiPV systems is found within the range from 1.7 to 2.7 years with GHG emission rate from 29 to 45 gCO_2-eq./kW h, which is an order of magnitude smaller than that of fossil-based electricity. In addition, the EPT and GHG emission rates of some advanced PV systems are considered, such as high-concentration, heterojunction and dye-sensitized technologies. The EBT of high-concentration PV system is found to be lower, ranging from 0.7 to 2.0 years. The CO_2 emission rate of dye-sensitized PV system is found higher than the ones of other PV systems at the moment. It is concluded that the PV technologies are already proved to be very sustainable and environmental friendly in the state of the art. With the emerging of new manufacturing technologies, the environmental performance of PV technologies is expected to be further improved in the near future.

3.2.2 LCA of Building Integrated Photovoltaic technologies and systems

In Frankl et al. (1998) [343], a quantitative evaluation of the benefits of BIPV systems over their entire life cycle is conducted. A number of existing applications of crystalline technologies are studied; including developing a parametric analysis of possible improvements in the BOS. Results are reported in terms of several indicators: EPT, CO_2 yield and specific CO_2 emissions. The indicators show that the integration of PV systems in buildings increases the environmental benefits of PV technology. Moreover, it is found that the BOS relevance in the total energy balance of PV systems is limited because of the very high energy content of crystalline silicon cells. Furthermore, it is concluded that future optimized PV roof-integrated systems are expected to have an EPT of around 1.5 years (1 year with heat recovery) and to save during their lifetime more than 20 times the amount of CO_2 emitted during their manufacturing (34 times with heat recovery).

Oliver and Jackson (2001) [344] assess the application of PV in buildings through energy and economic analyses. A comparison is established between electricity supplies from centralised PV plants and conventional electricity sources. The comparison with conventional sources reveals that there is a significant trade-off between the environmental and economic implications of PVs: there are substantial resource benefits to be gained from using PVs to supply electricity, but the economic cost of doing so is significantly higher than conventional sources. This trade-off is reduced when the benefits of building integrated PVs (BIPVs) are considered. By comparison with centralised PV plants, it is concluded that BIPV systems offer the “double dividend” of reduced economic costs and improved environmental performance, and this double dividend can be further increased if the economic and energy costs of avoided cladding materials are taken into account.

Keoleian and Lewis (2003) [345] present a LCI model that characterizes the energy and environmental performance of BIPV systems compared to the conventional grid and displaced building materials. The model is applied to a-Si PV roofing shingle in different regions across the USA. It is found that the electricity production efficiency for a reference BIPV system (2kWp PV shingle system with a 6% conversion efficiency and 20 year life time) ranges from 3.6 in Portland OR to 5.9 in Phoenix AZ, indicating a significant EROI. It is concluded that the reference system has the greatest air pollution prevention benefits in cities with conventional electricity generation mixes dominated by coal and natural gas, not necessarily in cities where the insolation and displaced conventional electricity are greatest.

In Battisti and Corrado (2005) [346], LCA is applied to derive a complete and extended energy and environmental profile of PV systems. As a reference case, a conventional m-Si BIPV is selected, retrofitted on a tilted roof, located in Rome (Italy) and connected to the national electricity grid. Then, improved configurations of the reference system are assessed, focusing on building integration issues and the operational phase (considering an experimental hybrid PV/T system with heat recovery). It is found that all the analyzed configurations are characterized by an EPT of one order of magnitude lower than their expected life time (3–4 years vs. 15–30 years). It is found that these results are further lowered by PV hybrid systems (environmental pay back times, depending on heat recovery configuration, go down to 40–50% of the values calculated for the reference case).

In Crawford et al. (2006) [347], three BIPV systems are studied: c-Si modules, c-Si modules with heat recovery unit, and a-Si modules with a heat recovery unit. A net energy analysis of these PV systems was previously performed, but recent improvements in the data used for this study are taken into consideration. The EPT periods are found between 4 and 16.5 years, depending on the BIPV system configuration. It is concluded that the use of a heat recovery unit reduce the EPT period of a typical BIPV system.

Seng et al. (2008) [348] present the findings of several studies regarding a wide range of technical, environmental and economic issues of the BIPV application in Malaysia. It is remarked that this article can serve as supplementary information to parties who are directly and indirectly involved in the PV sector in Malaysia. Numerous data presented in this article are indications of the benefits that PV systems can bring to the government, utility companies, and PV owners. It is concluded that the government may need to put in more efforts in research and development on solar energy in order to overcome the barriers to the advancement of PV market in Malaysia.

Li et al. (2009) [349] study the thermal and visual properties, energy performance, and financial issue of semi-transparent PV facades. Data measurements including solar irradiance, daylight illuminance, and output power for a semi-transparent PV panel are performed. Case studies based on a generic reference office building are conducted to elaborate the energy and cooling requirements, and the cost implications when the PV facades together with the daylight linked lighting controls are being used. It is concluded that such integrated system could produce electricity and cut down electric lighting and cooling energy requirements to benefit the environmental, and energy and economic aspects, where the annual emissions of CO_2, SO_2, NO_x and particulates could be reduced by 852, 2.62, 1.45 and 0.11 tons, respectively.

Radhi (2010) [350] explores the variation of the total energy of BIPV systems as a wall cladding system applied to the UAE commercial sector. The results show that for the southern and western facades in the UAE, the EPT for PV system is within the range of 12–13 years. When reductions in operational energy are considered, the EPT is reduced to 3–3.2 years. It is concluded that the reduction in operational energy due to PV panels represents an important factor in the estimation of the EPT.

Lu and Yang (2010) [351] report the EPT and GHG payback time of a rooftop 22 kWp PV array, grid-connected BIPV system in Hong Kong. The annual power output is found as 28,154 kWh. The results show that the EPT of the PV system is 7.3 years, and the GHG payback time is 5.2 years considering fuel mixture composition of local power stations. Results of different orientations are considered as well: ranging from 7.1 years (optimal orientation) to 20 years (west-facing vertical PV façade). It is concluded that the sustainability of a PV system is affected by it installation orientation and location, where choosing locations and orientations with higher incident solar irradiance is one key for the sustainability of BIPV technology applications.

Sumper et al. (2011) [352] perform a LCA of a 200kW roof top PV system with m-Si modules evaluating the EPT and GHG emissions rates. The EPT is determined for the installed technology and compared to other two PV technologies (c-Si and thin-film). The results show that the analysed PV system, located in Pineda de Mar (Catalonia, Spain), has an EPT of 4.36 years. Furthermore, a sensitivity analysis modifying the values of solar radiation in different locations is performed. It is concluded that It there is a strong trend on the decrease of the EPT due to an increased radiation, as well as a slight trend for its stabilization at very high values of solar radiation.

In Hammond et al. (2011) [353], the performance of a domestic BIPV system on a whole system basis is studied. The study uses energy appraisals, economic appraisals, and the EI99 methodology. It is found that the EPT of the system is around 4.5 years. Regarding the EI99 methodology, the analysis reveals that the embodied impacts are offset by the electricity generated to provide a net environmental benefit in most categories. Only carcinogens, ecotoxicity and minerals had a small net life time burden. In addition, a financial analysis is undertaken from the householder’s perspective, alongside cost-benefit analysis from a societal perspective. It is remarked that this study highlights the importance of the new government support scheme to the future uptake of BIPV systems.

Mohr et al. (2012) [354] present a LCA study of a roof-integrated flexible PV cell laminate with tandem PV cells composed of a-Si/nc-Si in the Netherlands. A comparison of the a-Si/nc-Si PV system with a roof-mounted m-Si PV system is also presented. The ReCiPe methodology and the EPT are used as environmental indicators for such analysis. It is found that the overall damage scores of the a-Si/nc-Si PV system and the multi-Si PV system are 0.012 and 0.010 Ecopoints/kWh, respectively. For both PV systems, the impacts due to climate change, human toxicity, particulate matter formation, and fossil resources depletion together are found contributing with 96% of the overall damage scores. The EPT is found as 4.3 years for the m-Si PV system, and 2.3 years for the a-Si/nc-Si PV system. For the latter one, it is concluded that the construction for roof integration, the silicon deposition, and etching are found to be the largest contributors to the primary energy demand, whereas the encapsulation and the construction for roof integration are the largest contributors to its impact on climate change. It is remarked that the implementation of optimisations in the production process, including another type of encapsulation foil, may improve the environmental performance of the a-Si/nc-Si PV system.

Perez et al. (2012) [355] present the life cycle impacts of the Solaire BIPV and extrapolates its performance to other façade systems. The Solaire BIPV employs waste-stream sc-Si wafers. Correspondingly, zero energy input is allocated to this BIPV from wafer production, resulting to a very low EPT and GWP burden (0.8years and 10.2gCO_2/kWh, respectively). In addition, data from PV dedicated silicon wafer supply are also used; and results in an EPT of 3.8 years and a GWP of 61gCO_2/kWh. Furthermore, these results are compared with those in the International Energy Agency PV Power Systems Task 2 inventory database. It is concluded that the drawback of façade BIPV is its vertical orientation, receiving lower incident irradiation than rooftop and ground installations. On the other hand, it is detailed how the replacement of traditional cladding materials can offset such performance drawback of BIPV, in terms of environmental burden and EPT.

In Cucchiella and D´ Adamo (2012) [356], environmental evaluations are presented for a BIPV system located in Italy using various indicators: EPT, GHG/kWh, EROI, GHG Payback Time and Greenhouse Gas Return on Investment. Different types of PV cells are considered (e.g., sc-Si, m-Si, a-Si, and CdTe) as well as different locations for the system installation (Milan, Rome and Palermo). It is concluded that the optimum energetic results are gained with thin film cells, whereas the best environmental results are achieved with crystalline cells. It is recommended that the estimated metrics could be used by policymakers to establish incentives and apply it to decision making beyond energy technology.

3.2.3 LCA of Concentrating Photovoltaic technologies and systems

In Peharz and Frank (2005) [357], the EPT of the high-concentration PV system FLATCON using III–V semiconductor multi-junction PV cells is evaluated. The energy demand for the system manufacturing, including transportation, balance of system and system losses are considered. The results show that the EPT turns out to be as low as 8–10 months for a FLATCON concentrator built in Germany and operated in Spain. The EPT rises slightly to 12-16 months for a system installed in Germany. It is found that the main energy demand in the production of such a high-concentration PV system is the zinced steel for the tracking unit.

In Lechon (2008) [358], the environmental impacts of the electricity produced in a 17 MW solar thermal plant with central tower technology and a 50 MW solar thermal plant with parabolic trough technology is evaluated. The results show that the EPT of both power plants is around 1 year, and the global warming impacts along the whole life cycle of the power plants are found around 200 g/kW h generated. Finally, the environmental impacts associated with the compliance of the solar thermal power objectives in Spain are computed. Those figures are then used to estimate the avoided environmental impacts including the potential CO_2 emission savings that could be accomplished by these promotion policies. These savings amounts for 634 kt of CO_2 equiv./year.

In Nishimura et al. (2010) [359], the environmental load and EPT of PV power generation systems are evaluated. Two hypothetical case studies in Toyohashi (Japan) and Gobi dessert (China) are considered, taking into account a high-concentration PV power generation system and a m-Si PV power generation system. The study shows that a system of 100MW size, the total impacts of the high-concentration PV system installed in Toyohashi is larger than that of the high-concentration PV system installed in Gobi desert by 5% without consideration of recycling stage. In addition, it is demonstrated that the EPT of the high-concentration PV system assumed to be installed in Gobi desert is shorter than the high-concentration PV system assumed to be installed in Toyohashi by 0.64 year. Comparing the high-concentration PV and m-Si PV, the ratio of the total impacts of the m-Si PV to that of the high-concentration PV is 0.34 without considering the recycling stage. Furthermore, it is found that the EPT of the high concentration PV is longer than that of the m-Si PV by 0.27 year. In addition, it is concluded that using m-Si PV in Gobi desert is the best option.

Piemonte et al. (2011) [360] present a LCA of a molten salt concentrating solar power (CSP) plant combined with a biomass Back-Up burner, developed by Italian Research Centre ENEA. Besides, the environmental performance of the CSP plant is compared with this of conventional oil and gas power plants. The results show that the molten salt CSP plant is preferable to the conventional (oil and gas) power plants. It is remarked that such finding confirms the high potentials, from an environmental point of view, of this innovative plant technology. However, it is also worth highlighting that the molten salt CSP plant technology is a very young technology in comparison to the conventional power plants, therefore further developments, mainly finalized to improve the conversion efficiency from thermal to electrical energy, must be carried out. It is concluded that due to the uncertainties associated with LCI data reliability, the results reported in this work can be useful to draw first considerations about the environmental reliability of molten salt CSP plant.

In Burkhardt et al. (2011) [361], LCA is used to evaluate a reference design of a parabolic trough Concentrating Solar Power (CSP) facility located in Daggett, CA, along four sustainability metrics: life cycle GHG emissions, water consumption, CED, and EPT. This wet-cooled, 103 MW plant utilizes mined nitrates salts in its two-tank, thermal energy storage (TES) system. Design alternatives of dry-cooling, a thermocline TES, and synthetically derived nitrate salt are evaluated. During its life cycle, the reference CSP plant is estimated to emit 26 gCO_2eq/kWh, consume 4.7 L/kWh of water, and an EPT of approximately 1 year. The dry-cooled alternative is estimated to reduce water consumption by 77% but increase the GHG emissions and CED by 8%. In addition, it is found that synthetic nitrate salts may increase the GHG emissions by 52% compared to the mined. In addition, it is concluded that switching from two-tank to thermocline TES configuration reduces GHG emissions, most significantly for plants using synthetically derived nitrate salts. It is also concluded that CSP can significantly reduce GHG emissions compared to fossil fuelled generation; however, dry-cooling may be required in many locations to minimize water consumption.

Fthenakis and Kim (2012) [362] detail the material and energy inventories in the life cycle of high-concentration PV systems, and evaluates their EPT, life cycle GHG emissions, and usage of land and water. It is found that, although operating high-concentration PV systems require considerable maintenance; their life cycle environmental burden is much lower than that of the flat-plate crystalline silicon systems operating in the same high-insolation regions. The estimated EPT of the Amonix 7700 PV system in operation at Phoenix, AZ, is found as 0.9 year, and its estimated GHG emissions are calculated as 27 g CO_2-eq/kWh over 30 years, or approximately 16 g CO_2-eq/kWh over 50 years.

Burkhardt III et al. (2012) [363] review the LCA literature of utility-scale Concentrating Solar Power (CSP) systems. The analysis focuses on reducing variability and clarifying the central tendency of published estimates of life cycle GHG emissions through harmonization. From 125 references reviewed, 10 produced 36 independent GHG emissions estimates passing screens for quality and relevance: 19 for parabolic trough (trough) technology and 17 for power tower (tower) technology. The interquartile range (IQR) of published estimates for troughs and towers are 83 and 20 gCO_2-eq/kWh respectively; median estimates are 26 and 38 g CO_2-eq/kWh for trough and tower, respectively. Two levels of harmonization are applied. Light harmonization reduces variability in published estimates by using consistent values for key parameters pertaining to plant design and performance. The IQR and median are reduced by 87% and 17%, respectively, for troughs. For towers, the IQR and median decreased by 33% and 38%, respectively. Next, five trough LCAs reporting detailed LCI are identified. The variability and central tendency of their estimates are reduced by 91% and 81%, respectively, after light harmonization. By harmonizing these five estimates to consistent values for global warming intensities of materials and expanding system boundaries to consistently include electricity and auxiliary natural gas combustion, variability is found to be reduced by an additional 32% while central tendency increases by 8%. It is concluded that these harmonized values provide useful starting points for policy makers in evaluating life cycle GHG emissions from CSP projects without the requirement to conduct a full LCA for each new project.

M. Zhang et al. (2012) [364] present an ecological accounting framework based on embodied energy and emergy analyses methods. The analyses are performed for the 1.5 MW Dahan solar CSP tower power plant in Beijing (China) and different evaluation indices used in the embodied energy and emergy analyses are employed to evaluate the plant performance. The analysis of the CSP plant is then compared to six Italian power plants with different energy sources and an American PV plant. The results demonstrate that the CSP is the superior technology. It is concluded that the CSP technology can be sustainable in the long run and that its sustainability is nearly the same as that of the Geothermal or Hydro power plants in Italy.

3.3 Discussion

In this chapter, a review is conducted demonstrating the most relevant environmental concerns spotted within solar technologies and systems life cycle. In addition, a critical analysis and a state of the art of LCA studies of solar technologies and systems is presented during the last fifteen years (from 1997 till 2012) based on filtering criteria as detailed previously at the beginning of section 2.

Within this context, some observations are derived regarding the LCA studies of solar technologies and systems, demonstrated as follows:

Figure 26 shows the chronological order of the presented studies. A fluctuating trend is noticed throughout the years. However, starting from the year 2007, a notable change and increment in the curve is noticed, reaching the top during the years 2011 and 2012.

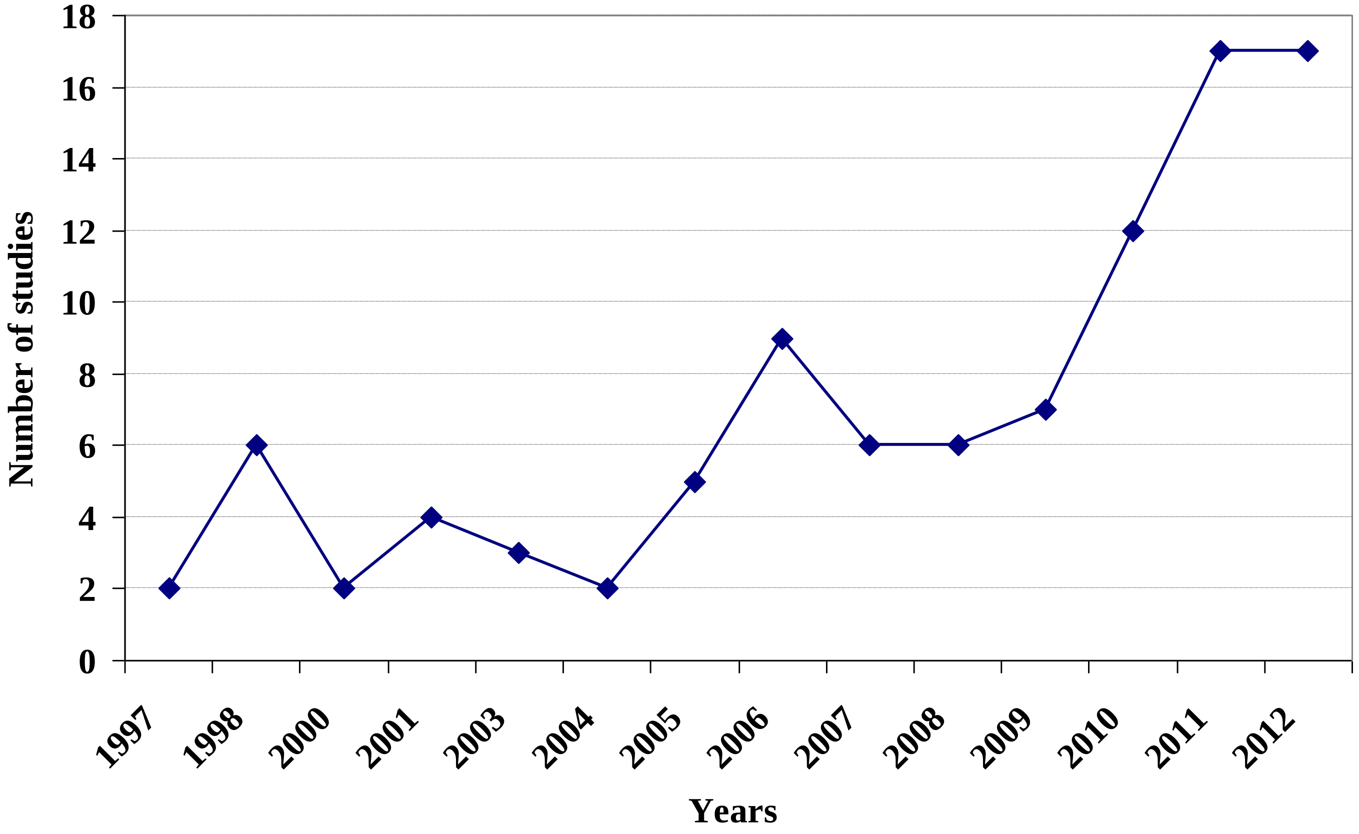

Figure 26. Chronological order of the presented studies

Figure 27 show the world continents contribution to LCA studies of solar technologies and systems, followed by Figure 28 that shows the corresponding contribution of the European continent countries. It is shown that Europe is the dominant continent regarding this domain of studies (52%), followed by Asia (25%) and North America (18%). Regarding the European countries, it is found that the Netherlands is the dominant country (20%), followed by Italy (20%) and Spain (18%).

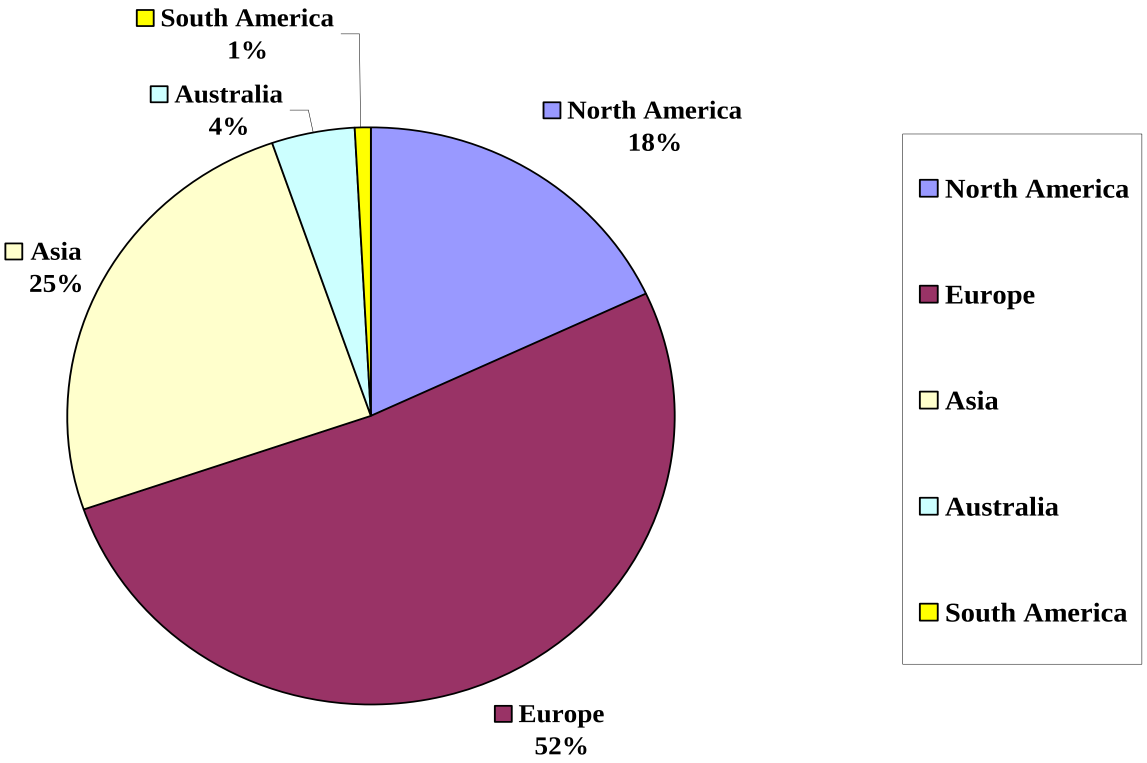

Figure 27. Comparison between the contribution of the world continents in the LCA studies of PV systems

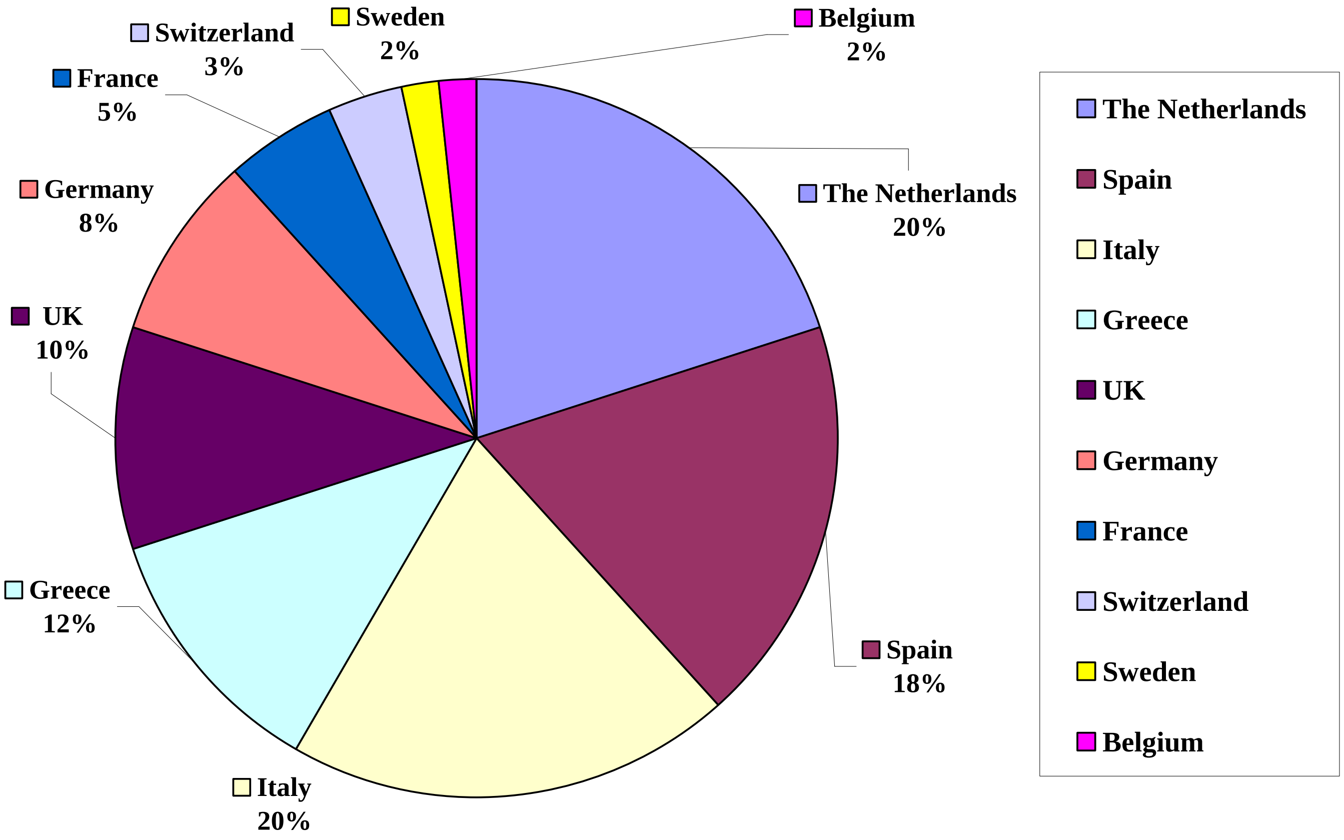

Figure 28. Comparison between the contribution of the European continent in the LCA studies of PV systems

Regarding the system types studies, Figure 29 and Figure 30 show the contribution percentage of the studied systems types. It is shown that 70% of the studies are concerning the PV systems with the most common configurations such as roof mounted or ground mounted whether within low or high power generation systems, while the building integration schemes represent about 14%. Regarding the concentration technology, it is found that only 8% of the studies are concerned with this theme, where all of them are about high concentration systems.

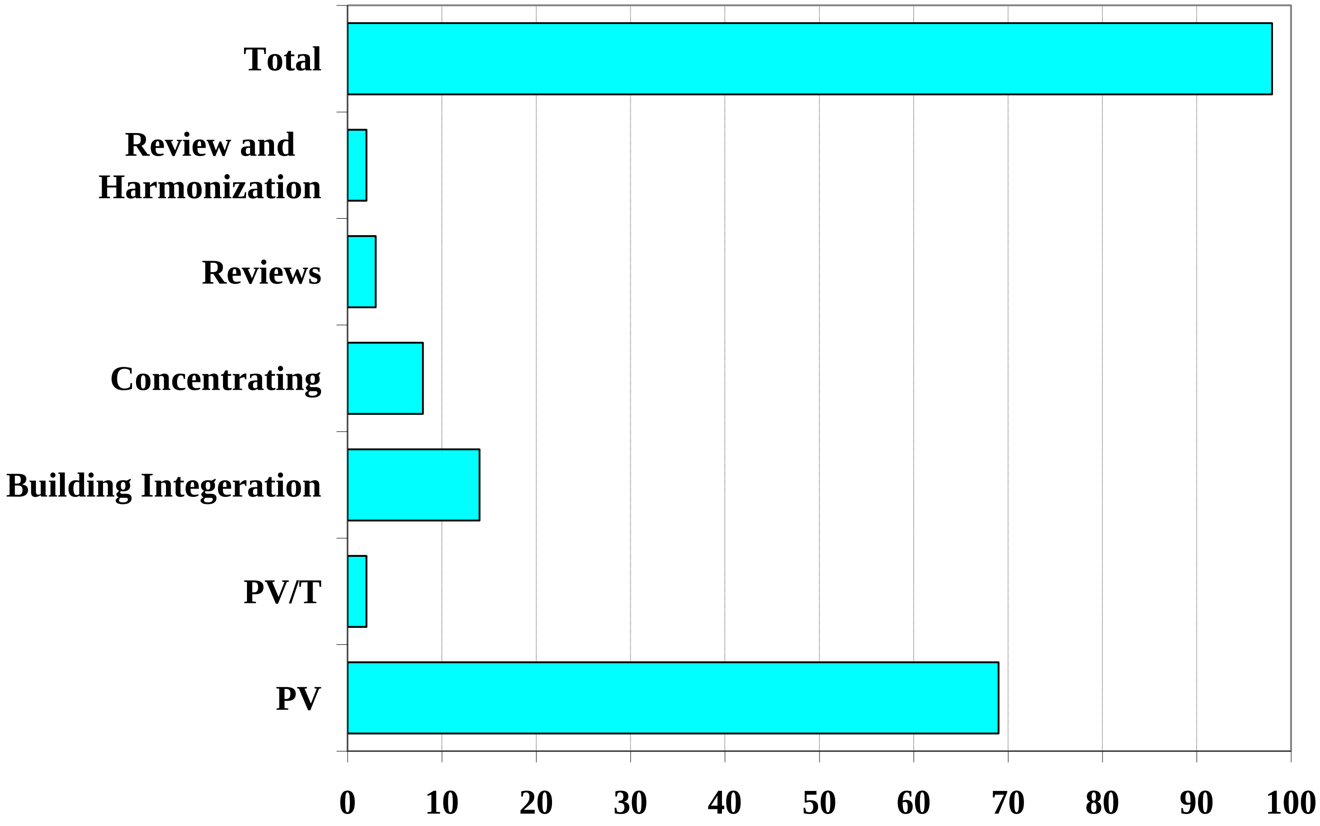

Figure 29. Comparison between the types of systems found in the corresponding studies

Within the building integration schemes, it is deduced that about 78% of the studies is referring to BIPV (Figure 30), while very small percentage is about other types, such BIPVT (14%), followed by only two studies about semi-transparent PV integrated into buildings: BISPV (Building Integrated Semi-transparent Photovoltaic) and BISPVT (Building Integrated Semi-Transparent Photovoltaic Thermal).

Figure 31 show the contribution percentage of the PV technology types found in the corresponding studies. It is observed that the silicon PV cells are the dominant ones, where they constitute 50% of the studies, followed by the thin film technology where they represent 32% of the studies (including a-Si, CdTe, etc.). The multijunction and nano structured technologies represent a fewer percentage, around 12% and 6%, respectively.

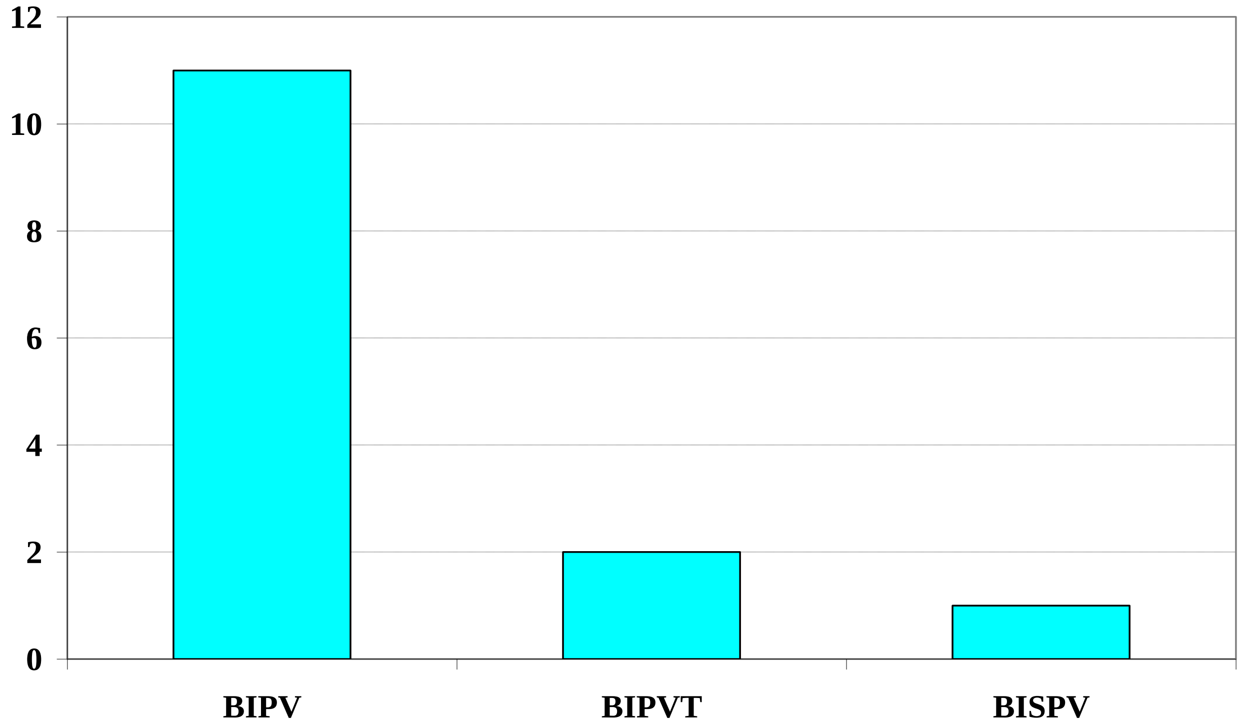

Figure 30. Comparison between the integration systems found in the corresponding studies

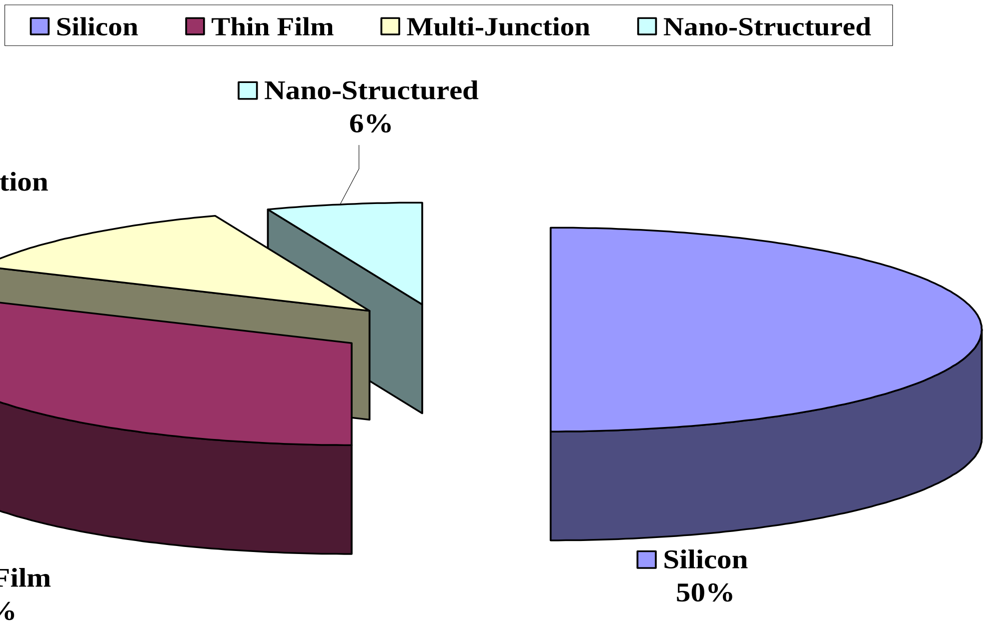

Figure 31. The contribution percentage of the PV technology types found in the corresponding studies

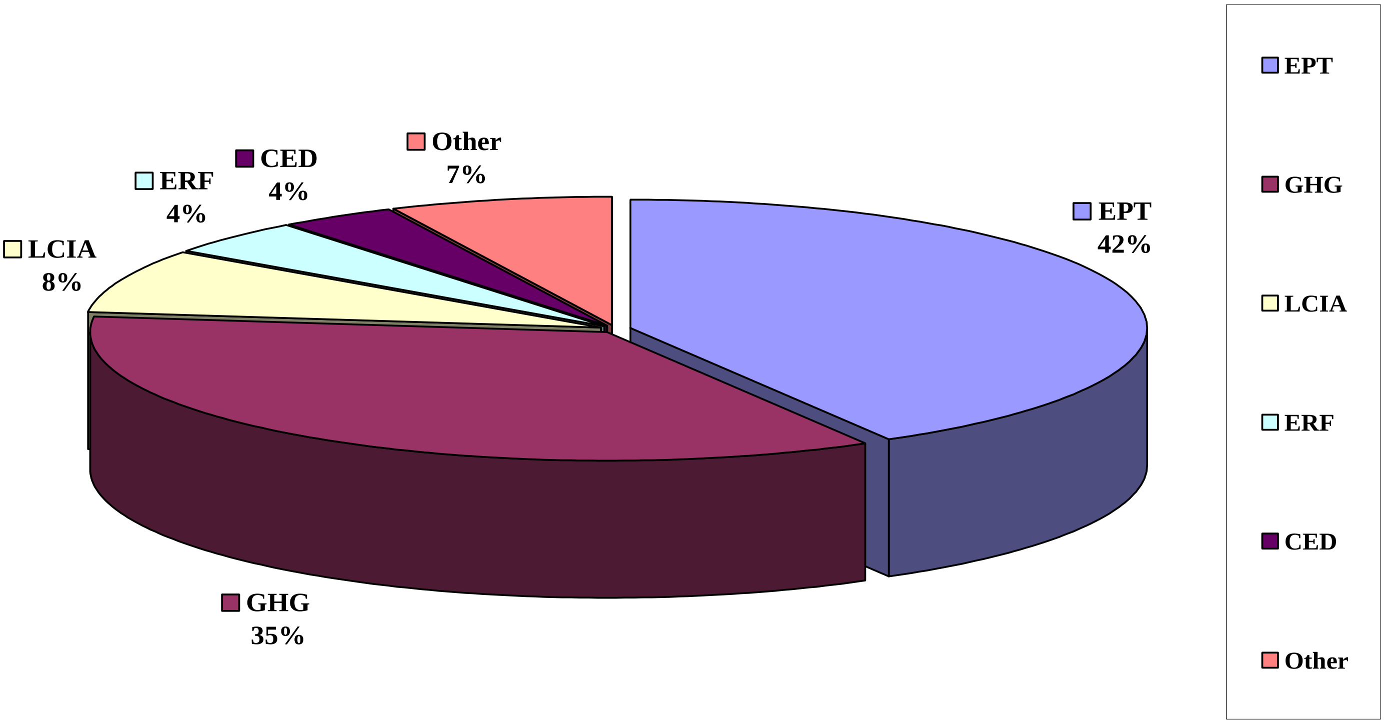

Figure 32. The percentage contribution of the environmental indicators used in the corresponding studies

Figure 32 show the contribution percentage of the environmental indicators found in the corresponding studies. It is concluded that the EPT and GHG indicators are the most dominant, where they exist in 42% and 35% of the corresponding studies, respectively. Besides, it is noticed that the environmental evaluation using the LCIA methodologies exist in only 8% of the studies. In addition, it is observed that other environmental indicators (Emergy Yield Ratio, GHG Payback time, especially developed methodologies, etc.) are less frequently found in the studies. Referring to the LCIA methodologies used (8% of the studies), it is found that the EI99 methodology is the most commonly used one, where it exist in more than half of these studies, followed by the CML methodology, and then comes the contribution of ReCiPe with an in insignificant contribution (Figure 33).

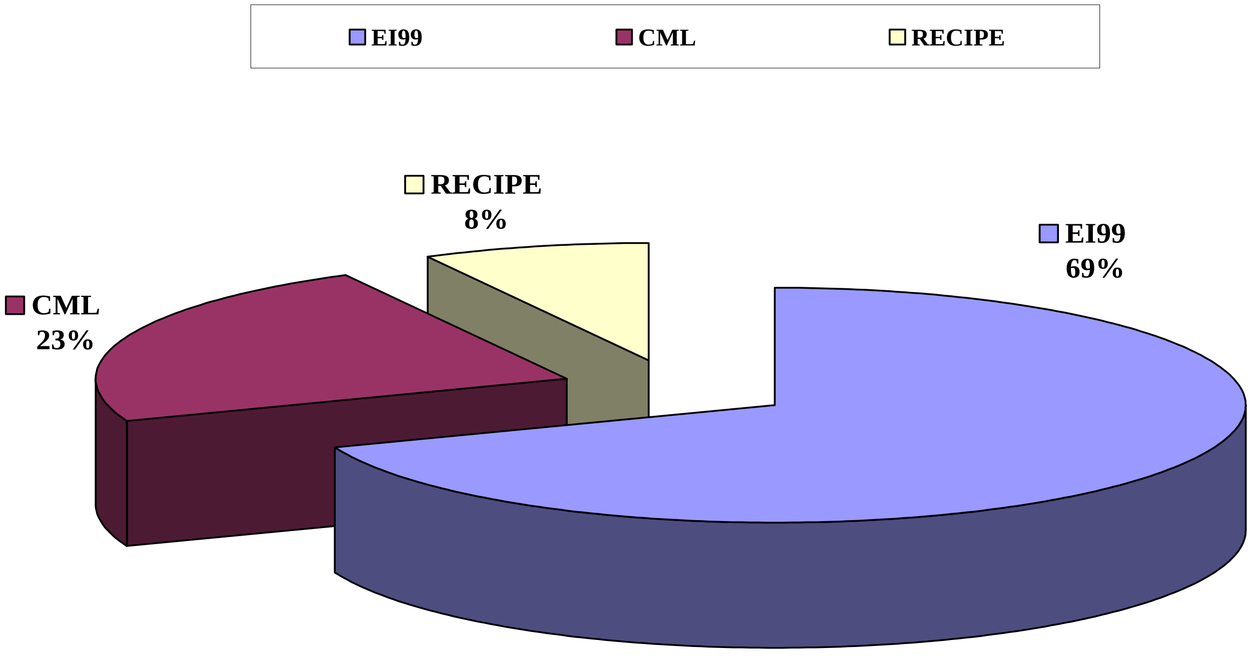

Figure 33. Contribution percentage of the LCIA methodologies found in the corresponding studies

Hence, in this regard, it is concluded that three gaps in the surveyed literature are found:

- Lack of using LCIA methodologies, and lack of combining between environmental and energy indicators: The EPT and GHG are the most dominant. Evaluating the EPT, and consequently working on finding solutions to reduce it through increasing the operational efficiency, is not sufficient for an overall environmental improvement performance. The high dependence on the EPT as the sole environmental indicator of a certain system does not provide a comprehensive environmental performance prospective, as this criterion does not take into consideration the instantaneous impact that is induced during the assembly phase. Therefore, through using the LCIA methodologies, and by focusing on the assembly phase, the explication of the temporal resolution of the environmental impact can be clearly spotted (i.e. the impact of a certain quantity of emissions of a specific substance on the environment during a period of one month is worse than the impact of the same amount of emissions spread throughout the whole year). Furthermore, some studies have shown that in the future, as more PV systems will be installed, the energy mix itself will be mostly powered by PV systems. This will make the EPT indicator no longer viable for providing the best guidance for the environmental performance improvements of PV systems [362]. In addition, the EPT does not take into consideration the whole system life time impact.
- The LCA of building integration of PV systems: A noticed lack of LCA studies of BIPV systems. In addition, no studies were found to be concerned about the LCA of BICPV systems.
- The LCA of concentrating systems: A lack of LCA studies of this novel technology. Besides, all the existing studies in literature are focused on high concentration systems.

Hence, the research work in the following chapter contributes in dealing with the aforementioned gaps by presenting two novel sustainable BICPV systems through LCA from an environmental and energy profiles viewpoints. The environmental profile is evaluated using a widely used LCIA methodology (EI99) and other supporting methodologies as well. In order to analyze the system from an energy profile viewpoint, the CED methodology is used, beside other life cycle indictaors (The ERF and The EPT).

4 Chapter 4

LCA of BICPV systems

4.1 Systems description

Two Building Integrated Concentrating Photovoltaic systems have been assembled and tested at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain). The two systems have been established based on the results and knowledge of previous related studies conducted by Chemisana and Rosell [7], Chemisana [366], and Nalis et al. [367]. In order to present more generalized approach, the results of this study are compared to those of a conventional BIPV system of the same power and aperture area as the BICPV ones.

4.1.1 The assembly phase

4.1.1.1 The BICPV-F system

The first system is installed to be integrated as a façade system to a building (Nominated as BICPV-F). The BICPV-F system is mainly composed of two main parts: The concentrating system, and the concentrating photovoltaic (CPV) system. For the concentrating system, it is composed of 22 flat coated reflectors (2 x 0.16 x 0.006 m), with a maximum achieved concentration ratio of 10 suns. In general, low concentrating systems are of particular interest as they are of linear geometry and thus one tracking axis is sufficient for efficient operation. Within the context of the presented system, the receiver remains static and the solar tracking is achieved in a simple and effective way through the rotation of the individual reflectors. Therefore, the overall movements are minimized, facilitating incorporation into buildings and offering different possibilities for suiting the varied requirements of specific installations. Hence, the presented system is to represent the installation of the reflectors as windows blinds (Figure 34). A steel frame is used to support and position the reflectors in place. An actuator (LINAK LA 12 [367]) is connected to the upper moveable part of the steel frame for the purpose of sun tracking adjustments. The concentrating system has been installed taking into consideration the integration aspect (environmental integration, appropriate materials, dimensions that fit the composition and harmony of the building, light weight), high compactness (this is the inverse of the aspect ratio, the aspect ratio being the ratio between the focal distance and the concentrator aperture), low mirror ratio (ratio between the surface area of the reflectors and the concentrator aperture), low characteristic length (ratio between the volume needed by the tracking system to the area of the receiver), high optical efficiency, and geometric concentration above 5 suns. Hence, following these requirements, the focal length has been found as 0.8 m, the characteristic length has been found as 0.16 m, and the mirror ratio has been found as 4.4 m.

