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Dissertation

End-of-Life Management of Photovoltaic Modules

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Em. O. Univ. Prof. Dipl.-Ing. Dr.h.c.mult. Dr.techn. Peter Kopacek
E325
Institut für Mechanik und Mechatronik

eingereicht an der Technischen Universität Wien
Fakultät für Maschinenwesen und Betriebswissenschaften

von

Mahsa Masoumian, MSc, BSc
0968565
Weisses Kreuz Gasse 96/29/4, 2340 Mödling

Wien, am_________

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Mahsa Masoumian, MSc, BSc

Kurzfassung

In den letzten Jahren hat sich das Interesse an alternativen Energiequellen, insbesondere Solarenergie, massiv erhöht. Die Photovoltaikindustrie befindet sich in einer wichtigen und interessanten Phase, wobei effiziente und günstige PV-Zellen, die mithilfe umweltfreundlicher Prozesse und Materialien hergestellt werden sollen, eine bedeutende Rolle spielen.

Ein herausragendes Thema in diesem Zusammenhang ist die Verwertung bzw. Nutzung von PV-Zellen am Ende ihres Lebenszyklus, dem sogenannten "End-of-Life Management". Diese Dissertation befasst sich mit dem End-of-Life Management von PV-Zellen. End-of-Life Management beschreibt die Systeme und Prozesse, die am Ende des Lebenszyklus eines Produkts stattfinden. Aufgrund ökologischer und ökonomischer Überlegungen können PV-Zellen am Ende ihres Lebenszyklus nicht als nutzloser Abfall, der konventionell entsorgt werden kann, angesehen werden. Stattdessen stellen sie eine interessante Quelle an Materialien dar, die auf verschiedene Arten wiederverwendet werden können. Zusätzlich beinhalten PV-Zellen gefährliche Materialien, die gesammelt und einer speziellen Weiterverarbeitung zugeführt werden müssen, um die negativen Auswirkungen auf die Umwelt und auf Menschen zu minimieren.

Diese Dissertation beinhaltet eine allgemeine Einführung in PV-Zellen und anschließend werden die Zielsetzung der Arbeit mit ihrem Umfang und ihren Grenzen beschrieben. In den nächsten Kapiteln wird der in zwei Hauptteile unterteilte theoretische Teil präsentiert: der erste Teil betrifft die PV-Zellenindustrie und der zweite Teil das EoL Mangement im Allgemeinen. Danach ist die Methodologie beschrieben, mit der für verschiedene PV-Zellenarten durchgeführten Datenbeschaffung und einer vertiefenden Untersuchung der aktuell existierenden EoL-Methoden. In weiterer Folge wird ein neues Gewichtungsmodell für PV Zellen entwickelt. Schlussendlich werden die Resultate der Untersuchung präsentiert und diskutiert, gefolgt von einer Schlussfolgerung und einem Vorschlag für weitere Verbesserungsbereiche.

In dieser Dissertation werden mögliche Strategien im Rahmen des End-of-Life Managements, basierend auf dem 4-R Modell beschrieben. Dieses Modell beinhaltet vier grundsätzliche

Strategien des EoL Managements, nämlich Reduzieren (Reduce), Wiederverwenden (Reuse), Recyclen (Recycle) und Energiewiederverwendung (Recover).

Unter Berücksichtigung dieser Punkte hat diese Dissertation das Ziel, die Frage zu beantworten, welcher PV-Zellentyp von einem EoL-Standpunkt aus optimal ist. Zu diesem Zweck werden mehrere Kriterien definiert, diese anschließend nach ihrer Wichtigkeit gewichtet und danach werden die evaluierten PV-Zellen anhand der einzelnen Kriterien analysiert und mit einer entsprechenden Anzahl an Punkten versehen. Die Gesamtsumme aller Kriterien eines PV-Zellentyps liefert einen Indikator für eine optimale Strategie während des EoL Managements und weiters einen Indikator für den optimalen PV-Zellentyp in Hinblick auf geringe Auswirkungen auf die Umwelt und kosteneffizienten Umgang mit den vorhandenen Ressourcen.

Das vorgeschlagene Modell hat einen generellen Fokus, es ist also nicht auf eine bestimmte Gruppe PV-Zellen oder eine spezifische Firma oder eine spezifische Situation in einem spezifischen Land beschränkt. Weiters ist das Modell einfach, nutzerfreundlich und einfach zu verstehen und zu verwenden. Das Model hat nicht zu viele Variablen, sondern deckt die wichtigsten Einflussfaktoren ab. Aufgrund des auf Kriterien basierenden Aufbaus des Modells ist es anpassbar und flexibel, sodass jeder seine eigenen Parameterwerte, basierend auf seiner spezifischen Situation, einfügen kann. Weiters nutzt das Modell mathematische Methoden und keine verbalen Beschreibungen und ist akkurat. Dadurch ist sichergestellt, dass das Modell exakte Informationen und keine unklaren und vagen Texte bereitstellen kann.