Figure 34. The reflectors facade: During the installation of the concentrating PV façade at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain). The tracking system is noticed on the left.

Referring to the CPV system, two CPV modules (Figure 35), 250 Wp each, which has been previously assembled and characterized ([367], [369]), are put in use to be the receiver units. Each CPV module consists of a 300 microns thickness layer of single-crystalline silicon CPV cell (52 cells, 48 x 36 mm each) manufactured by Narec Solar [370]. The CPV cells are insulated with a thermal tape (Thermattach T-404) [371] of 127 microns thickness. A cooling structure is installed, where it is composed of a copper U- shaped support that holds the CPV cells and the thermal tape internally, while allowing the passage of two copper cooling pipes from beneath. The cooling pipes are externally connected to a 5 watt water pump. This whole structure is enclosed within an aluminum frame box, and covered on top by a transparent white glass layer.

Figure 35. The CPV modules: designed and assembled at the applied physics laboratory at the University of Lleida (Spain)

4.1.1.2 The BICPV-S system

This system is considered as an improved modification of the previous one. In order to receive more incident radiation and therefore increase the energy output, the concentrating system is installed to be integrated with an inclination of 50º with respect to the horizontal plane, so that it can be integrated as a shading system (Nominated as BICPV-S). Fewer quantities of reflectors have been employed, with smaller thicknesses as well. The BICPV-S system installation has been established considering the fulfillment of three functions: The energy output to be optimum for the city location (Lleida, Spain), to act as an adequate shading screen, and to minimize the contour effect as much as possible. Following these requirements, the concentrator’s platform tilt angle has been found as 50º. Besides, the length of the reflectors has been selected to be 15.35% larger than the module. Additionally, similar to the BICPV-F system, the concentrating system has been installed taking into consideration the integration aspect, high compactness, low mirror ratio, low characteristic length, high optical efficiency, and geometric concentration above 5 suns. The concentrating system is composed of 17 flat coated reflectors (2.6 x 0.05 x 0.003 m), with a maximum achieved concentration ratio of 10 suns (Figure 36). The reflectors are covered from above and beneath by two protective glass sheets. A steel frame is used to support and position the reflectors in place. Following the system requirements, the focal length has been found as 2.12 m, the characteristic length has been found as 0.005 m, and the mirror ratio has been found as 0.85 m. In reference to the CPV system installed, it is the same as the CPV system used within the previously described BICPV-F system configuration.

Figure 36. The concentration system used: Assembled at the applied physics laboratory at the University of Lleida (Spain)

4.1.1.3 The BIPV system

Referring to the BIPV system included in the comparison, it mainly consists of two PV modules achieving the same power of the CPV ones (250 Wp each) from Isofoton [372]. Each module is made of a 200 microns sheet of single crystalline silicon PV cells (60 cells, 156 x 156 mm each). The PV cells are encapsulated with two 300 microns layers of PVB (Poly Vinyl Butyral), and surrounded by two transparent white glass covers. The whole configuration is supported by an aluminum frame. For a realistic presentation, the system has been characterized experimentally under the same conditions of the previously mentioned BICPV systems. It has been placed at the same tilt angle of the reflectors plane of the BICPV-S system (50º)

4.1.2 The operational phase

The energy output of each system is calculated experimentally as shown in Figure 37.

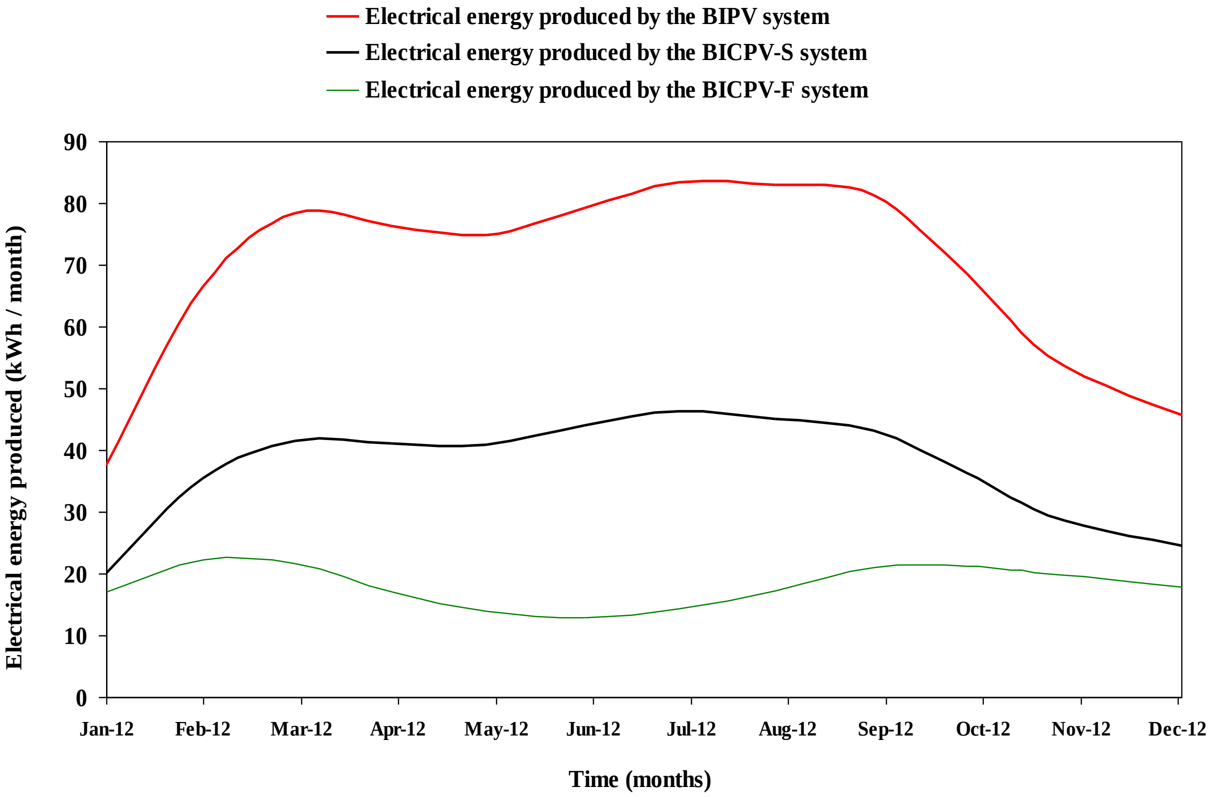

Figure 37. Electrical energy output measurements of the corresponding BACPV-F, BICPV-S, and BIPV systems during a one year period

The tests have been performed at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain) which is located in Lleida at latitude 41.36 °N and longitude 0.37 °E. The data have been collected within discrete outdoor tests from January 2012 until December 2012. The same experimental procedures detailed in [369] are adapted herein, and described briefly as follows: All the instruments and sensors were connected to data logger CR23X. The inlet and outlet fluid and ambient temperatures, wind speed, and solar radiation data were measured using type-K thermocouples, a Vector A-100R cup anemometer and a Kipp & Zonen CMP 11 pyranometer, respectively. Measurements were taken for several ambient temperatures, wind speed and solar radiation values during the corresponding one year period. The different input variables were measured every 1 second and their mean values were recorded every 10 seconds. In parallel and thus, under the same weather conditions, the electrical data were collected employing the IV tracer PVPM 2540C. The system was programmed to collect an IV characteristic curve every 10 min. Hence, the annual energy output values of the studied systems were found as follows: 215.68 kWh/year for the BICPV-F system, 444.17 kWh/year for the BICPV-S system, and 823.5 kWh/year for the BIPV system.

It is clearly observed that the BIPV system produces more energy output than both of the BICPV systems, where it produces 1.8 times more energy than the BICPV-S system, and 3.8 times more energy than the BICPV-F system. This is attributed to a number of factors that affects the irradiance from the concentrator plane to the CPV module. Those factors are mainly related to the geometry of the concentrator with respect to two aspects: First, the contour effects implies that, even trying to minimize it, the module will still receive the concentrating irradiance beam partially during some hours of the day; and second, the concentrator acceptance angle, which limits the operational daily time depending on the solar height. Hence, it is deduced that all these factors contributes in reducing the overall system efficiency significantly, leading to lower energy output.

By comparing the energy output of the two BICPV systems, it is observed that the BICPV-S system produces twice the energy output produced by the BICPV-F system. This is attributed to the 50º inclination of the reflectors plane in case of the BICPV-S system, which is different from the BICPV-F system that is installed as a vertical façade (90º). This in return affects the effective incident irradiance on the reflectors plane, allowing more radiation to be received on the reflectors plane of the BICPV-S system.

4.1.3 Systems boundaries

A service lifetime of 30 years is assumed for the three corresponding systems. In addition, an average degradation effect of 2.5% per year is assumed referring to the amount of energy output produced through the entire systems life cycle [373].

In reference to the study boundaries, two life cycle phases are taken into consideration: The assembly phase that comprises the systems components (extraction, manufacturing, etc,), and the operational phase during the entire systems lifetime, which is based on the experimental calculation of the energy output. That latter phase takes into consideration water consumption used for occasional cleaning. The impact of such consideration has been found insignificant. However, it has been included in the calculations in order to approximate the conditions to the closest actuality from an operational viewpoint. The disposal phase is not taken into consideration as no certainty about the post consumption phase is found after 30 years of service life time.

For simplification purposes, the transportation has been excluded. In this sense, this does not affect the results certainty. This is supported by the results of many other related studies, showing that the transportation does not affect the environmental impact and embodied energy significantly, ranging from 0.2% to a maximum contribution of 2% of the total ([351], [359]) and only reaching 6% in a specific case study, where the transportation included importing several parts of the corresponding PV systems from Asia to Europe [344].

4.2 Methods

The LCA study has been achieved concerning two aspects: The environmental profile, and the energy profile. Regarding the environmental profile, the evaluation is performed using different LCIA methodologies. For the energy profile analysis, it is achieved using the CED during the assembly stage, and consequently, the Energy Return Factor (ERF) and the Energy Payback Time (EPT) for the energy profile evaluation during the whole life cycle. The analysis has been achieved mainly using Simapro 7 software in conjunction with the Eco-Invent database.

4.2.1 Environmental profile evaluation methods

Since LCIA methodologies differ in several aspects (modeling approach, characterization factors, impact categories, etc.), it is then foreseen that different LCIA methodologies would lead to different results with respect to the same analyzed system. Hence, it is useful to use different LCIA methodologies in evaluating the systems environmental profiles, as this will assist in viewing the systems environmental performance from different perspectives. In addition, such analysis and comparisons will highlight the differences between the LCIA methodologies in a practical way through demonstrating them within a case study. Thus, four LCIA methodologies have been chosen for in order to conduct the environmental profile analysis: The EI99 methodology which is the default one used in the analysis (Hierarchist perspective), EPS 2000 methodology, IMPACT 2002+ methodology, and the ReCiPe methodology (Hierarchist perspective).

In the EI99 and the ReCiPe methodologies, the Hierarchist perspective is the default one, which balances between short and long term effects within the environmental modeling. In all the methodologies used, the final results are presented taking into consideration the characterization, normalization and weighting, leading to single score impact indicators (score points). Those score points express the severity of the contribution of the impact categories to the environmental load (Higher score of a product or a specific component means higher impact on the environment). They can be regarded as dimensionless figures. In other words, the absolute value of those points is not very relevant, as the main purpose is to compare relative differences between products and components. For example, in the EI99 methodology, the scale is chosen in a way that the value of one point is representative for one thousandth of the yearly environmental load of one average European inhabitant. This latter value is obtained by dividing the total environmental load in Europe by the number of inhabitants and multiplying it by 1000 (scale factor). The detailed description of the aforementioned LCIA methodologies is as follows:

4.2.1.1 EI99

The Eco indicator method is an endpoint oriented method that was first developed in 1995 under the Dutch NOH programme by PRé consultants [45] in a joint project with Philips Consumer Electronics [46], NedCar (Volvo/Mitshubishi) [47], Océ Copiers [48], Schuurink [49], CML Leiden [33], TU-Delft, IVAM-ER (Amsterdam)[50] and CE

Delft [51]. Several improvements were made until another methodology was developed in 1999 (EI99). The improvements done in the EI99 are represented in providing better scientific basis for the damage models, such that the approach is more reliable. Besides, the indicator list is expanded, and the methodology is further improved for calculating the indicators ([45], [52]). The environmental damage categories included are as follows: Climate change, ozone layer depletion, acidification, eutrophication, carcinogenic, respiratory effects, ionizing radiation, ecotoxicity, land use, mineral resources, and fossil resources. These categories are further aggregated into three areas of protection which are: Eco system quality, human health and natural resource. The calculation of characterization and normalization values have been carried out using the data on resource extraction and emissions which have been collected previously in a study carried out for the purpose of developing characterization and normalization values for the Dutch and the European territory. Those values are based on environmental interventions resulting from European production in 1990-1994. Weighting is done using the panel approach. In the EI99 methodology, the weighting approach is applied to three areas of protection. This is different from other methodologies where weighting is assigned for more than ten impact categories. Assigning the weights to the areas of protection is simpler than assigning the weights to the impact categories. Assigning the weights to the impact categories requires a great deal of knowledge on the mechanism of the effects, their probability and the way they cause the potential damage ([32], [52], [53]). The regional validity of the methodology impact categories is European; certain categories are a part of global concern such as climate change, ozone layer depletion and resources.

4.2.1.2 EPS 2000

The EPS methodology (Environmental Priority Strategies in product design) was first developed in 1989 by a co-operation between Volvo [54], the Swedish Environmental Research Institute (IVL) [55], and the Swedish Federation of Industries (known now as Confederation of Swedish Enterprise since 2001) [56] with the aim of developing a tool that meets the efficient environmental requirements of product development process ([45], [57]). The EPS is an endpoint oriented method. It considers the following damage categories: Life expectancy, severe morbidity and suffering, morbidity, severe nuisance, nuisance crop production capacity, wood production capacity, fish and meat production capacity, base cation capacity, production capacity for water, share of species extinction, depletion of element reserves, depletion of fossil reserves (gas), depletion of fossil reserves (coal), depletion of fossil reserves (oil) and depletion of mineral reserves. It encompasses four areas of protection: Human health, Eco system production capacity, biodiversity and abiotic stock resources. Characterization among the environmental categories is done based on the precautionary principle using three methods: the empirical method, the equivalency method and the mechanistic methods considering the global conditions in the year 1990 ([57], [58]). Normalization is not used in this method. Weighting is done based on monetisation methods (willingness to pay). The regional validity of the methodology impact categories is global except for the biodiversity damage category which is based on Swedish models. More information about the impact pathways can be found in [59].

4.2.1.3 IMPACT 2002+

IMPACT 2002+ is a methodology that combines between the two schools of damage modelling (midpoint and endpoint oriented method). It was developed by the Swiss Federal Institute of Technology [82] and the federal polytechnic school of Lausanne

(EPFL)-France [83]. The first version of the methodology was called Impact 2002. Later on, some modifications were introduced concerning the comparative assessment of some impact categories as well as developing public non-spatial, spatial European, and world versions of the environmental profile for other categories ([84], [85]). The methodology incorporates the following midpoint impact categories: Human toxicity , respiratory effects , ionizing radiation , ozone depletion , photochemical oxidant formation , aquatic ecotoxicity , terrestrial ecotoxicity , aquatic eutrophication , terrestrial eutrophication and acidification , land occupation , global warming , non renewable energy and mineral extraction. Through the midpoint categories, the inventory results are linked to four endpoint damage categories, which in this case are also the environmental areas of protection: Human health, Eco system quality, climate change and resources. Characterization factors are adapted from other methodologies such as IMPACT 2002, Eco indicator 99 and CML. Normalisation factors are based on European average values as annual impact scores for an average citizen.

No specified weighting methodologies exist for this methodology. However, in case weighting is needed, the developers suggest considering the four damage categories (Human health, Eco system quality, climate change, and resources). One of the methods suggested to analyze the different weightings is the mixing triangle method which is a simple decision support tool that is used to discuss the trade-off between impact categories. It illustrates evaluation issues, such as the weighting of different environmental effects when comparing product systems. The mixing triangle can only be used to compare three categories. Thus, in order to be able to apply this weighting method, two damage categories have to be summed (for example: climate change and resources, because of high correlations in most situations). The methodology has a

European regional validity; certain issues are of a global concern such as ozone layer depletion and resources ([32], [45], [86], [87]).

4.2.1.4 ReCiPe

The Recipe methodology development was conducted by the cooperation of many developers working within the LCA field such as RIVM [70], CML [33] , PRé Consultants [45], Radboud University Nijmegen [71] and CE Delft [51]. This methodology is considered as a follow up of the CML 2002 and the EI99 methodologies. The indicator scores are determined in a similar way as in the EI99 method. This method combines between both approaches of midpoint and endpoint modeling. Eighteen midpoint categories are addressed: Climate change, ozone depletion, terrestrial acidification , freshwater eutrophication , marine eutrophication , human toxicity, photochemical oxidant formation, particulate matter formation , terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation , urban land occupation, natural land transformation , water depletion , mineral resource depletion, fossil fuel depletion. At the endpoint level, three endpoint categories are considered, which in this case, are the same defined areas of environmental protection: damage to human health, damage to Eco system diversity and damage to resources availability. In the characterization and normalization steps, the year 2000 was chosen as a reference year, and information was gathered on the European level. However, concerning the midpoint normalization factors, some modifications were applied in the year 2010 ([72]-[74]). The weighting in this method is carried out using the panel approach. The regional validity is for Europe. However, as in the case of other methodologies, some issues are of a global concern, such as climate change, ozone layer depletion and resources.

4.2.2 Energy profile evaluation methods

The energy profile is evaluated using the Cumulative Energy Demand (CED) methodology for the assembly stage. For the energy profile evaluation during the whole systems life cycle, two indicators are used: the Energy Return Factor (ERF), and The Energy Payback Time (EPT).

Cumulative Energy Demand (CED) is a methodology used to quantify the direct and indirect energy use in units of MJ throughout the life cycle of a product or a process, including the energy consumed during the extraction, manufacturing and disposal of the materials. CED considers in its context the cumulative energy demand for fossil resources, such as hard coal, lignite, peat, natural gas, and crude oil, and for the nuclear and other renewable resources as well such as: biomass, water, wind, and solar energy. It represents the energy demand, valued as primary energy during the complete life cycle of products [111]. In another words, it is considered as a resource oriented indicator, expressing the demand of energy. In another words, to evaluate the life cycle energy of a product, the sum of three energy terms are considered: Embodied energy (consists of the energy consumed during manufacturing phase, and the energy utilized for maintenance and rehabilitation during the operational phase) and, operating energy and demolition energy. Cumulative energy demand has been used as a methodology to assess life cycle environmental impacts since the early seventies, but has also been criticized because it focuses on energy only. However, it is considered as an important energy parameter as it aggregates all forms of energy use over the whole life cycle (renewable and non renewable energy forms). Consequently, for the whole life cycle energy evaluation for a specific system, determining the CED leads to the calculation of the Energy Payback Time (EPT) and the Energy Return Factor (ERF) ([112]-[115]).

The Energy Return Factor (ERF) provides a numerical quantification of the benefit gained out of the exploitation of an energy resource in terms of how much energy is gained from an energy production process compared to how much of that energy (or its equivalent) is required to extract, process, deliver, and otherwise upgrade that energy to a socially useful form [358]. In the case of electricity generation technologies, the ERF entails the comparison of the electricity generated to the amount of primary energy used in different life cycle stages. The ERF is calculated as the ratio of energy delivered to energy costs, and given as follows:

$$ERF = \frac{E_{global}}{CED}$$

Where E_{global} is the sum of the total primary energy output produced during the system entire life time ($MJ_{primary}$), accounting for the average degradation effect of 2.5% per year for the energy output. E_{global} is calculated by converting the electrical energy output produced by each system from kWh to $MJ_{electrical}$ (1 kWh=3.6 $MJ_{electrical}$) and subsequently converting the electrical energy ($MJ_{electrical}$) produced into its primary form ($MJ_{primary}$) via a conversion factor of 0.35 $MJ_{electrical}/MJ_{primary}$. CED is the cumulative energy demand, which is an indicator used to quantify the direct and indirect energy use throughout the life cycle of a product or a process, including the energy consumed during the extraction, manufacturing and disposal of the materials, valued as primary energy during the complete life cycle of products ($MJ_{primary}$). The CED values for the BACPV and BIPV systems were calculated using the CED methodology with Simapro 7 software.

The Energy Payback Time (EPT, in years) is defined as the time needed for a PV system to generate the total energy that was invested during its production as given as follows:

$$EPT = \frac{LT}{ERF} = \frac{CED}{E_{global} / LT}$$

Where LT is the lifetime (30 years) and ERF is the energy return factor of the corresponding system (dimensionless).

4.3 *Results and discussion*

The Life Cycle Inventory of the corresponding systems is demonstrated in Table 1. It is divided into three main sections: The BICPV-F system, the BICPV-S system, and the BIPV system.

Item description/function	Materials used	Quantity (kg)
BICPV-F system		
CPV cells	Single-Crystalline Silicon	0.13
Insulation (Thermal tape)	Thermattach (T404)	0.02
CPV module cover	White glass	2.87
CPV module frame	Aluminum	5.15
Cooling pipes	Copper	1.14
U – Shaped support	Copper	1.01
Water pump	Steel	1.5
Reflectors	Float coated glass	109.82
Reflectors frame	Carbonated steel	59.75
Actuator gear	Steel	1
Actuator housing	Reinforced plastic	0.5
BICPV-S system		
CPV cells	Single-Crystalline Silicon	0.13
Insulation (Thermal tape)	Thermattach (T404)	0.02
CPV module cover	White glass	2.87
CPV module frame	Aluminum	5.15
Cooling pipes	Copper	1.14
U – Shaped support	Copper	1.01
Water pump	Steel	1.5
Reflectors	Float coated glass	17.24
Reflectors frame	Carbonated steel	61.92
Reflectors covers	White glass	81.12
Actuator gear	Steel	1
Actuator housing	Reinforced plastic	0.5
BIPV scheme		
PV cells	Single-Crystalline Silicon	1.36
Encapsulation	EVA (Ethyl Vinyl Acetate)	2.13
Cover	White glass	53.02
Frame	Aluminum	40.96

Table 1. Life Cycle Inventory of the studied systems

Table 2 shows the correspondence of the Life Cycle Inventory materials used within the analysis with the Eco-Invent database.

Materials	Correspondence with the Eco-Invent database
Single crystalline silicon CPV	CPV cell, single-Si, at plant/RER U
Thermattach (T404)	Chemicals organic, at plant/GLO U
White glass	Solar glass, low-iron, at regional storage/RER U
Aluminum	Aluminum, production, cast alloy, at plant/RER U
Copper	Copper, at regional storage/RER U
Steel	Steel, electric, un and low alloyed, at plant/RER U
Flat coated glass	Flat glass, coated, at plant/RER U
steel	Steel, electric, un and low alloyed, at plant/RER U
Reinforced plastic	Glass fibre reinforced plastic, at plant/RER U
Single crystalline silicon PV	Photovoltaic cell, single-Si, at plant/RER U
PVB (Poly Vinyl Butyral)	Ethylene vinyl acetate copolymer, at plant/RER U

Table 2. Correspondence of the Life Cycle Inventory materials used with the Eco-Invent database

In reference to the encapsulation applied on the PV cells of the BIPV system, no information has been found matching the PVB (Poly Vinyl Butyral) in the Eco-invent data base. Thus, instead, EVA (Ethyl Vinyl Acetate) has been considered in the evaluations. Nevertheless, this assumption will not vary the results certainty, as both of the PVB and EVA films are polymers of similar characteristics, having the same function, which is encapsulating the PV cells. The only spotted difference is that PVB is normally used in case of achieving semi-transparent PV modules [374].

Referring to the CPV cells used in the BACPV system, no information has been found in the Eco-Invent database matching the related processes of the buried contacts technology, which is the principal characteristic of a CPV cell [375]. Actually, screen printing metallization process is the default one used in the Eco-Invent database. In the present BICPV systems, CPV cells from Narec solar are used, where the contacts are created using a hybrid approach combining between buried contacts and screen printing. In this approach, the screen printing metallization technique is used for both front and back contacts, where it is applied over the entire cell rear and only into the laser grooves on the front. On the rear, aluminum compensates the back diffusion and forms the back surface field, and on the front silver forms the front contact fingers and bus bars. Accordingly, these differences have been taken into account by adjusting specific parameters while building a new unit process for the single crystalline silicon CPV cells in the Life Cycle Inventory (CPV cell, single-Si, at plant/RER U). This has been achieved taking into consideration the amount of metallization paste applied on the front contacts grooves, the copper plating, and the corresponding grooving using laser machining. The adjustments employed are shown below in Table 3.

Modification in the PV cell unit process	**Modification action**	**Quantity estimated**
Adding copper plating to the metallization process	Adding the following unit process: Copper, at regional storage/RER U	0.000095550 kg/ m^2
Adding silver filling to the laser grooves of the metallization process	Adding the following unit process: Silver, at regional storage/RER U	0.000165712 kg/ m^2
Adding laser machining to the metallization process	Adding the following unit process: Laser machining, metal, with YAG-laser, 30W power/RER U	1 hr/m^2

Table 3. Modification adapted while building a new unit process for the CPV cells

According to the industrial data available, no sufficient information has been found about the exact type of laser machining used. Hence, this has been regarded as an uncertainty, especially that there are many different types of laser machining in the Eco-Invent database. The main difference between these types is mainly related to the power of the machine used. Assuming a constant operation time of 1 Hour/ m^2 and by switching the laser machining parameter to be applied by using a machine of 3200W (Laser machining, metal, with CO2-laser, 3200W power/RER U), the environmental impact score per square meter of the CPV cell increases by around 13.5%. However, regarding the analysis of the complete BICPV systems, the total results does not vary significantly, where only an increment of 1.2% of the total impact score has been observed in each of the two BICPV systems.

Nevertheless, the environmental impact per square meter of that newly built process has been 1.7% more than that of the default one considering screen printing technology only (single crystalline silicon PV cell). Similarly, the difference in the CED has been found 2%. These findings are considered to be in accordance with the fact that the PV cell fabrication, with its corresponding operations sequence of high temperature diffusion, oxidation, deposition and anneals steps, represent only around 1-2% of the environmental load induced during PV modules fabrication. In other words, the entire manufacturing process embodied energy and environmental impact of a PV module is actually dominated by other fabrication steps other than the cell processing itself, such as the silicon Czochralski process and other related purification processes ([120], [122], [125], [346], [350], and [358]).

4.3.1 The assembly phase

The environmental and energy profiles of the assembly phase are evaluated. The functional unit used in the analysis of this phase is 500 Wp of system installed, referring to the two installed CPV modules (250 Wp each). The steps of the analysis are shown in details in the following subsections, where each system is evaluated separately, and then the three systems are compared to each other.

4.3.1.1 Environmental profile

4.3.1.1.1 EI99

The EI99 is used as the default methodology. Figure 38 shows the environmental impact of the BICPV-F system components using the EI99 methodology. It is shown that the impact of CPV cells constitute only 8.5 % of the total impact score of the BICPV-F system. On the other hand, the highest contributors are the reflectors, with a contribution percentage of 44%, mostly dominated by the climate change and respiratory inorganics damage categories. Furthermore, it is noticed that the cooling structure, consisting of a relatively few quantity of around 2 kilograms of copper (The cooling pipes and U-Shaped support), constitute 23.5 % of the total impact score. These latter components are mostly dominated by the fossil fuels and the minerals damage categories. The high impact of the minerals damage category reflects the severe scarcity of the copper material. Finally, the reflectors frame (steel) represents 15% of the total impact score, mostly dominated by the fossil fuels and respiratory inorganics damage categories.

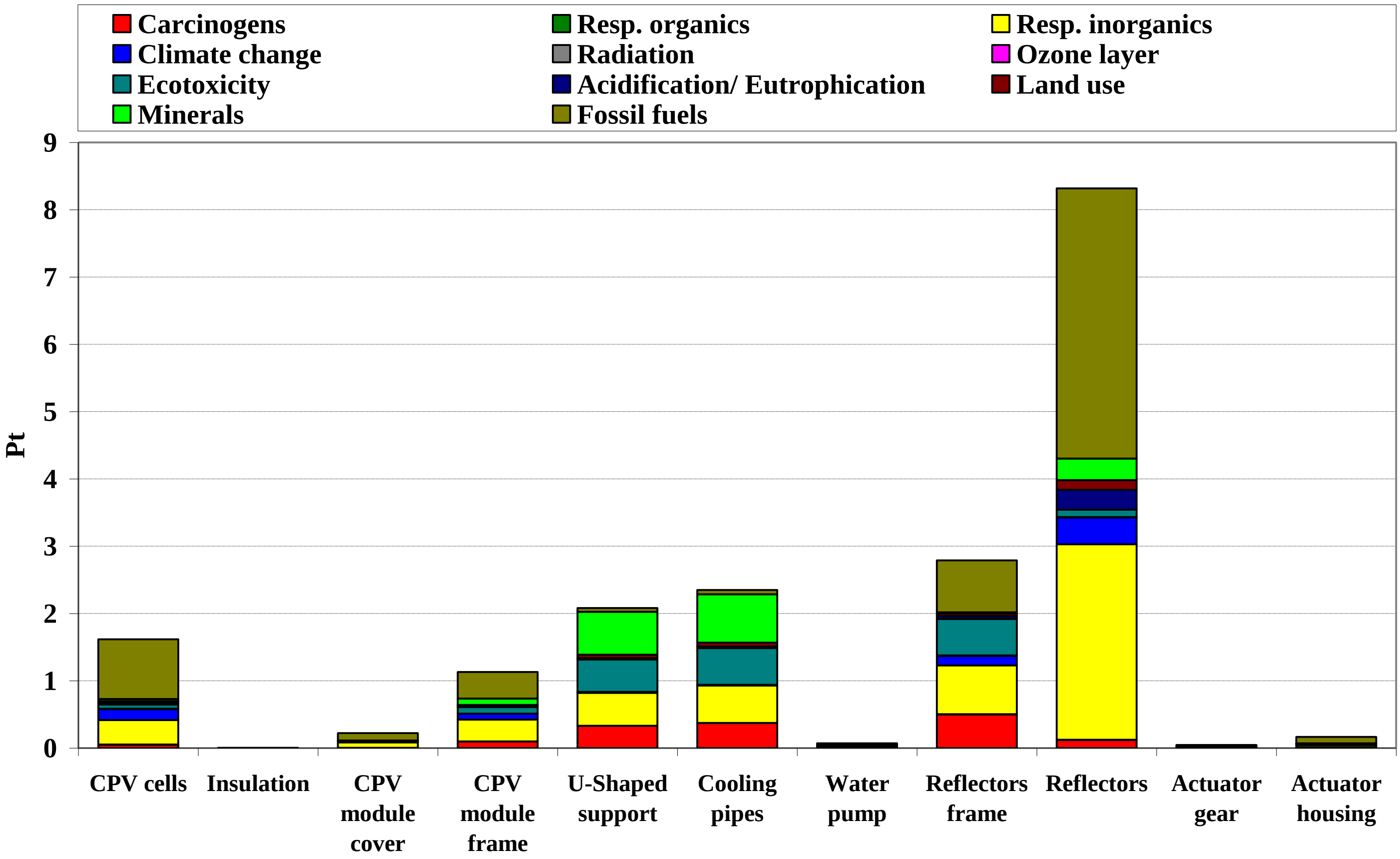

Figure 38. The environmental impact of the BICPV-F system components using the EI99 methodology represented by the damage categories

Figure 39 shows the environmental impact of the BICPV-S components using the EI99 methodology. The CPV cells represent 9% of the total impact score of the BICPV-S system. The most significant contributors to the total impact score are the reflectors covers, where they constitute 34.5% of the total impact score, mostly dominated by fossil fuels and respiratory inoragnics damage categories. Unlike the previous BICPV-F system, the reflectors represent only 7% of the total impact score. This is attributed to the fact that relatively less number of reflectors with much less thicknesses have been employed in the BICPV-S system. Similar to the BICPV-F system, the cooling structure (cooling pipes and U-Shaped support) and the reflectors frame represents 24% and 16% of the total impact score, respectively.

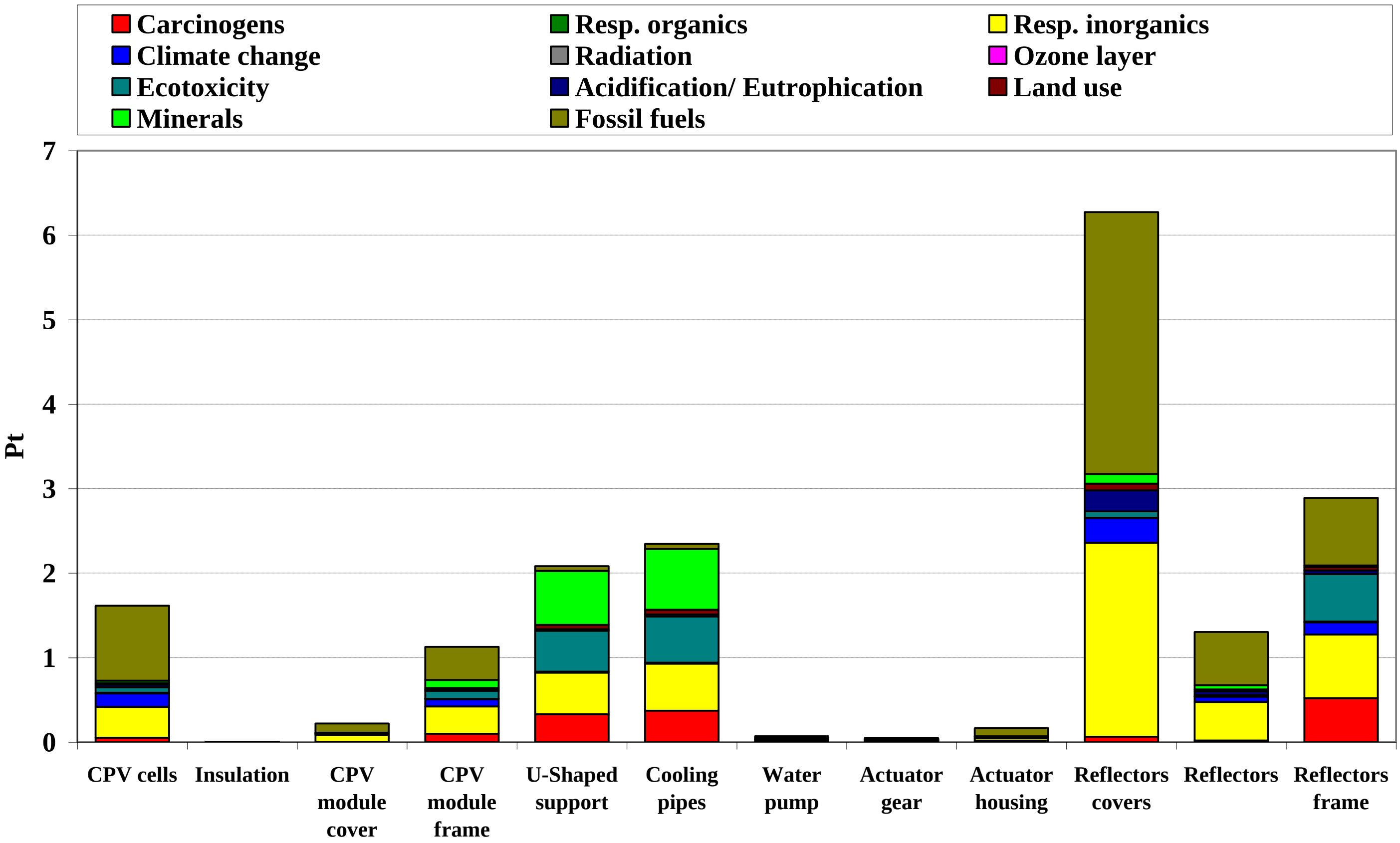

Figure 39. The environmental impact of the BICPV-S system components using the EI99 methodology represented by the damage categories

Figure 40 shows the environmental impact of the BIPV system components using the EI99 methodology. It is demonstrated that the impact of the PV cells constitute the majority of the total system impact score, where they represent 65% of the total impact score of the BIPV system, mostly dominated by fossil fuels and respiratory inorganics damage categories. The second significant contributor to the total impact score is the PV module frame, where it represents 23% of the total impact score of the BIPV system. It is noticed the higher contribution of the PV cells to the total impact score compared to the case of the BICPV systems. This is attributed to the use of smaller surface area of CPV cells in the BICPV systems.

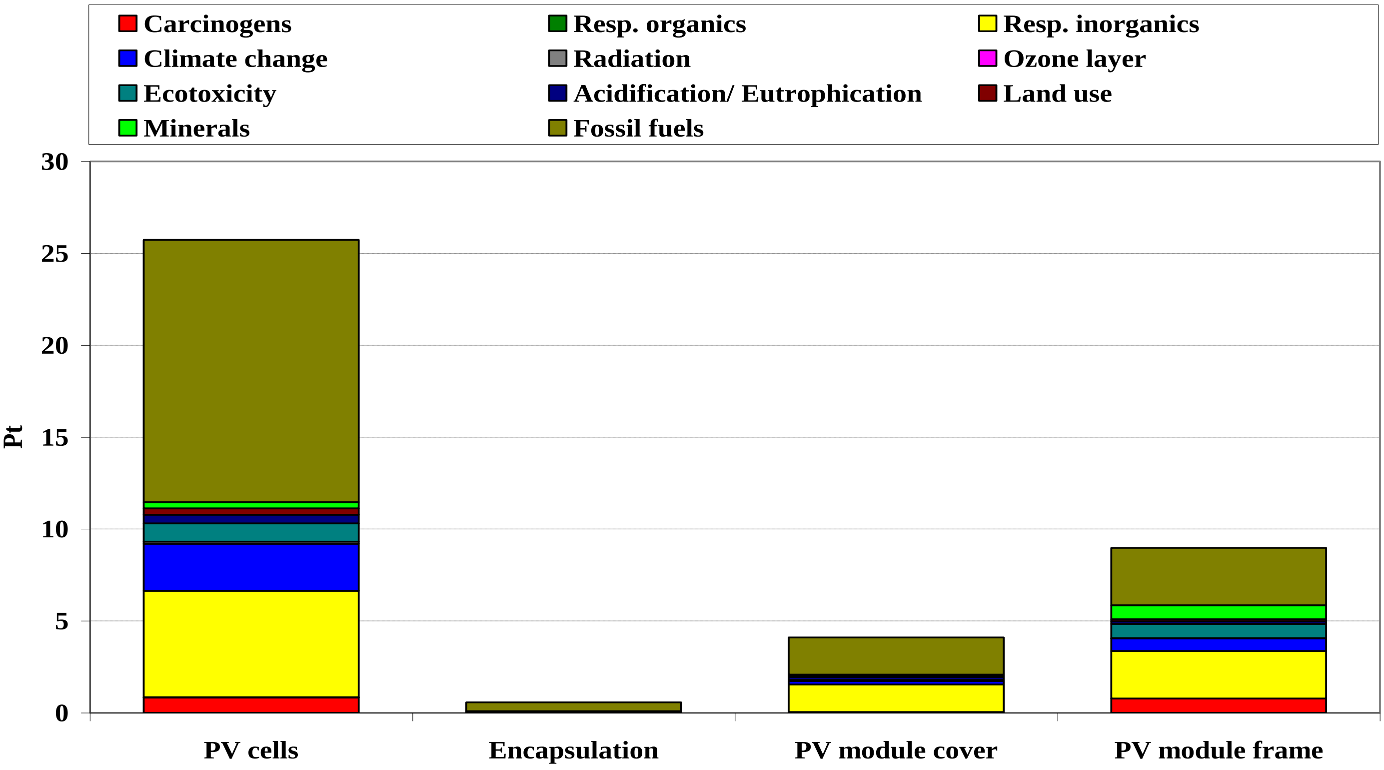

Figure 40. The environmental impact of the BIPV system components using the EI99 methodology represented by the damage categories

Figure 41 shows a comparison between the environmental impacts of the three corresponding systems (BICPV-F, BICPV-S, and BIPV). It is demonstrated that the impacts of the BICPV-F and BICPV-S systems are on the same range, where the impact of the BIPV system is a factor of 2 higher than both of the BICPV ones. This is mainly related to the use of a much larger area of PV cells compared to the BICPV systems. It is observed that although the BICPV-S system contains less number of reflectors with significantly reduced thickness, its total impact score is similar to that of the BICPV-F system. This is mainly related to the fact that two protective covers for the reflectors have been employed in the BICPV-S system. That is, the use of the protective covers in the BICPV-S system has balanced out the environmental impact reduction achieved due to the use of fewer amounts of reflectors. It is also observed that the impacts of both of the BICPV systems mostly dominate the areas of protection of the resources and human health. This is clearly observed within the analysis of each system in the previous figures, where the fossil fuels, minerals, and respiratory inorganics damage categories are the most dominant within each system.

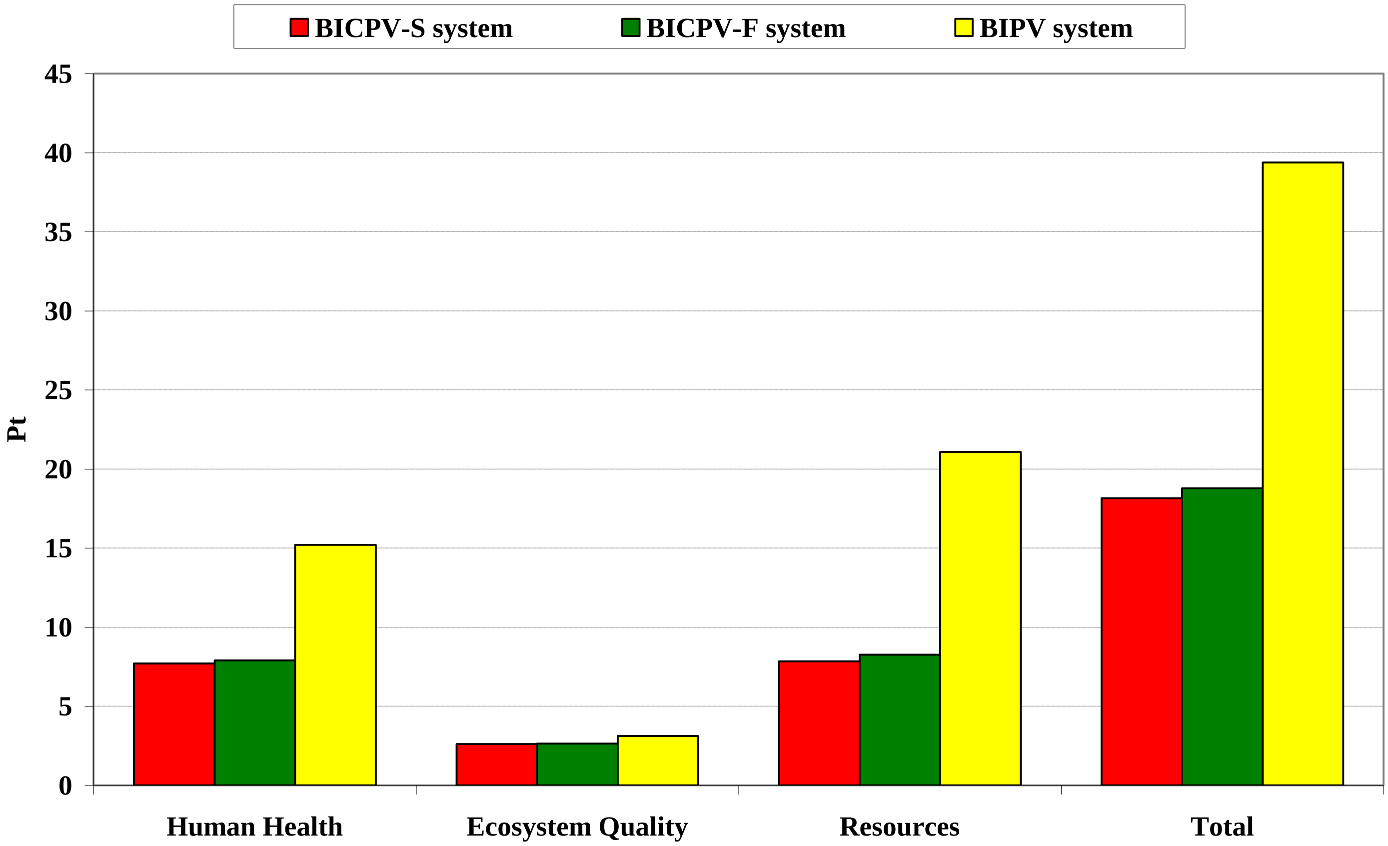

Figure 41. A comparison between the environmental impacts of the three corresponding studied systems using the EI99 methodology represented by the areas of protection

4.3.1.1.2 EPS 2000

Figure 42 shows the environmental impact of the BICPV-F system using the EPS 2000 methodology represented by the damage categories. It is observed that the impact of the cooling structure (cooling pipes and U-Shaped support) constitutes the majority of the total impact score of the BICPV-F system, where it represents 70% of the total. The second largest contributors to the total impact score are the reflectors, where they represent 16% of the total. On the other hand, the CPV cells and the reflectors frame represent relatively lower percentage of the total impact score (5% and 4%, respectively). The depletion of reserves is the most impacting damage categories in all the systems components. This reflects the high impact of the depletion of fossil resources used, in addition to the severe depletion of the metals used within the system assembly, such as steel, and especially copper.