Ein Resultat dieser Dissertation ist die Bereitstellung von einigen Verbesserungsvorschlägen, nämlich den folgenden: Ein Bereich potentieller Weiterentwicklung ist die Materialverbesserung, die einen Effekt auf das Design und die Konstruktion von PV-Zellen hat. Ein anderes potentielles Forschungsfeld ist die Verbesserung der Demontageprozesse für PV-Zellen. Der dritte potentielle Forschungsschwerpunkt ist mit dem Marktanteil verbunden. Um die optimale EoL Managementstrategie auswählen zu können, ist ein umfassendes Wissen über die Marktsituation der PV-Zellen und die Marksituation der Rohmaterialien wichtig. Der letzte potentielle Forschungsschwerpunkt ist die Entwicklung von standardisierten Recyclingprozessen, die durch spezielle Unternehmen oder Hilfsmittel durchgeführt werden.

Abstract

In recent years a widespread interest has been devoted to renewable energy sources, in particular solar energies. The photovoltaic (PV) industry is going to enter an important decade, which deals with efficient and low-cost PV cells based on environmental friendly production processes and materials.

An important issue within the industry of PV cells is the decommissioning of PV cells at the end of their useful life. End-of-Life management is describing the systems and processes that take place at the end of the life cycle of a product. This dissertation focuses on the End-of-Life management of PV cells. Due to various economic and ecologic reasons PV cells at the end of their life cannot be seen as an useless amount of waste that has to be disposed. Instead, they present interesting resources of materials that may be able to be further used in various ways. Furthermore, PV cells contain hazardous materials that have to be collected and treated in a special way in order to minimize the negative effects on the environment and human beings.

The structure of the dissertation includes an introduction to PV cells in general, and then the dissertation purposes with its scope and delimitations are described. In the next chapters the theoretical part is provided; which is divided into two main parts: the first part is on the PV cells industry and the second part is on EoL in general. Thereafter, the methodology is described with the data collection that was performed on different types of PV cells and a deep research on the currently existing EoL methods. In chapter twelve a new weighting model for PV cells is developed. Finally the results of the research are presented and discussed, followed by a conclusion and suggested further improvement points.

In this dissertation, possible strategies in the field of End-of-Life management are described based on the 4-R model. The 4-R model describes the different EoL strategies, which are: reduce, reuse, recycle and recover.

Considering the points mentioned above, this dissertation proposes a novel model to answer the question, what kind of PV cells is optimal from the EoL point of view. For this purpose, several

quantitative criteria are defined; these criteria are weighted according to their level of importance and finally each of the evaluated PV cells are reviewed due to the single criteria and respectively provided with a specific amount of points according to a predetermined schema. The total amount of points of all criteria of a PV cell indicates the optimal strategy at the End-of-Life and respectively the optimal PV cells to be produced, seen from a view regarding the minimization of ecological impacts as well as a cost-efficient handling of the available resources. Additionally, some case studies have been presented, which aim at considering the PV cells from different points of view.

The presented model has a general scope, as it is not restricted to a specific group of PV cells or to a specific company or to any specific situation in a specific country. Furthermore, the model is constructed to be simple, user-friendly and easy to understand and use. The model does not have too many variables, but covers the most important influence factors**.** Due to the criteria-based design, the model is adaptable and flexible, so that everybody can introduce his own parameter values, based on his specific situation**.** Furthermore, the model uses mathematic methods rather than verbal descriptions and is accurate. That ensures that the model can provide exact information rather than unclear and vague texts.

As a result of the dissertation, some potential elements of improvements are provided, which are as follows: One of the areas of potential research is the material improvement, which has an effect on the design and construction of the PV cells. Another potential field of research is the improvement of the low-cost disassembly processes for PV cells. The third potential point is related to the market share. In order to decide on an optimal EoL management strategy, a comprehensive knowledge on the market situation of the PV cells itself and also on the market situation of the raw/rare materials should be considered. Finally the last potential point is the development of standard recycling processes, which would be fulfilled through specific companies or utilities.

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List of Abbreviations

CIP	Competitiveness and Innovation Framework Program
DfE	Design for Environment
EMS	Environmental Management Systems
EoL	End-of-Life
EPA	United States Environmental Protection Agency
EPIA	European Photovoltaic Industry Association
ERA	European Research Area
EVA	Ethylene Vinyl Acetate
FP6	Europeans’ Sixth Framework Program for Research and Technological Development
FP7	Europeans’ Seventh Framework Program for Research and Technological Development
GHG	Green House Gases
GWP	Global Warming Potential
ICT	Information and Communication Technologies
IEE	Intelligent Energy Europe
INMETCO	International Metals Reclamation Company
ISO	International Standards Organization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
NMP	Nano sciences, Nanotechnologies, Materials and New Production Technologies
NREAPs	National Renewable Energy Action Plans
PPG	Pollution Prevention Guidelines
PV	Photovoltaic
SMEs	Small and Medium Enterprises
SVTC	Silicon Valley Toxics Coalition
TCO	Transparent Conducting Oxide
WEEE	Waste of Electrical and Electronic Equipment

1. Introduction

In recent years a widespread interest has been devoted to renewable sources of energies. By expansion of renewable energy industries, the consumption of scarce raw materials that are needed for the production of devices used within renewable energy industries will also grow. According to the U.S. Department of Energy, the consumption of raw materials of the clean energy technology sector such as photovoltaic cells, electric vehicles, wind turbines, and fluorescent lighting accounts for approximately 20% of the global consumption of “critical materials” including the rare elements. This increase of use of raw materials and minerals causes several environmental and material issues (REN21, 2011).

Among renewable sources of energies, the photovoltaic (PV) industry is entering a crucial decade of long-term reliability. Issues like reprocessing the used materials and recycling of photovoltaic modules which are at the end of their life cycle are at the highest importance.

By 2030, approximately 130,000 tons of PV modules at the end of their life-cycle level will be in the market in Europe (REN21, 2011). There are varieties of ways to recover a product at the end of its functional life. End-of-Life (EoL) management as a methodology to be used to recover the photovoltaic module at the end of its life cycle is a useful method, which leads the PV industry towards a more sustainable production and consumption. Considering the fact that we are living in a world with a limited amount of resources, developing methods for the EoL management of a product, through the recovery of the materials used inside the product is a crucial issue.

This research provides a review about the current methods of recycling in the area of photovoltaics. The overall aim of the thesis is to generate recycling process plans and models, which promote the environmental performance of photovoltaics and also improvement of the currently existing EoL management, as well as supporting the sustainability of the photovoltaics recovery/recycling sector.

2. Problem Definition

2.1. Research Purpose

The purpose of this dissertation consists of several aspects; firstly, the study intends to explore the feasibility of decommissioning of solar cells at the end of their useful life; that is associated with economic aspects as well as environmental aspects of views. Secondly, a discussion on different EoL strategies (reduce, reuse, recycle and recover) within the photovoltaic industry is provided. Thirdly, an optimal systematic EoL strategy for photovoltaic modules by using the methodology of EoL management is developed.

In order to achieve the dissertation purposes, the following questions drive the direction of the study:

1. What are the existing EoL strategies for photovoltaic around the world? And basically what is the optimal photovoltaic EoL treatment around the world?
2. What kind of PV cells is optimal from the EoL point of view?

In order to answer the second question, a first trial to quantify the EoL value of photovoltaic modules is presented. A model, which is developed in chapter 12, is used to describe such EoL values on a quantitative basis.

2.2. Delimitations

Beside the various applications of PV cells on the surface of the earth, PV cells are also used in space applications, where they serve as energy supplies for spaceships. These applications differ from terrestrial applications in many ways. In order to keep the focus of this paper on the EoL on the majority of PV cells, PV cells that are used in space applications are not included here.

The main difference between solar cells used in terrestrial applications and solar cells used in spaceships are the different constraints, under which the energy production is taking place. While cost efficiency plays an important role in installations based on the earth, power/weight efficiency is important in space applications. Additionally, the circumstances that are present on the surface of the earth are different from the circumstances in the space, so that different constructions and designs are necessary. As solar cells used in spaceships are not representing an important factor in the EoL cycle compared to the terrestrial based solar cell systems, there is no loss of generality connected to the exclusion of solar cells used in spaceships.

3. An overview of Europeans’ strategies in energy sector

In this chapter, an overview of the current strategies of the European Union in the energy sector is presented. There are a few different directions and fields of interest that are covered by these strategies. Additionally, existing legal frameworks which are important for the development in the field of PV cells are analyzed.

3.1. Europeans’ energy strategy developments

The European energy strategy with the focus on long-term decarburization and based on goals such as “security of supply, competitiveness, and sustainability” has faced some dramatic changes through the years 2007 to 2011. In 2007 the European Council has set three central energy and climate change objectives for the European energy strategy as follow:

- Reduction of greenhouse gas emissions by 20% up to 30% until 2020
- Extension of the renewable energy share of the market up to 20% until 2020
- Improvement in energy efficiency by 20% until 2020

Despite the continues commitment of European Council on these goals and being supported by the European Parliament, the data by the end of 2010 has revealed that these goals are not achievable by 2020. In 2010 the European Commission has proposed a new energy strategy, which is called “A strategy for competitive, sustainable and secure energy toward 2020” (European commission, 2010).