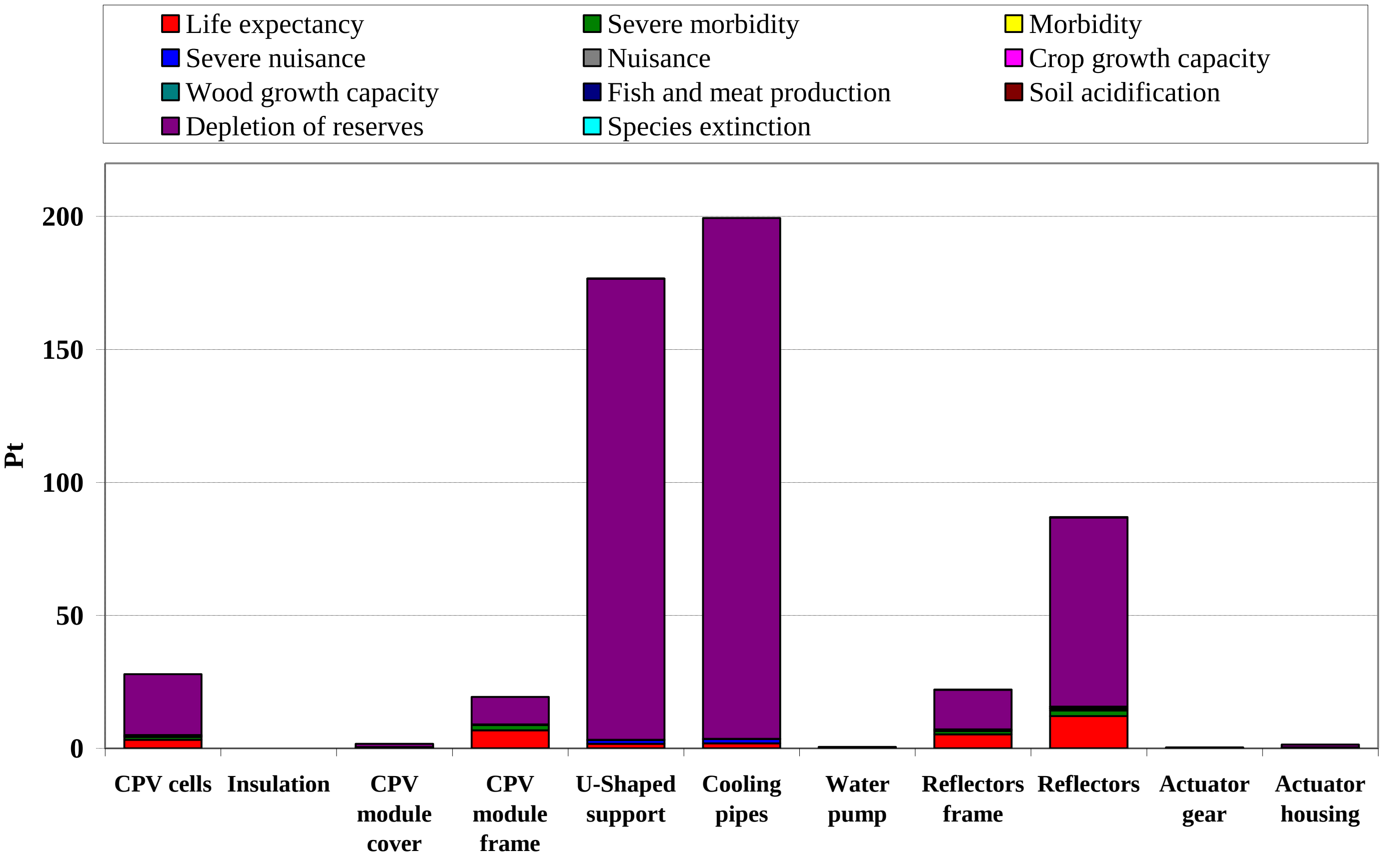

Figure 42. The environmental impact of the BICPV-F system components using the EPS 2000 methodology represented by the damage categories

Figure 43 shows the environmental impact of the BICPV-S system using the EPS 2000 methodology represented by the damage categories. It is observed that the impact of the cooling structure (cooling pipes and U-Shaped support) constitutes the majority of the total impact score of the BICPV-F system, where it represents 74% of the total. The second largest contributors to the total impact score are the reflectors covers, where they represent 9% of the total. On the other hand, the CPV cells, the reflectors, and the reflectors frame represent relatively lower percentage of the total impact score (5.5%, 3%, and 4.5%, respectively). The depletion of reserves is the most impacting damage categories in all the systems components. This reflects the high impact of the depletion of fossil resources used in the manufacturing of the components, in addition to the severe depletion of the metals used within the system assembly such as steel, and especially copper.

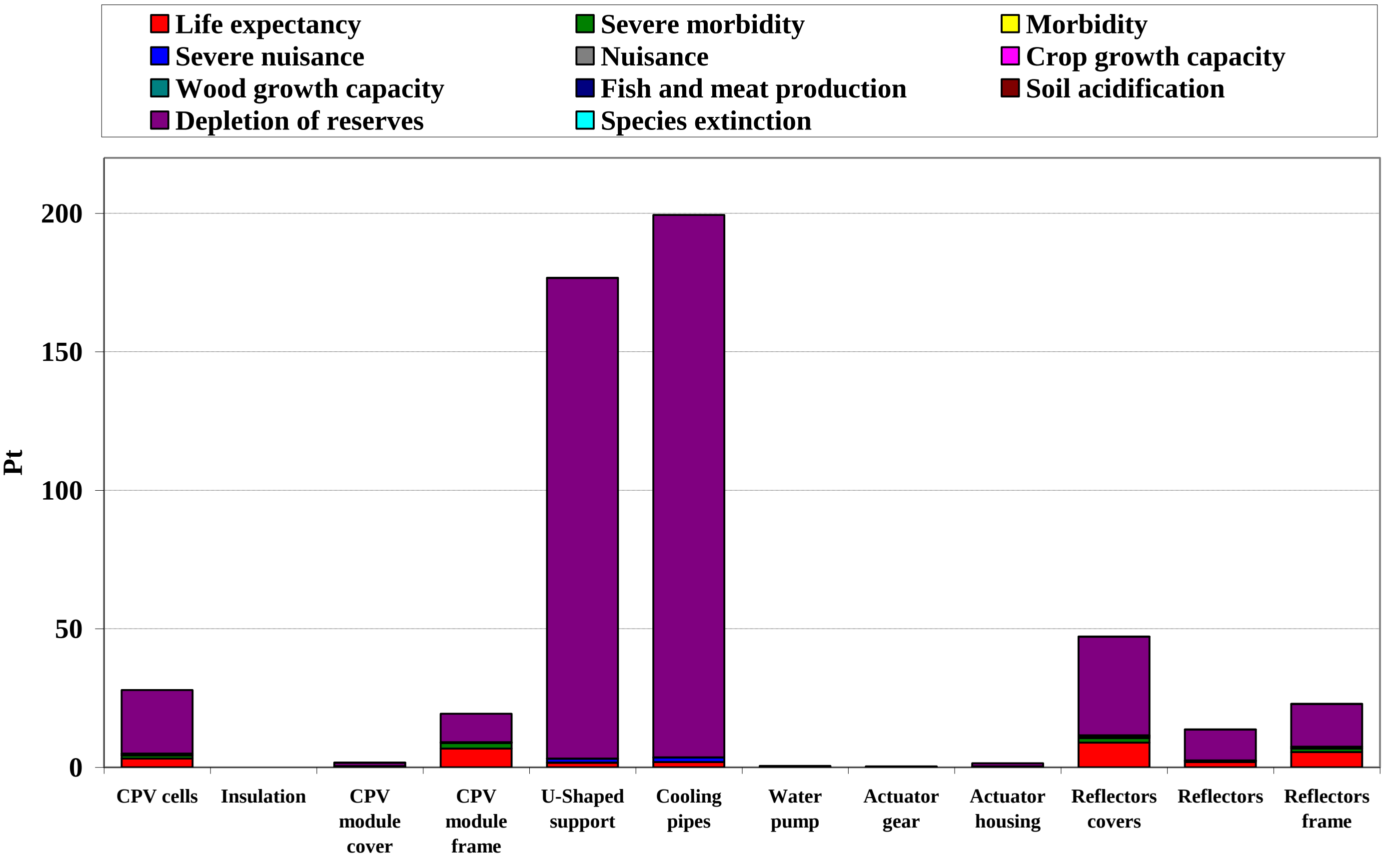

Figure 43. The environmental impact of the BICPV-S system components using the EPS 2000 methodology represented by the damage categories

Figure 44 shows the environmental impact of the BIPV system using the EPS 2000 methodology represented by the damage categories. The impact of the PV cells represents the majority of the impact score, where they constitute 68% of the total. The PV module frame is the second significant contributor to the total impact score, where it represents 26% of the total. The depletion of reserves is the most impacting damage categories in all the systems components. This reflects the high impact of the depletion of fossil resources used in the manufacturing of the system components, especially the PV cells.

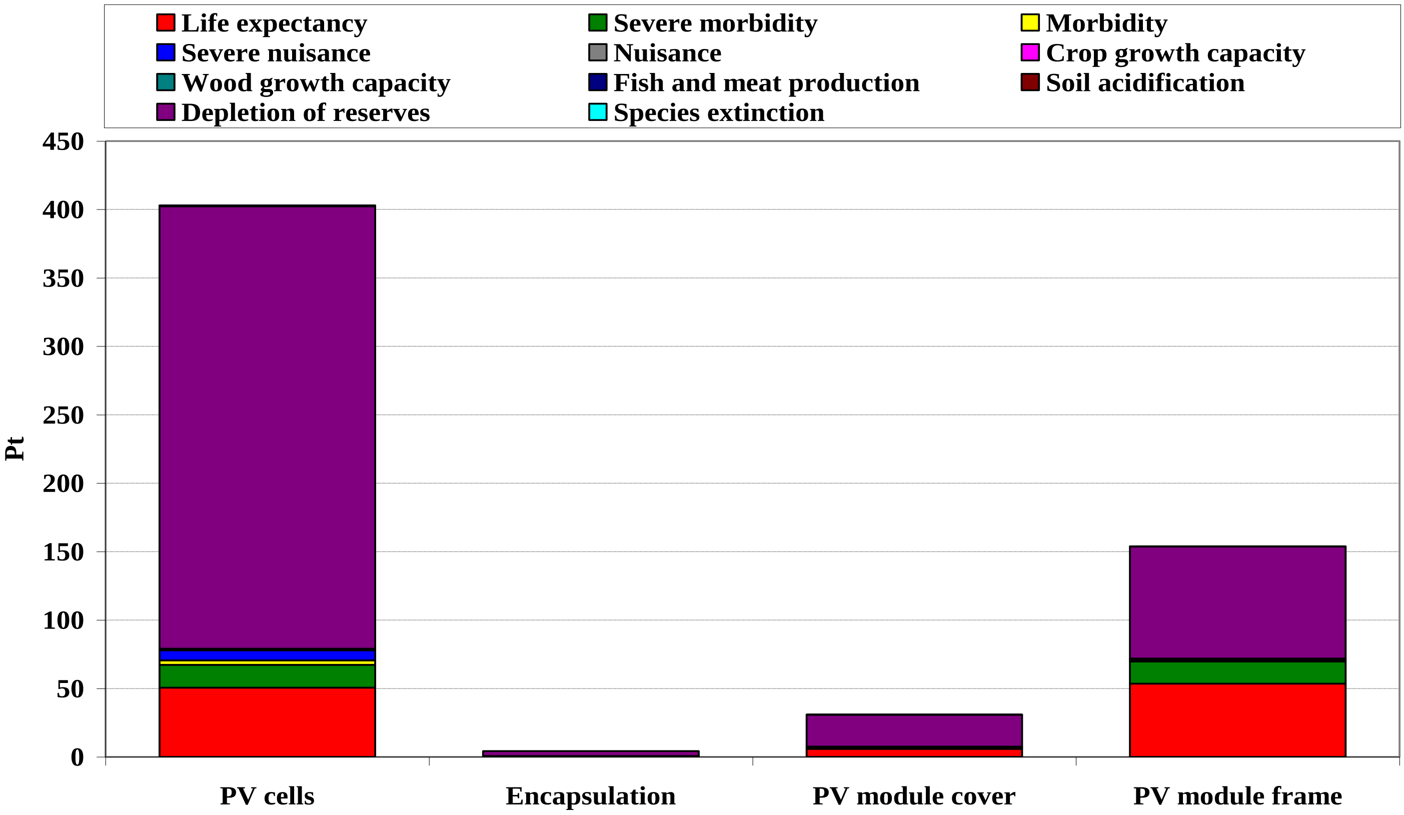

Figure 44. The environmental impact of the BIPV system components using the EPS 2000 methodology represented by the damage categories

Figure 45 shows a comparison between the environmental impacts of the three corresponding systems (BICPV-F, BICPV-S, and BIPV). It is demonstrated that the impacts of the BICPV-F and BICPV-S systems are on the same range, where the impact of the BIPV system is only a factor of 1.1 higher than both of the BICPV ones. Although there is much larger area of PV cells used in the BIPV system compared to the BICPV ones, the difference in the environmental impact insignificant. This is attributed to the significantly high impact induced by the cooling structure (cooling pipes and U-Shaped support). This appears in observing that both of the BICPV systems are dominated by the abitoic stock resource, where depletion of reserves damage category is the most and only dominant within each system.

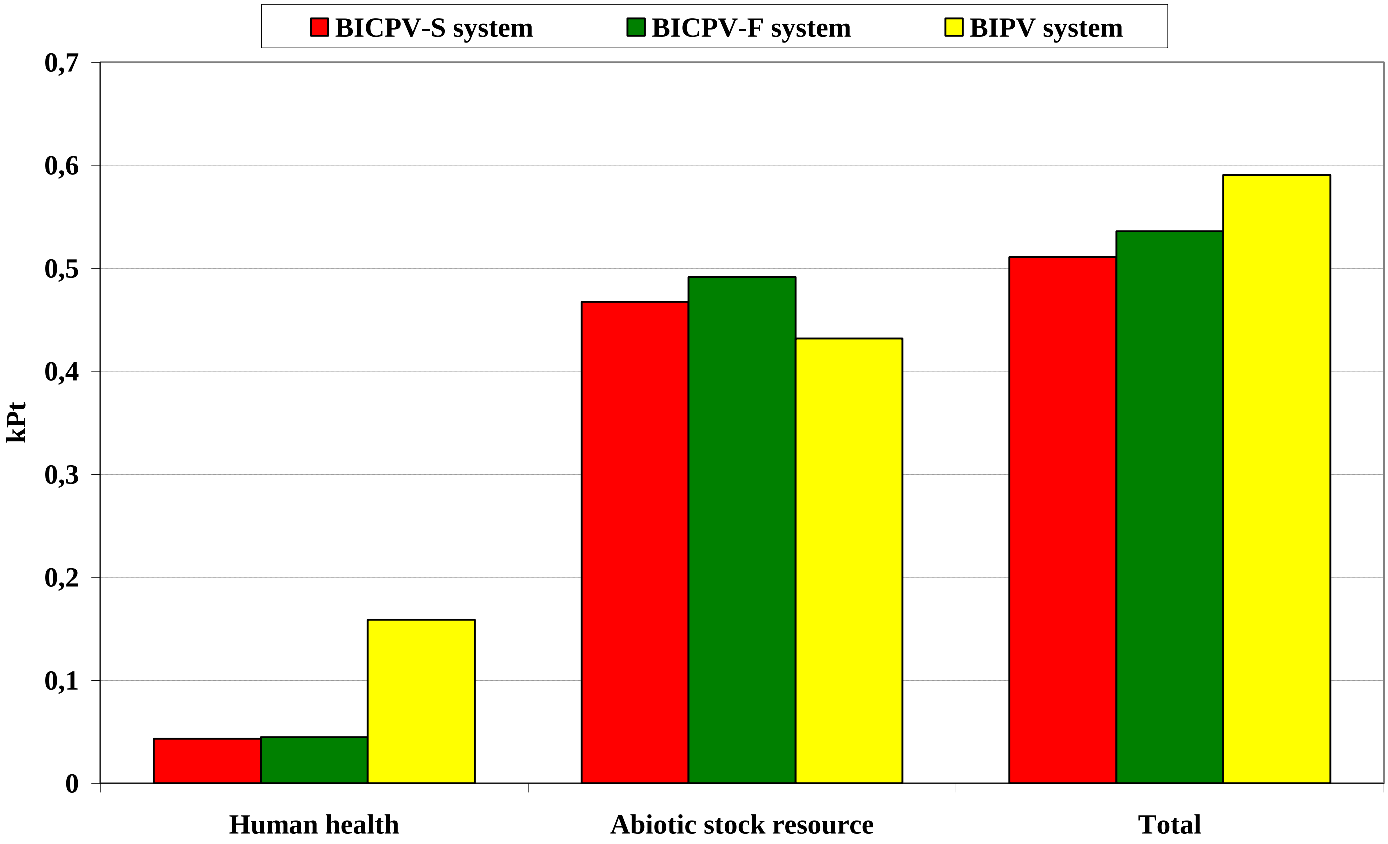

Figure 45. A comparison between the environmental impacts of the three corresponding studied systems using the EPS 2000 methodology represented by the areas of protection

In reference to the BICPV systems, it is observed that although the BICPV-S system contains less number of reflectors with significantly reduced thickness, its total impact score is similar to that of the BICPV-F system. This is mainly related to the fact that two protective covers for the reflectors have been employed in the BICPV-S system. That is, the use of the protective covers in the BICPV-S system has balanced out the environmental impact reduction achieved due to the use of fewer amounts of reflectors.

4.3.1.1.3 IMPACT 2002+

Figure 46 shows the environmental impact of the BICPV-F system using the IMPACT 2002+ methodology represented by the damage categories.

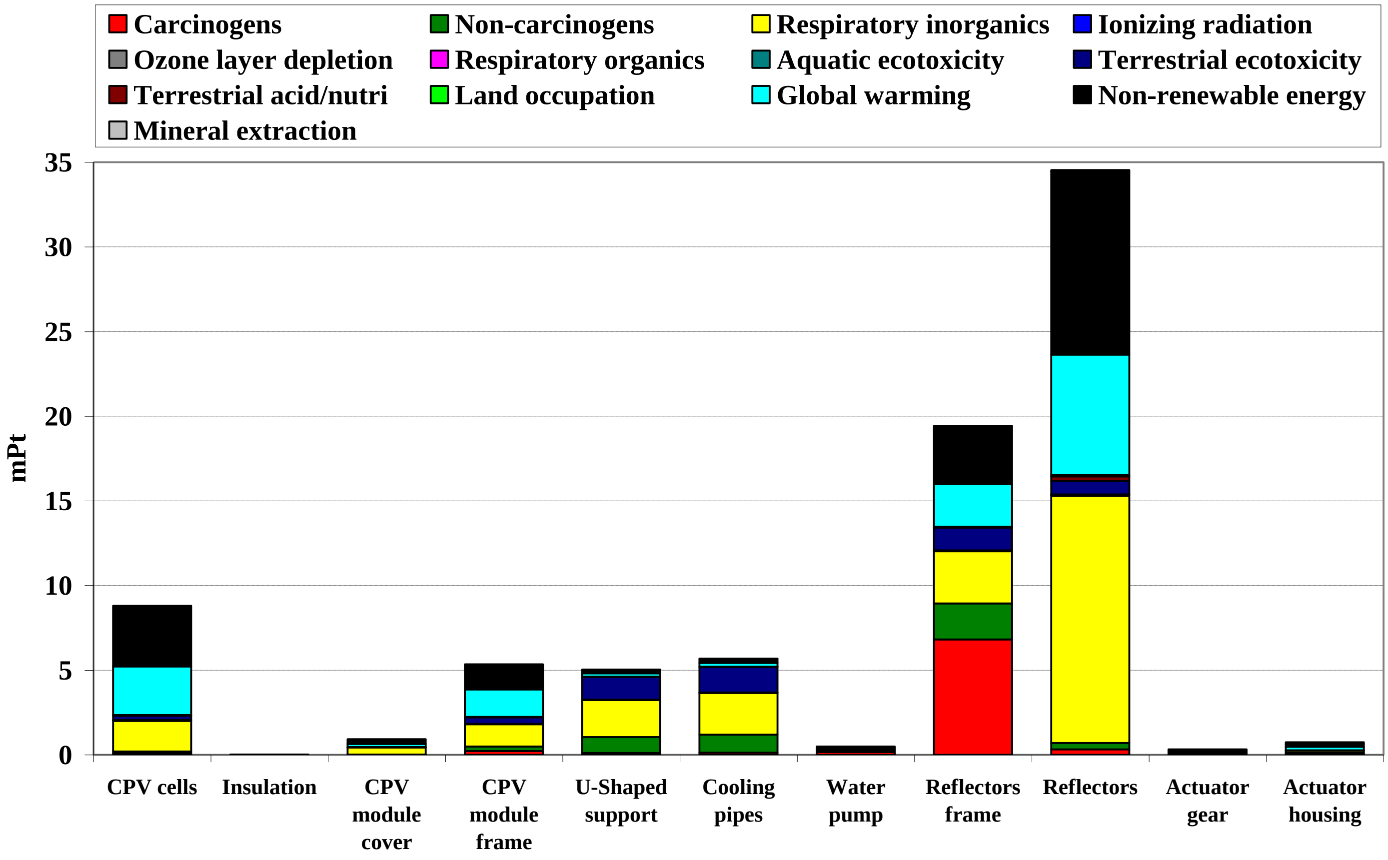

Figure 46. The environmental impact of the BICPV-F system components using the IMPACT 2002+ methodology represented by the damage categories

It is observed that the impact of the CPV cells represent 11% of the total impact score. The largest contributors are the reflectors, where they contribute by 42.5% of the total, mostly dominated by three damage categories: Non-renewable energy, respiratory inorganics, and global warming. The second largest contributor to the total impact score is the reflectors frame, where it represents 24% of the total, mostly dominated by four damage categories: Carcinogens, non-renewable energy, respiratory inorganics, and global warming. The cooling structure (cooling pipes and U-Shaped support) represent around 13% of the total impact score, mostly dominated by the respiratory inorganics and terrestrial ecotoxicity damage categories.

Figure 47 shows the environmental impact of the BICPV-S system using the IMPACT 2002+ methodology represented by the damage categories.

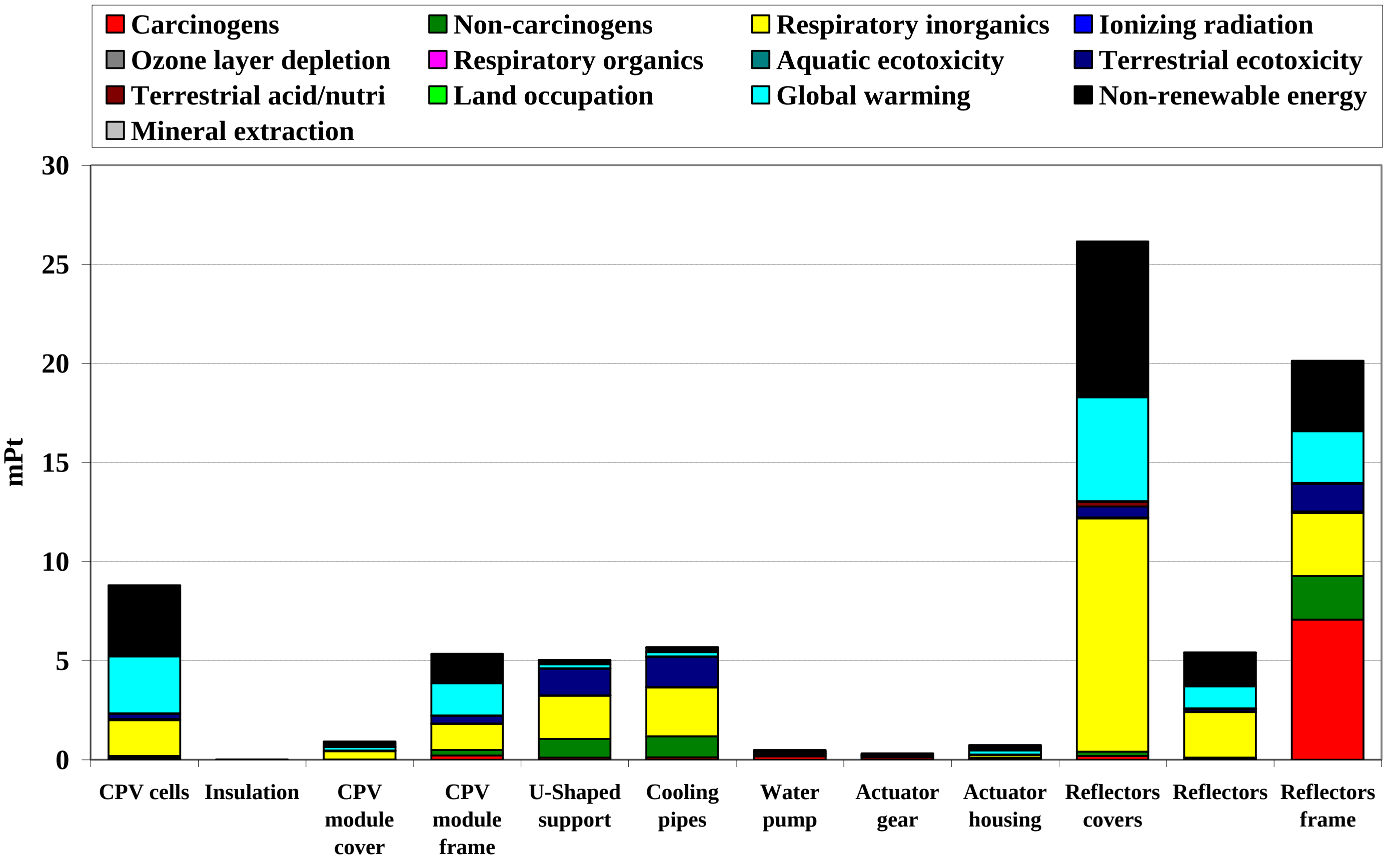

Figure 47. The environmental impact of the BICPV-S system components using the IMPACT 2002+ methodology represented by the damage categories

The CPV cells represent 11% of the total impact score. The highest contributors to the total impact score are the reflectors covers, where they contribute by 33% to the total, mostly dominated by three damage categories: Non-renewable energy, respiratory inorganics, and global warming. The second largest contributor is the reflectors frame, where it contributes by 25.5%, mostly dominated by four damage categories: Carcinogens, non-renewable energy, respiratory inorganics, and global warming. The cooling structure (cooling pipes and U-Shaped support) and the reflectors contribute by a relatively small percentage (13.5% and 7%, respectively).

Figure 48 shows the environmental impact of the BIPV system using the IMPACT 2002+ methodology represented by the damage categories.

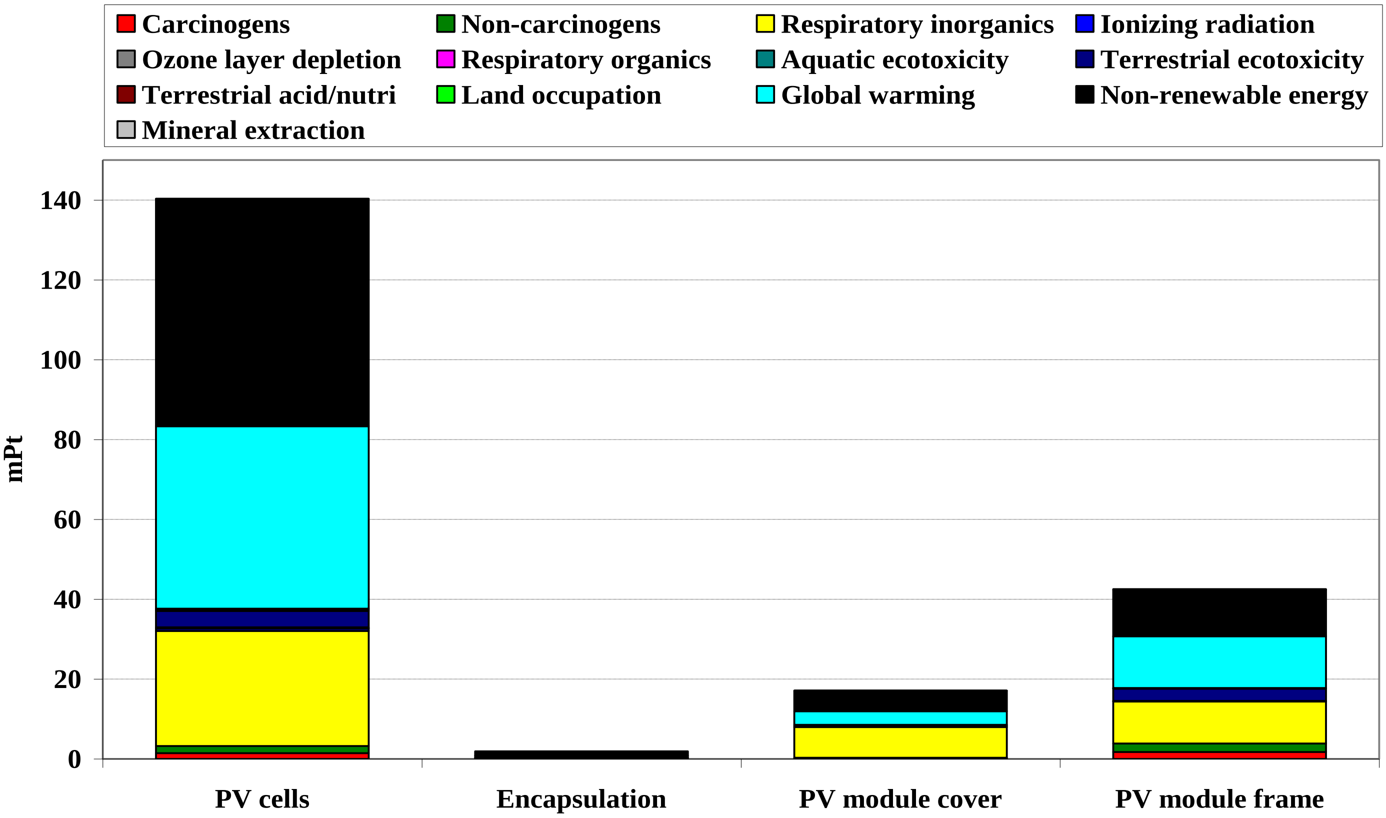

Figure 48. The environmental impact of the BIPV system components using the IMPACT 2002+ methodology represented by the damage categories

The PV cells represent the majority of the total impact score, where they constitute 69.5% of the total, dominated by three damage categories: Non-renewable energy, global warming, and respiratory inorganics. The PV module frame is the second largest contributor, where it constitutes 21% of the total impact score, mostly dominated by three damage categories: Non-renewable energy, global warming, and respiratory inorganics.

Figure 49 shows a comparison between the environmental impacts of the three corresponding systems represented by the environmental areas of protection. It is demonstrated that the impacts of the BICPV-F and BICPV-S systems are on the same range, where the impact of the BIPV systems is a factor of 2.5 higher than both of the BICPV ones. This is mainly related to the use of a much larger area of PV cells compared to the BICPV systems.

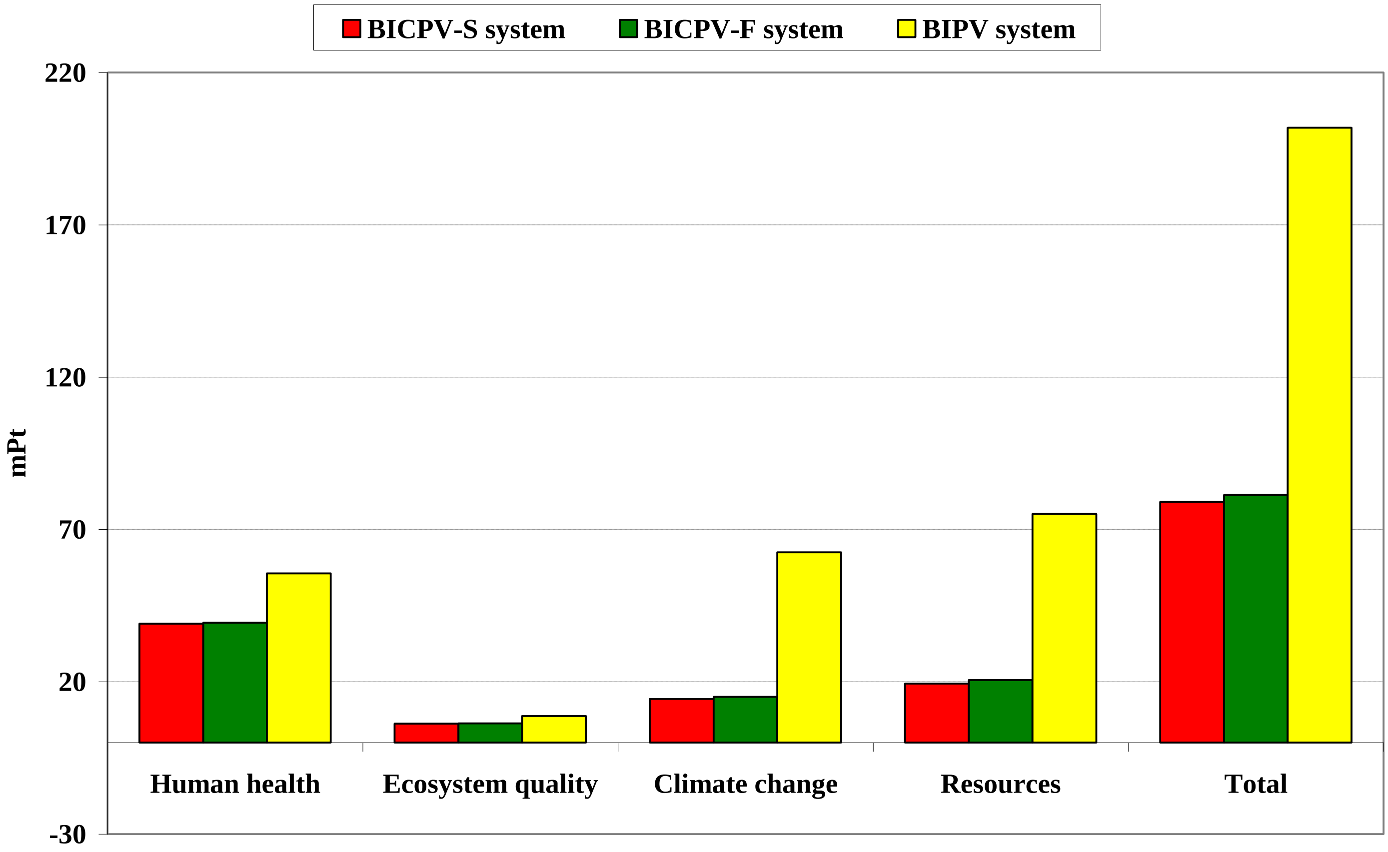

Figure 49. A comparison between the environmental impacts of the three corresponding studied systems using the IMPACT 2002+ methodology represented by the areas of protection

It is observed that although the BICPV-S system contains less number of reflectors with significantly reduced thickness, its total impact score is similar to that of the BICPV-F system. This is mainly related to the fact that two protective covers for the reflectors have been employed in the BICPV-S system. That is, the use of the protective covers in the BICPV-S system has balanced out the environmental impact reduction achieved due to the use of fewer amounts of reflectors. It is also observed that the impacts of both of the BICPV systems dominate the areas of protection of the human health and resources. This is clearly observed within the analysis of each system in the previous figures, where the respiratory inorganics and non-renewable energy damage categories are the most dominant within each system.

4.3.1.1.4 ReCiPe

Figure 50 shows the environmental impact of the BICPV-F system using the ReCiPe methodology represented by the damage categories.

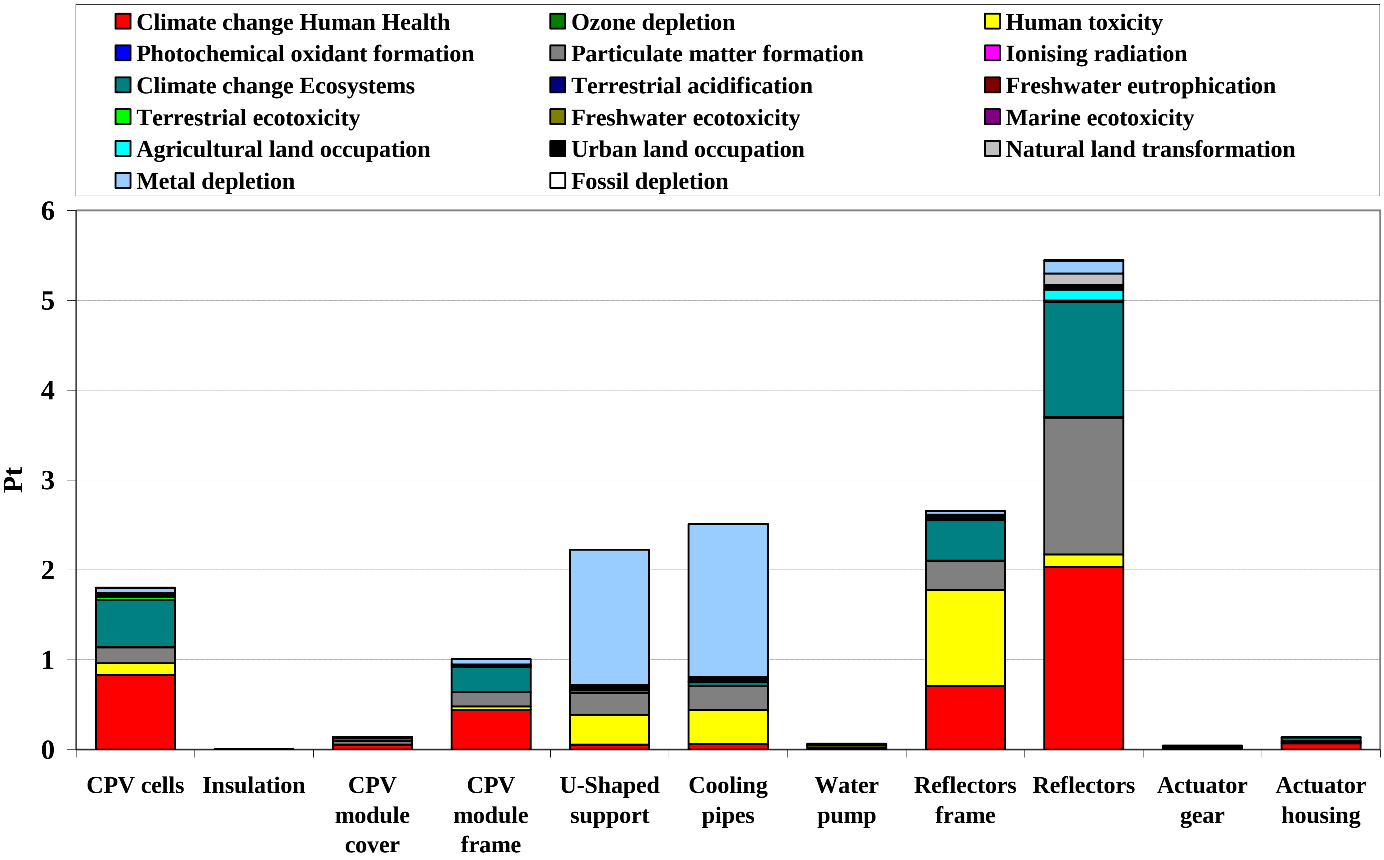

Figure 50. The environmental impact of the BICPV-F system components using the ReCiPe methodology represented by the damage categories

It is observed that the impact of the CPV cells represent around 11% of the total impact score. The largest contributors are the reflectors, where they contribute by 34% of the total, mostly dominated the climate change damage category. The second largest contributor to the total impact score is the cooling structure (cooling pipes and U-Shaped support), where it represent 29.5% of the total impact score, mostly dominated by the metal depletion damage category. The reflectors frame represents 16.5% of the total, mostly dominated by the climate change and human toxicity damage categories.

Figure 51 shows the environmental impact of the BICPV-S system using the ReCiPe methodology represented by the damage categories. The CPV cells represent 11.5% of the total impact score.

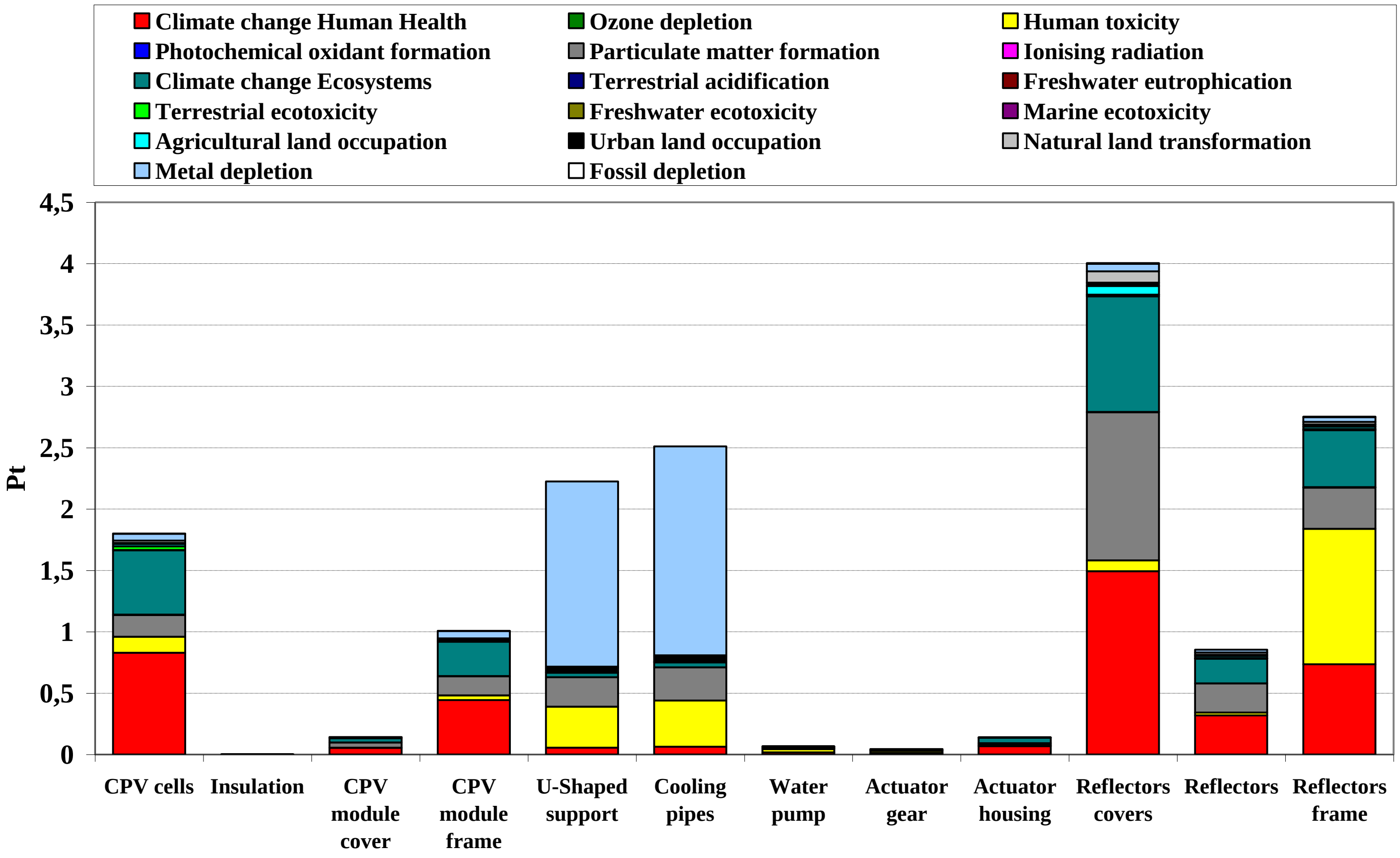

Figure 51. The environmental impact of the BICPV-S system components using the ReCiPe methodology represented by the damage categories

The highest contributor to the total impact score is the cooling structure (cooling pipes and U-Shaped support), where it contributes by 30.5% to the total impact score, mostly dominated by the depletion of metals damage category. The reflectors covers contribute by 26% of the total, mostly dominated by the climate change damage category. The reflectors frame contributes by 18% to the total impact score, mostly dominated by the climate change and human toxicity damage categories. The reflectors contribute by a relatively low percentage to the total impact score, where it represents 5.5% of the total.

Figure 52 shows the environmental impact of the BIPV system using the ReCiPe methodology represented by the damage categories.

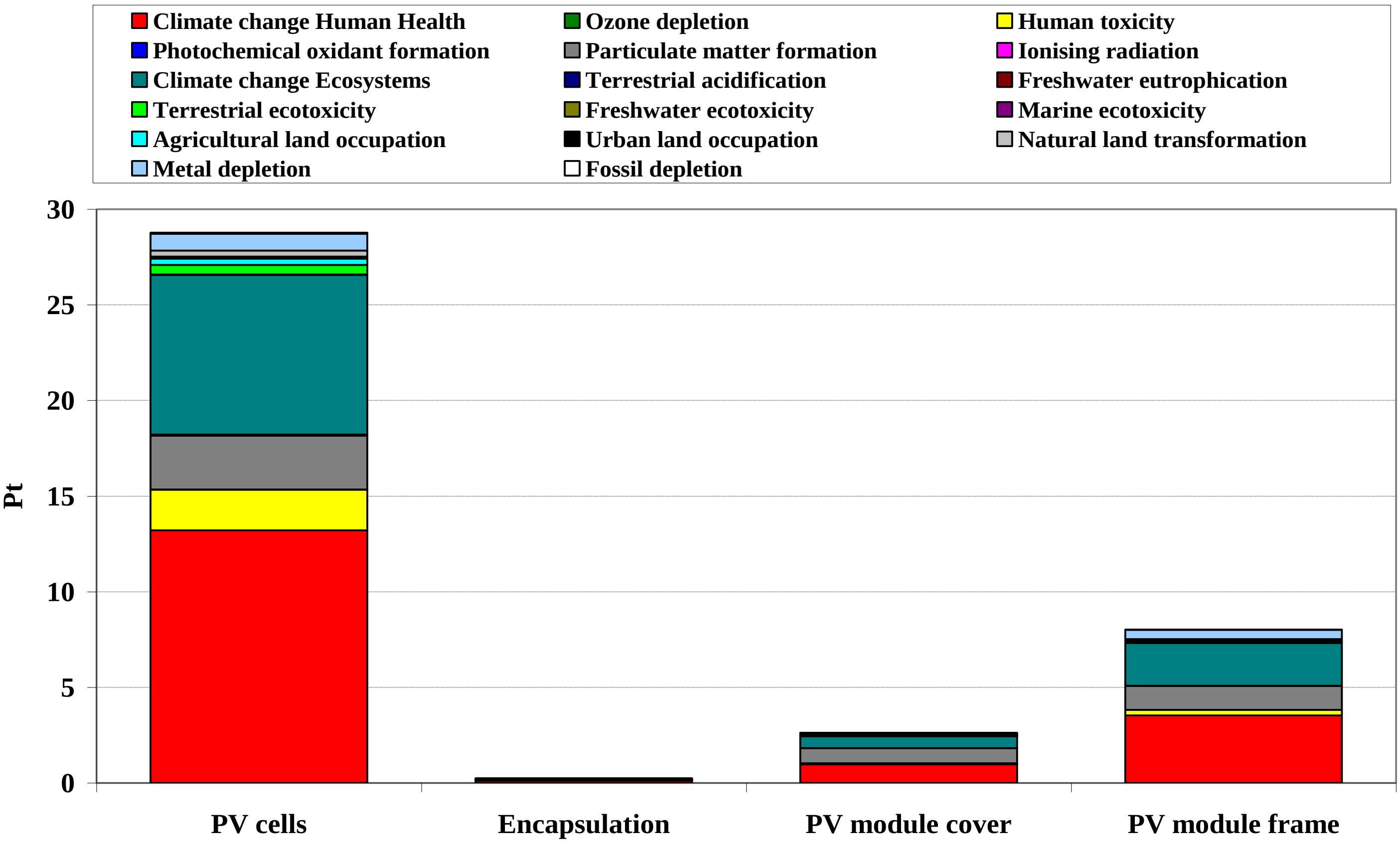

Figure 52. The environmental impact of the BIPV system components using the ReCiPe methodology represented by the damage categories

The PV cells represent the majority of the total impact score, where they constitute 73% of the total, dominated the climate change damage category. The PV module frame is the second largest contributor, where it constitutes 20% of the total impact score, mostly dominated by the climate change damage category.

Figure 53 shows a comparison between the environmental impacts of the three corresponding systems represented by the environmental areas of protection. It is demonstrated that the impacts of the BICPV-F and BICPV-S systems are on the same range, where the impact of the BIPV systems is a factor of 2.5 higher than both of the

BICPV ones. This is mainly related to the use of a much larger area of PV cells compared to the BICPV systems.

It is observed that although the BICPV-S system contains less number of reflectors with significantly reduced thickness, its total impact score is similar to that of the BICPV-F system. This is mainly related to the fact that two protective covers for the reflectors have been employed in the BICPV-S system. That is, the use of the protective covers in the BICPV-S system has balanced out the environmental impact reduction achieved due to the use of fewer amounts of reflectors.

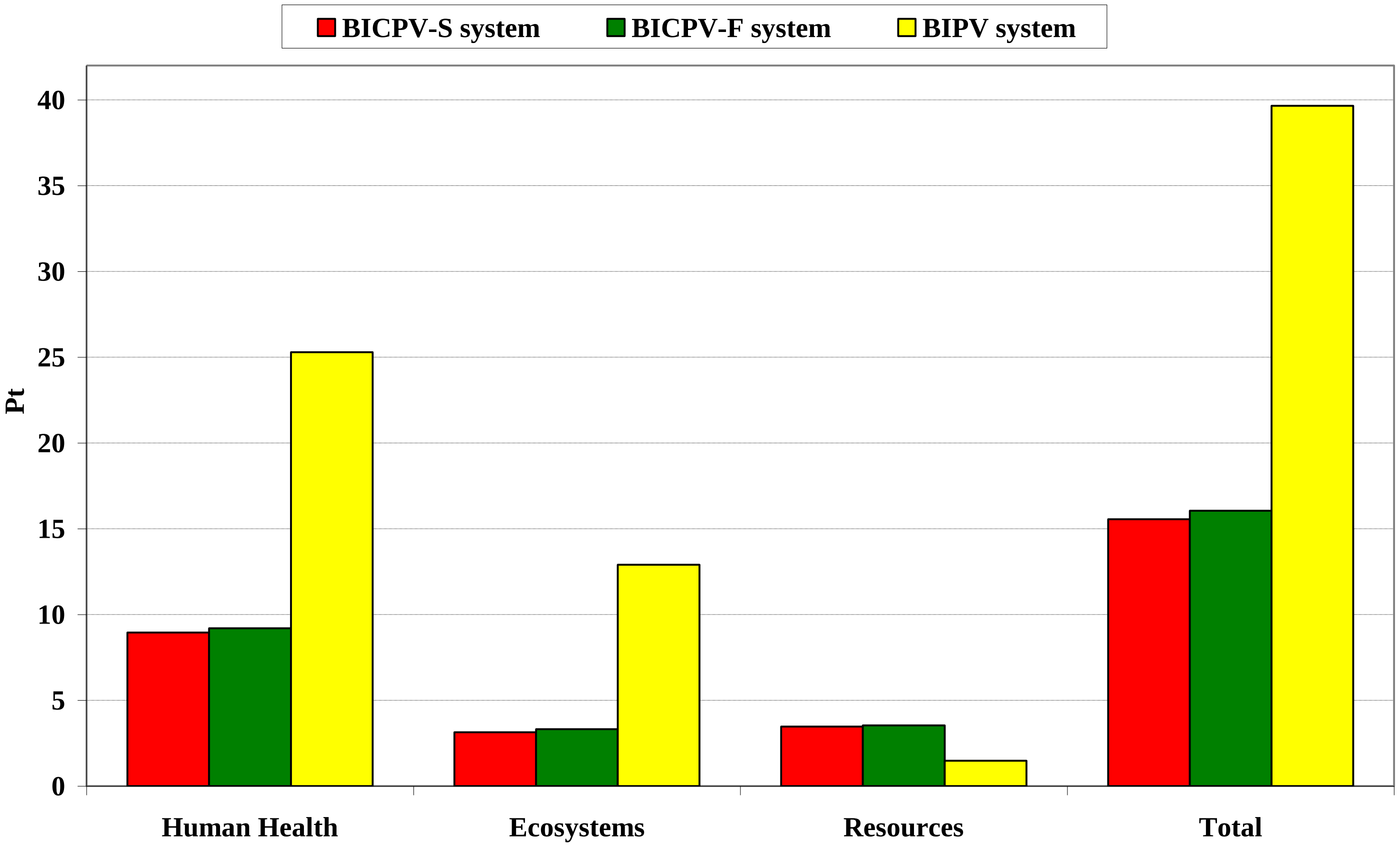

Figure 53. A comparison between the environmental impacts of the three corresponding studied systems using the ReCiPe methodology represented by the areas of protection

It is also observed that the impacts of both of the BICPV systems dominate the area of protection of the human health. This is clearly observed within the analysis of each system in the previous figures, where the climate change damage category (Climate change human health and climate change Eco systems) is the most dominant in each system. Furthermore, it is noticed that the resources in both of the BICPV systems have slightly higher impact than the resources in the BIPV one. This is mainly related to the extensive use of metals within the BICPV system, especially copper, which in return affects the depletion of metal damage category, and consequently the resources area of protection.

4.3.1.2 Energy profile

Figure 54 shows the Cumulative Energy Demand (CED) of the BICPV-F system components in terms of primary energy. It is observed that the reflectors represent the largest share of 51% of the total energy demand of the BICPV-F system.

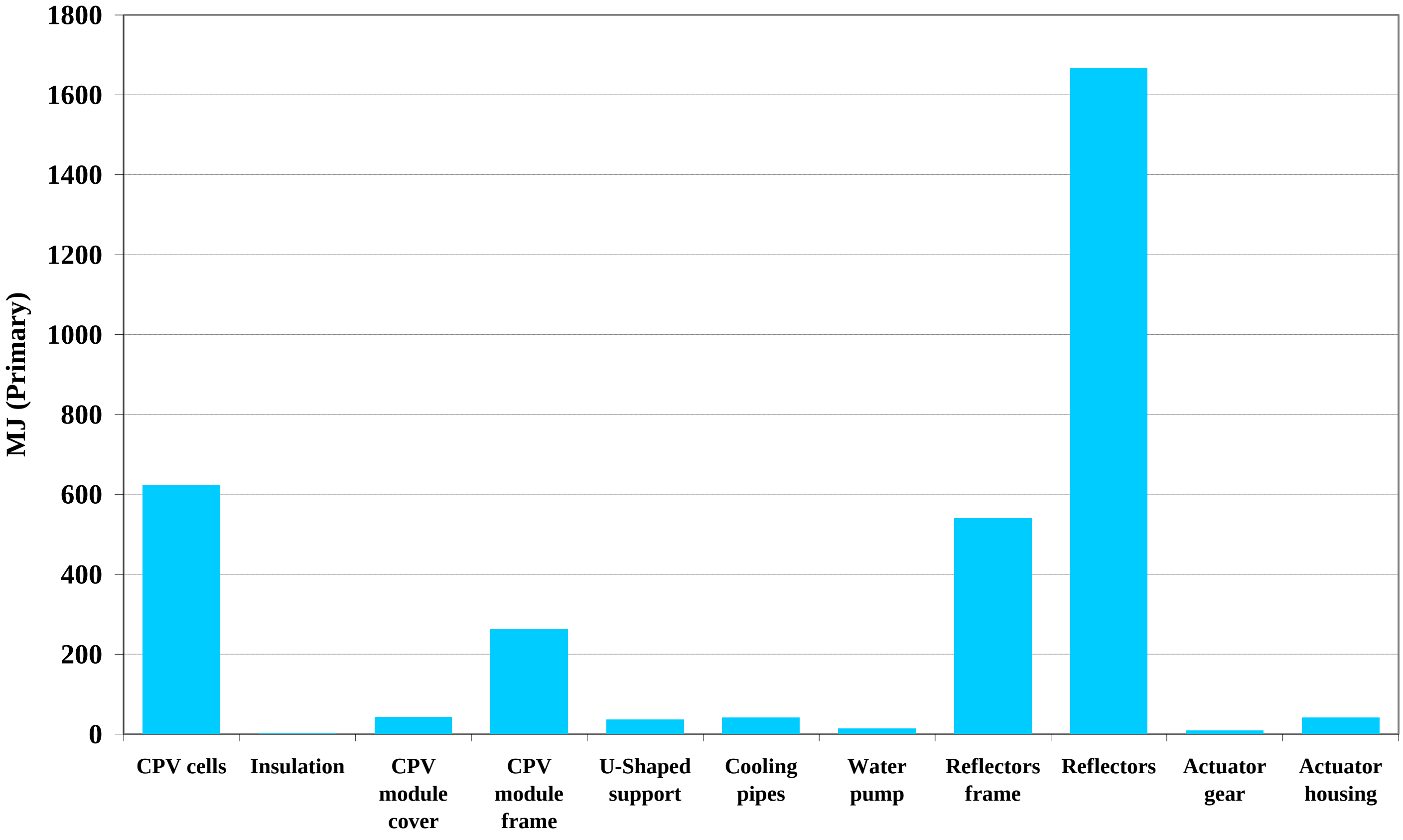

Figure 54. Cumulative energy demand of the BICPV-F system components in terms of primary energy

The second largest contributors are the CPV cells, where they represent 19% of the total. The reflectors frame constitutes 16.5% of the total energy demand. The CPV module frame constitutes around 8% of the total energy demand. The cooling structure (cooling pipes and U-Shaped support) represent a relatively low percentage of 2.5% of the total.

Figure 55 shows the Cumulative Energy Demand (CED) of the BICPV-S system components in terms of primary energy. It is observed that the reflectors covers represent the largest share of 39% of the total energy demand of the BICPV-S system. The second largest contributors are the CPV cells, where they represent 20% of the total.

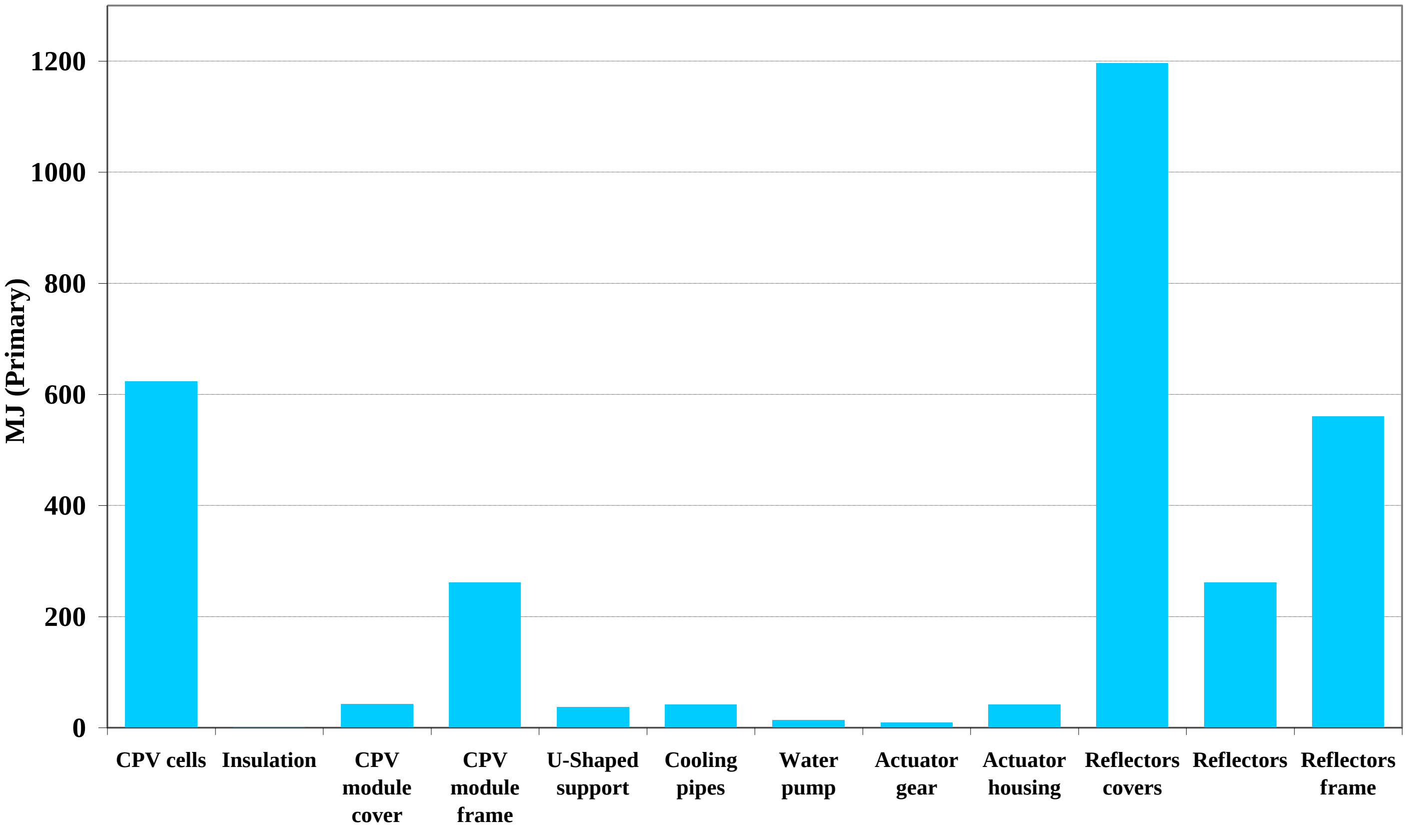

Figure 55. Cumulative energy demand of the BICPV-S system components in terms of primary Energy

The reflectors frame constitutes 18% of the total energy demand. The reflectors constitute 8.5% of the total energy demand; the CPV module frame represents 8.5% as well of the total energy demand. The cooling structure (cooling pipes and U-Shaped support) represent a relatively low percentage of 2.5% of the total.

Figure 56 shows the Cumulative Energy Demand (CED) of the BIPV system components in terms of primary energy. It is observed that the PV cells represent the largest share of 77% of the total energy demand. The second largest contributor is the PV module frame, where it represents 16% of the total energy demand.

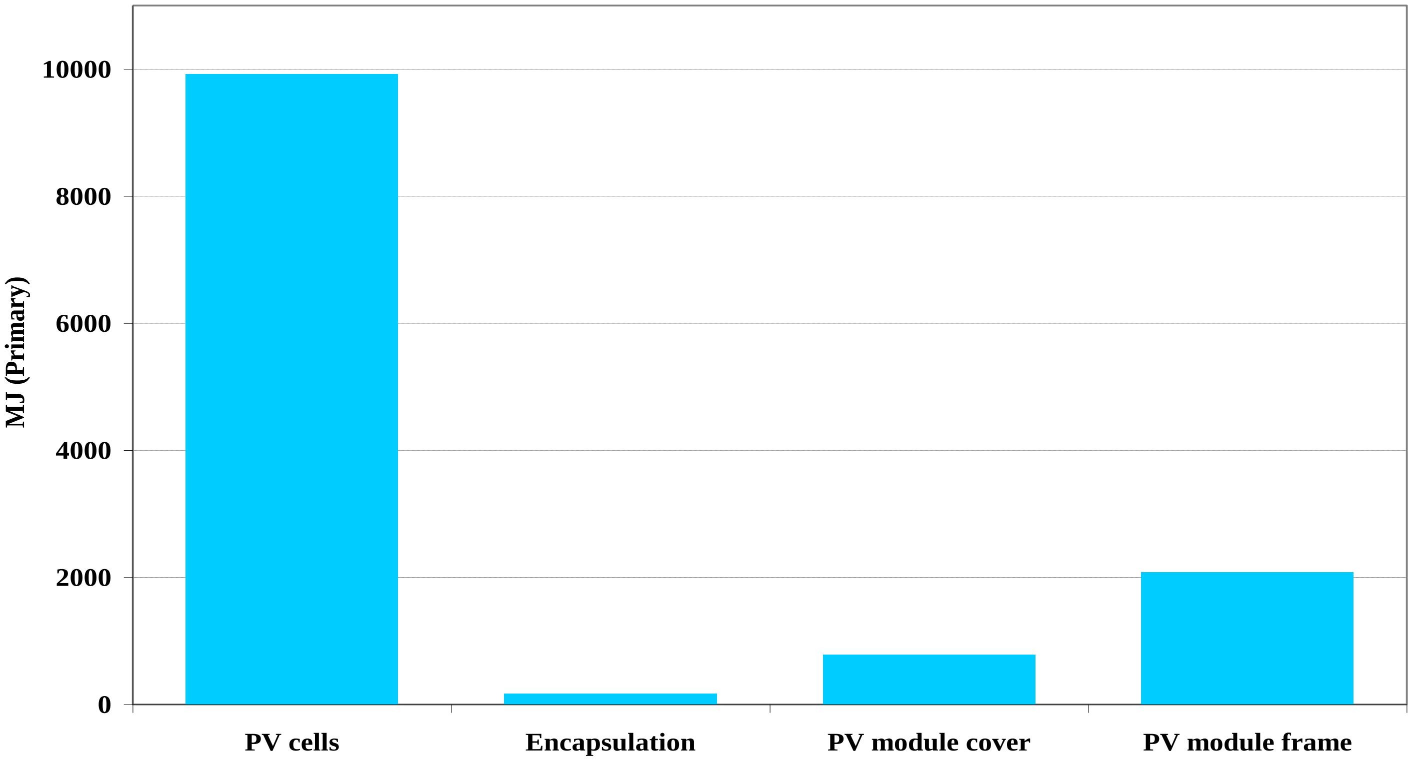

Figure 56. Cumulative energy demand of the BIPV system components in terms of primary energy

Figure 57 shows a comparison between the cumulative energy demand of the corresponding systems represented in terms of primary energy. It is demonstrated that the energy demands of the BICPV-F and BICPV-S systems are on the same range, where the energy demand of the BIPV systems is a factor of 4 higher than both of the

BICPV ones. This is mainly related to the use of a much larger area of PV cells compared to the BICPV systems. It is observed that although the BICPV-S system contains less number of reflectors with significantly reduced thickness, its total impact score is similar to that of the BICPV-F system. This is mainly related to the fact that two protective covers for the reflectors have been employed in the BICPV-S system.

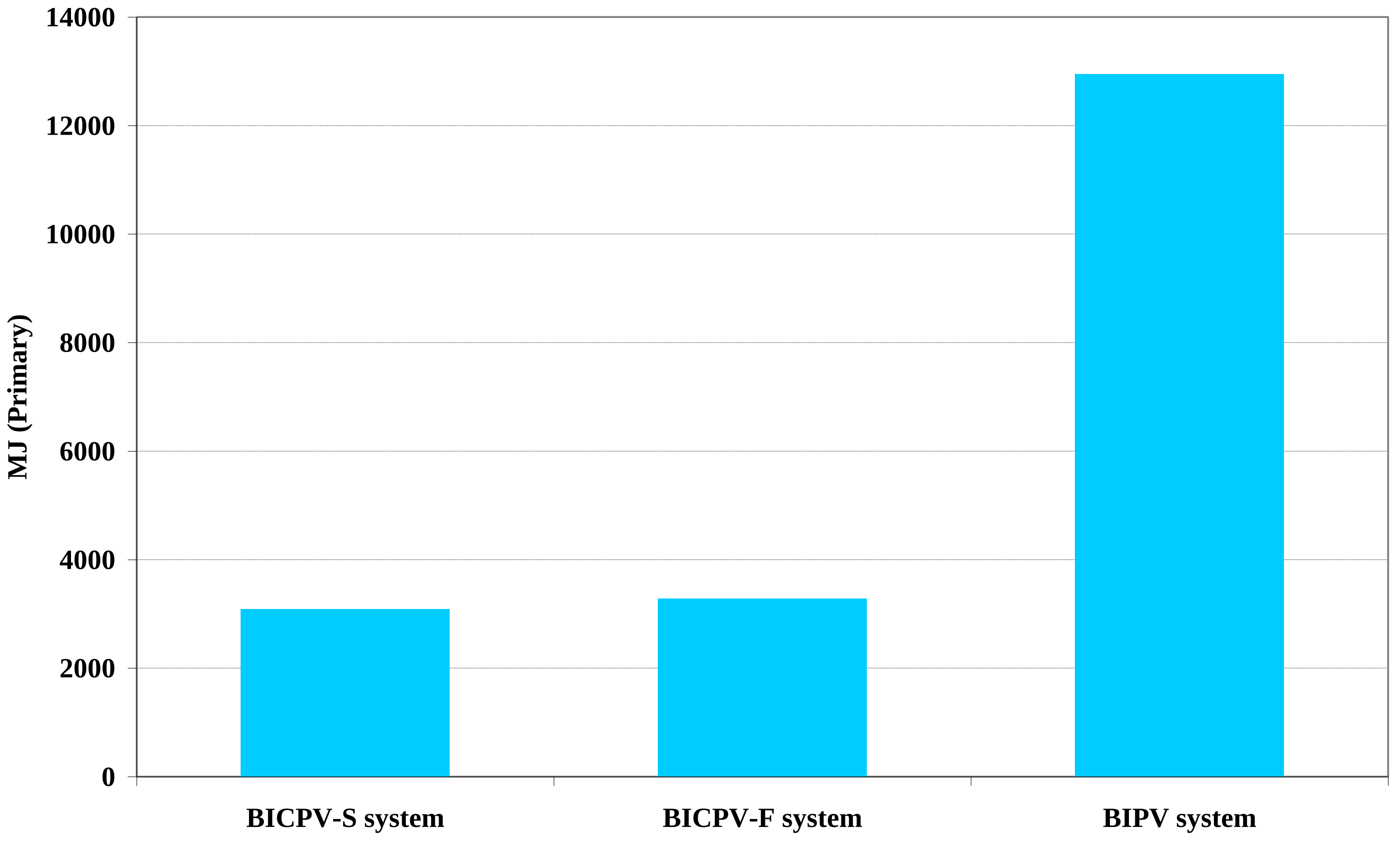

Figure 57. A comparison between the Cumulative Energy Demand of the three corresponding studied systems in terms of primary energy

That is, the use of the protective covers in the BICPV-S system has balanced out the environmental impact reduction achieved due to the use of fewer amounts of reflectors. It is also noticed that according to the average European energy mix considered (UCTE – Union of Coordination of Transmission of Electricity) in the Eco-Invent database, the Cumulative Energy Demand is dominated by non-renewable fossil resources (71%), followed by non-renewable nuclear resources (17%), where the renewable energy resources (Wind, solar, water, geothermal, and biomass) represents a relatively small share (11.3%).

4.3.2 The whole life cycle

Considering the assessment of the whole systems life cycle, the environmental and energy profiles are evaluated throughout the entire systems assumed life time of 30 years.

4.3.2.1 Environmental profile

4.3.2.1.1 EI99

Figure 58 shows a comparison between the environmental impacts of the three corresponding systems represented by the environmental areas of protection. It is demonstrated that the highest impact on the environment throughout the entire systems life cycle is induced by the BICPV-F system, where its impact of is a factor of 2 higher than both of the BICPV-S and BIPV systems. This is contrary to the results of the three systems during the assembly phase, where the BIPV system is the one with the higher environmental impact as demonstrated above. In addition, the impact of the BICPV-F system is similar to that of the BICPV-S system during the assembly stage. Those differences are mainly related to the lower energy output of the BICPV-F system in comparison to the BIPV and BICPV-S ones, where that lower energy output does not compensate for the high embodied environmental impact of the system during the assembly phase, while the larger energy output generated by the BIPV system balances out the significantly higher environmental impact during the assembly phase.

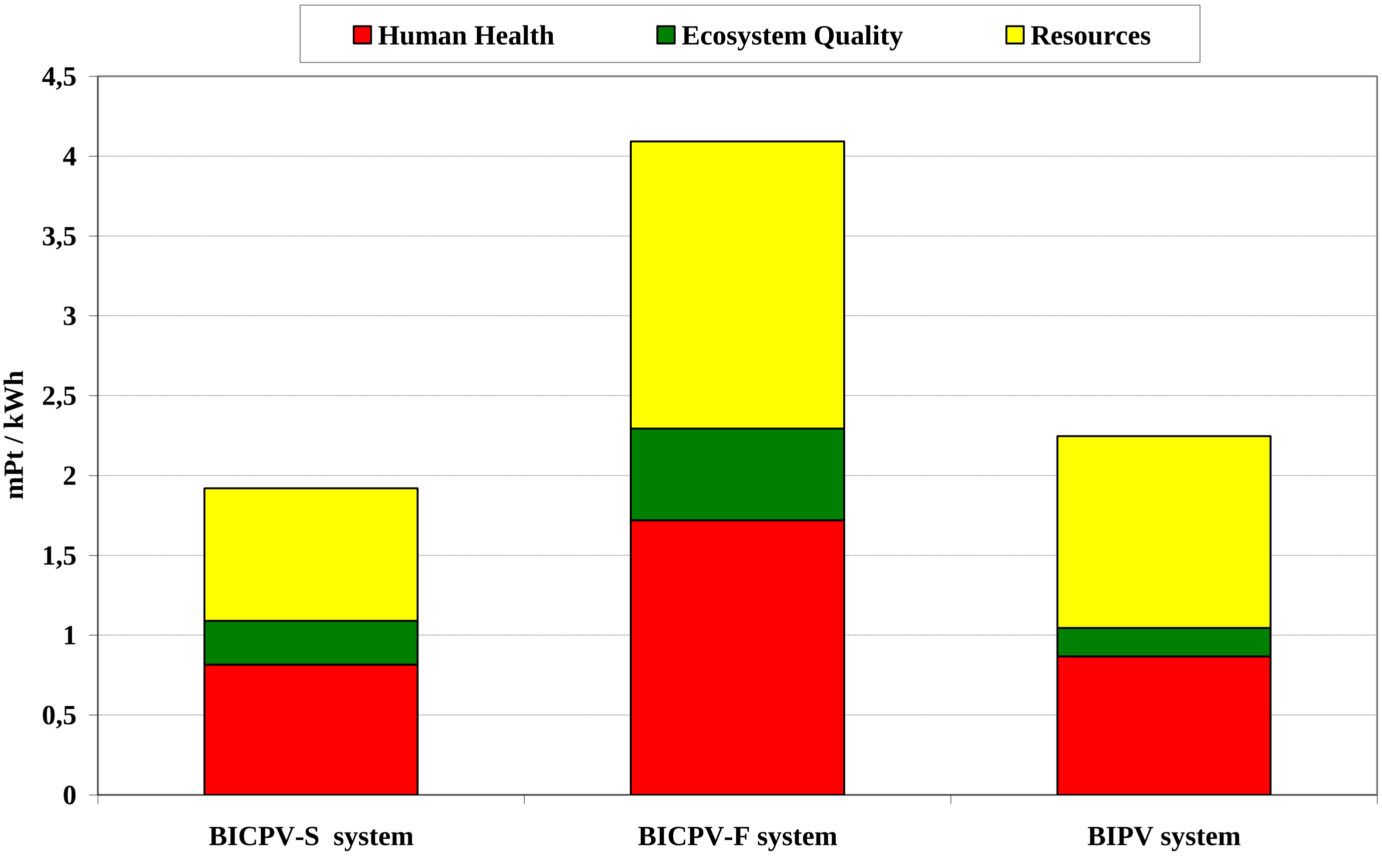

Figure 58. A comparison between the environmental impacts of the three corresponding studied systems using the EI99 methodology represented by the areas of protection during the whole life cycle

4.3.2.1.2 EPS 2000

Figure 59 shows a comparison between the environmental impacts of the three corresponding systems represented by the environmental areas of protection. It is demonstrated that the highest impact on the environment throughout the entire systems life cycle is induced by the BICPV-F system, where its impact of is a factor of 2 higher than that of the BICPV-S system, and a factor of 3.5 higher than that of the BIPV system. This is contrary to the results of the three systems during the assembly stage, where the BIPV system is the one with the higher environmental impact as demonstrated above. In addition, the impact of the BICPV-F system is similar to that of the BICPV-S system during the assembly stage. Those differences are mainly related to the lower energy output of the BICPV-F system in comparison to the BIPV and BICPV-

S ones, where that lower energy output does not compensate for the high embodied environmental impact of the system during the assembly phase, while the larger energy output generated by the BIPV system balances out the significantly higher environmental impact during the assembly phase.

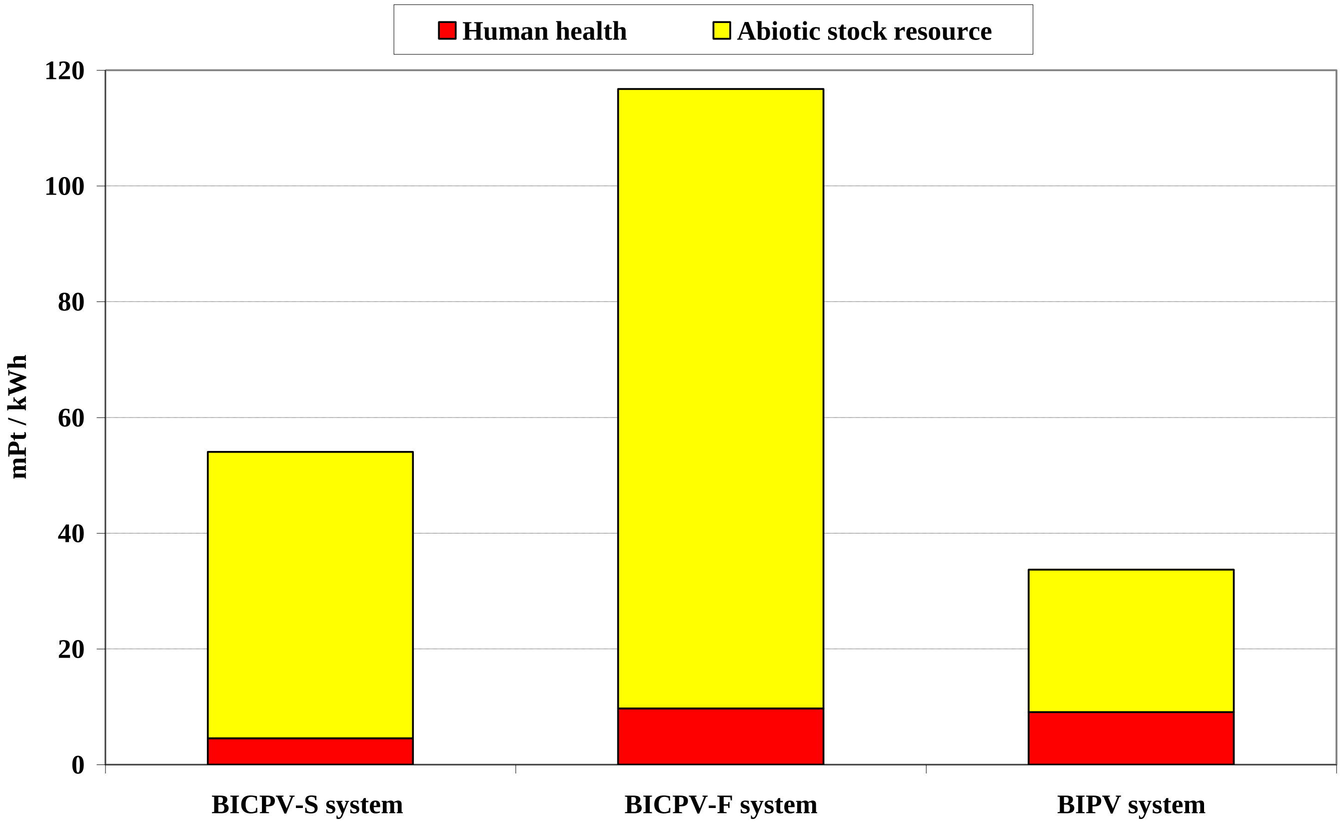

Figure 59. A comparison between the environmental impacts of the three corresponding studied systems using the EPS 2000 methodology represented by the areas of protection during the whole life cycle

In addition, it is observed that the impact of the BICPV-S system is a factor of 1.6 higher than that of the BIPV system.

4.3.2.1.3 IMPACT 2002+

Figure 60 shows a comparison between the environmental impacts of the three corresponding systems represented by the environmental areas of protection. It is demonstrated that the highest impact on the environment throughout the entire systems life cycle would be induced by the BICPV-F system, where its impact of is a factor of 2 higher than that of the BICPV-S system, and a factor of 1.5 higher than that of the BIPV system. This is contrary to the results of the three systems during the assembly stage, where the BIPV system is the one with the higher environmental impact as demonstrated above.

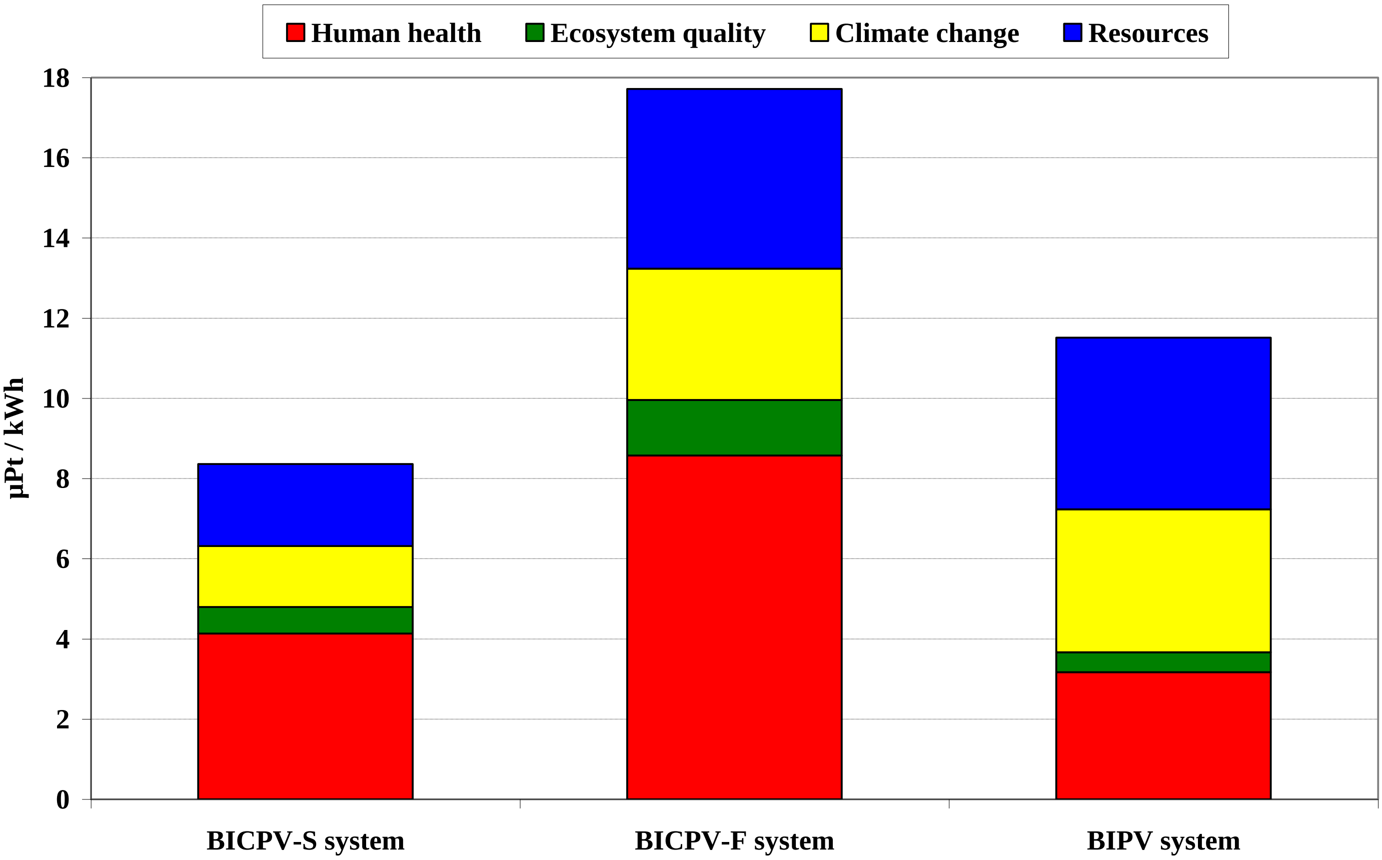

Figure 60. A comparison between the environmental impacts of the three corresponding studied systems using the IMPACT 2002+ methodology represented by the areas of protection during the whole life cycle

In addition, the impact of the BICPV-F system is similar to that of the BICPV-S system during the assembly stage. Those differences are mainly related to the lower energy output of the BICPV-F system in comparison to the BIPV and BICPV-S ones, where that lower energy output does not compensate for the high embodied environmental impact of the system during the assembly phase, while the larger energy output generated by the BIPV system balances out the significantly higher environmental impact during the assembly phase.

4.3.2.1.4 ReCiPe

Figure 61 shows a comparison between the environmental impacts of the three corresponding systems represented by the environmental areas of protection. It is demonstrated that the highest impact on the environment throughout the entire systems life cycle would be induced by the BICPV-F system, where its impact of is a factor of 2 higher than that of the BICPV-S system, and a factor of 1.5 higher than that of the BIPV system.

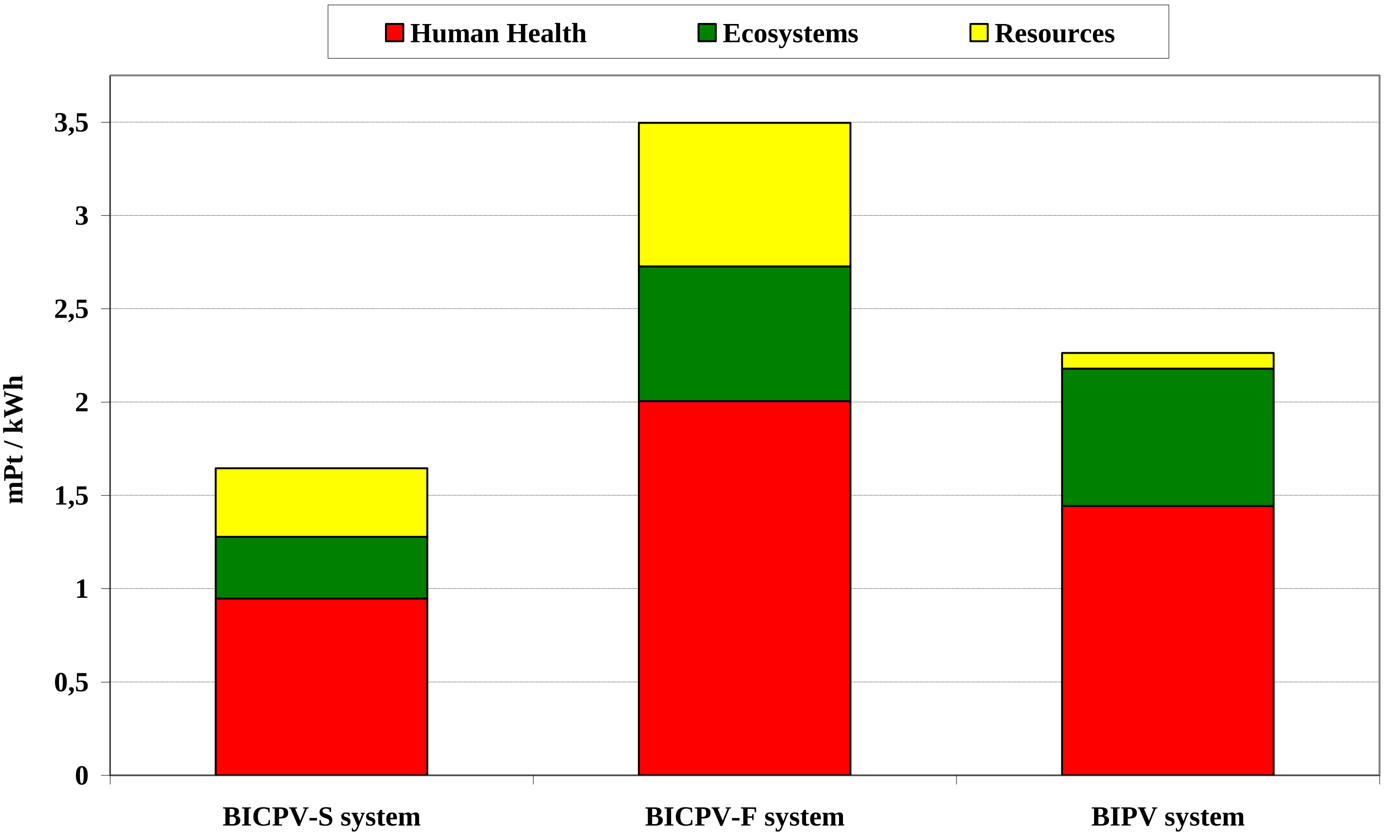

Figure 61. A comparison between the environmental impacts of the three corresponding studied systems using the ReCiPe methodology represented by the areas of protection during the whole life cycle

This is contrary to the results of the three systems during the assembly stage, where the BIPV system is the one with the higher environmental impact as demonstrated above. In addition, the impact of the BICPV-F system is similar to that of the BICPV-S system during the assembly stage. Those differences are mainly related to the lower energy output of the BICPV-F system in comparison to the BIPV and BICPV-S ones, where that lower energy output does not compensate for the high embodied environmental impact of the system during the assembly phase, while the larger energy output generated by the BIPV system balances out the significantly higher environmental impact during the assembly phase.

4.3.2.2 Energy profile

Regarding the CED values, they are calculated within the assembly stage analysis and found as 3278.61 MJ_{prim}, 3088.94 MJ_{prim}, and 12592.46 MJ_{prim} for the BICPV-F, BICPV-S, and BIPV systems, respectively. Regarding the ERF values, they are found as follows: 31.5 for the BICPV-S system, 14.4 for the BICPV-F system, and 14 for the BIPV system. This implies that with the energy generated by the corresponding systems, the BICPV-S system, the BICPV-F, and the BIPV system can be produced 31.5, 14.4, and 14 times, respectively. For the EPT, it is found that the EPT of the BICPV-S system is the shortest, where it is estimated as 1 years. On the other hand, the EPT of the BICPV-F and BIPV systems are found to be on the same range, where they are calculated as 2 years and 2.2 years, respectively. Although the BICPV-F embodied energy during the assembly phase is similar to that of the BICPV-S system, its EPT is a factor of 2 higher, and it is similar to that of the BIPV system. This is due to the higher energy output produced by the BICPV-S system, which balances out the embodied energy invested during the assembly phase. Similarly, as the BIPV system produces the highest amount of energy output, it balances out its highest embodied energy values during the assembly stage.

4.4 Discussion

Table 4, Table 5, Table 6, and Table 7 show a summary of the results demonstrating a comparison between the different used methods. This is mainly shown through highlighting the differences in the components impact contribution percentages between the four applied methodologies within the studied systems.

Table 4 shows a summary of the most significant results, comprising the assembly stage. As mentioned previously, the EI99 methodology is considered as a reference, and the other three methodologies (EPS 2000, IMPACT 2002+, and ReCiPe) methodologies are used in order to check and compare the coherency of the environmental performance results from another environmental perspective. It is clear that the utilization of the BICPV systems reduces the total environmental impact significantly in comparison to the conventional BIPV one. Hence, the results of the four methodologies can be summarized as follows:

- The EI99 methodology: This methodology demonstrates the high value of using BICPV systems instead of the BIPV ones (The impact of the BIPV system is 2.5 times the impact of the BICPV ones). Besides, the EI99 methodology highlights the significant impact of the reflectors with respect to the total impact points of the BICPV-F system (44%), which invokes the need to further investigate the use of low iron reflectors. Nevertheless, further purifying the reflectors during manufacturing in order to lower the iron percentages may lead counter productive results. Including further purification processes will, definitely, consume higher amounts of energy, which will be interpreted in higher impact through the fossil fuels impact category and other related emissions during processing. Similarly, in case of the BICPV-S system, the reflectors covers represent the highest share of 34.5% of the total impact score. Besides, the results show also that the copper constitutes between 23.5%-24% of the total impact points of both of the BICPV systems, which is considered to be significant with respect to the quantity used (around 2 kg for the cooling pipes and the U – Shaped support).

- The EPS 2000 methodology: Similar to the EI99 methodology, the results demonstrate the significant environmental benefits of using the BICPV systems instead of the BIPV ones. In the regard of the CPV system components, this methodology clarifies a high priority for the need to substitute the copper used in the cooling pipes and U-shaped support within the BICPV systems with another low impact materials. This is clearly presented in the results, where the copper generates more than half of the total impact points (70%-74%) demonstrated through the depletion of reserves impact category. In other words, these results reflect the severe degradation of the high quality copper reserves.
- The IMPACT 2002+ methodology: The components contributions demonstrated by this methodology are similar to those of the EI99 methodology. Nevertheless, it is noticed that the reflectors frame contribution to the total is bit higher compared to the case of the EI99 methodology, where it represents around 24%-25.5% of the total. On the other hand, it is observed that the cooling structure constitute less contribution to the total impact score (13%-13.5%). Thus, unlike the previous methodologies, it is concluded that this methodology does not gives a high value to the mineral extraction (Steel, copper, etc.). This can be clearly observed from the results, where the respiratory inorganics and the non-renewable energy damage categories are the most dominant.
- ReCiPe: The components contribution of this methodology are similar to those of the EI99 methodology, except for the results of the reflectors and reflectors covers, where the contribution value are a little less than those demonstrated by the EI99 methodology. On the other hand, it is observed that the results of the ReCiPe

methodology are dominated by the climate change impact category. In addition, the ReCiPe methodology contains the largest number of damage categories among the other methodologies. More damage categories are advantageous, as they demonstrate the contribution of specific damages to the total environmental load that is not taken into consideration by other methodologies. Furthermore, the ReCiPe version used in this study is the latest, developed in December 2012. Using such a recent methodology and compare it to the results of a widely used one (EI99) assists in having an overarching image, highlighting the effect of the changes in the characterization of each methodology over the time.