This new European energy strategy emphasizes on five factors as follows:

A) Efficient use of energy in Europe; in order to reach the planned 20% savings by 2020, a series of well-defined energy efficiency action plans, as well as comprehensive political and economic commitments from relevant authorities in public sector and industry sector is inevitable. In order to change the existing patterns, new educational programs and trainings are also defined in the efficiency action plans. Furthermore, in the new strategy there would be a special attention to the sectors with the highest potentiality to save energy, namely buildings stocks and transportation systems. For example the role of information and communication technologies to provide a good means to further energy-savings actions in buildings and transportation systems through electricity networks and also intelligent transport systems is highlighted.

B) Integrated European energy market; in order to create a fully reliable benefit from the European energy market, the European commission aims to provide a robust framework, which focuses on the authentic implementation of the interconnected market legislation within Europe. This legislation should encourage investors to invest in new methods of production, transportation and stock for renewable sources of energies. For example, this new European energy strategy aims on the investments in low-carbon energy industries to be focused on market-based policies such as emissions trading and taxation.

   Furthermore, this framework could be based on the best practices, which focuses on the more cost-effective feed-in values, more technological support and also mobilization of financing policies, which are similar to state rules.

   Nevertheless, European renewable energy policies suffer the lack of a grid infrastructure. Parts of the actions in this category are based on developing an infrastructure across Europe, which can create an efficient flow of gas and electricity to the consumption areas.

C) Consumers’ empowerment and achievement of the highest level of safety and security; considering the interconnected market legislation within Europe, that has been discussed in part B, it is also necessary that all the consumers are aware of the benefits that this integrated internal market scheme would provide them with. An integrated market offers more openings of markets, which would create consumers with a broader set of choices, better services and lower prices. But all of these benefits are achievable when the consumers are aware of their rights under the EU legislation and to actively participate in the energy market.

To achieve energy at affordable prices and from reliable supplies is one of the important tasks of the internal market. The integrated market should define some sort of market mechanisms that guarantee the security of supplies. However, definitions of safety policies for the time of supply crisis, when market mechanisms may not function sufficiently, are also demanded.

D) Extension of the Europe’s leadership in energy and innovation; ever-increasing technological development is a competitive issue in any market as well as in the energy market. International technology markets in countries such as Japan, China, South Korea and the United States of America are tackling strategic planning in renewable sources of energy industries, especially solar and wind power as well as nuclear industries. In order to remain competitive with these markets, the European Commission has set up plenty of specific sets of plans and projects. For example the Commission has introduced some cooperation plans with third-world countries with the aim of particular energy industries or a budget of € 1 billion is proposed as an initiative in terms of supporting the research specifically in the area of low-carbon energy knowledge and a few other plans and projects.

E) Stronger international partnership in the energy market for the European; in order to enhance the EU market internationally, the “Energy Community Treaty” has defined several focused frameworks to strengthen the participation of neighbor countries within the European internal energy market. It is necessary that the EU energy market models being integrated and extended to all the EU neighbors, which are willing to adopt the EU energy market models. The EU rules in this context are based on the “European Neighborhood Policy and the Enlargement” process, which considers in particular the Mediterranean region and also countries such as Ukraine and Turkey with transit issues.

Among the EU focused frameworks to strengthen the European energy market internationally, it is worth to refer to some of the agreements with third countries that have been accomplished by the EU. Agreements such as; “Free Trade Agreements”, “Association Agreements”, “Partnership and Cooperation Agreements”, etc. are among those. Moreover, in order to promote the role of the EU in a low-carbonization energy market, the Commission has established a cooperation project with Africa. This project, which is based on the “Green Paper on Development Policy”, aims to provide all citizens with sustainable energy.

To summarize, the member states have emphasized on the scale of the challenges in energy supplies. All the points above (A-E) are in alliance with the efficient use of energy supplies at defined affordable prices. Member states have agreed that the challenges in the sustainability of the energy supplies could be tackled by the strategies at the EU level and with the EU funding.

3.2. Europeans’ renewable energy developments

As mentioned in a previous sector, one of the key factors of the European energy policy is moving toward the low-carbon energy sectors, which draws the attention on the renewable sources of energies. EU structures, frameworks and development policies defined in the European energy strategy, are all supporting the renewable sources of energy (European Commission, 2011).

According to the "Renewable Electricity Directive", the EU share of renewable energy in electricity sector was expected to reach the generation of 21% by 2010 and respectively a share of 34% by 2020. Moreover, in the transportation sector, a share of 5.75% by 2010 for renewable energy, by replacing petrol and diesel with these renewable sources of energy was estimated.