In reference to the energy profile during the assembly stage, Table 5 shows a comparison between the impact contribution percentages of the systems components to the total CED. It is observed that the comparison results coincide with those of the LCIA methodologies. However, there are some differences noticed as well. Within this context, it is found that the CPV cells contribute by a significant share to the total CED (19%-20%). In addition, it is observed that the CPV module frame constitute an elevated share of the CED (8%-8.5%). Furthermore, the cooling structure (cooling pipes and U-Shaped support) constitutes only around 2.5% of the total, while they contribute significantly by a larger percentage to the total impact points using the LCIA methodologies. By observing the results of both of Table 4 and Table 5 and the differences that exist between the systems components regarding their share to the total environmental profile and the total CED, it is realized the importance of using both of the environmental and energy profile analysis for a corresponding system. This assists in providing an overarching image of the systems performances, highlighting the system areas that need attention from energy and environmental viewpoints simultaneously, without compromising any aspect of them.

Systems components	**Environmental profile**			
	EI99	**EPS 2000**	**IMPACT 2002+**	**ReCiPe**
BICPV-F system				
Environmental impact ratio of the BIPV system to the BICPV-F system	2	1.1	2.5	2.5
Contribution percentage of the CPV cells to the total impact points of the BICPV-F system	8.5%	5%	11%	11%
Contribution percentage of the reflectors to the total impact points of the BICPV-F system	44%	16%	42.5%	34%
Contribution percentage of the reflectors frame to the total impact points of the BICPV-F system	15%	4%	24%	16.5%
Contribution percentage of the cooling structure (copper cooling pipes and U-Shaped support) to the total impact points of the BICPV-F system	23.5%	70%	13%	29.5%
BICPV-S system				
Environmental impact ratio of the BIPV system to the BICPV-S system	2	1.1	2.5	2.5
Contribution percentage of the CPV cells to the total impact points of the BICPV-S system	9%	5.5%	11%	11.5%
Contribution percentage of the reflectors to the total impact points of the BICPV- S system	7%	3%	7%	5.5%
Contribution percentage of the reflectors frame to the total impact points of the BICPV-S system	16%	4.5%	25.5%	18%
Contribution percentage of the reflectors covers to the total impact points of the BICPV-S system	34.5%	9%	33%	26%
Contribution percentage of the cooling structure (copper cooling pipes and U-Shaped support) to the total impact points of the BICPV-S system	24%	74%	13.5%	30.5%

Table 4. A comparison between the environmental profile results of the BICPV systems components using different LCIA methodologies at the assembly phase

Table 6 shows the environmental profile results throughout the systems entire life cycle. It is noticed that there are similarities between results of the EI99, IMPACT 2002+, and the ReCiPe methodologies, where the EPS 2000 methodology differ in estimating the ratio of environmental impact of the BICPV-F system to the BIPV one. Similarly, the BICPV-S system shows a better environmental performance than both of the BICPV-F and BIPV system, except when using the EPS 2000 methodology, where the impact of the BICPV-S is slightly higher than that of the BIPV one (A factor of 1.6).

Systems components	Energy profile (CED)
BICPV-F system	
Environmental impact ratio of the BIPV system to the BICPV-F system	4
Contribution percentage of the CPV cells to the total impact points of the BICPV-F system	19%
Contribution percentage of the reflectors to the total impact points of the BICPV-F system	51%
Contribution percentage of the reflectors frame to the total impact points of the BICPV-F system	16.5%
Contribution percentage of the CPV module frame to the total impact points of the BICPV-F system	8%
Contribution percentage of the cooling structure (copper cooling pipes and U-Shaped support) to the total impact points of the BICPV-F system	2.5%
BICPV-S system	
Environmental impact ratio of the BIPV system to the BICPV-S system	4
Contribution percentage of the CPV cells to the total impact points of the BICPV-S system	20%
Contribution percentage of the reflectors to the total impact points of the BICPV- S system	8.5%
Contribution percentage of the reflectors frame to the total impact points of the BICPV-S system	18%
Contribution percentage of the reflectors covers to the total impact points of the BICPV-S system	39%
Contribution percentage of the CPV module frame to the total impact points of the BICPV-S system	8.5%
Contribution percentage of the cooling structure (copper cooling pipes and U-Shaped support) to the total impact points of the BICPV-S system	2.5%

Table 5. A comparison between the energy profile results of the BICPV systems components using the CED indicators at the assembly phase

Systems components	Environmental profile			
	EI99	EPS 2000	IMPACT 2002+	ReCiPe
Environmental impact ratio of the BICPV-F system to the BICPV-S system	2	2	2	2
Environmental impact ratio of the BICPV-F system to the BIPV system	2	3.5	1.5	1.5

Table 6. A comparison between the environmental profile results of the BICPV systems components using different LCIA methodologies throughout the systems entire life cycle

Table 7 shows the energy profile result of the studied systems. It is observed that the best EPT estimate is for the BICPV-S system (1 year), while those of the BICPV-F and BIPV systems are bit higher and quite similar as well (2 years and 2.2 years, respectively). Similarly, the ERF values are 31.5, 14.4, and 14 for the BICPV-S system, the BICPV-F system, and the BIPV system, respectively.

The studied systems	Energy profile	
	EPT (Years)	ERF
The BICPV-F system	2	14.4
The BICPV-S system	1	31.5
The BIPV system	2.2	14

Table 7. A summary table of the results of the energy profile evaluations throughout the systems entire life cycle

4.5 Sensitivity analyses

Referring to the newness of the BICPV systems installed, it is necessary to conduct sensitivity analyses in order to further examine the environmental benefits that could be gained.

4.5.1 Increasing the concentration ratio

For the BICPV-F system, Figure 62 show that the higher concentration ratio, the lower the impact scores.

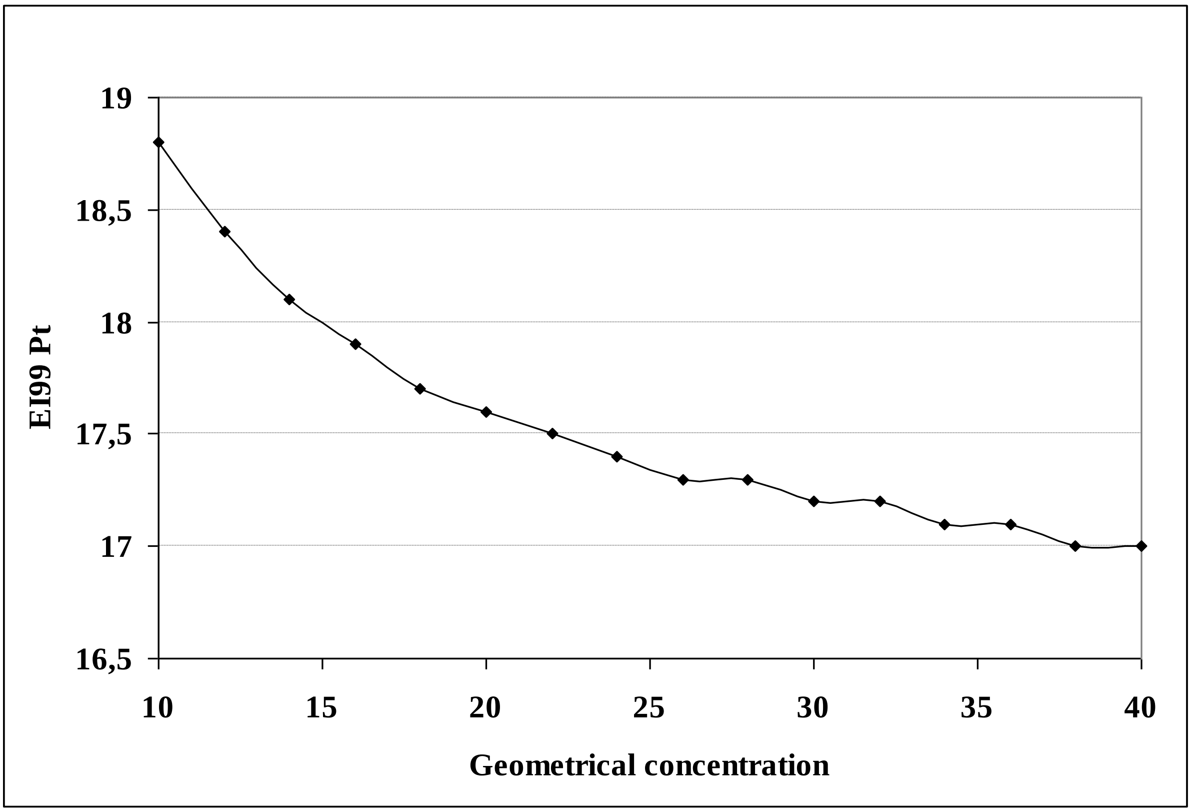

Figure 62. The effect of increasing the concentration ratio of the BICPV-F system on the impact score using the EI99 methodology

It is noticed that increasing the concentration ratio to 18 suns can reduce the system impact score by around 6%. On the other hand, it is observed that further augmenting the concentration ratio from 18 suns and up to 40 suns, although still reduces the impact score; the rate of reduction is not as much as before, where the impact score is reduced by only 4 %.

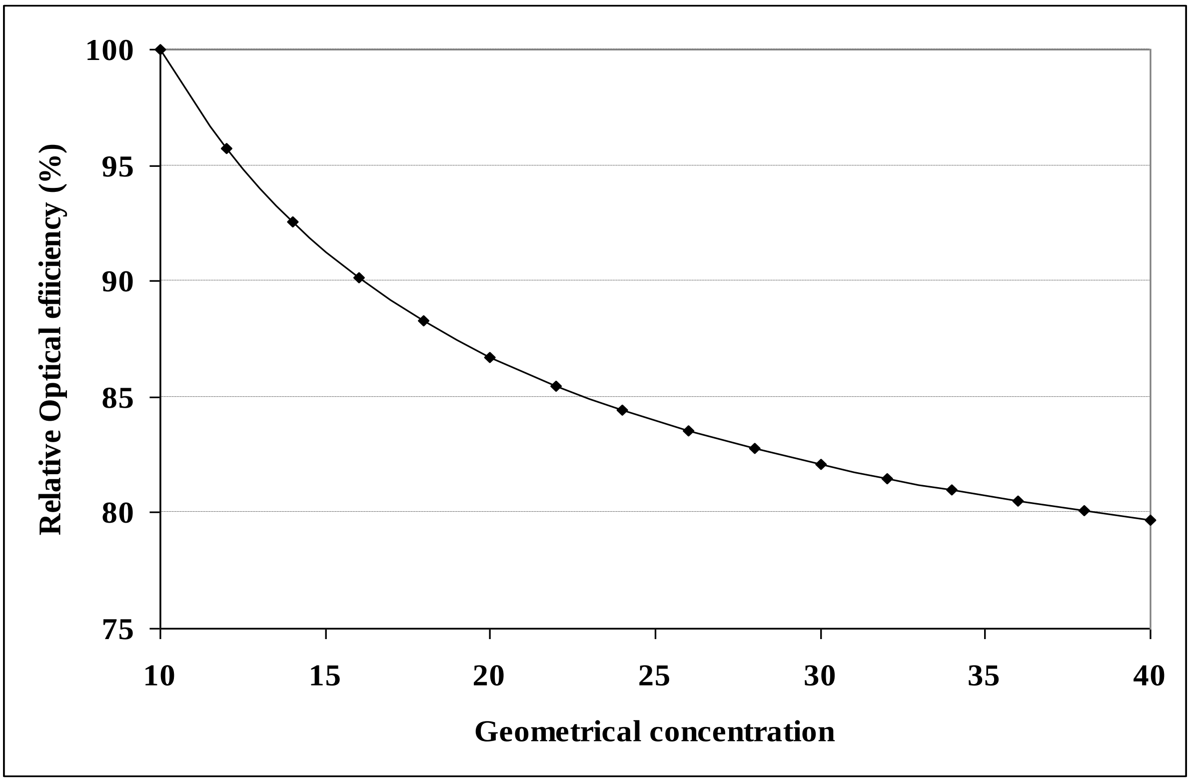

Figure 63. The effect of increasing the concentration ratio of the BICPV-F system on the optical efficiency relative to 10 suns concentration ratio

However, as shown in Figure 63, the increase of the concentration is also associated with higher optical loses (relative to a concentration factor of 10 suns). Hence, it would be essential to consider this aspect in case further system modification is needed within the assembly phase, as increasing the concentration ratio could lead to counter results.

For the BICPV-H system, the concentration ratio could not be assumed to be incremented because of some geometrical restrictions. Hence, the sensitivity analysis is conducted showing the effect of decreasing the concentration ration on the relative optical efficiency and the environmental impact points (Figure 64 and Figure 65).

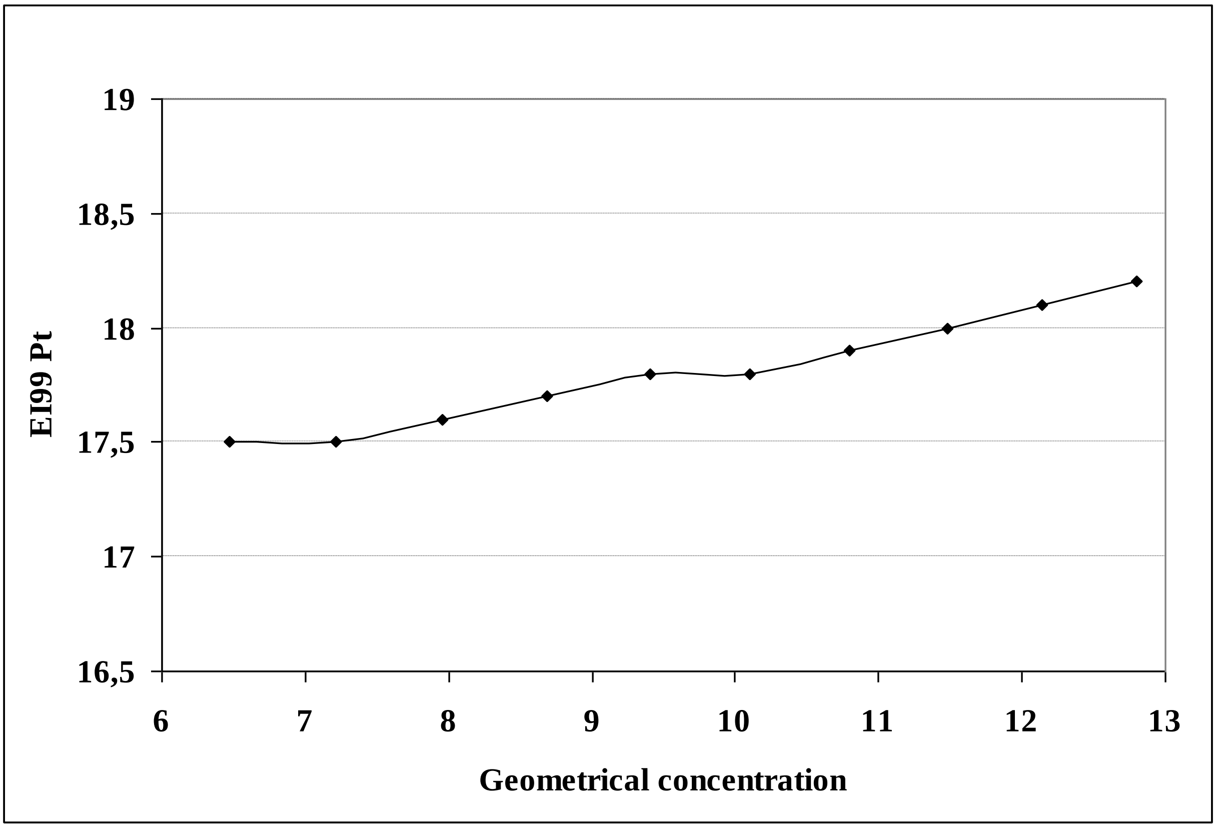

Figure 64. The effect of increasing the concentration ratio of the BICPV-S system on the impact score using the EI99 methodology

It is noticed that decreasing the concentration ratio to 6 suns can reduce the system impact score by only 4%. Furthermore, it is observed that the decrease of the concentration improves the relative optical efficiency significantly (relative to a concentration factor of 10 suns). Hence, it would be essential to consider this aspect a further system modification within the assembly phase, as decreasing the concentration ratio would decrease the environmental impact (4%), and increase the optical efficiency, which consequently leads to higher energy output, and therefore better environmental and energy performance throughout the whole system life cycle.

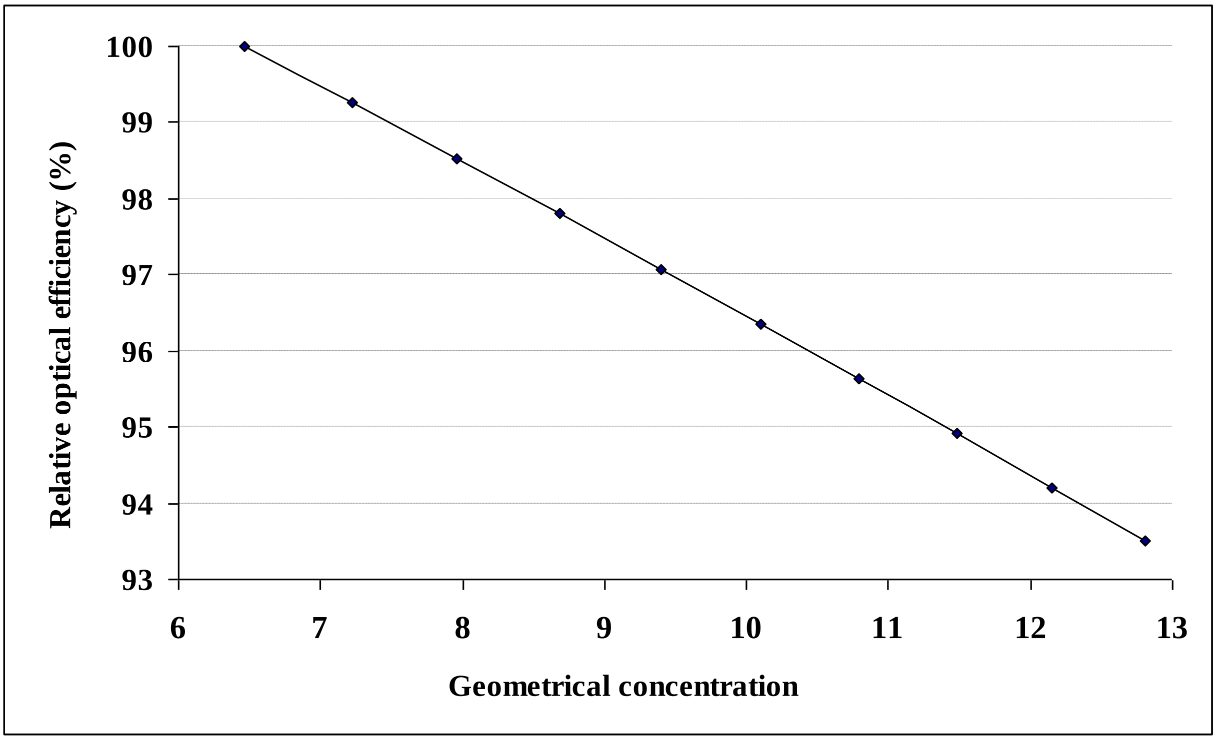

Figure 65. The effect of increasing the concentration ratio of the BICPV-S system on the optical efficiency relative to 10 suns concentration ratio

4.5.2 Using Fresnel lenses

As presented in previous studies conducted within the University of Lleida [8], Fresnel Lenses represent a successful candidate for concentration. Thus, it has been considered interesting to conduct a sensitivity analysis in this regard. Figure 66 and Figure 67 shows that by using Fresnel lenses instead of the reflectors (while considering the same corresponding area and dimensions), the environmental impact of the BICPV systems increases. It is noticed that the increment in the BICPV-F system is twice, while it is only 16.4% in case of the BICPV-S system.

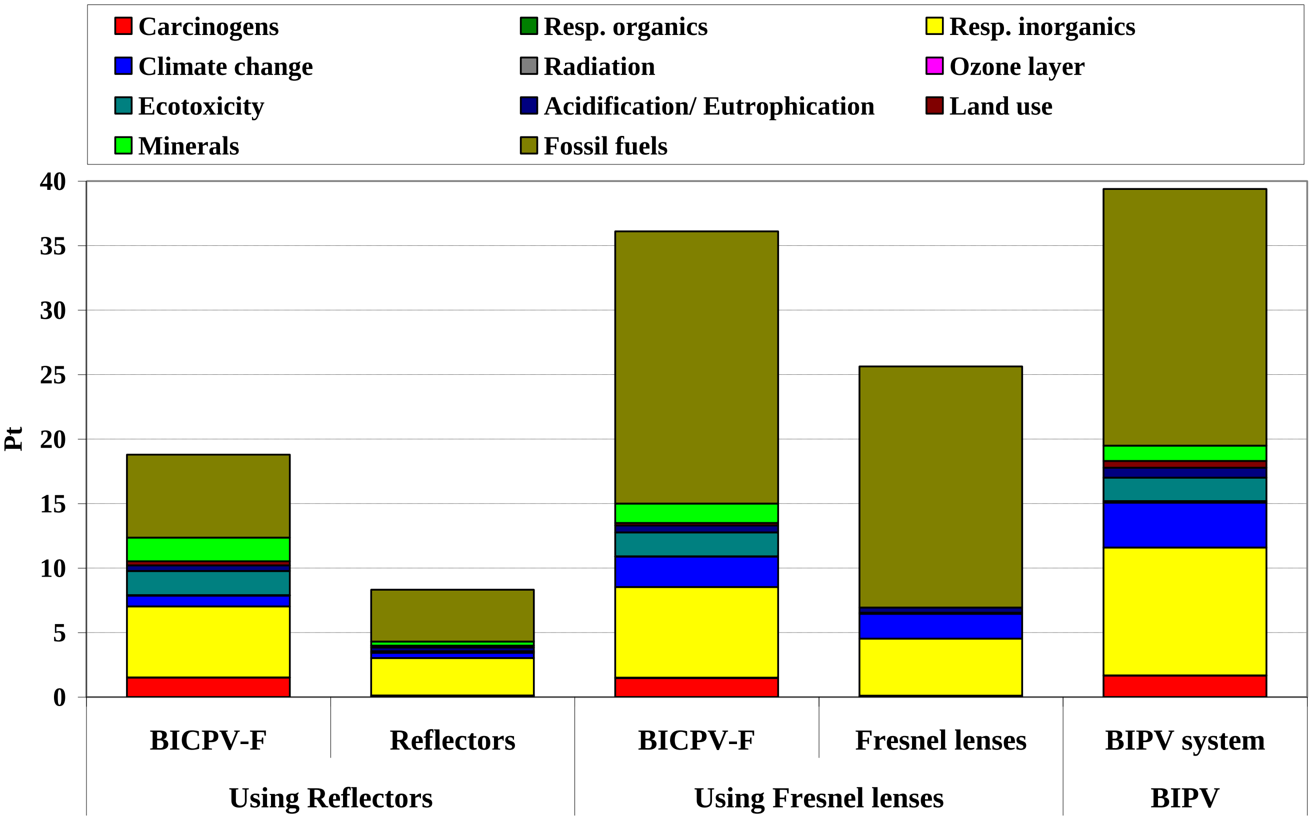

Figure 66. A comparison between the environmental impacts of the BICPV-F system in case of using reflectors, and using Fresnel lenses instead, using the EI99 methodology

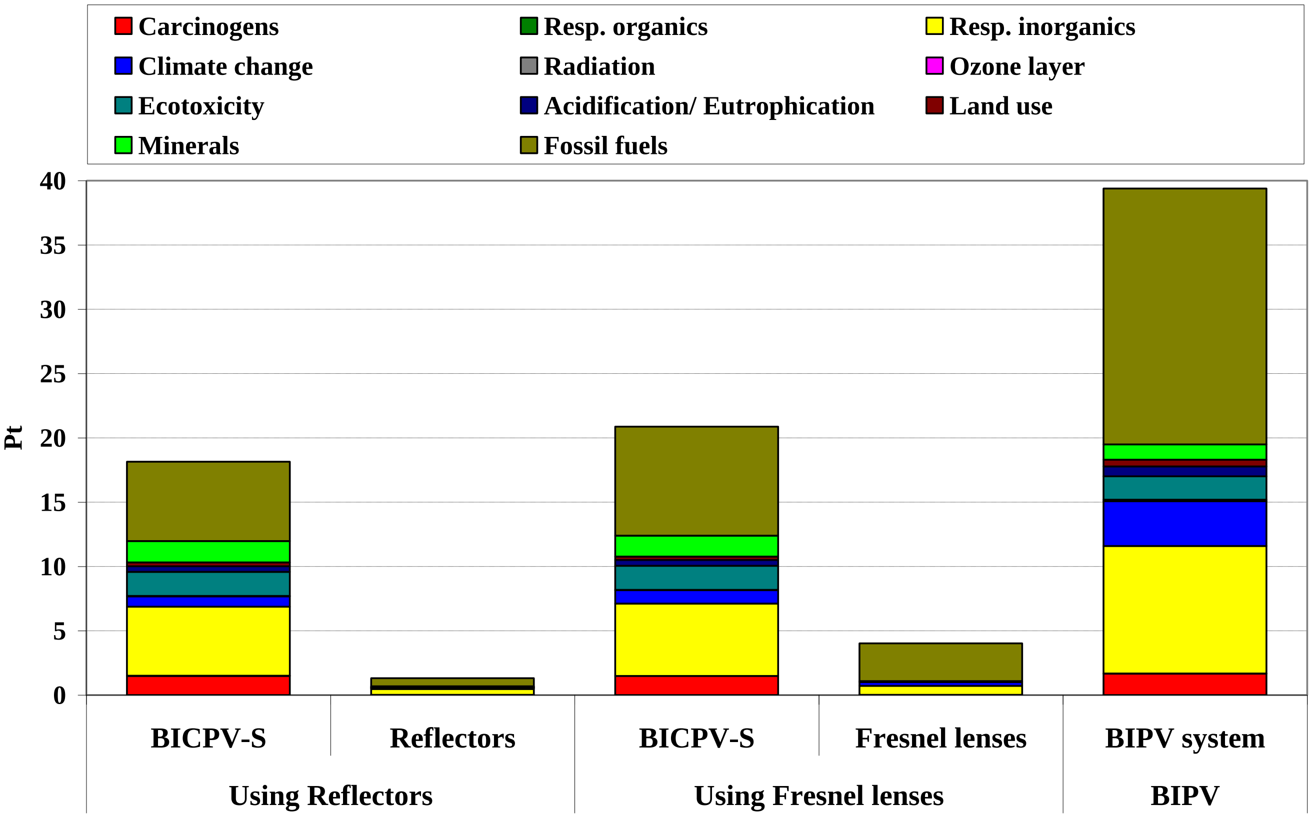

Figure 67. A comparison between the environmental impacts of the BICPV-S system in case of using reflectors, and using Fresnel lenses instead, using the EI99 methodology

This is mainly related to the use of larger quantities of reflectors/lenses in case of the BICPV-F system as entailed previously. Such analysis presents an interesting opportunity for further investigating novel BICPV system that employs Fresnel lenses during their entire lifetime.

4.5.3 The cooling structure materials

In a study conducted previously by Chemisana [376], it has been demonstrated that copper is the most suitable material to be employed within the CPV modules, referring to their convenient thermal properties (high thermal conductivity). Nevertheless, as it has been demonstrated in the previous subsections, the copper represents a significant contribution to the total environmental impact score of both of the BICPV systems. Hence, sensitivity analyses revealing other candidate materials to replace copper are presented (Figure 68 and Figure 69). The BICPV systems environmental impact has been reassessed considering other materials to replace copper within the cooling structure (Nickel, brass, silver, chromium, aluminum, lead, zinc, iron, and graphite). The analysis was achieved using the endpoint indicators of the ReCiPe methodology. The thickness of each material was determined according to its fulfilment to the same thermal conductivity of copper during the operational phase.

In reference to Figure 68, it is shown that graphite, aluminium, and iron represent the best candidates to replace copper within the cooling structure of the BICPV-F system, where they reduce the environmental impact by 23.5%, 22.5%, and 20.5%, respectively. Furthermore, lead and zinc represent suitable candidates as well, as they reduce the environmental impact by 14% and 9%, respectively. On the other hand, it is observed that using brass increases the environmental impact by 15%, and using chromium increases the environmental impact by 19.5%. In addition, it is noticed that using nickel or silver increases the environmental impact of the BICPV-F system to be a factor of 2 in case of using nickel, and a factor of 3.5 in case of using silver.

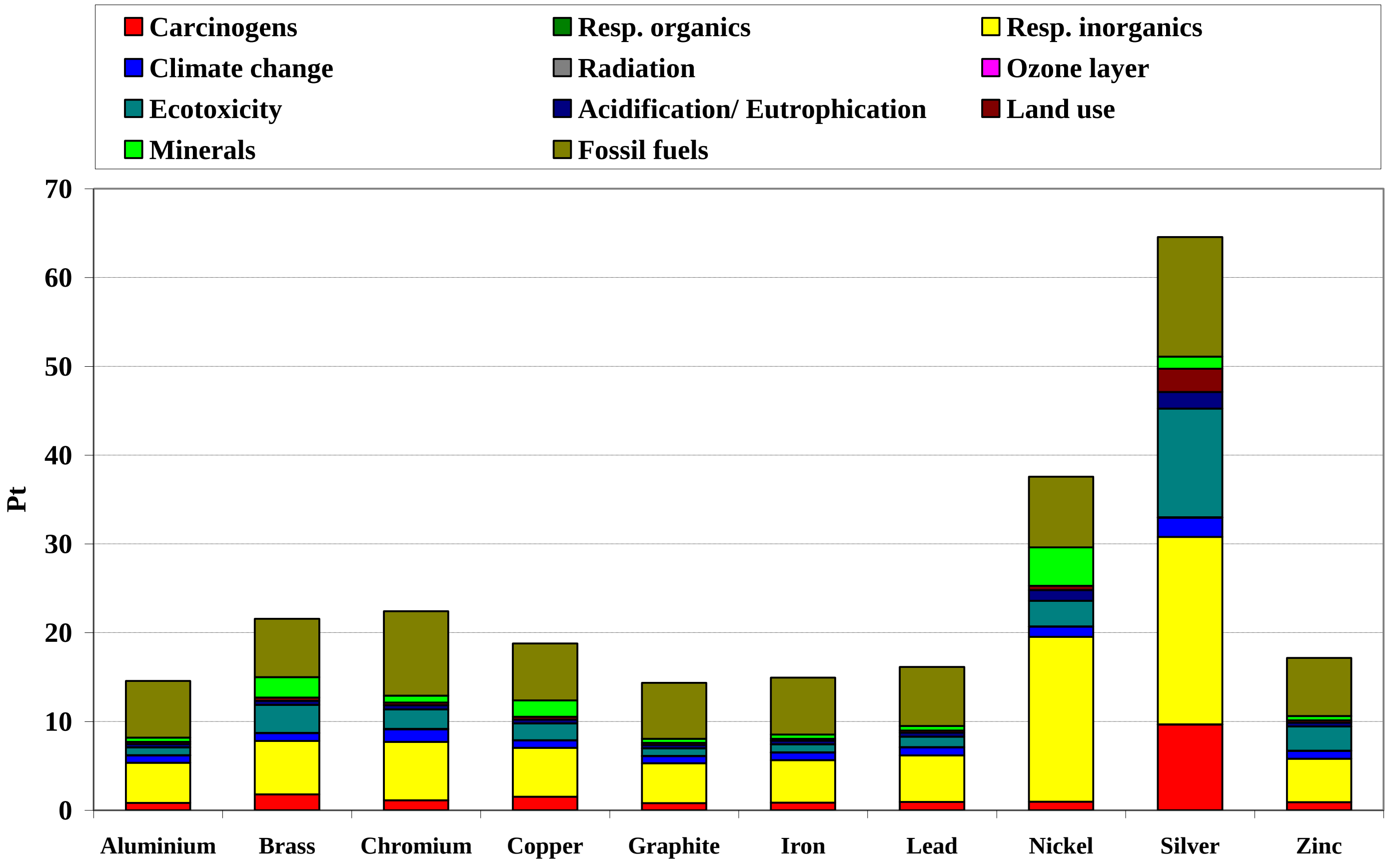

Figure 68. A comparison showing the environmental impact of the BICPV-F system in case of using different materials within the cooling structure of the CPV modules instead of copper, using the EI99 methodology

In reference to Figure 69, it is shown that graphite, aluminium, and iron represent the best candidates to replace copper within the cooling structure of the BICPV-F system, where they reduce the environmental impact by 24.5%, 23%, and 21%, respectively. Furthermore, lead and zinc represent suitable candidates as well, as they reduce the environmental impact by 14.5% and 9%, respectively. On the other hand, it is observed that using brass increases the environmental impact by 15%, and using chromium increases the environmental impact by 20%. In addition, it is noticed that using nickel or silver increases the environmental impact of the BICPV-F system to be a factor of 2 in case of using nickel, and a factor of 3.5 in case of using silver.

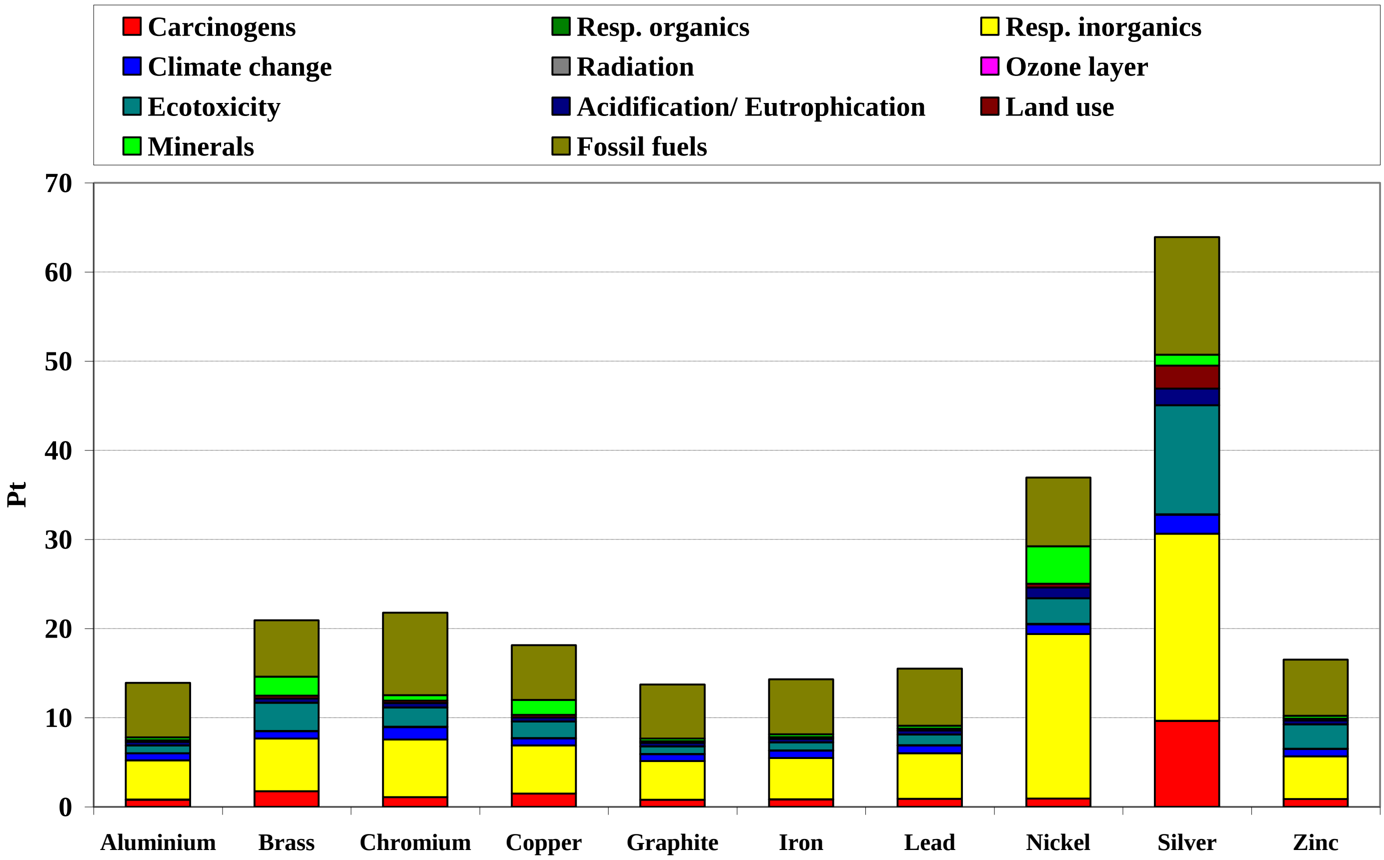

Figure 69. A comparison showing the environmental impact of the BICPV-S system in case of using different materials within the cooling structure of the CPV modules instead of copper, using the EI99 methodology

5 Chapter 5

Conclusions

Conclusions

This thesis mainly comprises a Life Cycle Assessment (LCA) study of Building Integrated Concentrated Photovoltaic (BICPV) systems. The thesis has started with a detailed explanation about the LCA concept and the LCA methods, enclosed within Chapter 1. A review about solar technologies and systems within the context of low and medium solar concentration has been presented in Chapter 2, where the most up to date utilized process, materials, and systems configurations have been demonstrated.

In Chapter 3, a critical analysis has been conducted, demonstrating the LCA studies related to solar technologies and systems. The results of this analysis indicate the existence of some gaps in that field of studies, represented in the following three aspects: The first: The LCA indicators are not widely varied, where most of the LCA studies are based on the Energy Payback Time (EPT) and the Global Warming Potential (GWP) as the sole environmental indicators. Such focus on the EPT and GWP disregards the environmental profile analysis. The second: A lack has been noticed in the LCA studies of building integrated systems. In addition, no studies have been found about BICPV systems. The third: A lack has been noticed in the LCA studies of concentrating systems. Additionally, all of the related studies have been found about high concentration systems only.

Therefore, referring to the aforementioned gaps, two BICPV systems has been presented and analyzed from an LCA view point in Chapter 4. The first system represents an integrated façade system (BICPV-F), and the second system represents an integrated shading system (BICPV-S). The analysis has been achieved with respect to two aspects: Evaluating the environmental profile using LCIA methodologies, and evaluating the energy profile using the Cumulative Energy Demand (CED), in addition to other whole life cycle indicators, which are the Energy Return Factor (ERF), and the Energy Payback Time (EPT). In addition, the results are compared to those of a conventional Building Integrated Photovoltaic (BIPV) system. The conclusions of that analysis are listed as follows:

- Regarding the assembly phase, the two BICPV systems show a better environmental and energy profiles than the BIPV one. This is mainly attributed to the use of relatively much less surface area of photovoltaic cells in the BICPV systems, which consequently means less embodied energy and other related emissions to the environment. It is observed that although the BICPV-S system contains less number of reflectors with significantly reduced thickness, its total impact score is similar to that of the BICPV-F system. This is mainly related to the fact that two protective covers for the reflectors have been employed in the BICPV-S system. That is, the use of the protective covers in the BICPV-S system has balanced out the environmental impact reduction achieved due to the use of fewer amounts of reflectors.
- Regarding the whole life cycle assessment, it has been found that the BICPV-S system outperforms the BIPV and BICPV-F systems environmentally and energetically. Additionally, it has been found that the BICPV-F system induces the highest impact on the environment, and that it has a similar energy profile to that of the BIPV system. This is mainly related to its significantly lower energy output, which does not compensate for the high embodied energy and environmental impact induced during the assembly phase.
- Regarding the analysis of the components of each system, it has been noticed that the concentrating photovoltaic (CPV) cells does not constitute a significant contribution to the total environmental load of the BICPV system, where their contribution has been

found within the range of 9% and 12%, and from an embodied energy aspect this share increments to be only around 20%. On the other hand, other supporting components has been found to be the most impacting ones, such as the reflectors in case of the BICPV-F system, and the two protective covers in case of the BICPV-S system. Furthermore, it has been noticed that although the cooling structure (cooling pipes and U-Shaped support) comprises a relatively low quantity of copper, its share to the environmental load is significant (around 24%), while its contribution to the embodied energy is relatively low (2.5%). This reflects the severe scarcity of the copper material and its impact on the different environmental areas of protection, represented in the depletion of metals and reserves.

- Regarding the damage categories, it is concluded that the fossil fuels is the most impacting one. This refers to the significant effect of the fossil fuel depletion and the related energy mix. In addition, other damage categories have been found to be impacting significantly as well, such as the climate change, depletion of reserves/metals, and the respiratory effects.
- On the subject of using different environmental profile evaluation methods (Life Cycle Impact Assessment - LCIA methodologies), it is concluded that, although some differences can be spotted in the results, they are all in accordance with respect to the sustainability achieved by the BICPV-S system. This highlights the importance of using different LCIA methodologies, as this assists in providing an overarching view from different environmental perspectives.

In order to further quantify the environmental benefits that could be gained from the BICPV systems, and in order to integrate LCA within further improved designs, sensitivity analyses have been conducted. The conclusions of that analysis are as follows:

- Increasing the concentration ratio in case of the BICPV-F system will reduce the environmental impact during the assembly phase, but it will cause more optical losses, affecting the energy output and consequently the whole life cycle environmental and energy profiles. Additionally, it has been observed that decreasing the concentration ratio in case of the BICPV-S will reduce the environmental impact during the assembly phase, and simultaneously enhance the optical efficiency.
- Regarding the use of lenses, it has been noticed that the environmental impact will increase in comparison to the use of reflectors.
- In reference to the cooling structure, it has been found that graphite, aluminum, and iron, are the best candidate materials to replace copper, achieving a reduction of around 20-23% of the total impact score, taking into consideration the same thermal conductivity requirements achieved by copper.

Some opportunities and recommendation for future work can be derived as follows:

- It is deduced that more studies are needed within the domain of Life Cycle Assessment of solar technologies and systems, especially those related to building integration and concentrating photovoltaic systems. Additionally, using LCA in the preliminary design phase is essential for achieving sustainability while employing those novel technologies.
- Conducting sensitivity analyses that show the environmental impact using different underlying energy mix scenarios for the related processes of the studied systems. This can highlight the effect of the variations of the future energy mix on the environmental impact of the solar technologies and systems.

- Increasing the surface area of the concentrating photovoltaic modules employed within the BICPV systems, as this could lead to higher energy output, and consequently better environmental and energy profiles throughout the whole systems life cycle. Those improvements shall be adapted while taking into consideration the sensitivity analyses results, where it has been recommended not incrementing the concentration ratio of the BICPV-F system significantly. This is in order to have a relevant environmental impact reduction while not compromising the system energy output, and consequently the whole life cycle environmental and energy evaluations. Similarly, decreasing the concentration ratio of the BICPV-S system in that regard has been recommended as well.

Conclusiones (Español)

Esta tesis se compone principalmente un estudio de Análisis de Ciclo de Vida (LCA) de unos sistemas de concentración de fotovoltaica integrados en los edificios (BICPV). La tesis ha iniciado con una explicación detallada sobre el concepto y los métodos de LCA en el Capítulo 1. Una revisión de las tecnologías y sistemas de energía solar en el contexto de concentración solar baja y media ha sido presentada en el Capítulo 2, demostrando los materiales, las procesas relacionadas, y los sistemas de configuraciones mas recientes.

En el Capítulo 3, un análisis crítico ha sido presentado, que demuestra los estudios de LCA relacionados con las tecnologías y los sistemas de energía solar. Los resultados de este análisis indican la existencia de algunas lagunas en este campo de estudios, representado en los tres aspectos siguientes: El primero: Los indicadores del LCA no son muy variadas, y la mayoría de los estudios de LCA se basan en la utilización del tiempo de retorno energético (EPT) y el potencial de calentamiento global (GWP) como los únicos indicadores ambientales. Tal enfoque no tiene en cuenta el análisis del perfil ambiental. El segundo: se ha encontrado una ausencia de estudios de LCA relativos a sistemas integrados en los edificios. Además, no se ha encontrado ningún estudio sobre sistemas de BICPV. La tercera: Se han encontrado muy pocos estudios sobre LCA de los sistemas de concentración, y todos ellos relacionados exclusivamente con sistemas de alta concentración.

Por lo tanto, al referirse a las lagunas encontradas, dos sistemas BICPV han sido presentados y analizados desde un punto de vista de LCA en el Capítulo 4. El primer sistema representa un sistema de fachada integrado (BICPV-F), y el segundo sistema representa un sistema de sombra integrado (BICPV-S). El análisis ha sido realizado respecto a dos aspectos: Evaluación del perfil ambiental utilizando metodologías LCIA, y evaluación del perfil energético, utilizando la demanda de energía acumulada (CED), además de otros indicadores del ciclo de vida entera, que son el factor de retorno de energía (ERF), y el tiempo de retorno energético (EPT). Además, los resultados se han sido comparados con los de un sistema convencional de fotovoltaicos integrado en los edificios (BIPV). Las conclusiones de ese análisis son las siguientes:

- En la fase de montaje, los dos sistemas BICPV muestran un mejor perfil de ambiental y enérgico que la del BIPV. Esto se atribuye principalmente a la utilización de relativamente mucho menos área de superficie de las células fotovoltaicas en los sistemas BICPV, que en consecuencia significa menos energía incorporada y otras emisiones relacionadas con el medio ambiente. Se observa que aunque el sistema BICPV-S contiene menos número de reflectores con espesor reducido de manera significativa, su impacto total es similar a la del sistema BICPV-F. Esto es debido principalmente a las dos cubiertas de protección de vidrio para los reflectores que han sido empleados en el sistema BICPV-S. Es decir, el uso de las cubiertas de protección en el sistema de BICPV-S ha equilibrado la reducción del impacto ambiental logrado debido a la utilización de menor cantidad de reflectores.
- En cuanto a toda la evaluación de todo el ciclo de vida, se ha sido descubierto que el sistema BICPV-S mejora a los sistemas BIPV y BICPV-F en el sentido ambiental y energético. Adicionalmente, se ha sido encontrado que el sistema BICPV-F induce el mayor impacto ambiental, y que tiene un perfil de energía similar a la del sistema BIPV. Esto es relacionado principalmente a su producción de energía que es significativamente baja, que no compensa el elevado impacto energético y ambiental en la fase de montaje.

- En cuanto al análisis de los componentes de cada sistema, se ha sido observado que las células de fotovoltaico de concentración (CPV) no constituyen una contribución significativa a la carga ambiental total del sistema BICPV, donde se ha sido encontrado que su contribución al impacto total es dentro del 9 % y 12 %, y energéticamente incremente este valor cerca del 20 %. Por otra parte, otros componentes han sido encontrados como los más impactantes, tales como los reflectores en caso del sistema de BICPV-F, y las dos cubiertas de protección en caso del sistema de BICPV-S. Además, se ha sido notado que aunque la estructura de refrigeración (tubos y el apoyo en forma de U de refrigeración) esta constituido por una relativamente baja cuantidad de cobre, su contribución a la carga ambiental es significativa (alrededor de 24 %), mientras que su contribución a la energía incorporada es relativamente baja (2.5 %). Esto refleja la severa escasez del material de cobre y su impacto en las diferentes zonas ambientales de protección, representados en el agotamiento de los metales y de las reservas.
- En cuanto a las categorías de impacto ambiental, se concluye que los combustibles fósiles son las más impactantes. Esto se refiere al efecto significativo del agotamiento de los combustibles fósiles y de la mezcla de energía relacionada. Además, también se han encontrado otras categorías de impacto ambiental con impacto significativo, por ejemplo, el cambio climático, el agotamiento de las reservas / metales, y los efectos respiratorios.
- Sobre el tema de la utilización de diferentes métodos de evaluación de perfil ambiental (Evaluación del Impacto del Ciclo de Vida - metodologías LCIA), se concluye que, a pesar de algunas diferencias que se pueden observar en los resultados, se ha encontrado que todas las metodologías utilizadas son conformes respecto de la sostenibilidad lograda por el sistema BICPV-S. Esto demuestra la importancia de utilizar diferentes

metodologías LCIA, que esto ayuda a dar una visión general de los sistemas correspondientes desde diferentes perspectivas ambientales.

Con el fin de cuantificar los beneficios ambientales que se pueden lograr de los sistemas BICPV, y con el fin de integrar la LCA en el diseño de nuevos sistemas BICPV mejorados, se han realizados diferentes análisis de sensibilidad. Las conclusiones del análisis son las siguientes:

- Aumentar la concentración en el caso del sistema BICPV-F reducirá el impacto ambiental durante la fase de montaje, pero causará más pérdidas ópticas, lo que afecta la producción de energía y en consecuencia todo el ciclo de vida de los perfiles ambientales y energéticos. Además, se ha observado que la disminución de la relación de concentración en el caso de los BICPV-S reducirá el impacto ambiental durante la fase de montaje, y al mismo tiempo mejora la eficiencia óptica.
- Al respecta del uso de lentes, se ha observado que el impacto ambiental aumentará en comparación con el uso de reflectores.
- En referencia a la estructura de refrigeración, se ha encontrado que el grafito, el aluminio, y el hierro, son los mejores materiales candidatos para sustituir el cobre, logrando una reducción de alrededor del 20-23 % del impacto total, teniendo en consideración de los mismos requisitos de conductividad térmica del cobre.

Se puede derivar algunas oportunidades y recomendaciones para el trabajo del futuro:

- Se deduce que es necesario realizar más estudios en el campo del LCA de las tecnologías y sistemas de energía solar, especialmente en relación con la integración en los edificios y la concentración fotovoltaica. Además, el uso de LCA en la fase de diseño es esencial para el logro de la sostenibilidad usando esas nuevas tecnologías.

- La realización de un análisis de sensibilidad que muestra el impacto ambiental utilizando diferentes escenarios de mix energético subyacente de los procesos relacionados con los sistemas estudiados. Esto puede demostrar el efecto de las variaciones del mix energético en el futuro sobre el impacto ambiental de las tecnologías y sistemas de energía solar.
- Incrementar la superficie de los módulos fotovoltaicos de concentración empleada en los sistemas BICPV, que esto mejoraría la producción de energía, y por lo tanto mejoraría los perfiles ambientales y energéticos de todo el ciclo de vida de los sistemas. Se pueden adaptar esas modificaciones teniendo en cuenta los resultados del análisis de sensibilidad, donde se ha recomendado no incrementar la concentración del sistema BICPV-F significativamente. Esto es con el fin de lograr una reducción del impacto ambiental sin afectar la producción de energía del sistema, y por lo tanto las evaluaciones ambientales y energéticas de todo el ciclo de vida. Del mismo modo, la disminución de la concentración del sistema BICPV-S en el mismo contexto ha sido recomendado también.

Conclusions (Català)

Aquesta tesi es compon principalment un estudi d'Anàlisi de Cicle de Vida (LCA) d'uns sistemes de concentració de fotovoltaica integrats en els edificis (BICPV). La tesi s'ha iniciat amb una explicació detallada sobre el concepte i els mètodes de LCA en el Capítol 1. Una revisió de les tecnologies i sistemes d'energia solar en el context de concentració solar baixa i mitjana ha estat presentada en el Capítol 2, demostrant els materials, les processes relacionades, i els sistemes de configuracions més recents.

En el Capítol 3, una anàlisi crítica ha estat presentat, que demostra els estudis de LCA relacionats amb les tecnologies i els sistemes d'energia solar. Els resultats d'aquesta anàlisi indiquen l'existència d'algunes llacunes en aquest camp d'estudis, representat en els tres aspectes següents: El primer: els indicadors de l' LCA no són molt variades, i la majoria dels estudis de LCA es basen en la utilització del temps de retorn energètic (EPT) i el potencial d'escalfament global (GWP) com els únics indicadors ambientals . Tal enfocament no té en compte l'anàlisi del perfil ambiental. El segon: s'ha trobat una absència d'estudis de LCA relatius a sistemes integrats en els edificis. A més, no s'ha trobat cap estudi sobre sistemes de BICPV. La tercera: S'han trobat molt pocs estudis sobre LCA dels sistemes de concentració, i tots ells relacionats exclusivament amb sistemes d'alta concentració.

Per tant, quan es refereix a les llacunes trobades, dos sistemes BICPV han estat presentats i analitzats des d'un punt de vista de LCA al Capítol 4. El primer sistema representa un sistema de façana integrat (BICPV-F), i el segon sistema representa un sistema d'ombra integrat (BICPV-S). L'anàlisi ha estat realitzat respecte a dos aspectes: Avaluació del perfil ambiental utilitzant metodologies LCIA, i avaluació del perfil energètic, utilitzant la demanda d'energia acumulada (CED), a més d'altres indicadors del cicle de vida sencera, que són el factor de retorn d'energia (ERF), i el temps de retorn energètic (EPT). A més, els resultats han estat comparats amb els d'un sistema convencional de fotovoltaics integrat en els edificis (BIPV). Les conclusions d' aquesta anàlisi són les següents:

- En la fase de muntatge, els dos sistemes BICPV mostren un millor perfil d'ambiental i enèrgic que la del BIPV. Això s'atribueix principalment a la utilització de relativament molt menys àrea de superfície de les cèl·lules fotovoltaiques en els sistemes BICPV, que en conseqüència significa menys energia incorporada i altres emissions relacionades amb el medi ambient. S'observa que encara que el sistema BICPV-S conté menys nombre de reflectors amb gruix reduït de manera significativa, el seu impacte total és similar a la del sistema BICPV-F. Això és degut principalment a les dues cobertes de protecció de vidre per als reflectors que han estat emprats en el sistema BICPV-S. És a dir, l'ús de les cobertes de protecció en el sistema de BICPV-S ha equilibrat la reducció de l’impacte ambiental aconseguit causa de la utilització de menor quantitat de reflectors.
- Pel que fa a tota l'avaluació de tot el cicle de vida, s'ha estat descobert que el sistema BICPV-S millora als sistemes BIPV i BICPV-F en el sentit ambiental i energètic. Addicionalment, s'ha estat trobat que el sistema BICPV-F indueix el major impacte ambiental, i que té un perfil d'energia similar a la del sistema BIPV. Això és relacionat principalment a la seva producció d'energia que és significativament baixa, que no compensa l'elevat impacte energètic i ambiental en la fase de muntatge.
- Quant a l'anàlisi dels components de cada sistema, s'ha estat observat que les cèl·lules de fotovoltaic de concentració (CPV) no constitueixen una contribució significativa a la càrrega ambiental total del sistema BICPV, on ha estat trobat que la seva contribució a

l’impacte total és dins del 9% i 12%, i energèticament incrementi aquest valor prop del 20 %. D'altra banda, altres components han estat trobats com els més impactents, com ara els reflectors en cas del sistema de BICPV-F, i les dues cobertes de protecció en cas del sistema de BICPV-S. A més, s'ha estat notat que encara que l'estructura de refrigeració (tubs i el suport en forma de U de refrigeració) està constituït per una relativament baixa quantitat de coure, la seva contribució a la càrrega ambiental és significativa (al voltant de 24%), mentre que la seva contribució a l'energia incorporada és relativament baixa (2.5 %). Això reflecteix la severa escassetat del material de coure i el seu impacte en les diferents zones ambientals de protecció, representats en l'esgotament dels metalls i de les reserves.

- Pel que fa a les categories d'impacte ambiental, es conclou que els combustibles fòssils són les més impactents. Això es refereix a l'efecte significatiu de l'esgotament dels combustibles fòssils i de la barreja d'energia relacionada. A més, també s'han trobat altres categories d'impacte ambiental amb impacte significatiu, per exemple, el canvi climàtic, l'esgotament de les reserves/metalls, i els efectes respiratoris.
- Sobre el tema de la utilització de diferents mètodes d'avaluació de perfil ambiental (Avaluació de l’Impacte del Cicle de Vida - metodologies LCIA), es conclou que, tot i algunes diferències que es poden observar en els resultats, s'ha trobat que totes les metodologies utilitzades són conformes respecte de la sostenibilitat assolida pel sistema BICPV-S. Això demostra la importància d'utilitzar diferents metodologies LCIA, que això ajuda a donar una visió general dels sistemes corresponents des de diferents perspectives ambientals.

Per tal de quantificar els beneficis ambientals que es poden aconseguir dels sistemes BICPV, i per tal d'integrar la LCA en el disseny de nous sistemes BICPV millorats, s'han realitzats diferents anàlisis de sensibilitat. Les conclusions de l'anàlisi són les següents:

- Augmentar la concentració en el cas del sistema BICPV-F reduirà l’impacte ambiental durant la fase de muntatge, però causarà més pèrdues òptiques, pel que fa la producció d'energia i en conseqüència tot el cicle de vida dels perfils ambientals i energètics. A més, s'ha observat que la disminució de la relació de concentració en el cas dels BICPV-S reduirà l’impacte ambiental durant la fase de muntatge, i al mateix temps millora l'eficiència òptica.
- Al fa l'ús de lents, s'ha observat que l’impacte ambiental augmentarà en comparació amb l'ús de reflectors.
- Pel que fa a l'estructura de refrigeració, s'ha trobat que el grafit, l'alumini, i el ferro, són els millors materials candidats per substituir el coure, aconseguint una reducció del voltant del 20-23 % de l’impacte total, tenint en consideració dels mateixos requisits de conductivitat tèrmica del coure.

Es pot derivar algunes oportunitats i recomanacions per al treball del futur:

- Es dedueix que és necessari realitzar més estudis en el camp de l' LCA de les tecnologies i sistemes d'energia solar, especialment en relació amb la integració en els edificis i la concentració fotovoltaica. A més, l'ús de LCA en la fase de disseny és essencial per a l'assoliment de la sostenibilitat usant aquestes noves tecnologies.
- La realització d'una anàlisi de sensibilitat que mostra l’impacte ambiental utilitzant diferents escenaris de mix energètic subjacent dels processos relacionats amb els sistemes estudiats. Això pot demostrar l'efecte de les variacions del mix energètic en el futur sobre l’impacte ambiental de les tecnologies i sistemes d'energia solar .

- Incrementar la superfície dels mòduls fotovoltaics de concentració emprada en els sistemes BICPV, que això milloraria la producció d'energia, i per tant milloraria els perfils ambientals i energètics de tot el cicle de vida dels sistemes. Es poden adaptar aquestes modificacions tenint en compte els resultats de l'anàlisi de sensibilitat, on s'ha recomanat no incrementar la concentració del sistema BICPV-F significativament. Això és per tal d'aconseguir una reducció de l’impacte ambiental sense afectar la producció d'energia del sistema, i per tant les avaluacions ambientals i energètiques de tot el cicle de vida. De la mateixa manera, la disminució de la concentració del sistema BICPV-S en el mateix context ha estat recomanat també.

Bibliography

[1] US Environmental Protection Agency .Inventory of US GreenHouse Gas Emissions and Sinks: 1990-2009. EPA 430-R-11-005. April 2011.

[2] Renewable Energy Policy Network for the 21st Century (REN21), Renewables 2011Golabl Status Report. www.Ren21.net. Consulted in September 2011.

[3] S. Kalogirou. Solar Energy Engineering-procresses and systems. ISBN 978-0-12-374501-9. El Sevier, USA. 2010

[4] M.F.Hordeski. Megatrends for energy efficiency and renewable energy. -13: 978-1-4398-5354-2. Taylor and Francis Ltd. USA. ISBN. 2010

[5] M. Brower. Cool energy: renewable solutions to environmental problems. ISBN: 0-262-02349-0. Massachusetts institute of technology, USA. 1998.

[6] D. Chemisana. Building Integrated Concentrating Photovoltaics: A review. Renewable and Sustainable Energy Reviews 15 (2011) 603–611.

[7] D. Chemisana and J. I. Rosell. Design and optical performance of a nonimaging Fresnel transmissive concentrator for building integration applications. Energy Conversion and Management 52 (2011) 3241–3248.

[8] D. Chemisana and M. Ibanez. Linear Fresnel concentrators for building integrated applications. Energy Conversion and Management 51 (2010) 1476–1480.

[9] D. Chemisana, J. L. Villada, A. Coronas, J. I. Rosell, C. Lodi. Building integration of concentrating systems for solar cooling applications. Applied Thermal Engineering (2012). , doi:10.1016/j.applthermaleng.2011.12.005.

[10] D. Chemisana, M. Ibanez, J. Barrau. Comparison of Fresnel concentrators for building integrated photovoltaics. Energy Conversion and Management 50 (2009) 1079–1084.

[11] K. Menoufi. Master Thesis. Life Cycle Analysis and Life Cycle Impact Assessment methodologies: A state of the art. University of Lleida. 2011.

[12] The Society of Environmental Toxicology and Chemistry (SETAC), http://www.setac.org/. Consulted in March, 2011.

[13] ISO International Standard 14040:2006, Environmental Management – Life cycle assessment. Principles and framework. International Organisation for Standardisation (ISO).

[14] G.K.C. Ding, Sustainable construction—the role of environmental assessment tools, Journal of Environmental Management 86 (2008) 451–464.

[15] A.M. Tillman, Significance of decision-making for LCA methodology, Environmental Impact Assessment Review 20 (2000) 113–123.

[16] I. Zabalza, A. Aranda, S. Scarpellini, Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, Building and Environment 44 (2009) 2510-2520.

[17] H. Lewis and J.Gertsakis, Design + Environment, a global guide to designing greener goods, Sheffield UK: green leaf publishing, UK, ISBN 1874719438, 2011.

[18] Life Cycle Assessment (LCA) - A guide to approaches, experiences and information sources, EEA (European Environmental Agency), Denmark, ISBN: 92-9167-079-0, 1998.

[19] Regulation (EC) No 66/2010 of the European Parliament and of the council of 25 November 2009 on the EU Eco labels.

[20] ISO 14024:1999 - Environmental labels and declarations - Type I environmental labelling - Principles and procedures.

[21] ISO 14025:2006 - Environmental labels and declarations - Type III environmental

declarations – Principles and procedures. International Organisation for Standardisation (ISO).

[22] Summary of discussions at the 2nd integrated product policy expert workshop, environmental product declarations (ISO 14025), European commission, Brussels, 16th may 2001.

[23] ISO International Standard 14041:1998, Environmental Management – Life cycle assessment. Goal and scope definition and Inventory analysis. International Organisation for Standardisation (ISO).

[24] ISO International Standard 14042:2000, Environmental Management – Life cycle assessment. Life cycle Impact assessment. International Organisation for Standardisation (ISO).

[25] ISO International Standard 14043:2000, Environmental Management – Life cycle assessment. Life cycle Interpretation. International Organisation for Standardisation (ISO).

[26] M.A.Curran, Life Cycle Assessment: principles and practice, environmental protection agency (EPA), USA, EPA/600/R-06/060, May 2006.

[27] ILCD handbook: General guide for life cycle assessment – detailed guidance, first edition, 2010, Institute for Environment and Sustainability, Joint research centre, European Commission.

[28] D.W. Pennington, J. Potting, G. Finnveden, E. Lindeijer, O. Jolliet, T. Rydberg, G. Rebitzer, Life cycle assessment Part 2: Current impact assessment practice, Environment International 30 (2004) 721– 739.

[29] ENLSIC buildings, Energy Saving through Promotion of Life Cycle Assessment in Buildings, http://circe.cps.unizar.es/enslic/texto/home.html, consulted in April, 2011.

[30] E. Lindeijer, Normalisation and Valuation, Part VI of the SETAC Working Group Report on LCA Impact Assessment, IVAM Environmental Research, University of Amsterdam, The Netherlands.

[31] G. Finnveden, Valuation methods within LCA—where are the values? The International Journal of Life Cycle Assessment 2 (3) 163 - 169 (1997).

[32] ILCD handbook: Analysing of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment, first edition, 2010, Institute for Environment and Sustainability, Joint research centre, European Commission.

[33] University of Leiden, Institute of environmental sciences (CML), cml.leiden.edu, consulted in March, 2011.

[34] Gorrée, M.; Heijungs, R.; Huppes, G.; Kleijn, R.; Koning, A. de; Oers, L. van; Wegener Sleeswijk, A.; Suh, S.; Udo de Haes, H.A.; Bruijn, H. de; Duin, R. van; Huijbregts, M.A.J. Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002, 692 pp.

[35] Institute for Product development at the Danish Technical University, http://www.dtu.dk, consulted in March, 2011.

[36] Background for spatial differentiation in life cycle impact assessment: The EDIP2003 methodology, Environmental Protection Agency (EPA), USA, 1994.

[37] Spatial differentiation in life cycle impact assessment, the EDIP2003 methodology, J. Potting, M. Hauschild, Environmental Protection Agency (EPA), USA, 2005.

[38] S. Bellekom, J. Potting, R. Benders, Feasibility of applying site-dependent impact assessment of acidification in LCA, The International Journal of Life Cycle

Assessment 11 (6) 417 – 424 (2006).
[39] US Environmental Protection Agency (EPA), www.epa.gov, consulted in March, 2011.
[40] Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual, Office of Emergency and Remedial Response, Environmental Protection Agency, USA, EPA/540/1-89/002, December 1989.
[41] National Center for Environmental Assessment, Office of Research and Development, Exposure Factors Handbook, Environmental protection agency (EPA), USA, August 1997.
[42] J.C. Bare, G.A. Norris, D.W. Pennington, T. McKone, TRACI, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Journal of Industrial Ecology, Volume 6, Number 3–4, (2003) 49–77.
[43] G.A. Norris, Impact Characterization in the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, Journal of Industrial Ecology, 6 (2002) 79–101.
[44] J. bare, T. Gloria, G. Norris, Development of the Method and U.S. Normalization Database for Life Cycle Impact Assessment and Sustainability Metrics, Journal of Environmental Science and Technology 40 (2006) 5108-5115.
[45] PRé Consultants (Product Ecology consultants), http:// www.pre.nl, consulted in March, 2011.
[46] Philips consumer electronics (www.consumer.philips.com), consulted in March, 2011.
[47] NedCar (Volvo/Mitshubishi) (www.nedcar.nl), consulted in March, 2011.
[48] Océ Copiers (www.oce.com), consulted in March, 2011.
[49] Schuurink (http://www.schuurink.com/), consulted in March, 2011.
[50] Delft University of Technology (http://www.tudelft.nl/), consulted in March, 2011.
[51] CE delft (http://www.cedelft.eu/), consulted in March, 2011.
[52] Eco-indicator 99, Manual for designers, damage oriented method for life cycle impact assessment, October 2000, Ministry of Housing, Spatial planning and the Environment, The Netherlands.
[53] M. Goedkoop and R. Spriensma, Eco-indicator 99, a damage oriented method for life cycle impact assessment, methodology report, Third edition, June 2001, Ministry of Housing, Spatial planning and the Environment, The Netherlands.
[54] Volvo group, http://www.volvogroup.com, consulted in March, 2011.
[55] The Swedish environmental research institute (www.ivl.se), consulted in March, 2011.
[56] Confederation of Swedish Enterprise (www.svensktnaringsliv.se), consulted in March, 2011.
[57] EPS methodology (Environmental Priority Strategies in product design), http://eps.esa.chalmers.se, consulted in March, 2011.
[58] B. Steen, A systematic approach to environmental priority strategies in product development (EPS), Version 2000 – General system characteristics, CPM report 1999:5.
[59] B. Steen, A systematic approach to environmental priority strategies in product development (EPS), Version 2000 – Models and data of default method, CPM report 1999:5.
[60] Swiss Ecological Scarcity Method: The New Version 2006, R. Frischknecht, R. Steiner, B. Arthur, E. Norbert, H. Gabi, the International Conference on EcoBalance, Tsukuba, Japan, November, 2006.

[61] Weighting in Eco balances using the Eco scarcity methods-Eco factors 1997, Environment series No.297, G. Brand, A. Scheidegger, O. Schwank, A. Braunschweig, The Swiss Federal Agency for the Environment, Forests and Landscape (SAEFL), Switzerland.
[62] Implementation of Life Cycle Impact Assessment Methods, ecoinvent report No. 3, July 2010, H. Althaus, C. Bauer, G.Doka, R. Dones, R. Frischknecht, S. Hellweg, S. Humbert, N. Jungbluth, T. Köllner, Y. Loerincik, M. Margni, T. Nemecek, Swiss center for life cycle inventories, Switzerland.
[63] The Ecological Scarcity method, Eco factors 2006, a method for impact assessment in LCA, R. Frischknecht, R. Steiner, N. Jungbluth, Federal Office for the Environment (FOEN), Switzerland.
[64] The Japanese Environmental Ministry (MoE), www.env.go.jp, consulted in March, 2011.
[65] The Ministry for Economy Trade and Industry (METI), Japan, www.meti.go.jp, consulted in March, 2011.
[66] The Ministry for Education and Technology (MEXT), Japan, www.mext.go.jp, consulted in March, 2011.
[67] The JEPIX method (Japan Environmental Policy Priorities Index), www.jepix.org, consulted in March, 2011.
[68] C. Patrick, S. Kumagai, E. Shinozuka, Development of Eco Scarcity Japanese Version, The Fifth International Conference on Ecobalance, November 2002, Tsukuba, Japan.
[69] Miyazaki N., Siegenthaler C., Schoenbaum T. and Azuma K., Japan Environmental Policy Priorities Index (JEPIX) - Calculation of Ecofactors for Japan: Method for Environmental Accounting based on the EcoScarcity Principle, International Christian University Social Science Research Institute, Monograph Series No. 7, Tokyo, 2004.
[70] RIVM (National institute for public health and the environment), The Netherlands, www.rivm.nl, consulted in March, 2011.
[71] Radboud University Nijmegen, http://www.ru.nl/, consulted in March, 2011.
[72] The ReCiPe methodology, http://www.lcia-recipe.net/, consulted in March, 2011.
[73] M. Goedkoop, R.t Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. van Zelm, ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level: First edition, Report I: Characterisation. , Ministry of Housing, Spatial Planning and Environment (VROM), The Netherlands, 2009.
[74] A.W. Sleeswijka, L.F. van Oersc, J.B. Guinéec, J. Struijsd, M.A.J. Huijbregtsb, Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000, Science of the total environment 390(2008) 227 – 240.
[75] METI: Ministry of economy, trade and industry, Japan, http://www.meti.go.jp, consulted in March, 2011.
[76] NEDO, Global environmental technology development, Japan, www.nedo.go.jp, consulted in March, 2011.
[77] K. Hayashi, M.I. Okazaki, N. Itsubo, A. Inaba, Development of damage function of acidification for terrestrial ecosystems based on the effect of Aluminium toxicity on net primary production, The International Journal of Life Cycle Assessment, 9 (1) 13 - 22 (2004).
[78] JEMAI (Japan environmental management association for industry), http://www.jemai.or.jp/english/lca/project.cfm, consulted in March, 2011.

[79] K. Nakano, C. Nakaniwa, T. Kabeya, T. Iguchi, R. Aoki, Current activities of the Life Cycle Assessment society of Japan, The International Journal of Life Cycle Assessment, 12 (7) 546 (2007).

[80] N. Itsubo, M. Sakagami , T. Washida , K.O. Kokubu , A. Inaba, Weighting across safeguard subjects for LCIA through the application of conjoint analysis, The International Journal of Life Cycle Assessment 9 (3) 196 - 205 (2004).

[81] N. Itsubo and A. Inaba, A New LCIA Method: LIME has been completed, The International Journal of Life Cycle Assessment 8 (5) 305 (2003).

[82] The Swiss Federal Institute of Technology, www.ethz.ch, consulted in March, 2011.

[83] The federal polytechnic school of Lausanne, www.epfl.ch, consulted in March, 2011.

[84] University of Michigan, Risk Science Centre, www.sph.umich.edu/riskcenter/, consulted in March, 2011.

[85] D. Rochat, M. Margni, O. Jolliet, Continent-specific Intake Fractions and Characterization Factors for Toxic Emissions: Does it make a Difference? The International Journal of Life Cycle Assessment 11, Special Issue 1 (2006) 55 – 63.

[86] S. Humbert, M. Margni, O. Jolliet, A user guide for the New Life Cycle Impact Assessment Methodology IMPACT 2002+, (for v2.1), 2005.

[87] M. Goedkoop, M. Oele, A. de Schryver, M. Vieira, SimaPro Database Manual, Methods library, v2.2, 2008, PRé Consultants, the Netherlands.

[88] CIRAIG – Interuniversity Reference Center for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services, École Polytechnique de Montréal, Montreal, Quebec, Canada, http://www.ciraig.org, consulted in April, 2011.

[89] L. Toffoletto, C. Bulle, J. Godin, C. Reid, L. Deschênes, LUCAS – A New LCIA Method Used for a CAnadian-Specific Context, The International Journal of Life Cycle Assessment 12 (2) 93 – 102 (2007).

[90] Statistics Canada: Canada national statistical agency, www.statcan.gc.ca, consulted in March, 2011.

[91] Environment Canada, www.ec.gc.ca, consulted in March, 2011.

[92] VHK consultants, Netherlands, (www.vhk.nl), consulted in March, 2011.

[93] Directive 2005/32/EC of the European parliament and of the council of 6 July 2005.

[94] Methodology study Eco design of energy using products, MEEup methodology report, 2005, European commission.

[95] The National Institute of Standards and Technology, www.nist.gov, consulted in March, 2011.

[96] American Society for Testing and Materials , (ASTM) (1993), standard practice for measuring Life Cycle Costs of buildings and building systems, ASTM designation E 917-93, West Conshohocken, PA, USA.

[97] American Society for Testing and Materials (ATSM) (1995) standard practice for applying the analytic hierarchy Process to Multi Attribute Decision Analysis (MADA) of investments related to buildings and building systems, ASTM designation E 1765-95, West Conshohocken, PA, USA.

[98] B.C. Lippiatt, The BEES model for selecting environmentally and economically balanced building products, proceedings of the conference of Environmental and Economic balance, The 21st Century Outlook, November 6-9, 1997, Miami, Florida.

[99] Building for Environmental and Economic Sustainability (BEES), CIB World Building Congress 1998: Construction and the environment, Gavle, Sweden, June

1998.

[100]W.E. Rees, Ecological footprints and appropriated carrying capacity: what urban economics leaves out, Environment and Urbanization vol.4 no.2 (1992) 121–130.

[101]M. Wackernagel (1994), Ecological Footprint and Appropriated Carrying Capacity: A Tool for Planning Toward Sustainability. (PhD thesis), School of Community and Regional Planning, The University of British Columbia, Vancouver, Canada, OCLC 41839429.

[102]Ecological footprints standards 2009, Global footprint network standards committee, www.footprintstandards.org, consulted in April, 2011.

[103]M.A.J. Huijbregts, S. Hellweg, R. Frischknecht, K. Hungerbühler, A. Jan Hendriks, Ecological footprint accounting in the life cycle assessment of products, Ecological Economics 64 (2008) 798 – 807.

[104]M.Z. Hauschild, M. Huijbregts, O.Jolliet, M. macleod, M. margin, D. Van De Meent, R.K . Rosenbaum, T.E. Mckone, Building a Model Based on Scientific Consensus for Life Cycle Impact Assessment of Chemicals: The Search for Harmony and Parsimony, Environmental Science and Technology, 2008, 42, 7032–7037.

[105]R.K. Rosenbaum, T.M. Bachmann, L.S. Gold, M.A.J. Huijbregts, O. Jolliet, R. Juraske, A. Koehler, H.F. Larsen, M.M. Manuele Margni, T.E. McKone, J. Payet, M. Schuhmacher, D. van de Meent, M.Z. Hauschild, USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, The International Journal of Life Cycle Assessment 13 (2008) 532–546.

[106]T. Koellner and R. W. Scholz, Assessment of Land Use Impacts on the Natural Environment, Part 1: An Analytical Framework for Pure Land Occupation and Land Use Change, The International Journal of Life Cycle Assessment 12 (1) 16 – 23 (2007).

[107]T. Koellner and R. W. Scholz, Assessment of Land Use Impacts on the Natural Environment, Part 2: Generic Characterization Factors for Local Species Diversity in Central Europe, The International Journal of Life Cycle Assessment 13 (1) 32 – 48 (2008).

[108]World Meteorological Organization (WMO), www.wmo.int, consulted in March, 2011.

[109]Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

[110]Climate Change 2007: Impacts, Adaptation and Vulnerability, Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson, Eds. Cambridge University Press, Cambridge, UK, 976 pp.

[111]M.A.J. Huijbregts, S. Hellweg, R. Frischknecht, H.W. Hendrik, K. Hungerbhler, A. J. Hendriks, Cumulative Energy Demand as Predictor for the Environmental Burden of Commodity Production, Environmental Science and Technology 2010, 44, 2189–2196.

[112]W. Klopffer, In Defence of the Cumulative Energy Demand, The International Journal of Life Cycle Assessment 2 (2) 61 (1997).

[113] D. Giirzenich , J. Mathur, N.K. Bansal , H.J. Wagner, Cumulative Energy Demand for Selected Renewable Energy Technologies, The International Journal of Life Cycle Assessment, 4 (3) 143 - 149 (1999).

[114] H. J. Wagner, E. Pick, Energy yield ratio and cumulative energy demand for wind energy converters, Energy 29 (2004) 2289–2295.

[115] R. Frischknecht, M.A.J. Huijbregts, L.J.A. Rombouts, S. Hellweg, Is Cumulative Fossil Energy Demand a Useful Indicator for the Environmental Performance of Products?, Journal of Environmental Science and Technology, 40 (3) 641-648 (2006).

[116] Emergy systems, University of Florida, www.emergysystems.org, consulted in March, 2011.

[117] H.T. Odum, Emergy evaluation, The international workshop on Advances in Energy Studies: Energy flows in ecology and economy, May 27, 1998, Porto Venere, Italy.

[118] S. Ulgiati , H.T. Odum , S. Bastianoni, Emergy use, environmental loading and sustainability an emergy analysis of Italy, Ecological Modelling 73 (1994) 215-268.

[119] R. Siche, L. Pereira, F. Agostinho, E. Ortega, Commun Nonlinear Convergence of ecological footprint and emergy analysis as a sustainability indicator of countries: Peru as case study, International Journal of Nonlinear Sciences and Numerical Simulation 15 (2010) 3182–3192.

[120] B. Parida, S. Iniyan, R. Goic. A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews 15 (2011) 1625–1636.

[121] V.V. Tyagi, S.C. Kaushik, S.K. Tyagi. Advancement in solar photovoltaic/thermal (PV/T) hybrid collector technology. Renewable and Sustainable Energy Reviews 16 (2012) 1383– 1398.

[122] A. Luque and S. Hegedus. Handbook of Photovoltaic Science and Engineering. ISBN 0-471-49196-9 John Wiley & Sons Ltd, UK. 2002.

[123] P. Gevorkian. Solar power in building design: The engineers complete design resource. ISBN: 0-07-159444-2. The McGraw-Hill Companies, USA. 2008.

[124] A. Goetzberger and V.U. Hoffmann. Photovoltaic Solar Energy Generation. ISBN: 3-540-23676-7. Springer Berlin Heidelberg, New York, USA. 2005.

[125] German Solar Energy Society. Planning and Installing Photovoltaic Systems: A guide for installers, architects and engineers, second edition. ISBN-13: 978-1-84407-442-6. 2008. Earthscan, London, UK.

[126] G.N.Tiwari and S.Dubey. Fundamentals of photovoltaic modules and their applications. ISBN: 978-1-84973-020-4. The Royal Society of Chemistry, UK. 2010.

[127] G. Hsu, N. Rohatgi, J. Houseman. Silicon Particle Growth in a Fluidized-Bed Reactor. AIChE Journal. vol.33. no.5, 1987.

[128] W.O. Filtvedt, M.Javidi, A.Holt, M.C.Melaaen, E.Marstein, H.Tathgar, P.A.Ramachandran. Development of fluidized bed reactors for silicon production. Solar Energy Materials & Solar Cells 94 (2010) 1980–1995.

[129] A. Muller, M. Ghosh, R. Sonnenschein, P. Woditsch. Silicon for photovoltaic applications. Materials Science and Engineering B 134 (2006) 257–262.

[130] J.O. Odden, P.K. Egeberg, A. Kjekshus. From monosilane to crystalline silicon, Part I: Decomposition of monosilane at 690–830K and initial pressures 0.1–6.6MPa in a free-space reactor. Solar Energy Materials & Solar Cells 86 (2005) 165–176.

[131] Solar Grade-Silicon, Ingot, Wafer Technology and Market Forecast (2008~2012). Technical report, 2009. http://www.displaybank.com. Consulted in November 2011.

[132] C.P. Khattak, D.B. Joyce, F. Schmid. Production of Solar Grade (SoG) Silicon by

Refining Liquid Metallurgical Grade (MG) Silicon. National Renewable Energy Laboratory. December 1999. NREL/SR-520-27593.

[133] K. M. Itoh, J. Kato, M. Uemura, A. K. Kaliteevskii, O.N. Godisov, G. G. Devyatych, A.D. Bulanov, A. V. Gusev, I. D. Kovalev, P. G. Sennikov, H.. J. Pohl, N. V. Abrosimov, H. Riemann. High Purity Isotopically Enriched ^{29}Si and ^{30}Si Single Crystals: Isotope Separation, Purification, and Growth. Jpn. J. Appl. Phys. Vol. 42 (2003) pp. 6248–6251.

[134] A. Dong, L. N. W. Damoah, L. Zhang, H. Zhu.Purification of solar grade Silicon using Electromagnetic field. Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE. ISBN: 978-1-4244-5890-5.

[135] R.W. Miles. Photovoltaic solar cells: Choice of materials and production methods. Vacuum 80 (2006) 1090–1097.

[136] T. Markvart and L. Castaner. Solar Cells: Materials, Manufacture and Operation. ISBN: 13:978-1-85617-457-1. El Sevier, UK. 2005.

[137] Martin Helgesen, Roar Søndergaard and Frederik C. Krebs. Advanced materials and processes for polymer solar cell devices. Journal of Materials Chemistry. 2010, 20, 36–60.

[138] L.Q. Zhu, J.Gong, J.Huang, P.She, M.L.Zeng, L.Li, M.Z.Dai, Q.Wann. Improving the efficiency of crystalline silicon solar cells by an intersected selective laser doping. Solar Energy Materials & Solar Cells 95 (2011) 3347–3351.

[139] Daisuke Niinobe, Hiroaki Morikawa,Shuichi Hiza,Takehiko Sato,Shigeru Matsuno, Hirofumi Fujioka, Tomotaka Katsura,Tatsuki Okamoto,Satoshi Hamamoto,Takashi Ishihara,Satoshi Arimoto. Large-size multi-crystalline silicon solar cells with honeycomb textured surface and point-contacted rear toward industrial production. Solar Energy Materials & Solar Cells 95 (2011) 49–52.

[140] Frederik C. Krebs. Polymer solar cell modules prepared using roll-to-roll methods: Knife-over-edge coating, slot-die coating and screen printing. Solar Energy Materials & Solar Cells 93 (2009) 465–475.

[141] Shuich Fujii, Yuko Fukawa, Hiroaki Takahashi, Yosuke Inomata, Kenichi Okada, Kenji Fukui, Katsuhiko Shirasawa. Production technology of large-area multicrystalline silicon solar cells. Solar Energy Materials & Solar Cells 65 (2001) 269}275.

[142] P. Engelhart, J. Wendt, A. Schulze, C. Klenke, A. Mohr, K. Petter, F. Stenzel, S. Hörnlein, M. Kauert, M. Junghänel, B. Barkenfelt, S. Schmidt, D. Rychtarik, M. Fischer, J.W. Müller, P. Wawer. R&D pilot line production of multi-crystalline Si solar cells exceeding cell efficiencies of 18 %. Energy Procedia 8 (2011) 313–317.

[143] T.Y. Kwon, D.H.Yang, M.K.Ju, W.W.Jung, S.Y.Kim, Y.W.Lee, D.Y.Gong, J.Yi. Screen printed phosphorus diffusion for low-cost and simplified industrial mono-crystalline silicon solar cells. Solar Energy Materials & Solar Cells 95 (2011) 14–17.

[144] Sophie Gledhill, Anton Zykov,Nicholas Allsop,Thorsten Rissom, Jan Schniebs, Christian A.Kaufmann, Martha Lux-Steiner, Christian-Herbert Fischer. Spray pyrolysis of barrier layers for flexible thin film solar cells on steel. Solar Energy Materials & Solar Cells 95 (2011) 504–509.

[145] David B.Mitzi, Oki Gunawan, Teodor K.Todorov, KejiaWang, Supratik Guha. The path towards a high-performance solution-processed kesterite solar cell. Solar Energy Materials & Solar Cells 95 (2011) 1421–1436.

[146] Jianhua Zhao, Aihua Wang and Martin A. Green. 24.5% Effciency Silicon PERT Cells on MCZ Substrates and 24.7% Effciency PERL Cells on FZ Substrates. Progress in PhotoVolatics: Research and Applucations 7, 471- 474 (1999).

[147]T.F. Ciszek, T.H. Wang. Silicon defect and impurity studies using float-zone crystal growth as a tool. Journal of Crystal Growth 237–239 (2002) 1685–1691.

[148]S. Ranjan, S. Balaji, Rocco A. Panella, B. Erik Ydstie. Silicon solar cell production. Computers and Chemical Engineering 35 (2011) 1439– 1453.

[149]Jack I. Hanoka. An overview of silicon ribbon growth technology. Solar Energy Materials & Solar Cells 65 (2001) 231-237.

[150]S.L. Morelhfio and S. Majan. An X-ray topography study of the dendritic web silicon growth process. Journal of Crystal Growth 177 (1997) 41-51.

[151]Dong Seop Kim, Vijay Yelundur, Kenta Nakayashiki, Brian Rounsaville, Vichai Meemongkolkiat, Andrew M. Gabor, Ajeet Rohatgi. Ribbon Si solar cells with efficiencies over 18% by hydrogenation of defects. Solar Energy Materials & Solar Cells 90 (2006) 1227–1240.

[152]M. Spiegel, C. Zechner, B. Bitnar, G. Hahn, W. Jooss, P. Fath, G. Willeke, E. Bucher, H.-U. Hofs, C. Habler. Ribbon growth on substrate (RGS) silicon solar cells with microwave-induced remote hydrogen plasma passivation and efficiencies exceeding 11%. Solar Energy Materials & Solar Cells 55 (1998) 331-340.

[153]J. Qian, S. Steegen, E. Vander Poorten, D. Reynaerts, H. Van Brussel. EDM texturing of multicrystalline silicon wafer and EFG ribbon for solar cell application. International Journal of Machine Tools & Manufacture 42 (2002) 1657–1664.

[154]J. Cichoszewski and M. Reuter. Metal Assisted Surface Texture for String Ribbon Solar Cells and Modules. Energy Procedia 8 (2011) 635–641.

[155]M.A. Green. Photovoltaics: technology overview. Energy Policy 28 (2000) 989-998.

[156]K. L. Chopra, P. D. Paulson, V. Dutta. Thin-Film Solar Cells: An Overview. Progress in photovoltacis: Research and applications. 2004; 12:69–92 (DOI: 10.1002/pip.541).

[157]Major S and Chopra KL. Indium-doped zinc oxide films as transparent electrodes for solar cells. Solar Energy Materials. 1988; 17(5): 319–327.

[158]Joachim Muller, Bernd Rech, Jiri Springer, Milan Vanecek. TCO and light trapping in silicon thin film solar cells. Solar Energy 77 (2004) 917–930.

[159]Kuang-Chieh Lai, Jen-HungWan, Chun-hsiungL, Fu-JiTsai, Chih-HungYeh, Mau PhonHoung. Plasma-induced TCO texture of ZnO:Ga back contacts on silicon thin film solar cells. Solar Energy Materials & Solar Cells 95 (2011) 415–418.

[160]Jef Poortmans and Vladimir Arkhipov. Thin Film Solar Cells Fabrication, Characterization and Applications. ISBN-13: 978-0-470-09126-5. Library of Congress Cataloging-in-Publication Data. John Wiley & Sons Ltd. UK. 2006.

[161]L. B. Freund and S. Suresh. Thin Film Materials Stress, Defect Formation and Surface Evolution. ISBN:0-521-82281-5. Library of Congress Cataloging-in-Publication Data. Cambridge university press. UK. 2003.

[162]John A. Venables. Introduction to Surface and Thin Film Processes. ISBN: 0-521-62460-6. The library of congress. Cambridge university press. UK. 2003.

[163]Arturo Morales-Acevedo. Thin film CdS/CdTe solar cells: Research perspectives. Solar Energy 80 (2006) 675–681.

[164]A. Jager-Waldau. Status of thin film solar cells in research, production and the market. Solar Energy 77 (2004) 667–678.

[165]R.W. Miles, G. Zoppi, I. Forbes. Inorganic photovoltaic cells. Materials today, Volume 10, Issue 11, November 2007, Pages 20-27.

[166]V. Avrutin, N. Izyumskaya, H. Morkoc. Semiconductor solar cells: Recent progress in terrestrial applications. Superlattices and Microstructures 49 (2011) 337–364.

[167] T.M. Razykov, C.S. Ferekides, D. Morel, E. Stefanakos, H.S. Ullal, H.M. Upadhyaya. Solar photovoltaic electricity: Current status and future prospects. Solar Energy 85 (2011) 1580–1608.

[168] M.A. Green. Photovoltaics: technology overview. Energy Policy 28 (2000) 989}998.

[169] M. A. Green. Thin-film solar cells: review of materials, technologies and commercial status. Journal of Materials Science Materials in Electronics (2007), Volume 18, Issue S1, Publisher: Springer New York LLC, Pages: 15-19.

[170] A. G. Aberle. Thin-film solar cells. Thin Solid Films 517 (2009) 4706–4710.

[171] Y. Yuan, J. Huang, G. L2. Intermediate Layers in Tandem Organic Solar Cells. Green, Vol. 1 (2011), pp. 65–80.

[172] T. K. Manna and S. M. Mahajan. Nanotechnology in the Development of Photovoltaic Cells. Proceedings of international conference on clean electrical power, 21-23 May 2007, Capri, Italy.

[173] N. A.Nismy, K. D. G. I. Jayawardena, A. A. D. T. Adikaari , S. R.P. Silva. Photoluminescence Quenching in Carbon Nanotube- Polymer/Fullerene Films: Carbon Nanotubes as Exciton Dissociation Centres in Organic Photovoltaics. Advanced Materials, 2011, 23, 3796–3800.

[174] B. Moselle, J. Padilla, R. Schmalensee. Harnessing renewable energy in electric power systems. ISBN: 978-1-933115-90-0. Earthscan, london, UK. 2010.

[175] F. M. Sukki, R. Ramirez-Iniguez, S.G. McMeekin, B.G. Stewart, B. Clive. Solar Concentrators. International Journal of Applied Sciences (IJAS) 1(1), 1–15 (2010).

[176] A. Antonini, Chapter 2: Photovoltaic Concentrators. In R. M. Ochieng, Solar Collectors and Panels, Theory and Applications -Fundamentals, Applications, Market & Prospective (pp.31-54). ISBN 978-953-307-142-8. Sciyo, Rijeka, Croatia. 2010.

[177] F.H. Klotz, H.D. Mohring, C. Gruel, M. Alonso Abella, J. Sherborne, T. Bruton, P. Tzanetakis. Field test results of the Archimedes photovoltaic V-trough concentrator systems. In Proceedings of the 17th European Photovoltaic Solar Energy Conference and Exhibition, Munich, Germany, 2001, pp. 492–495.

[178] H. Cotal, C. Fetzer, J. Boisvert, G. Kinsey, R. King, P. Hebert, H. Yoon, N. Karam. III–V multijunction solar cells for concentrating photovoltaics. Energy and Environmental Science, 2009, 2, 174–192.

[179] A. Vossier, D. Chemisana, G. Flamant, A. Dollet. Very high fluxes for concentrating photovoltaics: Considerations from simple experiments and modeling. Renewable Energy 38 (2012) 31-39.

[180] R. M. Swanson, Chapter 11: Photovoltaic Concentrators. In A. Luque and S. Hegedus, Handbook of Photovoltaic Science and Engineering (pp. 449-503). ISBN 0-471-49196-9. John Wiley & Sons Ltd, UK. 2003.

[181] J.D. Nixon, P.K. Dey, P.A. Daviesñ. Which is the best solar thermal collection technology for electricity generation in north-west India? Evaluation of options using the analytical hierarchy process. Energy 35 (2010) 5230-5240.

[182] A. Thomas. Solar steam generating systems using parabolic trough concentrators. Energy conversion management Vol. 37, No. 2, pp. 215-245, 1996.