A few member states were expected to achieve their targets until 2010. Among those, countries like Austria, Finland, Germany, Malta, Netherlands, Poland, Romania, Spain and Sweden expected to achieve their agreed targets for renewable energy in transport sector and countries like Denmark, Germany, Hungary, Ireland, Lithuania, Poland and Portugal expected to achieve their wished targets for renewable energy in electricity sector. This inefficient progress towards the defined targets, led to a definition of a new “Renewable Energy Directive” in 2009. The new “Renewable Energy Directive” defines “cooperation mechanisms" within all the member states. These "cooperation mechanisms" are based on the statistical transfers of renewable energies between the member states and also some joint projects and joint support schemes between the member states, which are described below:

The Renewable Energy Directive's "cooperation mechanisms”	
Statistical Transfers	A member state with a surplus of renewable energy could "sell" its renewable supply of energy statistically to another member state, which renewable energy supplies may be more expensive.
Joint Projects	A new renewable energy project launched in one member state could be co- financed by another member state, while the production is shared between the two of them. Furthermore, there could be a joint project between a third country and a member state, for example the electricity that has been produced in North Africa being imported to Europe.
Joint Support Schemes	In order to develop a renewable energy industry, which is an integrated single European market, member states agree upon adjusting their support schemes together.

Table 1: The renewable energy directive`s “Cooperation Mechanisms” (European Commission, 2011)

By applying the cooperation mechanisms, European would reach a comprehensive national perspective in the renewable energy sector. Moreover, with the joint projects/schemes European countries would be able to reach their renewable energy targets at more cost effective levels.

Furthermore, the recent EU "Renewable Energy Directive" aims to provide a stable development framework within Europe by the means of all the member states. The new "Renewable Energy Directive" considers the energy consumption as a whole and defines a set of provisions and reforming planning regimes to develop "National Renewable Energy Action Plans" (NREAPs). NREAPs include plans for the future developments of PV. Until the end of August 2010, nineteen out of the twenty seven member states have announced their renewable energy action plans to the European Commission. In the NREAPs, notified by these nineteen members, it is estimated that PV electricity would reach a share of larger than 7% of their renewable electricity consumption by the year 2020. However, countries like Finland, Sweden and Ireland are not counting on the PV electricity at all. Countries like Greece, Italy, Luxembourg, Malta and Spain estimate that about 10% of their renewable electricity could be produced by PV.

In summary, the EU new "Renewable Energy Directive" in combination with the new targeted financing systems as well as new scheme programs and frameworks are all aiming to support the development of more competitive renewable sources of energies as well as the photovoltaic industry.

3.3. Europeans' Directive on Waste of Electrical and Electronic Equipment (WEEE)

As the production of electrical and electronic equipment is ever increasing around the globe, issues like collecting and recycling of these equipment has always been an important topic. The EU legislation (Directive 2002/96/EC) on the management of the Waste of Electrical and Electronic Equipment (WEEE) with the aim of promoting the recycling or the re-use of such equipment has been in use since February 2003. The WEEE sets a couple of rules on the collection and recycling of the materials in the contents of the electrical and electronic equipment. According to a report created by the European Union, only one third of the electronic waste is treated appropriately within the EU and some part of the other two thirds is sent to landfills outside the European Union and consequently these amounts of the WEEE are treated inappropriately, which causes damages to the environment, due to its hazardous contents.

3.4. Europeans’ Directive on the Restriction of Hazardous Substances (RoHS)

The RoHS 2 directive (Directive 2011/65/EC) is restricting the use of several hazardous substances for the production of electric and electronic products (European Union 2011). These restricted substances are:

- Lead
- Mercury
- Cadmium
- Hexavalent chromium
- Polybrominated biphenyls (PBB)
- Polybrominated diphenyl ether (PBDE)

The maximum permitted concentrations are 100 ppm (parts per million) for cadmium and 1000 ppm for the other five substances. The basis is not the final product or a module, but a homogenous material, which can be any single substance that can be separated.

The ROHS 2 directive made some amendments to the directive compared to the first RoHS directive (Directive 2003/95/EC), e.g. the above mentioned maximum permitted concentrations were introduced, but the list of restricted substances remained the same (European Union 2003).

This directive includes many exceptions for cases, where the use of these substances cannot be avoided. Photovoltaic modules are explicit mentioned to be outside the scope of this directive (Directive 2011/65/EC).

3.5. Photovoltaic modules within or without the scope of the WEEE Directive?

Recycling procedures for photovoltaic modules are quite similar to recycling methods of some of the electrical and electronic equipment with a large proportion of glass like LCDs and screen glass. Due to the fact that the large volumes of end-of-life photovoltaic modules would enter the market in years 2025 or 2030, currently the recycling of photovoltaic modules is not economically viable (European commission, DG ENV 2011).

Regarding the recycling of photovoltaic modules, within the scope of the WEEE or outside the scope of the WEEE two potential baseline scenarios (“No policy action”, “photovoltaic modules are outside the scope of the WEEE directive”), as well as two potential policy options (“policy action”, “inclusion of the photovoltaic modules in the scope of the WEEE directive”) have been considered (European commission, DG ENV 2011).

Two potential baseline scenarios:

- Baseline scenario A (“No policy action”, “improper waste treatment”): This involves improper disposal with no treatment and recycling practices of end-of-life PV modules. (“Worst case”)
- Baseline scenario B (“No policy action”): It considers that photovoltaic modules are outside the scope of the WEEE directive; this involves the continuation of current recycling practices. (“Voluntary action”)

Two potential policy options

- Policy action A: This involves the inclusion of only residential photovoltaic modules within the scope of the WEEE directive. (“Residential PVs in the scope of the WEEE directive”)
- Policy action B (“Inclusion of the photovoltaic module in the scope of the WEEE directive”): This involves the inclusion of all photovoltaic modules within the scope of the WEEE directive. (“All PVs in the scope of the WEEE directive”)

Based on the data on these scenarios and their assessments, the following conclusion is definable: including photovoltaic modules in the WEEE Directive would reduce the potential negative environmental impacts of improper disposal and would generate economic benefits. Limiting the quantity of the photovoltaic modules improperly disposed, has the positive environmental impacts of avoiding lead and cadmium leaching and avoiding potential recourse loss due to non-recovery of valuable conventional recourses and rare metals in photovoltaic modules.

Quantities of lead leached into the environment are reduced by a factor of 4 when comparing policy option A with baseline scenario A and by a factor of 6 when comparing policy option B with baseline scenario B, with external costs of leaching being reduced by the same factor. In 2030, 2040 and 2050 recycling of photovoltaic modules is expected to be profitable (European Commission, DG ENV 2011).

According to the report from European Commission DG ENV in April 2011, Policy option B has been identified as the recommended policy option. Taking into account the benefits and costs of collection, proper treatment and recycling based on current knowledge and assumptions described policy option B yields the highest net benefits. In 2050, these nets benefits would annually amount to about €16.6 billion, compared to baseline scenario A, €16.5 billion, compared to baseline scenario B, and €1.67 billion compared to policy option A. The nets benefits of policy option A are also clearly positive and would in 2050 amount annually to about €14.9 billion, compared to baseline scenario A, and nearly €14.8 billion compared to baseline scenario B. For the recommended policy option B, the benefits identified stem to a very high share from the gain of resources through recycling (European Commission DG ENV, 2011).

4. An overview of photovoltaics industry

This chapter presents the current developments of the global photovoltaic market and the developments of the global photovoltaic production. Additionally, with the focus on the situation in Europe, the current research and innovation undertaken in this field and especially the main projects ongoing in the innovation process are described.

4.1. Photovoltaic global market developments

In 2010 the PV industry has reached a significant growth. The total capacity installed in 2010 around the whole globe is approximately 40 Gigawatt (GW), which shows a sustainable growth from 1.5 GW in 2000 to 39.5 GW in 2010 (EPIA, 2011).

Among the globe, Europe has been dominating the PV market by countries like Germany and Italy on the top. The total capacity installed in 2010 in Europe is 16.6 GW in 2010, which is more than double of the capacity of 7.2 GW in 2009. Germany, by installation of 7.4 GW in 2010, dominates the PV market in the whole globe. Following Germany, countries like Italy (2.3 GW), the Czech Republic (1.5 GW) and France (0.7 GW) are having the highest amount of installation in Europe (Menna et al., 2011).