[183] S. A. Kalogirou. Chapter 3: Solar energy collectors. In Solar Energy Collectors, Solar Energy Engineering (pp. 121-217). ISBN 9780123745019. Academic Press, Boston, UK. 2009.

[184] Q.B. Liutal. Experimental investigation on a parabolic trough solar collector for thermal power generation. Science china technological sciences 53 (1) (2010) 52–56).

[185]J. Nilsson, R. Leutzb, B. Karlsson. Micro-structured reflector surfaces for a stationary asymmetric parabolic solar concentrator. Solar Energy Materials & Solar Cells 91 (2007) 525–533.

[186]C.Y. Tsai and P. D. Lin. Optimized variable-focus-parabolic-trough reflector for solar thermal concentrator system. Solar Energy.doi:10.1016/j.solener.2012.01.009.

[187]A. F.Garcia, E. Zarza, L. Valenzuela, M. Perez. Parabolic-trough solar collectors and their applications. Renewable and Sustainable Energy Reviews 14 (2010) 1695–1721.

[188]M.C. Pereira. High temperature solar collector with optimal concentration: Non-focusing Fresnel lens with secondary concentrator. Solar Energy Volume 23, Issue 5, 1979, Pages 409–420

[189]E.M. Kritchman, A.A. Friesem, G. Yekutieli. Efficient Fresnel lens for solar concentration.Solar Energy Volume 22, Issue 2, 1979, Pages 119–123.

[190]P. C. Eames, A. Zacharopoulos, D. McLarnon, T J Hyde, B Norton. Development and experimental characterization of low cost facades integerated photovoltaics. Centre for Sustainable Technologies, University of Ulster.

[191]K.P. Ho and J. M. Kah. Compound parabolic concentrators for narrowband wireless infrared receivers. Optical Engineering 34(5), 1385—1395 (May 1995)..

[192]C.S. Solanki, C.S.Sangani, D.Gunashekar, G.Antony. Enhanced heat dissipation of V-trough PV modules for better performance. Solar Energy Materials & Solar Cells 92 (2008) 1634–1638.

[193]R.Tang and X.liu. Optical performance and design optimization of V-trough concentrators for photovoltaic applications. Solar Energy 85 (2011) 2154–2166.

[194]R. Winston, J. C. Miñano, P. Benítez. Nonimaging optics. ISBN: 0-12-759751-4, El Sevier academic press, UK. 2005.

[195]W.T. Xie, Y.J. Dai, R.Z. Wang, K. Sumathy. Concentrated solar energy applications using Fresnel lenses: A review. Renewable and Sustainable Energy Reviews 15 (2011) 2588– 2606.

[196]D. Barlev, R. Vidu, P. Stroeve. Innovation in concentrated solar power. Solar Energy Materials & Solar Cells 95 (2011) 2703–2725.

[197]D. R. Mills and G. L. Morrison. Compact linear Fresnel reflector solar thermal power plants. Solar Energy Vol. 68, No. 3, pp. 263–283, 2000.

[198]F.M. Sukki, R. R. Iniguez, S. G. McMeekin, B. G. Stewart, B. Clive. Knowledge based and intelligent information and engineering systems, lecture notes in Computer Science, 2010, Volume 6279/2010, pp. 633-641. Springer-Verlag Berlin Heidelberg 2010.

[199]J. A. Soules, D. R. Buchele, C. H. Castle, R. P. Macosko. Design and Fabrication of a Dielectric Total Internal Reflecting Solar Concentrator and Associated Flux Extractor for Extreme High Temperature (2500K) Applications. NASA Contractor Report 204145.

[200]L.H. Slooff, A.R. Burgers, M.G. Debije. Reduction of escape cone losses in luminescent solar concentrators with cholesteric mirrors. Proc. of SPIE Vol. 7043, 2008 SPIE Digital Library.

[201]B. C. Rowan, L. R. Wilson, B.S. Richards. Advanced Material Concepts for Luminescent Solar Concentrators. IEEE journal of selected topics in quantum electronics. Vol. 14, No. 5, pp. 1312-1322, September/October 2008.

[202]. Bomm, A. Buchtemann, A. J.Chatten, R. Bose, D. J.Farrell, N. L. A. Chan, Y. Xiao, L. H. Slooff , T. Meyer, A. Meyer, W. F.G.J.H.M.van Sark, R, Koole. Fabrication and full characterization of state-of-the-art quantum dot luminescent solar concentrators. Solar Energy Materials & Solar Cells 95 (2011) 2087–2094.

[203] M. Kennedy, S.J. McCormack, J. Doran, B. Norton. Improving the optical efficiency and concentration of a single-plate quantum dot solar concentrator using near infra-red emitting quantum dots. Solar Energy 83 (2009) 978–981.

[204] S.J. Gallagher, B. Norton, P.C. Eames. Quantum dot solar concentrators: Electrical conversion efficiencies and comparative concentrating factors of fabricated devices. Solar Energy 81 (2007) 813–821.

[205] A.J. Chatten, K.W.J. Barnham, B.F. Buxton, N.J. Ekins-Daukes, M.A. Malik. A new approach to modelling quantum dot concentrators. Solar Energy Materials & Solar Cells 75 (2003) 363–371.

[206] S.J. Gallagher, B.C. Rowan, J. Doran, B. Norton. Quantum dot solar concentrator: Device optimisationusing spectroscopic techniques. Solar Energy 81 (2007) 540–547.

[207] J. C. Goldschmidt, M. Peters, A. Bosch, H. Helmers, F. Dimroth, S. W. Glunz, G.Willeke. Increasing the efficiency of fluorescent concentrator systems. Solar Energy Materials & Solar Cells 93 (2009) 176–182.

[208] C. Wang, H. A Rahman, S.P. Rao. Daylighting can be fluorescent: Development of a fiber solar concentrator and test for its indoor illumination. Energy and Buildings 42 (2010) 717–727.

[209] M.G. El-Shaarawy, S.M. El-Bashi, M. Hammam, M.K. El-Mansy. Bent fluorescent solar concentrators (BFSCs): Spectroscopy, stability and outdoor performance. Current Applied Physics 7 (2007) 643–649.

[210] R. Koeppe and N. S. Sariciftci. Enhancing photon harvesting in organic solar cells with luminescent concentrators. Applied physics letters 90, 181126, pp.181126-1 to 181126-3, 2007.

[211] A.A. Earp, G.B. Smith, P.D. Swift, J. Franklin. Maximising the light output of a Luminescent Solar Concentrator. Solar Energy 76 (2004) 655–667.

[212] W.G.J.H.M. van Sark. Luminescent solar concentrators e A low cost photovoltaics alternative. doi:10.1016/j.renene.2012.01.030.

[213] N. K. Mohan, Q. T. Islam, P. K. Rastogi. Recent developments in holographic optical elements (HOEs). Optics and Lasers in Engineering 44 (2006) 871–880.

[214] A. V. da Rosa. Chapter14 – Photovoltaic Converters, In Fundamentals of Renewable Energy Processes (Second edition), Pages 625–720, ISBN: 978-0-12-374639-9, El Sevier, UK.

[215] J. E. Ludman, J.L. Sampson, R.A. Bradbury, J. G. Martin, J.R. Riccobono, G. Sliker, E. Rallis. Photovoltaic systems based on spectrally selective holographic concentrators. SPIE Practical Holography VI, Proceedings Vol. 1667, pp. 182-189, (1992).

[216] R. K. Kostuk and G. Rosenberg. Analysis and Design of Holographic Solar Concentrators. 2008 SPIE Digital Library, Proceedings of SPIE Vol. 7043, pp. from 70430I-1 to 70430I-8.

[217] Abhishek Kumar, Nirmalendu Deo2, H.L. Yadav. Analysis of Design Parameters of Holographic Solar Concentrators for Large Acceptance Angle. 33rd IEEE Photovoltaic Specialists Conference, pp.1-4, 2008.

[218] R. Xuechang, L. Shou, Z. Xiangsu, C. Xiaoyun. Fabrication of holographic Fresnel lens used as solar concentrador. 2008 SPIE Digital Library, Proc. of SPIE Vol. 6832, pp. 68321N-1 to 68321N-7.

[219] C. Bainier, C. Hernandez, D. Courjon. Solar concentrating systems using holographic lenses. Solar & Wind Technology Vol. 5, No. 4, pp. 395 404. 1988.

[220]. K. Kostuk, J, Castro, B. Myer, D. Zhang, G. Rosenberg. Holographic Elements in Solar Concentrator and Collection Systems. 2009 SPIE Digital Library.

Proceedings of SPIE Vol. 7407, pp. 74070E-1 to 74070E-8.

[221] S.A. Kalogirou and Y. Tripanagnostopoulos. Industrial application of PV/T solar energy systems. Applied Thermal Engineering 27 (2007) 1259–1270.

[222] T.T. Chow. A review on photovoltaic/thermal hybrid solar technology. Applied Energy 87 (2010) 365–379.

[223] P.G. Charalambous, G.G. Maidment, S.A. Kalogirou, K. Yiakoumetti. Photovoltaic thermal (PV/T) collectors: A review. Applied Thermal Engineering 27 (2007) 275–286.

[224] S.C. Solanki, S. Dubey, A. Tiwari. Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors. Applied Energy 86 (2009) 2421–2428.

[225] R. Kuma and Marc A. Rosen. Performance evaluation of a double pass PV/T solar air heater with and without fins. Applied Thermal Engineering 31 (2011) 1402-1410.

[226] F. Sarhaddi, S. Farahat, H. Ajam, A. Behzadmehr, M. M. Adeli. An improved thermal and electrical model for a solar photovoltaic thermal (PV/T) air collector. Applied Energy 87 (2010) 2328–2339.

[227] S.Kumar and A. Tiwari. Design, fabrication and performance of a hybrid photovoltaic/thermal (PV/T) active solar still. Energy Conversion and Management 51 (2010) 1219–1229.

[228] A. Ibrahim, M.Y.Othman, M. H. Ruslan, S. Mat, K. Sopian. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. Renewable and Sustainable Energy Reviews 15 (2011) 352–365.

[229] C. Peng, Y.Huang, Z. Wu. Building-integrated photovoltaics (BIPV) in architectural design in China. Energy and Buildings 43 (2011) 3592–3598.

[230] B. P.Jelle, C.Breivik, H.D.Rokenes. Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. Solar Energy Materials & Solar Cells 100 (2012) 69–96.

[231] S. Pantic, L. Candanedo, A.K. Athienitis. Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems. Energy and Buildings 42 (2010) 1779–1789.

[232] K. Vats and G.N. Tiwari. Performance evaluation of a building integrated semitransparent photovoltaic thermal system for roof and façade. Energy and Buildings 45 (2012) 211–218.

[233] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, E. D. Dunlop. Solar cell efficiency tables (version 39). Progress in photovoltaics: Research and applications 2012; 20:12–20.

[234] Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells, EPRI, Palo Alto, CA, and California Energy Commission, Sacramento, CA: 2003. 1000095.

[235] V.M. Fthenakis. Chapter VII-2: Overview of potential hazards, in: T. Markvart and L. Castaner. Practical Handbook of Photovoltaics: Fundamentals andApplications. ISBN 1-856-17390-9. Elsevier, UK. 2003.

[236] V.M. Thenakis and P.D. Moskowitz. Photovoltaics: Environmental Health and Safety Issues and Perspectives. Progress in Photovoltaics: Research and Applications, Vol. 8, pp. 27-38 (2000).

[237] V.M. Thenakis. Prevention and Control of Accidental Releases of Hazardous Materials in PV Facilities. Progress in Photovoltaics: Research and Applications, Vol. 6, pp. 91-98 (1998).

[238] V. M. Fthenakis, M. Fuhrmann, J. Heiser, A. Lanzirotti, J. Fitts, W. Wang. Emissions and Encapsulation of Cadmium in CdTe PV Modules during Fires.

Progress in Photovoltaics: Research and Applications 13 (2005) 713–723.

[239] E. Mason and S. K. Thompson. A brief overview of crystalline Silica. Journal of Chemical Health and Safety. Volume 17, Issue 2, Pages 6–8 (2010)

[240] M. de Wild-Scholten and E. Alsema. Towards cleaner solar PV: Environmental and health impacts of crystalline silicon photovoltaics. Volume 5, Issue 5, Pages 46–49 (2004)

[241] V. M. Fthenakis. Life cycle impact analysis of cadmium in CdTe PV production. Renewable and Sustainable Energy Reviews 8 (2004) 303–334

[242] P. D. Moskowitz. Health and environmental hazards of CdTe photovoltaic module production, use and decommissioning. First World Conference on Photovoltaic Energy Conversion (WCPEC). 5-9 of December, 1994. Hawaii, USA.

[243] V. M. Fthenakis and H. C. Kim. CdTe photovoltaics: Life cycle environmental profile and comparisons. Thin Solid Films 515 (2007) 5961–5963.

[244] K. Zweibel, P. Moskowitz, V. M. Fthenakis. Thin-Film Cadmium Telluride Photovoltaics: ES&H Issues, Solutions, and Perspectives. National Renewable Energy Laboratory (NERL). NREL/TP-520-24057. February 2008.

[245] V. M. Fthenakis, S. C. Morris, P. D. Moskowitz, D. L. Morgan. Toxicity of Cadmium Telluride, Copper Indium Diselenide, and Copper Gallium Diselenide. Progress in Photovoltaics: Research and Applications 7 (1999) 489- 497.

[246] P.K. Basu, H. Dhasmana, N. Udayakumar, D.K. Thakur. A new energy efficient, environment friendly and high productive texturization process of industrial multicrystalline silicon solar cells. Renewable Energy 34 (2009) 2571–2576.

[247] M. H. Kang, A. Rohatgi, A. Ebong, B. Rounsaville. Optimizing the silane-free silicon carbon nitride (SiC_xN_y) antireflection coating Final report for the project# 2106ANQ, "Sixtron Advanced Materials/Quebec, Canandahttp://smartech.gatech.edu/. Accessed on July 2012.

[248] M. H. Kang, A. Ebong, B. Rounsaville, A. Rohatgi, J. Hong. Silane-free PECVe silicon carbon nitride (SiCxNy) passivation and anti-reflection coatings for high efficiency silicon solar cells. 34th IEEE Photovoltaic Specialists Conference (PVSC). June 2009. Philadelphia, PA, USA.

[249] A. Halm, M. Loscher, J. Theobald, E. Lemp, P. Hering, L. Popescu, R. Kopecek, K. Peter. Eco-friendly minimodules made of n-type Aluminum rear emitter solar cells. Energy Procedia 8 (2011) 409–414.

[250] C. H. Chen, W. C. Shih, C. Y. Chien, C. H. Hsu, Y. H. Wu, C. H. Lai. A promising sputtering route for one-step fabrication of chalcopyrite phase Cu (In,Ga)Se_2 absorbers without extra Se supply. Solar Energy Materials & Solar Cells 103 (2012) 25–29.

[251] K. Jimbo, R. Kimura, T. Kamimura, S. Yamada, W. S. Maw, H. Araki, K. Oishi, H. Katagiri. Cu2ZnSnS4-type thin film solar cells using abundant materials. Thin Solid Films 515 (2007) 5997–5999.

[252] V. Chawla and B. Clemens. Inexpensive, abundant, non-toxic thin films for solar cell applications grown by reactive sputtering. 35th IEEE Photovoltaic Specialists Conference (PVSC). June 2010. Hawaii, USA.

[253] H. Wang. Progress in Thin Film Solar Cells Based on Cu_2ZnSnS_4. International Journal of Photoenergy Volume 2011, Article ID 801292, 10 pages. doi:10.1155/2011/801292.

[254] L. Reijnders. Design issues for improved environmental performance of dye-sensitized and organic nanoparticulate solar cells. Journal of Cleaner Production 18 (2010) 307–312.

[255] M. Zach, C. Hagglund, D. Chakarov, B. Kasemo. Nanoscience and

nanotechnology for advanced energy systems. Current Opinion in Solid State and Materials Science 10 (2006) 132–143.

[256] E. Serrano, G. Rus, J. G. Martıinez. Nano technology for sustainable energy. Renewable and Sustainable Energy Reviews 13 (2009) 2373–2384.

[257] L. J. Chen,Q. L. Song, Z. H. Xiong, J. H. Huang, F. He. Environment friendly energy from all-carbon solar cells based on fullerene-C_{60}. Solar Energy Materials & Solar Cells 95 (2011) 1138–1140.

[258] M. Raugei, M. Isasa, P. F. Palmer. Potential Cd emissions from end-of-life CdTe PV. The Internacional Journal of Life Cycle Assessment (2012) 17:192–198.

[259] J. Kichoi and V. M. Fthenakis. Design and Optimization of Photovoltaics Recycling Infrastructure. Environmental Science & Technology. 2010, 44, 8678–8683.

[260] M.A. Kreiger, D.R. Shonnard, J.M. Pearce. Life cycle analysis of silane recycling in amorphous silicon-based solar photovoltaic manufacturing. Resources, Conservation and Recycling 70 (2013) 44– 49.

[261] V. M. Fthenakis. End-of-life management and recycling of PV modules. Energy Policy 28 (2000) 1051-1058.

[262] S. Kang, S. Yoo, J. Lee, B. Boo, H. Ryu. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. Renewable Energy 47 (2012) 152-159.

[263] E. K. Radziemska, P. Ostrowski, K. Drabczyk, P. Panek, M. Szkodo. Experimental validation of crystalline silicon solar cells recycling by thermal and chemical methods. Solar Energy Materials & Solar Cells 94 (2010) 2275–2282.

[264] W. Berger, F. G. Simon, K. Weimann, E.A. Alsema. A novel approach for the recycling of thin film photovoltaic modules. Resources, Conservation and Recycling 54 (2010) 711–718.

[265] W. Palitzsch and U. Loser. A new and intelligent De-Metalization STEP OF broken silicon cells And silicon cell production waste in the recycling procedure of crystalline SI modules. 37th IEEE Photovoltaic Specialists Conference (PVSC). June 2011. Seattle, USA.

[266] Y. P. Xiao and Y. X. Yang. Potential Routes for Recycling and Reuse of Silicon Kerf. Advanced Materials Research 295 - 297 (2011) 2235-2240.

[267] G. A. Keoleian and G. McD. Lewis. Application of Life-cycle Energy Analysis to Photovoltaic Module Design. Progress in Photovoltaics: Research and Applications, Vol. 5, pp. 287-300 (1997)

[268] K. Tahara, T. Kojima, A. Inaba. Evaluation of CO_2 payback time of power plants by LCA. Energy Conversion and Management 38 (1997) 615-620

[269] R. Dones and R. Frischknecht. Life-cycle Assessment of Photovoltaic Systems: Results of Swiss Studies on Energy Chains. Progress in Photovoltaics: Research and Applications 6 (1998) 117-125.

[270] E. Alsema. Energy requirements of thin film solar cell modules - a review. Renewable and Sustainable Energy Reviews 2 (1998) 387- 415.

[271] E. Nieuwlaar and E. Alsema. PV Power Systems and the Environment: Results of an Expert Workshop. Progress in Photovoltaics: Research and Applications 6 (1998) 87-90.

[272] K. Kato, A. Murata, K. Sakuta. Energy Pay-back Time and Life-cycle CO2 Emission of Residential PV Power System with Silicon PV Module. Progress in Photovoltaics: Research and Applications 6 (1998) 105-115.

[273] M. E. Watt, A. J. Johnson, M. Ellis, H. R. Outhred. Life-cycle Air Emissions from PV Power Systems. Progress in Photovoltaics: Research and Applications 6 (1998)

127-136.

[274] E. Alsema. Energy Pay-back Time and CO_2 Emissions of PV Systems. Progress in Photovoltaics: Research and Applications 8 (2000) 17-25.

[275] E.A. Alsema and E. Nieuwlaar. Energy viability of photovoltaic systems. Energy Policy 28 (2000) 999-1010.

[276] K. Knapp and T. Jester. Empirical Investigation of the Energy Payback Time for Photovoltaic modules. Solar Energy Vol. 71, No. 3, pp. 165–172 (2001)

[277] K. Kato, T. Hibino, K. Komoto, S. Ihara, S. Yamamoto, H. Fujihara. A life-cycle analysis on thin-film CdS/CdTe PV Modules. Solar Energy Materials & Solar Cells 67 (2001) 279-287.

[278] H. Greijer, L. Karlson, S. E. Lindquist, A. Hagfeldt. Environmental aspects of electricity generation from a nanocrystalline dye sensitized solar cell system. Renewable Energy 23 (2001) 27–39.

[279] A. Meijer, M. A. J. Huijbregts, J. J. Schermer, L. Reijnders. Life-cycle Assessment of Photovoltaic Modules: Comparison of mc-Si, InGaP and InGaP/mc-Si Solar Modules. Progress in Photovoltaics: Research and Applications 11 (2003) 275–287

[280] M. Ito, K. Kato, H. Sugihara, T. Kichimi, J. Song, K. Kurokawa. A preliminary study on potential for very large scale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints. Solar Energy Materials & Solar Cells 75 (2003) 507–517.

[281] D. Gurzenich and H.J. Wagner. Cumulative energy demand and cumulative emissions of photovoltaics production in Europe. Energy 29 (2004) 2297–2303.

[282] S. Krauter and R. Ruther. Considerations for the calculation of greenhouse gas reduction by photovoltaic solar energy. Renewable Energy 29 (2004) 345–355.

[283] N. Jungbluth. Life Cycle Assessment of Crystalline Photovoltaics in the Swiss ecoinvent Database. Progress in Photovoltaics: Research and Applications 13 (2005) 429–446.

[284] H. Hondo. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy 30 (2005) 2042–2056.

[285] T. Tsoutsos, N. Frantzeskaki, V.Gekas. Environmental impacts from the solar energy Technologies. Energy Policy 33 (2005) 289–296.

[286] R. Kannan, K.C. Leong, R. Osman, H.K. Ho, C.P. Tso. Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore. Solar Energy 80 (2006) 555–563.

[287] V. Fthenakis and and E. Alsema. Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status. Progress in Photovoltaics: Research and Applications 14 (2006) 275–280.

[288] Y. Tripanagnostopoulos, M. Souliotis, Battisti, A. Corrado. Performance, Cost and Life-cycle Assessment Study of Hybrid PVT/AIR Solar Systems. Progress in Photovoltaics: Research and Applications 14 (2006) 65–76.

[289] C. Koroneos, N. Stylos, N. Moussiopoulos. LCA of Multicrystalline Silicon Photovoltaic Systems. Part 1: Present Situation and Future Perspectives. The International Journal of Life Cycle Assessment 11 (2) 129 – 136 (2006).

[290] C. Koroneos, N. Stylos, N. Moussiopoulos. LCA of Multicrystalline Silicon Photovoltaic Systems. Part 2: Application on an Island Economy. The International Journal of LCA 11 (3) 183 – 188 (2006)

[291] I. Nawaz and G.N. Tiwari. Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. Energy Policy 34 (2006) 3144–3152.

[292] J. L. B. Agustin and R. D. Lopez. Economical and environmental analysis of grid

connected photovoltaic systems in Spain. Renewable Energy 31 (2006) 1107–1128.

[293]J. E. Mason, V. M. Fthenakis, T. Hansen, H. C. Kim. Energy Payback and Life-cycle CO_2 Emissions of the BOS in an Optimized 3.5MW PV Installation. Progress in Photovoltaics: Research and Applications 14 (2006) 179–190.

[294]M. Raugei, S. Bargigli, S. Ulgiati. Life cycle assessment and energy pay-back time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy 32 (2007) 1310–1318.

[295]N. J. Mohr, J. J. Schermer, M. A. J. Huijbregts, A. Meijer, L. Reijnders. Life Cycle Assessment of Thin film GaAs and GaInP/GaAs Solar Modules. Progress in Photovoltaics: Research and Applications 15 (2007) 163–179.

[296]S. Pacca, D. Sivaraman, G. A. Keoleian. Parameters affecting the life cycle performance of PV technologies and Systems. Energy Policy 35 (2007) 3316–3326.

[297]V. M. Fthenakis and H. C. Kim. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. Energy Policy 35 (2007) 2549–2557.

[298]S. Srinivasan. The Indian solar photovoltaic industry: a life cycle Analysis. Renewable and Sustainable Energy Reviews 11 (2007) 133–147

[299]B.S. Richards and M.E. Watt. Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. Renewable and Sustainable Energy Reviews 11 (2007) 162–172

[300]V. M. Fthenakis, H. C. Kim, E. Alsema. Emissions from Photovoltaic Life Cycles. Environmental Science and Technology 42 (2008) 2168–2174

[301]M. Ito, K. Kato, K. Komoto, T. Kichimi, K. Kurokawa. A Comparative Study on Cost and Life-cycle Analysis for 100MW Very Large-scale PV (VLS-PV) Systems in Deserts Using m-Si, a-Si, CdTe, and CIS Modules. Progress in Photovoltaics: Research and Applications 16 (2008) 17–30

[302]A. Stoppato. Life cycle assessment of photovoltaic electricity generation. Energy 33 (2008) 224–232.

[303]A. N. Celik, T. Muneer, P. Clarke. Optimal Sizing and Life Cycle Assessment of Residential Photovoltaic Energy Systems with Battery Storage. Progress in Photovoltaics: Research and Applications 16 (2008) 69–85.

[304]N. Mohr, A. Meijer, M.A. J. Huijbregts, L. Reijnders. Environmental impact of thin-film GaInP/GaAs and multicrystalline silicon solar modules produced with solar electricity. The International Journal of Life Cycle Assessment (2009) 14:225–235.

[305]R. G. Valverde, C. Miguel, R. M. Bejar, A. Urbina. Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. Solar Energy 83 (2009) 1434–1445.

[306]O. Perpinan, E. Lorenzo, M. A. Castro, R. Eyras. Energy Payback Time of Grid Connected PV Systems: Comparison between Tracking and Fixed Systems. Progress in Photovoltaics: Research and Applications 17 (2009) 137–147.

[307]M. Raugei and P. Frankl. Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks. Energy 34 (2009) 392–399.

[308]J.K. Kaldellis, M. Simotas, D. Zafirakis, E. Kondili. Optimum autonomous photovoltaic solution for the Greek islands on the basis of energy pay-back analysis. Journal of Cleaner Production 17 (2009) 1311–1323.

[309]J.K. Kaldellis, D. Zafirakis, E. Kondili. Optimum autonomous stand-alone photovoltaic system design on the basis of energy pay-back analysis. Energy 34 (2009) 1187–1198.

[310]M. Chamsilpa, N. Vorayos, T. Kiatsiriroat. Environmental impact analysis of solar cell power plant compared with fossil fuel power plants in Thailand. Asian Journal on Energy and Environment 2010, 11(02), 103-117

[311]B. Azzopardi and J. Mutale. Life cycle analysis for future photovoltaic systems using hybrid solar cells. Renewable and Sustainable Energy Reviews 14 (2010) 1130–1134.

[312]M. Ito, K. Komoto, K. Kurokawa. Life-cycle analyses of very-large scale PV systems using six types of PV modules. Current Applied Physics 10 (2010) S271–S273.

[313]A.F. Sherwani, J.A. Usmani, Varun. Life cycle assessment of solar PV based electricity generation systems: A review. Renewable and Sustainable Energy Reviews 14 (2010) 540–544.

[314]R. V. der Meulen and E. Alsema. Life-cycle greenhouse gas effects of introducing nanocrystalline materials in thin-film silicon solar cells. Progress in Photovoltaics: Research and Applications 19 (2011) 453–463.

[315]J.K. Kaldellis, D. Zafirakis, E. Kondili. Energy pay-back period analysis of stand-alone photovoltaic systems. Renewable Energy 35 (2010) 1444–1454.

[316]P. Zhai and E. D. Williams. Dynamic Hybrid Life Cycle Assessment of Energy and Carbon of Multicrystalline Silicon Photovoltaic Systems. Environmental Science and Technology 44 (2010) 7950–7955.

[317]A. D. Ramos, M. Held, R. Aldaco, M. Fischer, A. Irabien. Prospective CO2 emissions from energy supplying systems: photovoltaic systems and conventional grid within Spanish frame conditions. The International Journal of Life Cycle Assessment (2010) 15:557–566

[318]R. G, Valverde, J. A. Cherni, A. Urbina. Life cycle analysis of organic photovoltaic Technologies. Progress in Photovoltaics: Research and Applications 18 (2010) 535–558.

[319]V.M. Fthenakis and H.C. Kim. Photovoltaics: Life-cycle analyses. Solar Energy 85 (2011) 1609–1628.

[320]M. Bravi, M. L. Parisi, E. Tiezzi, R. Basosi. Life cycle assessment of a micromorph photovoltaic system. Energy 36 (2011) 4297-4306.

[321]H. Sengul and T. L. Theis. An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. Journal of Cleaner Production 19 (2011) 21-31.

[322]A. Chel and G.N. Tiwari. A case study of a typical 2.32 kWP stand-alone photovoltaic (SAPV) in composite climate of New Delhi (India). Applied Energy 88 (2011) 1415–1426.

[323]R. Laleman, J. Albrecht, J. Dewulf. Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renewable and Sustainable Energy Reviews 15 (2011) 267–281.

[324]A. A. B. Rujula, A. M. L. Lafuente, F. C. Oto. Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules Systems. Energy 36 (2011) 3148-3158.

[325]Z.W. Zhong, B. Song, P.E. Loh. LCAs of a polycrystalline photovoltaic module and a wind turbine. Renewable Energy 36 (2011) 2227-2237.

[326]N.H. Reich, E.A. Alsema, W.G.J.H.M. van Sark, W.C. Turkenburg, W.C. Sinke. Greenhouse gas emissions associated with photovoltaic electricity from crystalline silicon modules under various energy supply options. Progress in Photovoltaics: Research and Applications 19 (2011) 603–613.

[327]M. Held and R. Llg. Update of environmental indicators and energy payback time of CdTe PV systems in Europe. Progress in Photovoltaics: Research and Applications 19 (2011) 614–626.

[328]M. Ito, M. Kudo, M. Nagura, K. Kurokawa. A comparative study on life cycle

analysis of 20 different PV modules installed at the Hokuto mega-solar plant. Progress in Photovoltaics: Research and Applications 19 (2011) 878–886.

[329]D. Turney and V. Fthenakis. Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews 15 (2011) 3261– 3270.

[330]H.C. Kim and V.M. Fthenakis. Comparative life-cycle energy payback analysis of multi-junction a-SiGe and nanocrystalline/a-Si modules. Progress in Photovoltaics: Research and Applications 19 (2011) 228–239

[331]P. Gottesfeld and C. R.Cherry. Lead emissions from solar photovoltaic energy systems in China and India. Energy Policy 39 (2011) 4939–4946.

[332]D. Zhang, S. Tang, B. Lin, Z. Liu, X. Zhang, D. Zhang. Co-benefit of polycrystalline large-scale photovoltaic power in China. Energy 41 (2012) 436-442.

[333]J. Zhang, F. Lv, L. Zhang. Discussion on Environment Impact Assessment in the Life cycle of PV Systems. Energy Procedia 16 (2012) 234-239.

[334]M. Raugei, P. F. I. Palmer, V. Fthenakis. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. Energy Policy 45 (2012) 576–582.

[335]A. Beylot, J. Payet, C. Puech, N. Adra, P. Jacquin, I. Blanc, D. B. S. Pierre. Environmental impacts of large-scale grid-connected ground-mounted PV Installations. doi:10.1016/j.renene.2012.04.051 (2012).

[336]H. C. Kim, V. Fthenakis, J. K. Choi, D. E. Turney. Life Cycle Greenhouse Gas Emissions of Thin-film Photovoltaic Electricity Generation. Journal of Industrial Ecology. DOI: 10.1111/j.1530-9290.2011.00423.x (2012).

[337]M. Traverso, F. Asdrubali, A. Francia, M. Finkbeiner. Towards life cycle sustainability assessment: an implementation to photovoltaic modules. The International Journal of Life Cycle Assessment (2012) 17:1068–1079.

[338]M. T. Brown, M. Raugei, S. Ulgiati. On boundaries and ‘investments’ in Emergy Synthesis and LCA: A case study on thermal vs. photovoltaic electricity. Ecological Indicators 15 (2012) 227–235.

[339]M. Ozturk, N. Ozek, H. Batur, M. Koc. Thermodynamic and life cycle assessment of flat-plate collector, photovoltaic system and photovoltaic thermal collector. International Journal of Exergy Vol. 11, No.2 pp. 229 – 251 (2012).

[340]U. Desideri, S. Proietti, F. Zepparelli, P. Sdringola, S. Bini. Life Cycle Assessment of a ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production Systems. Applied Energy 97 (2012) 930–943.

[341]U. Desideri, F. Zepparelli, V. Morettini, E. Garroni. Comparative analysis of concentrating solar power and photovoltaic technologies: Technical and environmental evaluations. Applied Energy 102 (2013) 765–784.

[342]J. Peng, L. Lu, H.Yang. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renewable and Sustainable Energy Reviews 19 (2013) 255–274.

[343]P. Frankl, A. Masini, M. Gamberale, D. Toccaceli. Simplified Life-cycle Analysis of PV Systems in Buildings: Present Situation and Future Trends. Progress in Photovoltaics: Research and Applications 6 (1998) 137-146.

[344]M. Oliver and T. Jackson. Energy and economic evaluation of building-integrated Photovoltaics. Energy 26 (2001) 431–439.

[345]G. A. Keoleian and G. McD. Lewis. Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the US. Renewable Energy 28 (2003) 271–293.

[346]R. Battisti and A. Corrado. Evaluation of technical improvements of photovoltaic

systems through life cycle assessment methodology. Energy 30 (2005) 952–967.

[347] R.H. Crawford, G.J. Treloar, R.J. Fuller, M. Bazilian. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. Renewable and Sustainable Energy Reviews 10 (2006) 559–575.

[348] L. Y. Seng, G. Lalchand, G. M. S. Linb. Economical, environmental and technical analysis of building integrated photovoltaic systems in Malaysia. Energy Policy 36 (2008) 2130–2142.

[349] D. H.W. Li, T.N.T. Lam, W. W.H. Chan, A. H.L. Mak. Energy and cost analysis of semi-transparent photovoltaic in office buildings. Applied Energy 86 (2009) 722–729.

[350] H. Radhi. Energy analysis of facade-integrated photovoltaic systems applied to UAE commercial buildings. Solar Energy 84 (2010) 2009–2021.

[351] L. Lu and H.X. Yang. Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. Applied Energy 87 (2010) 3625–3631.

[352] A. Sumper, M. R. Garcia, R. V. Robles, J. B. Jane, J. A. Peiro. Life-cycle assessment of a photovoltaic system in Catalonia (Spain). Renewable and Sustainable Energy Reviews 15 (2011) 3888–3896.

[353] G. P. Hammond, H. A. Harajli, C. I. Jones, A, B. Winnett. Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations. Energy Policy 40 (2012) 219–230.

[354] N. J. Mohr, A. Meijer, M. A. J. Huijbregts, L. Reijnders. Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. Progress in Photovoltaics: Research and Applications DOI: 10.1002/pip.2157 (2012).

[355] M. J. R. Perez, V. Fthenakis, H. C. Kim, A. O. Pereira. Façade–integrated photovoltaics: a life cycle and performance assessment case study. Progress in Photovoltaics: Research and Applications. DOI: 10.1002/pip.1167 (2012).

[356] F. Cucchiella and I. D'Adamo. Estimation of the energetic and environmental impacts of a roof-mounted building-integrated photovoltaic system. Renewable and Sustainable Energy Reviews 16 (2012) 5245–5259.

[357] G. Peharz and F. Dimroth. Energy Payback Time of the High-concentration PV System FLATCON. Progress in Photovoltaics: Research and Applications 13 (2005) 627–634.

[358] Y. Lechon, C. de la Rua, R. Saez. Life Cycle Environmental Impacts of Electricity Production by Solar thermal Power Plants in Spain. Journal of Solar Energy Engineering. MAY 2008, Vol. 130 / 021012-(1-7).

[359] A. Nishimura, Y. Hayashi, K. Tanaka, M. Hirota, S. Kato, M. Ito, K. Araki, E.J. Hu. Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. Applied Energy 87 (2010) 2797–2807.

[360] V. Piemonte, M. De Falco, P. Tarquini, A. Giaconia. Life Cycle Assessment of a high temperature molten salt concentrated solar power plant. Solar Energy 85 (2011) 1101–1108.

[361] J. J. Burkhardt III, G. A. Heath, C. S. Turchi. Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives. Envirommental Science and Technology 45 (2011) 2457–2464.

[362] V.M. Fthenakis and H. C. Kim. Life cycle assessment of high-concentration photovoltaic Systems. Progress in Photovoltaics: Research and Applications.DOI: 10.1002/pip.1186 (2012).

[363] J. J. Burkhardt III, G. Heath, E. Cohen. Life Cycle Greenhouse Gas Emissions of Trough and Tower Concentrating Solar Power Electricity Generation: Systematic Review and Harmonization. Journal of Industrial Ecology. DOI: 10.1111/j.1530-9290.2012.00474.x (2012).

[364] M. Zhang, Z. Wang, C. Xu, H. Jiang. Embodied energy and emergy analyses of a concentrating solar power (CSP) system. Energy Policy 42 (2012) 232–238.

[365] M. Raugei. Energy pay-back time: methodological caveats and future scenarios. Progress in Photovoltaics: Research and Applications (2012). DOI: 10.1002/pip.1249

[366] D. Chemisana Villegas. Building Integration Solutions for CPV. Advances in Science and Technology 74 (2010) pp 278-287.

[367] N. Amrizal, D. Chemisana, J.I. Rosell. Hybrid photovoltaic–thermal solar collectors dynamic modeling. Applied Energy 101 (2013) 797–807.

[368] LINAK. http://www.linak.es/. Consulted in January 2013.

[369] N. Amrizal, D. Chemisana, J.I. Rosell, J. Barrau. A dynamic model based on the piston flow concept for the thermal characterization of solar collectors. Applied Energy 94 (2012) 244–250.

[370] Narec Solar. www.narecsolar.com. Consulted in December, 2012.

[371] Chomerics. www.chomerics.com. Consulted in December, 2012.

[372] Isofoton. www.isofoton.com. Consulted in December, 2012

[373] D.C. Jordan and S. R. Kurtz. Photovoltaic Degradation Rates — An Analytical Review. NREL (National Renewable Energy Laboratory). The U.S. Department of Energy, office of Energy Efficiency & Renewable Energy. Journal Article NREL/JA-5200-51664 June 2012.

[374] T. Gorter and A.H.M.E. Reinders. A comparison of 15 polymers for application in photovoltaic modules in PV-powered boats. Applied Energy 92 (2012) 286–297.

[375] N. Jungbluth, M. Stucki, R. Frischknecht. Photovoltaics. In R. Dones et al. Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. Ecoinvent report No. 6-XII, et al. (eds). Swiss Centre for Life Cycle Inventories, Dübendorf, CH, 2009.

[376] D. Chemisana. PhD Thesis. Diseño y caracterización de un concentrador térmico-fotovoltaico cuasiestacionario para integración arquitectónica. University of Lleida. March 2009.

6 Appendix

Pubished articles from this PhD theiss:

- Karim Menoufi, Daniel Chemisana, Joan I. Rosell. Life Cycle Assessment of a Building Integrated Concentrated Photovoltaic scheme. Applied Energy (Volume 111, November 2013, Pages 505–514)

Articles submitted for publication from this PhD thesis:

- Life Cycle Assessment of a Building Added Concentrating Photovoltaic system through environmental and energy evaluation (Submitted to the Journal of Applied Energy).

Applied Energy 111 (2013) 505–514

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Life Cycle Assessment of a Building Integrated Concentrated Photovoltaic scheme

Karim Menoufi *, Daniel Chemisana, Joan I. Rosell

University of Lleida, C/Pere de Cabrera s/n, 25001 Lleida, Spain

HIGHLIGHTS

- A gap is found in literature regarding the LCA studies of BICPV schemes.
- The BICPV scheme installed has significantly lower environmental impact compared to the conventional widely used BIPV ones.
- Some design improvements are foreseen within the installed BICPV scheme components.

ARTICLE INFO

Article history:
Received 8 February 2013
Received in revised form 11 April 2013
Accepted 14 May 2013
Available online 7 June 2013

Keywords:
Life Cycle Assessment (LCA)
Building Integrated Concentrated Photovoltaics (BICPV)
Life Cycle Impact Assessment (LCIA)
Environmental impact
Concentrated photovoltaics
Reflectors

ABSTRACT

A Life Cycle Assessment (LCA) study of a Building Integrated Concentrated Photovoltaic (BICPV) scheme at the University of Lleida (Spain) is conducted. Assumptions for representing a real building are considered, and a comparison to a hypothetical conventional Building Integrated Photovoltaic (BIPV) scheme is established. The Life Cycle Impact Assessment (LCIA) is performed using the EI99 methodology, which is considered to be the reference. In addition, the environmental impact is re-evaluated using the EPS 2000 methodology. The results show a significant extent of the environmental benefits gained using the BICPV schemes. Some differences in the components impact contribution percentages are noticed between the EI99 and the EPS 2000 methodologies. Nevertheless, both methodologies coincide in the conclusion of the significant environmental impact reduction reached from replacing the conventional BIPV schemes with the BICPV ones. Recommendations for future work and system improvements are discussed as well.

1. Introduction

Although the photovoltaic (PV) technology is one of the vital renewable energy trends [1], it is associated with some environmental concerns. The production of PV cells is accompanied by a high rate of emissions during manufacturing, and consequently causes a high impact on the environment. This impact can be induced whether in a direct way (process emissions) or in an indirect way (fossil fuels consumed during manufacturing). Furthermore, the PV industry utilizes a variety of chemicals, where many of which are relatively toxic to the human health and the environment [2–5].

In spite of those facts, the PV technology market is growing rapidly, especially for Building Integrated applications (BIPV). The building integration schemes are gaining a world wide acceptance. This is due to the savings that can be achieved in building materials during construction, and simultaneously reducing the environmental load during the operational phase through replacing the fossil fuels resources. In addition, the integration of PV into buildings permits the use of various PV technology types, which are characterized by their flexibility and reduced thickness. This means that fewer amounts of PV materials are used in comparison to the quantities used in the assembly of the conventional ground mounted PV systems. Therefore, these whole innovative solutions mainly aim at reducing the overall environmental burdens caused by both the building sector and the PV industry during the construction and operational phases [6–8].

On the subject of further reducing the environmental burdens, several research works have shown that the use of the concentrating technology can be energetically beneficial. This is because a concentrating system mainly consists of simple lenses or reflectors, which are especially fabricated and designed to focus the solar radiation on smaller PV cell areas in different concentration ratios depending on the application. Such types of schemes contribute significantly in reducing the amount of materials and energy used in PV cells fabrication [9–15]. Hence, Life Cycle Assessment (LCA) studies are essential in the PV domain, in correlation with the

---

* Corresponding author. Tel.: +34 973003572; fax: +34 973003575.
E-mail address: kmenoufi@macs.udl.cat (K. Menoufi).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.05.037

building industry, due to the high environmental impact induced from various components specifically during the assembly/production stage [16–21].

Several studies of LCA about PV systems can be found in literature. These studies have used various LCA indicators, such as the Energy Payback Time, which has been the principal interest for most of the corresponding LCA articles [22–35]. Other studies have been interested in investigating different related environmental aspects of PV systems, such as the exergy analysis [36–39]. A fewer number of studies is found to be interested in conducting LCA of PV systems using various developed LCIA methodologies: The RECIPE methodology [40], the Eco-Indicator 99 (EI99) methodology [41–43], and the Eco-Scarcity methodology [43].

Within this framework of LCA studies, it is found that a wide range of PV technologies has been considered. This includes single-crystalline, poly-crystalline, and thin film; installed within different schemes, whether integrated in buildings, ground mounted or applied for large scale power plants [22–55]. Novel technology concepts of PV have been considered as well, such as quantum dot PVs [56], micromorph systems [57] and nano-crystalline materials [58]. Regarding the concentrating technology, which is the main interest of the present work, it is noticed that all the surveyed studies are mainly directed at the high concentration applications [59–70].

Hence, in this regard, it is concluded that three gaps in the surveyed literature are found:

- Variety of LCA indicators: The Energy Payback Time is the most dominant.
- LCA studies of Building Integration Concentrated Photovoltaics (BICPV) schemes.
- The relative impact of a PV system/facade with respect a whole building (in case of BIPV studies)

In the regard of the first gap, evaluating the Energy Payback Time, and consequently working on finding solutions to reduce it through increasing the operational efficiency, is not sufficient. High dependence on the Energy Payback Time as the sole environmental indicator of a specific system does not provide a comprehensive environmental performance prospective, as this criterion does not take into consideration the instantaneous impact that is induced during the assembly stage [71]. Therefore, through using the LCIA methodologies, and by focusing on the assembly stage, the explication of the temporal resolution of the environmental impact can be clearly spotted (i.e. the impact of a certain quantity of emissions of a specific substance on the environment during a period of 1 month is worse than the impact of the same amount of emissions spread throughout the whole year). Furthermore, some studies have shown that in the future, as more PV systems will be installed, the energy mix itself will be mostly powered by PV systems. This will make the Energy Payback Time indicator no longer viable for providing the best guidance for the environmental performance improvements of PV systems [72–73].

The second gap highlighted is the lack of LCA studies of BICPV schemes, as it has been found that all of the related case studies are interested in high concentration applications specified for large scale power plants.

Finally, the third gap is about the whole system analysis. Most of the LCA studies of BIPV schemes are concerned with the environmental impact of the PV system corresponding components (The PV panel, PV cells, encapsulations, etc.) without taking into consideration the environmental impact of the PV system with respect to the whole building installation.

Therefore, for the purpose of contributing in reducing these gaps, the present research examines the environmental performance of a BICPV scheme through LCA. This study emphasizes the assembly stage, taking into consideration the impact of the Concentrating Photovoltaic (CPV) system with respect to the whole installation. Furthermore, the study is conducted using a widely used methodology (EI99), and then the impact is re-assessed using the EPS 2000 methodology.

2. Case study

A BICPV scheme assembled and tested at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain) is described and studied. In addition, in order to present more representative results, a comparative study with a conventional BIPV system is performed.

2.1. The building model

In order to be able to represent a BICPV scheme of relatively small scale and wattage requirements in a realistic manner, a typical widely known Mediterranean building design is assumed. This type of building design has been used in several studies [74–78]. Nevertheless, in the present case study, such construction assumption is highly dependent on the data provided by Bribian et al. [76]. This data includes a wide range of information about building materials, concerning the recommended dimensions, mass and mass per unit volume. The assumed building model ($3.51 \times 2.11 \times 2.05$ m) is built on a precast concrete base. The walls are composed of bricks (solid and hollow), a layer of expanded polystyrene insulation, and the finishing is done with plaster and cement mortar. The roof is mainly based on a light weight precast concrete block, and its overall construction comprises layers of expanded polystyrene, asphalt, plaster, cement mortar, and the external finishing is done with concrete roof tiles. The north façade is made of the materials of the side walls, in addition to a wooden door.