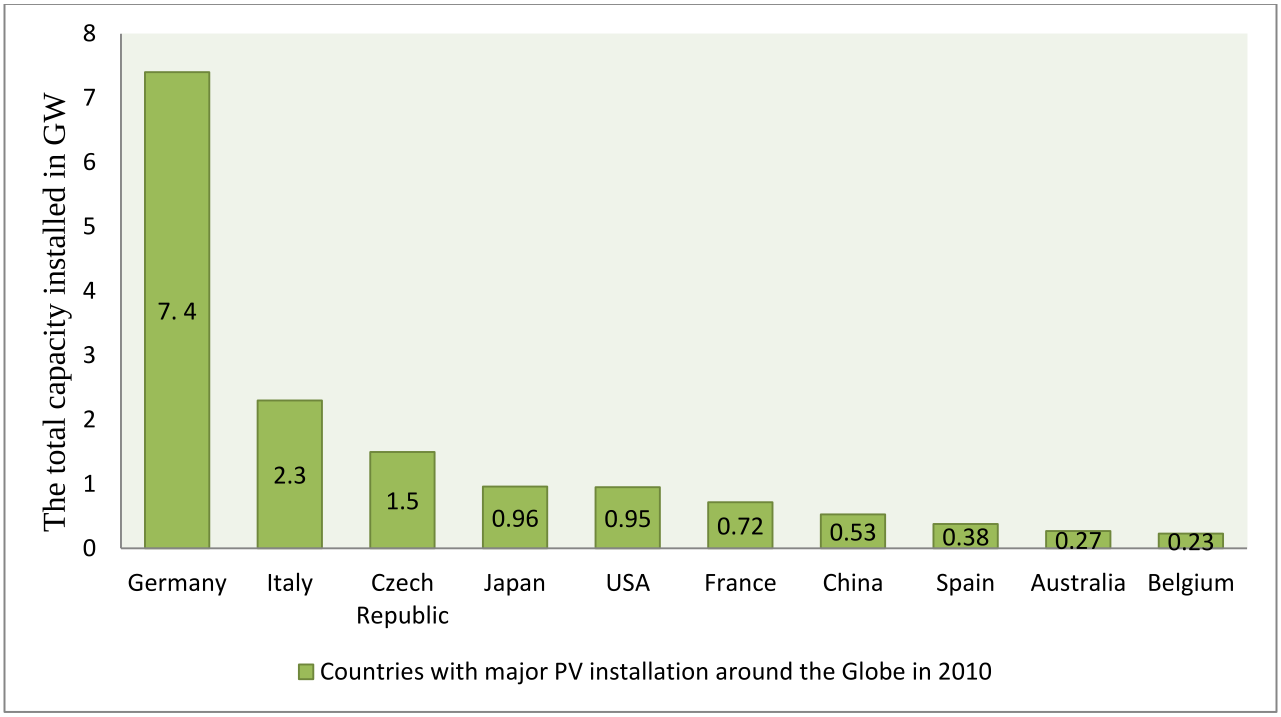

Figure 1: Countries with major PV installations around the Globe in year 2010

PV industry significant growth in 2010 is not just summarized in the total capacities that have been installed but also the amount of investment in PV industry is increasing rapidly. In 2009 the total investment in PV industry has been $160 billion; nevertheless this amount has increased to

$211 billion in 2010. Countries that have devoted the most investment in the PV industry in 2010 were Germany, Italy, China, the United States and Brazil (REN21, 2011).

In Austria, a total capacity of about 363 MW (0,363 GW) has been installed in the year 2012, which produced about 344 GWh in 2012. The energy obtained by these PV modules represents a share of about 0.61% of the total energy produced in Austria in 2012 (PV-Austria, 2012).

4.2. Photovoltaic global production developments

The large reduction of technology cost in solar PV has led to high growth of manufacturing in solar PV industry during the year 2010. This cost reduction has also aided an expansion of manufacturing capacity in regions like China, which has respectively led to price reductions of PV cells and modules.

55% of the total global PV cells production in 2010 has been produced by fifteen top solar cell manufacturers (See Fig. 2). These fifteen top solar cell manufacturers with their percentage of production are shown in Fig. 2 (REN21, 2011).

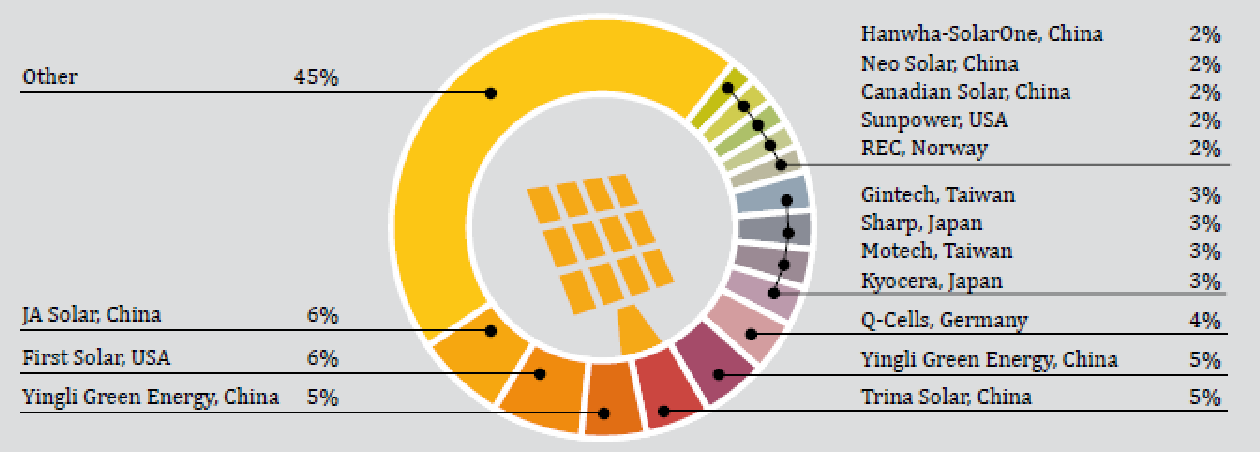

Figure 2: Market shares of top fifteen solar PV sell manufacturers in year 2010 (REN21, 2011)

Considering the diagram in Fig. 2, it is remarkable that in 2010 ten out of the top fifteen manufacturers were located in Asia. The amount of production in China and Taiwan alone accounted for 59% of global production in 2010, which means a 9% increase comparing with 50% of the whole global production in 2009. The company “JA Solar” from China with a market share of 6% is at the first place among all manufacturers.