2.2. The BICPV system

The integrated concentrating system is composed of 22 flat coated reflectors ($2 \times 0.16 \times 0.006$ m), with a maximum achieved concentration ratio of 10× (suns). This scheme is to represent the installation of the reflectors as windows blinds (Fig. 1). A steel

Fig. 1. The reflectors facade: during the installation of the concentrating PV façade at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain). The tracking system is noticed on the left.

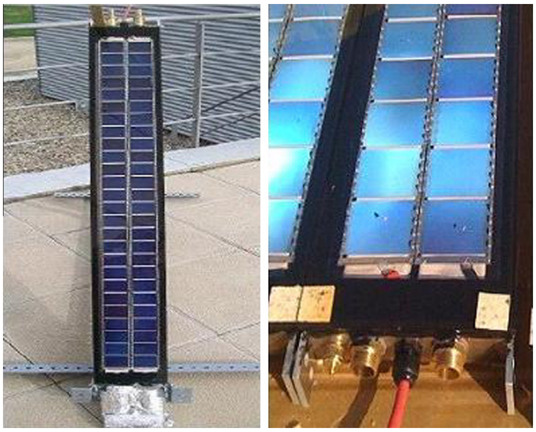

Fig. 2. The CPV modules: designed and assembled at the applied physics laboratory at the University of Lleida (Spain) [80].

structure is used to support and position the reflectors in place. An actuator (LINAK LA 12 [79]) is connected to the upper moveable part of the steel structure for the purpose of sun tracking adjustments. Two CPV modules (Fig. 2), 250 Wp each, which have been previously assembled and characterized [80,81], are put in use to be the receiver units. Each CPV module consists of a 300 μm thickness layer of single-crystalline silicon PV cell (52 cells, 48 × 36 mm each) manufactured by Narec Solar [82]. The PV cells are insulated with a thermal tape (Thermattach T-404) [83] of 127 μm thickness. A copper *U*-shaped support structure is installed to hold and support the PV cells layer and the thermal tape internally, while allowing the passage of two copper cooling pipes from beneath. The cooling pipes are externally connected to a 5 Watt water pump. This whole structure is enclosed within an aluminum frame box, and covered on top by a transparent white glass layer.

2.3. The BIPV system

A comparison is established in order to examine the differences between the environmental impact of the actual BICPV scheme and the conventional BIPV schemes. For this purpose, a hypothetical BIPV scheme is assumed to replace the BICPV one. It mainly consists of two transparent PV modules achieving the same power as the CPV ones (250 Wp each) from Isofoton [84] (MÓDULO MONOCRISTALINO ISF-240/245/250/255) installed at the south wall instead of the reflectors. Each module is made of a 200 μm layer of transparent single-crystalline PV cells (60 cells, 156 × 156 mm each). The PV cells are encapsulated with two 300 μm layers of PVB (Poly Vinyl Butyral), and surrounded by two transparent white glass layers. This configuration is supported by an aluminum framework.

3. Methodology

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by: compiling an inventory of relevant inputs and outputs of a product system, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study [85]. According to the ISO 14040 recommendations [85–88], a framework is provided for conducting a LCA. This framework is summarized in the following four main steps [89]: Definition of goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation of results.

In fact, the LCIA step is the most critical and data intensive one, due to the associated complex environmental modeling. The LCIA methodologies were developed in order to deal with such complexity. A LCIA methodology normally assigns a factor to single elementary flows in a LCA database. There are different types of factors (Characterization, normalization and weighting factors). According to the ISO recommendations, the application of these factors is obligatory in case of the characterization, and optional in case of the normalization and weighting. The LCIA methodologies can be easily dealt with through different LCA software programs.

In the present study, the final results are presented taking into consideration the characterization, normalization and weighting, leading to single score impact indicators (score points). Those score points express the severity of the contribution of the impact categories to the environmental load (Higher score of a product or a specific component means higher impact on the environment). They can be regarded as dimensionless figures [90–92]. In other words, the absolute value of those points is not very relevant, as the main purpose is to compare relative differences between products and components. For example, in the EI99 methodology, the scale is chosen in a way that the value of one point is representative for one thousandth of the yearly environmental load of one average European inhabitant. This latter value is obtained by dividing the total environmental load in Europe by the number of inhabitants and multiplying it by 1000 (scale factor).

The LCIA methodologies differ in some parameters, mainly in the approach of modeling the environmental impact (Midpoint approach, endpoint approach, or combined midpoint–endpoint approach). Other distinctions exist as well: the impact categories in each methodology, the endpoint and damage categories considered, characterization, normalization, and weighting factors [93]. The LCIA methodologies considered in this article are the Eco-Indicator 99 (EI99) methodology [92] which is taken as the reference methodology, and the EPS 2000 methodology [94], all in correlation with the Eco-Invent database [91]. Applying various methodologies assists in having a more comprehensive image of a system's environmental performance and its relative effects on the different environmental areas of protection.

For further demonstrating the transparency of the results, it is worth mentioning that according to the structure of the version used of the EPS 2000 methodology; only characterization and weighting are considered, disregarding the normalization step. This is unlike the EI99 methodology, which considers characterization, normalization and weighting.

4. Results and discussions

In this section, the steps of applying LCA on the corresponding case study are explained. The LCI and LCIA results are interpreted as follows:

4.1. Life Cycle Inventory

Table 1 shows the LCI of the studied BICPV and the hypothetical BIPV schemes. It is divided into three main sections: The building model, the CPV system of the BICPV scheme, and the PV system of the BIPV scheme.

Regarding the CPV system, it is know that the CPV cells have special contacts configuration (laser grooved buried type) [95]. This differs from the widely used screen printing processes of the conventional PV cells, which exists by default among the unit processes contributing in the fabrication of the PV cells within the Eco-Invent database. However, this difference cannot have an effect on the results certainty. This is because the principal high environ-

Table 1
LCI of the BICPV and BIPV schemes.

Item description/ function	Materials used	Quantity (kg)
Building model		
Base	Concrete	2676,32
Walls	Bricks	5834,14
Walls and roof	Polystyrene	23,56
Walls and roof	Plaster	602,17
Walls and roof	Cement mortar	505,45
Roof	Asphalt	156,12
Roof	Concrete roof tile	28,25
Roof	Light weight precast concrete slab	1440,75
Door	Wood	20,43
CPV system		
PV cells	Single-crystalline silicon	0.13
Insulation (thermal tape)	Thermattach (T404)	0.02
Cover	White glass	2.87
Frame	Aluminum	5.15
Cooling pipes	Copper	1.14
U-shaped support	Copper	1.01
Water pump	Steel	1.5
Reflectors	Float coated glass	109.82
Support frame	Carbonated steel	59.75
Actuator gear	Steel	1
Actuator housing	Reinforced plastic	0.5
PV system		
Transparent PV cells	Single-crystalline silicon	1.36
Encapsulation	PVB (poly vinyl butyral)	2.13
Cover	White glass	53.02
Frame	Aluminum	40.96

mental impact of CPV or PV modules is normally induced during the associated intensive energy processes (Purification, wafering, etc.) [96–98].

In reference to the encapsulation used in the PV modules of the BIPV system, no specific environmental impact information has been found about the PVB (Poly Vinyl Butyral) in the Eco-invent database. Thus, instead, EVA (Ethyl Vinly Acetate) has been considered in the impact assessment. Due to the relatively small quantity used within the PV modules, such assumption will not affect the results certainty. Moreover, the PVB and EVA films are both actually polymers of similar characteristics, having the same function, which is encapsulating the PV cells. The only spotted difference is that PVB is normally used in case of encapsulating the transparent PV cells [99].

As the studied BICPV scheme can function as both grid-connected or stand-alone, other connection components (Inverters, batteries, etc.) has been neglected. This helps highlighting the principal objective, which is to evaluate the environmental impact of a BICPV scheme, and compare it to a typical widely used BIPV one.

For simplification purposes, the installation and transportation impacts have been excluded from the study [100]. However, those parameters are not expected to affect the results, as most of the installation components are locally produced, and the assembly and operation of the CPV system has been conducted at the laboratories of the University of Lleida (Spain). This supports the disregarding of the ton–kilometer impact of the components transportation. Nevertheless, related assumptions can be established and included in further case studies, which includes the operational stage in the life cycle study.

4.2. Impact assessment and interpretation of results

The last two steps of the LCA study (Impact assessment and interpretation of results) are both gathered as follows:

4.2.1. Eco-indicator 99 (EI99)

Fig. 3 shows the impact assessment results using the EI99 methodology, which is the reference methodology used in this research. The CPV system represents about 10% of the total impact points of the BICPV scheme, while the building model constitutes the rest (90%). In order to highlight the impact of integration of concentrators into buildings: a comparison is presented between the impact of the actual BICPV and the BIPV schemes (the left side), and the corresponding CPV and PV systems, respectively (on the right side). The results show that installing the BIPV scheme instead of the BICPV one causes an increment of about 13.5% of the total environmental impact.

Further analysis is shown in Fig. 4, which entails the impact of each component within the LCI. The results in this figure are represented by the impact categories incorporated within the damage categories demonstrated in Fig. 3. It is shown that the light weight concrete block and the bricks are the most impacting materials within the inventory list.

On the subject of the impact categories, it is shown that the total impact score is mostly dominant by three impact categories: Fossil fuels, respiratory inorganics, and climate change. These results demonstrate the significance of the depletion of the fossil fuel resources and simultaneously the surplus energy that will be needed by the future generation in order to extract fossil fuels and use it to manufacture the corresponding components. The respiratory inorganics and climate change impact categories represents a significant impact of the total impact score as well. This is attributed to the emissions induced (CO_2, SO_2, NO_x, etc.) during the processing of the building model major constituting components and the corresponding PV technologies. This in return directly affects the respiratory health system and the global warming potential. In other words, the results show that the fossil fuels impact category represents about 61.6% of the total impact, while the respiratory inorganics represents about 17%, and the climate change represents 9.1%.

A deeper analysis can be achieved through emphasizing the comparison solely between the CPV and PV systems installed within the related schemes (BICPV and BIPV, respectively). In Fig. 5, it is shown that the PV system (38.89 impact points) generate more than twice the environmental impact induced by the CPV one (16.55 impact points). Similar to the analysis of the whole installation detailed above, the most dominant impact categories are found be the fossil fuels, respiratory inorganics and climate change.

Within the PV system, it is found that the PV cells are the most dominant component, where they contribute mostly to the impact percentage (66.4%) followed by the aluminum frame (23%). These results show the significant environmental impact caused due to the associated processing of the PV cells, in addition to the large quantities used for assembling the modules.

Breaking down the analysis of CPV system components shows that the CPV cells represent only 9.6% of the CPV system, while the reflectors represents about 45%. Although the amount of copper used is in manufacturing the cooling pipes and the *U*-shaped support structure is relatively insignificant (around 2 kg), the impact of this quantity constitutes about 19% of the total impact points. This is principally demonstrated by the impact points presented by the minerals impact category. This reflects the current scarcity of the high quality copper material that is severely declining with time.

4.2.2. EPS 2000

The results using the EPS 2000 methodology are presented in the figures from Figs. 6–8. Fig. 6 shows that the impact of the CPV system represents about 18% of the total impact points. The rest of the impact is represented by the building model (82%),

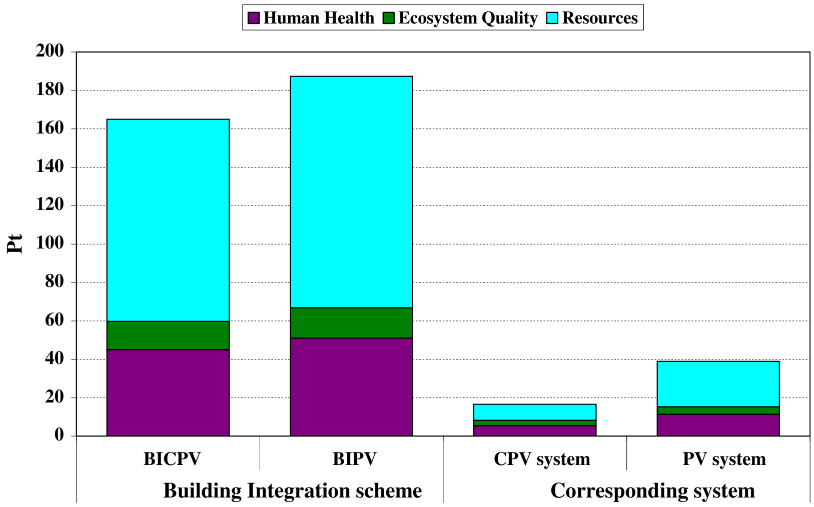

Fig. 3. Comparison between the BICPV and BIPV schemes on the left, and the corresponding CPV and PV schemes on the right, using the EI99 methodology.

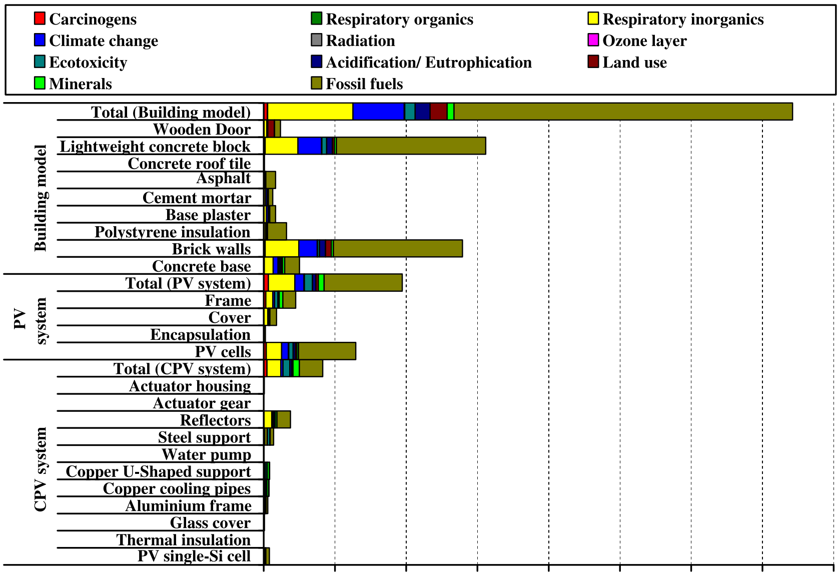

Fig. 4. Impact assessment results using the EI99 methodology (Per impact category).

which is mainly affected by the bricks and the light weight concrete block (Fig. 7).

Fig. 7 shows that three impact categories are the most dominant: Depletion of reserves, life expectancy and severe morbidity. The high score of the depletion of reserves impact category, which constitutes about 75% of the total impact points, explains the high amount of fossil fuels extracted and used for the manufacturing of the used materials. The second high impact score, which comes from the life expectancy impact category (17% of the total), reflects the expected shortening of average individual lifetimes (years of lost life) due to the impact of the corresponding manufacturing processes.

It is also shown that replacing the BICPV scheme by the BIPV one induces an increment of about 10% of the total impact score. This is further explained by the emphasized comparison of the environmental impact between the PV and the CPV systems where the environmental impact of the PV system is more than the impact of the CPV one (less than twice).

Within the analysis of the PV system (Fig. 8), it is shown that the PV cells, similar to the EI99 methodology results, are the most impacting components (68%) followed by the aluminum frame (26%).

In reference to the components of the CPV system, the CPV cells represent about 6.5% of the total impact points, while the reflectors represent about 23%. It is found that the copper used within the cooling pipes and the *U*-shaped support, although used in relatively very small quantities; represents 59% of the total impact points. This is reflected in the high impact score represented by the depletion of reserves impact category. Such analysis explains the severity of depletion of the reserves of minerals in general, especially copper.

4.3. Results summary

As a comparison between the differences in the components impact contribution percentages between the two applied

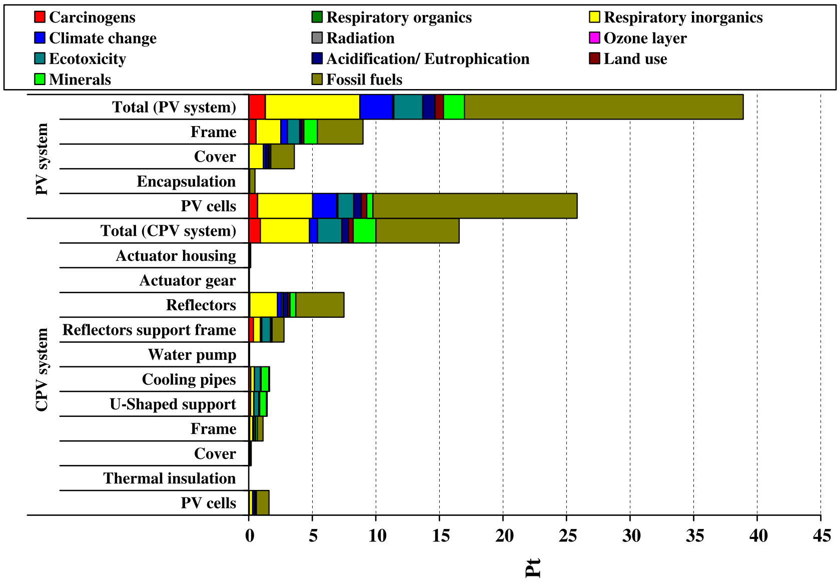

Fig. 5. Comparison between the CPV and PV systems using the EI99 methodology (per impact category).

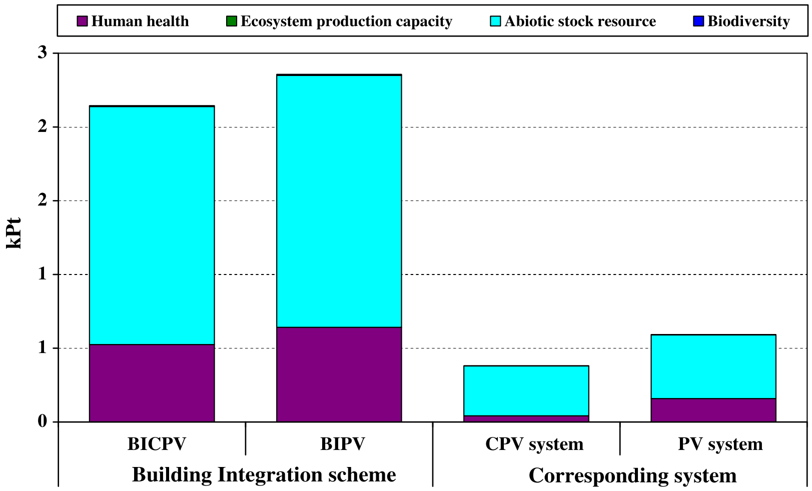

Fig. 6. Comparison between the BICPV and BIPV schemes on the left, and the corresponding CPV and PV systems on the right, using the EPS 2000 methodology.

methodologies, Table 2 shows a summary of the most significant results. As mentioned previously, the EI99 methodology is considered as a reference, and EPS 2000 methodology is used in order to check and compare the coherency of the environmental performance results from another methodology perspective.

There are significant differences between the percentage results of the two methodologies. The EI99 methodology highlights the significant impact of the reflectors with respect to the total impact points of the CPV system (45%), which invokes the need to further investigate the use of low iron reflectors. Nevertheless, indulging further purification processes will, definitely, consume higher amounts of energy, which will be interpreted in higher impact through the fossil fuels impact category. The EPS methodology clarifies a high priority for the need to substitute the copper used in the cooling pipes and *U*-shaped support (59% of the total impact points represented by the depletion of reserves impact category) with another low impact materials. However, in general, both methodologies clarify the significant impact reduction achieved through achieved through implementing the CPV system instead of the conventional PV one.

4.4. Sensitivity analysis

Due to the newness of the actual CPV system installed, it is useful to present a sensitivity analysis in order to further quantify the environmental benefits gained from the concentration ratio increase. For the present LCA study, it is shown in Fig. 9a that the higher the concentration factors, the lower the impact scores. Besides, it is noticed that increasing the concentration factor to 18× can reduce the CPV system impact score by about 6.1%. On the other hand, it is observed that further augmenting the concentration factor from 18× and up to 40×, although still reduces the impact score; the rate of reduction is not as much as before, where the impact score is reduced only by 4.5%. However, as shown in Fig. 9b, the increase of the concentration factor is also associated with higher optical losses (relative to a concentration factor of

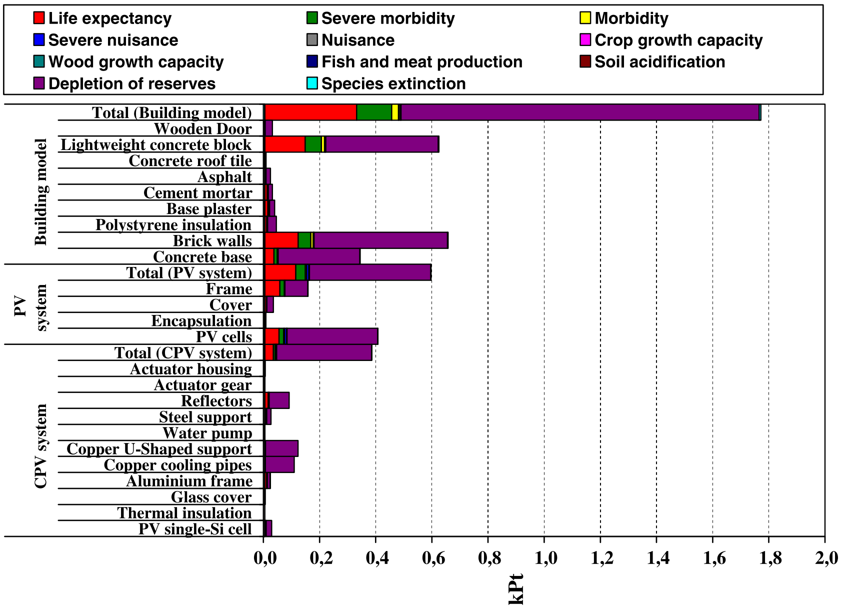

Fig. 7. Impact assessment results using the EPS 2000 methodology (per impact category).

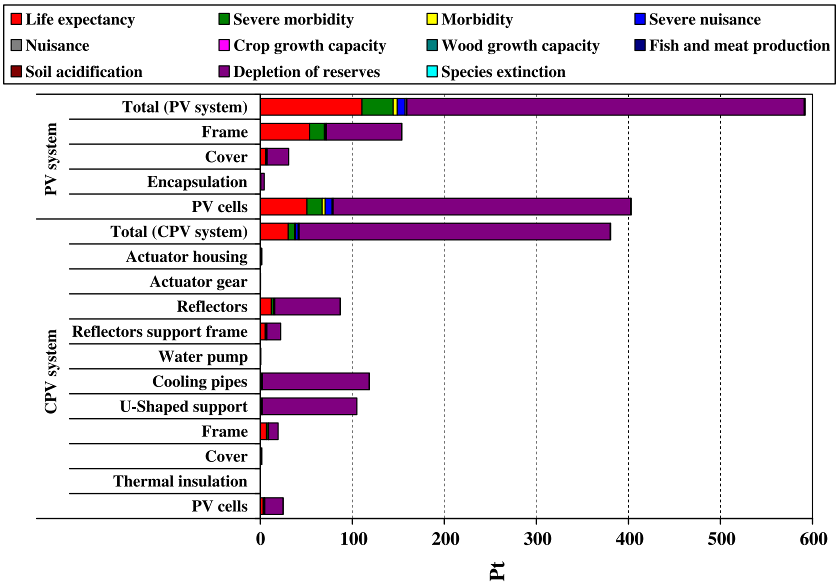

Fig. 8. Comparison between the CPV and PV systems using the EPS 2000 methodology (per impact category).

Table 2
A summary table highlighting the most significant results including a comparison between the results of the used LCIA methodologies.

	EI99	EPS 2000
The increment percentage of impact score after replacing the BICPV system with the BIPV system	13.5%	10%
Environmental impact ratio of the PV system to the CPV system	2.35	1.55
Contribution percentage of the CPV system to the total impact score of the BICPV scheme	10%	18%
Contribution percentage of the CPV cells to the total impact points of the CPV system	9.6%	6.5%
Contribution percentage of the reflectors to the total impact points of the CPV system	45%	23%
Contribution percentage of the copper cooling pipes and *U*-shaped support to the total impact points of the CPV system	20%	59%

10×). This effect is not considered in the LCA study that is focusing on the assembly stage; but it would be essential to consider within a complete design fulfilling the most efficient operation requirements.

5. Conclusions

A LCA of a BICPV scheme located at the Applied Energy Research Centre (CREA) at the University of Lleida (Spain) is conducted. The analysis is performed highlighting the assembly stage, which induces high impact on the environment, comprising both instantaneous and long run effects.

The results demonstrate the significantly low environmental impact of using the CPV technology, where the CPV system represents only 10% of the total impact points of the BICPV scheme. In addition, it is shown that replacing the BICPV scheme with a BIPV

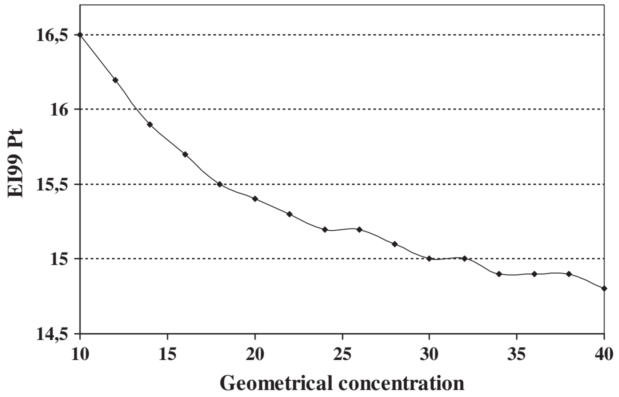

Fig. 9a. The effect of increasing the concentration ratio on the impact score using the EI99 methodology.

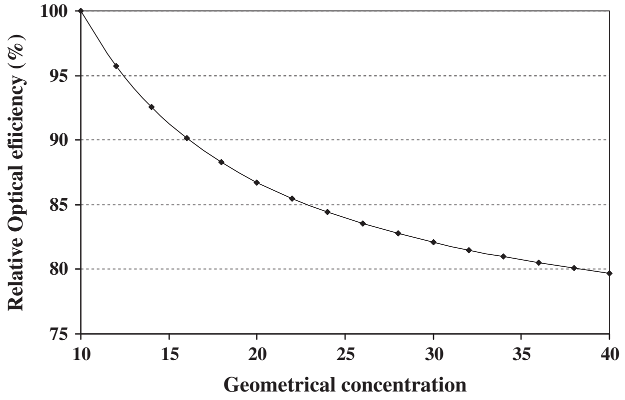

Fig. 9b. The effect of increasing the concentration ratio on the optical efficiency relative to 10X concentration ratio.

one causes an increment in the corresponding environmental impact by about 13.5%, where the impact of the PV system is about 2.35 times the impact of the CPV one.

Regarding the breakdown analysis of the CPV system components, the significance of the environmental impact is attributed to two components: the cooling pipes and the *U*-shaped support (Copper), and the reflectors (Coated glass). This clarifies the essentiality of the substitution of copper with another suitable material (stainless steel, etc.) that is expected to have less environmental impact. In addition, such results encourage further innovative designs of mini-reflectors. This in return may lead to less impact on the environment, depending on other contributing factors affecting the whole design goal and purpose. Nevertheless, the aim of that relative comparison between the CPV system components is to further investigate the improvements that can be achieved within the CPV system. This, however, does not omit the significant environmental benefits that can be achieved by using the CPV system instead of the PV one.

In reference to the LCIA methodologies used, clear differences are noticed in the components impact contribution percentages of the two used methodologies (from 3.1% to 39%). This is attributed to the differences mentioned previously in Section 3 between the LCIA methodologies. However, the results of the two methodologies clarify the significant environmental benefits acquired from adopting a well designed BICPV scheme instead of a conventional BIPV one of the same function, power, and aperture area.

Referring to the environmental impact categories, it is noted that the fossil fuel (EI99) and the depletion of reserves (EPS 2000) are the most dominant ones. From this, it is concluded that the use of renewable energy resources to supply the processes of the corresponding materials can lead to significant differences in the results. This can assist in reducing the impacts that affect the human health damage category as well (respiratory inorganics in case of the EI99 methodology, and life expectancy in the EPS 2000 methodology), where a lot of indirect emissions would be omitted and thus further reduction of the environmental impact could be achieved. The extent of applying such idea can be presented in a future study, considering different energy mix scenarios where the PV energy resources can be assumed to be the most dominant.

Regarding the sensitivity analysis conducted, it is clearly observed that increasing the concentration factor contributes in reducing the CPV system environmental impact. Nevertheless, this is required to be further analyzed and confirmed taking into consideration the efficiency of the CPV cells and the optical efficiencies under different concentration ratios during operation. Within this context, in a future study, the BICPV scheme will be environmentally evaluated taking into consideration the operational stage. This will enable establishing different comparisons with other LCA studies of BIPV in literature, where most of them, as indicated in section 1, are based on the Energy Payback Time as an environmental indicator.

Acknowledgments

This work is supported by the Project ENE2010-18357 under Grant reference BES-2009-028293, funded by the Spanish Ministry of Science and Innovation (MICINN).

References

[1] Renewable Energy Policy Network for the 21st Century (REN21), Renewables 2011Golabl Status Report. www.Ren21.net. Consulted in October; 2012.
[2] Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells, EPRI, Palo Alto, CA, and California Energy Commission, Sacramento, CA; 2003. 1000095.
[3] Fthenakis V. Chapter VII-2: overview of potential hazards. In: Markvart T, Castaner L. Practical handbook of photovoltaics: fundamentals and applications. Elsevier, UK. ISBN 1-856-17390-9; 2003.
[4] Fthenakis V, Moskowitz PD. Photovoltaics: environmental health and safety issues and perspectives. Prog Photovoltaics Res Appl 2000;8:27–38.
[5] Fthenakis V. Prevention and control of accidental releases of hazardous materials in PV facilities. Prog Photovoltaics Res Appl 1998;6:91–8.
[6] Jelle BP, Breivik C, Rokenes HD. Building integrated photovoltaic products: a state-of-the-art review and future research opportunities. Sol Energy Mater Sol Cells 2012;100:69–96.
[7] Bloema JJ, Lodi C, Ciprianoc J, Chemisana D. An outdoor test reference environment for double skin applications of building integrated photovoltaic systems. Energy Build. 2012;50:63–73.
[8] Quesada G, Rousse D, Duti Y, Badache M, Halle S. A comprehensive review of solar facades. Opaque solar facades. Renew Sustain Energy Rev 2012;16:2820–32.
[9] Chemisana D. Building integrated concentrating photovoltaics: a review. Renew Sustain Energy Rev 2011;15:603–11.
[10] Chemisana D, Rosell JI. Design and optical performance of a nonimaging Fresnel transmissive concentrator for building integration applications. Energy Convers Manage 2011;52:3241–8.
[11] Chemisana D, Ibáñez M. Linear Fresnel concentrators for building integrated applications. Energy Convers Manage 2010;51:1476–80.
[12] Chemisana D, Villada JL, Coronas A, Rosell JI, Lodi C. Building integration of concentrating systems for solar cooling applications. Appl Therm Eng 2012. http://dx.doi.org/10.1016/j.applthermaleng.2011.12.005.
[13] Kostic LT, Pavlovic TM, Pavlovic ZT. Influence of reflectance from flat aluminum concentrators on energy efficiency of PV/thermal collector. Appl Energy 2010;87:410–6.
[14] Nkwetta DN, Smyth M. The potential applications and advantages of powering solar air-conditioning systems using concentrator augmented solar collectors. Appl Energy 2012;89:380–6.
[15] Sellami N, Mallick TK. Optical efficiency study of PV crossed compound parabolic concentrator. <http://dx.doi.org/10.1016/j.apenergy.2012.08.052>.
[16] Thormark C. A low energy building in a life cycle – its embodied energy, energy need for operation and recycling potential. Build Environ 2002;37:429–35.

[17] Ramesh T, Prakasha Ravi, Shukla KK. Life cycle energy analysis of buildings: an overview. Energy Build 2010;42:1592–600.

[18] Bribian IZ, Valero Capilla A, Aranda Uson A. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 2011;46:1133–40.

[19] Menoufi K, Castell A, Navarro L, Pérez G, Boer D, Cabeza LF. Evaluation of the environmental impact of experimental cubicles using life cycle assessment: a highlight on the manufacturing phase. Appl Energy 2012;92:534–44.

[20] Proietti S, Desideri U, Sdringola P, Zepparelli F. Carbon footprint of a reflective foil and comparison with other solutions for thermal insulation in building envelope. Appl Energy 2013. http://dx.doi.org/10.1016/j.apenergy.2013.01.086.

[21] Fong KF, Lee CK. Towards net zero energy design for low-rise residential buildings in subtropical Hong Kong. Appl Energy 2012;93:686–94.

[22] Fthenakis V, Kim HC. Photovoltaics: life-cycle analyses. Sol Energy 2011;85:1609–28.

[23] Fthenakis V, Kim HC, Frischknecht R, Raugei M, Sinha P, Stucki M. Life cycle inventories and life cycle assessment of photovoltaic systems. International Energy Agency (IEA) PVPS Task 12, Report T 2011;12–02:2011.

[24] Fthenakis V, Frischknecht R, Raugei M, Kim HC, Alsema E, Held M, de Wild-Scholten M. Methodology guidelines on life cycle assessment of photovoltaic electricity, 2nd ed., IEA PVPS Task 12. International energy agency photovoltaic power systems programme; 2011.

[25] Alsema EA. Energy pay-back time and CO_2 emissions of PV systems. Prog Photovoltaics Res Appl 2000;8(1):17–25.

[26] Alsema EA, Nieuwlaar E. Energy viability of photovoltaic systems. Energy Policy 2000;28(14):999–1010.

[27] Fthenakis V, Alsema EA. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–2005 status. Prog Photovoltaics Res Appl 2006;14:275–80.

[28] Fthenakis V, Kim HC. Greenhouse-gas emissions from solar electric- and nuclear power: a life-cycle study. Energy Policy 2007;35:2549–57.

[29] Perez MJR, Fthenakis V, Kim HC, Pereira AO. Façade-integrated photovoltaics: a life cycle and performance assessment case study. Prog Photovoltaics Res Appl 2012. http://dx.doi.org/10.1002/pip.1167.

[30] Kim HC, Fthenakis V, Choi JK, Turney DE. Life cycle greenhouse gas emissions of thin-film photovoltaic electricity generation. J Indust Ecol. doi: 10.1111/j.1530-9290.2011.00423.x.

[31] Perpinan O, Lorenzo E, Castro MA, Eyras R. Energy payback time of grid connected PV systems: comparison between tracking and fixed systems. Prog Photovoltaics Res Appl 2009;17:137–47.

[32] Bizzarri G, Gillott M, Belpoliti V. The potential of semitransparent photovoltaic devices for architectural integration: the development of device performance and improvement of the indoor environmental quality and comfort through case-study application. Sustain Cities Soc 2011;1:178–85.

[33] Lu L, Yang HX. Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. Appl Energy 2010;87:3625–31.

[34] Crawford RH, Treloar GJ, Fuller RJ, Bazilian M. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. Renew Sustain Energy Rev 2006;10:559–75.

[35] Radhi H. Energy analysis of facade-integrated photovoltaic systems applied to UAE commercial buildings. Sol Energy 2010;84:2009–21.

[36] Koroneos C, Tsarouhis M. Exergy analysis and life cycle assessment of solar heating and cooling systems in the building environment. J Clean Prod 2012;32:52–60.

[37] Vats K, Tiwari GN. Energy and exergy analysis of a building integrated semitransparent photovoltaic thermal (BISPVT) system. Appl Energy 2012;96:409–16.

[38] Wu SY, Guo FH, Xiao L. Comparative study on exergy efficiency of solar photovoltaic/thermal (PV/T) system. Adv Mater Res 2012;347–353:476–80.

[39] Rajoria CS, Agrawal S, Tiwari GN. Overall thermal energy and exergy analysis of hybrid photovoltaic thermal array. Sol Energy 2012;86:1531–8.

[40] Mohr NJ, Meijer A, Huijbregts MAJ, Reijnders L. Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. Prog Photovoltaics Res Appl 2012. http://dx.doi.org/10.1002/pip.2157.

[41] Hammond GP, Harajli HA, Jones C, Winnett AB. Whole systems appraisal of a UK building integrated photovoltaic (BIPV) system: energy, environmental, and economic evaluations. Energy Policy 2012;40:219–30.

[42] Laleman R, Albrecht J, Dewulf J. Life cycle analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation. Renew Sustain Energy Rev 2011;15:267–81.

[43] Jungbluth N. Life cycle assessment of crystalline photovoltaics in the swiss ecoinvent database. Prog Photovolt: Res Appl. doi: 10.1002/pip.614.

[44] Peng J, Lu L, Yang H. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renew Sustain Energy Rev 2013;19:255–74.

[45] Celik AN, Muneer T, Clarke P. Optimal sizing and life cycle assessment of residential photovoltaic energy systems with battery storage. Prog Photovoltaics Res Appl 2008;16:69–85.

[46] Azzopardi B, Mutale J. Life cycle analysis for future photovoltaic systems using hybrid solar cells. Renew Sustain Energy Rev 2010;14:1130–4.

[47] Rujula AAB, Lafuente AML, Cirezoto F. Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems. Energy 2011;36:3148–58.

[48] Chel A, Tiwari GN. A case study of a typical 2.32 kWP stand-alone photovoltaic (SAPV) in composite climate of New Delhi (India). Appl Energy 2011;88:1415–26.

[49] Nayak S, Tiwari GN. Energy and exergy analysis of photovoltaic/thermal integrated with a solar Greenhouse. Energy Build 2008;40:2015–21.

[50] Cucchiella F, D'Adamo I. Estimation of the energetic and environmental impacts of a roof-mounted building-integrated photovoltaic systems. Renew Sustain Energy Rev 2012;16:5245–59.

[51] Kaldellis JK, Zafirakis D, Kondili E. Energy pay-back period analysis of stand-alone PV systems. Renew Energy 2010;35:1444–54.

[52] Sherwani AF, Usmani JA, Varun. Life cycle assessment of solar PV based electricity generation systems: a review. Renew Sustain Energy Rev 2010;14:540–4.

[53] Valverde RG, Miguel C, Bejar RM, Urbina A. Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. Sol Energy 2009;83:1434–45.

[54] Sumpera A, Garcíaa MR, Roblesa RV, Janéc JB, Peiroa JA. Life-cycle assessment of a photovoltaic system in Catalonia (Spain). Renew Sustain Energy Rev 2011;15:3888–96.

[55] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy 2007;35(6):3316–26.

[56] Sengul H, Theis TL. An environmental impact assessment of quantum dot photovoltaics (QDPV) from raw material acquisition through use. J Clean Prod 2011;19:21–31.

[57] Bravi M, Paris ML, Tiezzi E, Basosi R. Life cycle assessment of a micromorph photovoltaic system. Energy 2011;36:4297–306.

[58] der Meulen RV, Alsema Erik. Life-cycle greenhouse gas effects of introducing nanocrystalline materials in thin-film silicon solar cells. Prog Photovolt: Res Appl 2011;19:453–63.

[59] Kim HC, Fthenakis V. Amonix high-concentrator photovoltaic system: life cycle energy demand and greenhouse gas emissions. IEEE 4th world conference on photovoltaic energy conversion, Hawaii, May 8–12; 2006.

[60] Fthenakis V, Kim HC. Life cycle assessment of high-concentration photovoltaic systems. Prog Photovolt: Res Appl. doi: 10.1002/pip.1186.

[61] Peharz G, Dimroth F. High-concentration PV system FLATCON. Prog Photovolt Res Appl 2005;13:627–34.

[62] Desideri U, Zepparelli F, Morettini V, Garroni E. Comparative analysis of concentrating solar power and photovoltaic technologies: technical and environmental evaluations. Appl Energy; 2012. <http://dx.doi.org/10.1016/j.apenergy.2012.08.033>.

[63] Burkhardt JJ, Health GA, Turchi CS. Life cycle assessment of a parabolic trough concentrating solar power plant and the impacts of key design alternatives. Environ Sci Technol 2011;45:2457–64.

[64] Burkhardt JJ, Heath G, Cohen E. Life cycle greenhouse gas emissions of trough and tower concentrating solar power electricity generation systematic review and harmonization. J Ind Ecol 2012. http://dx.doi.org/10.1111/j.1530-9290.2012.00474.x.

[65] Lechon Y, De La Rua C, Saez R. Life cycle environmental impacts of electricity production by solarthermal power plants in Spain. J Sol Energy Eng 021012; 2008. doi:10.1115/1.2888754.

[66] Nishimura A, Hayashi Y, Tanaka K, Hirota M, Kato S, Ito M, et al. Life cycle assessment and evaluation of energy payback time on high-concentration photovoltaic power generation system. Appl Energy 2010;87:2797–807.

[67] Zhang M, Wang Z, Jiang CXH. Embodied energy and emergy analyses of a concentrating solar power (CSP) system. Energy Policy 2012;42:232–8.

[68] Koroneos CJ, Piperidis SA, Tatazikidis CA, Rovas DC. Life cycle assessment of a solar thermal concentrating system. The WSEAS conferences. Santander, Cantabria, Spain, September; 2008.

[69] Pihl E, Kushnir D, Sanden B, Johnsson F. Material constraints for concentrating solar thermal power. Energy 2012;44:944–54.

[70] Piemonte V, Falco MD, Tarquini P, Giaconia A. Life cycle assessment of a high temperature molten salt concentrated solar power plant. Sol Energy 2011;85:1101–8.

[71] Life cycle assessment: principles and practice, National risk management research laboratory, office of research and development, U.S. environmental protection agency (EPA), EPA/600/R-06/060; May 2006.

[72] Raugei M. Energy pay-back time: methodological caveats and future scenarios. Prog Photovoltaics Res Appl 2012. http://dx.doi.org/10.1002/pip.1249.

[73] Richards BS, Watt ME. Permanently dispelling a myth of photovoltaics via the adoption of a new net energy indicator. Renew Sustain Energy Rev 2007;11:162–72.

[74] Menoufi K, Castell A, Farid MM, Boer D, Cabeza LF. Life cycle assessment of experimental cubicles including PCM manufactured from natural resources (esters): a theoretical study. Renew Energy 2013;51:398–403.

[75] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in the Negev desert. Energy Build 2008;40:837–48.

[76] Bribian IZ, Capilla AV, Uson AA. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco efficiency improvement potential. Build Environ 2011;46:1133–40.

[77] Batle BR, Moia A, Cladera A, Martinez V. Energy use, CO_2 emissions and waste throughout the life cycle of a sample of hotels in the Balearic Islands. Energy Build 2010;42:547–58.

[78] Sharma A, Saxena A, Sethi M, Shree V, Varun. Life cycle assessment of buildings: a review. Renew Sustain Energy Rev 2011;15:871–5.

[79] LINAK. <http://www.linak.es/>. Consulted in January 2013.

[80] Amrizal N, Chemisana D, Rosell JI. Hybrid photovoltaic–thermal solar collectors dynamic modeling. Appl Energy 2013;101:797–807.

[81] Amrizal N, Chemisana D, Rosell JI, Barrau J. A dynamic model based on the piston flow concept for the thermal characterization of solar collectors. Appl Energy 2012;94:244–50.

[82] Narec Solar. <www.narecsolar.com>. Consulted in December, 2012.

[83] Chomerics. <www.chomerics.com>. Consulted in December, 2012.

[84] Isofoton. <http://www.isofoton.com>. Consulted in December, 2012.

[85] ISO International Standard 14040. Environmental management – life cycle assessment. Principles and framework. International Organisation for Standardisation (ISO); 2006.

[86] ISO International Standard 14041. Environmental Management – life cycle assessment. Goal and scope definition and Inventory analysis. International Organisation for Standardisation (ISO); 1998.

[87] ISO International Standard 14042. Environmental Management – life cycle assessment. Life cycle Impact assessment. International Organisation for Standardisation (ISO); 2000.

[88] ISO International Standard 14043. Environmental management – life cycle assessment. Life cycle Interpretation. International Organisation for Standardisation (ISO); 2000.

[89] Life Cycle Assessment (LCA) – a guide to approaches, experiences and information sources. EEA (European Environmental Agency), Denmark, ISBN: 92-9167-079-0; 1998.

[90] Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Hirschier R, Hellweg S, Humbert S, Margni M, Nemecek T, Spielmann M. Implementation of life cycle impact assessment methods. Ecoinvent report No. 3. Swiss Centre for Life Cycle Inventories, Dübendorf; 2004.

[91] The Ecoinvent Center. A competence centre of ETH; PSI; Empa & ART. <http://www.ecoinvent.ch/>. Ecoinvent data v2.1, consulted in November; 2012.

[92] Goedkoop M, Spriensma R. Eco-indicator 99, a damage oriented method for life cycle impact assessment. Methodology report; June 2001.

[93] Menoufi K. Life cycle analysis and life cycle impact assessment methodologies: a state of the art. Master Dissertation. University of Lleida; 2011.

[94] Steen B. A systematic approach to environmental priority strategies in product development (EPS), Version 2000 – general system characteristics, CPM report; 1999: 5.

[95] Serenelli L, De Iuliis S, Izzi M, Tucci M, Salza E, Pirozzi L, Cole A, Brown LM, Devenport S, Drew K, Heasman KC, Morrison DJ, Bruton TM, Dewallef S. Screen printing in laser grooved buried contact solar cells: the Lab2Line hybrid processes. Narec solar (Brochures and papers for download). <http://www.narecsolar.com>. Consulted in November, 2012.

[96] Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. Renew Sustain Energy Rev 2011;15:1625–36.

[97] Luque A, Hegedus S. Handbook of photovoltaic science and engineering. ISBN 0-471-49196-9. UK: John Wiley & Sons Ltd; 2002.

[98] German Solar Energy Society. Planning and installing photovoltaic systems: a guide for installers, architects and engineers, 2nd ed. ISBN-13: 978-1-84407-442-6. London, UK: Earthscan; 2008.

[99] Gorter T, Reinders AHME. A comparison of 15 polymers for application in photovoltaic modules in PV-powered boats. Appl Energy 2012;92:286–97.

[100] Bribian IZ, Uson AA, Scarpellini S. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 2009;44:2510–20.