In 2010, Europe’s and Japan’s shares have dropped respectively by 13% and 9% in comparison with the amount of production in the year 2009. In North America the amount of production is 5% of the market share, out of which half of this amount is due to thin-film products. According to Fig. 2, the US-american Company “First Solar” is ranked at the second place (REN21, 2011).

4.3. Photovoltaic research and innovation in Europe

Photovoltaic industry in Europe is highly involved with innovations in both areas; a) nanostructured applications as well as b) industrial applications. In the “Europeans’ Seventh Framework Program for Research and Technological Development” (FP7) a number of various Nano technological sciences and new production processes and technologies, particularly in nanotechnology sectors, are supporting the PV industry (European Commission, 2011). A series of joint projects between the PV industry and "Nano sciences, Nanotechnologies, Materials and New Production Technologies" (NMP) in the FP7, highlight the impact of nanotechnology in the PV industry.

The main objectives of the FP7 research projects specifically in the area of PV research and developments, during the years of running between the years 2007-2013, are listed below:

- Compared with the “Europeans’ Sixth Framework Program for Research and Technological Development” (FP6), the allocated budget to the PV research in the FP7 has increased,
- A specific European fund is allocated to the PV manufacturing process development and material development for long-term usability,
- A specific fund is allocated to the thin-film technology,
- A specific fund is allocated to the development of new methods for construction elements based on photovoltaic,

- There is a less amount of emphasis to the traditional wafer-based silicon photovoltaics,
- There is a higher emphasis to the material development for sustainability of the elements, (Menna et al., 2011).

4.4. Photovoltaic Clusters of Projects in Europe

The projects’ proposals in the area of photovoltaics in the FP7 and CIP can be categorized in the portfolio of almost forty projects, which are grouped into seven main clusters. These projects are supporting the PV industry in various perspectives, such as; Energy, "Nanosciences, Nanotechnologies, Materials and New Production Technologies" (NMP), Information and Communication Technologies (ICT), “Intelligent Energy Europe” Program (IIE). The total budget allocated for the PV projects supported by FP7 and CIP-IEE is €142.8 million. €128.6 million of this fund is from FP7 and €14.2 million is from CIP-IEE. Respectively, the costs that are estimated for these projects is €210.2 million in total, which is divided to €191.7 million for the FP7 PV projects and €18.5 million for the CIP-IEE PV projects. Considering the huge amount of the total cost of these projects, it is essentially very important that the results of these projects could be exploited and turned into innovations that have the capacity to optimize the investments on the development of PV projects.

Seven main clusters of PV projects supported by FP7 and CIP are described below:

- Cluster 1 - First generation PV cells; Wafer-based semiconductor PV cells
- Cluster 2 - Second generation PV cells; Thin film PV cells
    i) Subcluster 2.1. - Innovative or improved PV manufacturing processes
    ii) Subcluster 2.2. - Innovative PV materials
- Cluster 3 - Third generation PV cells; PV cells obtained through the application of advanced concepts and materials, such as various nanomaterials, including quantum dots, super lattices, nanoparticles, nanowires, dyes and organic/ polymer materials and also hybrid organic-inorganic concepts, biomimetic materials and combinations of these.
    i) Subcluster 3.1. – Nanodots- or nanowire-based PV
    ii) Subcluster 3.2. – Organic PV cells or DSC
    iii) Subcluster 3.3. – Innovative nanostructures

- Cluster 4 - Concentrator PV cells; PV based on optical concentration and tracking.
- Cluster 5 - Innovative installations and grid interconnections; PV for distribution systems.
- Cluster 6 - Production equipment & processes – Demonstration of high performance equipment and processes for PV.
- Cluster 7 - Industry support – Cross-cutting issues addressing infrastructure, market, quality, legal and training aspects of PV.

5. An Overview of Research in Product Life Cycle

This chapter gives an overview over the current research topics covering Product Life Cycle. The three concepts Life Cycle Assessment (LCA), Life Cycle Management (LCM) and End-of-Life Management (EoL Management) are explained and discussed briefly.

5.1. Life Cycle Assessment (LCA)

The environmental performance of products and processes is an important issue for all types of industries. The role of the manufacturing industries in providing a sustainable development for the products is to reduce the huge amount of the use of the raw materials and also reducing the impact of the products on the environment throughout the product whole life cycle.

In order to evaluate the products and processes impacts on the environment several strategies such as Environmental Management Systems (EMS), Pollution Prevention Guidelines (PPGs), ISO 14000/14001, Life Cycle Assessment (LCA), Design for Environment (DfE) and so on have been defined. LCA is a concept that assesses the environmental impacts of the product/service or a process during the different stages of the product’s life cycle, including raw material extraction, transportation, manufacture, distribution, use, remanufacturing, recycling and finally product disposal (Alting & Brabech Legarth, 1995).

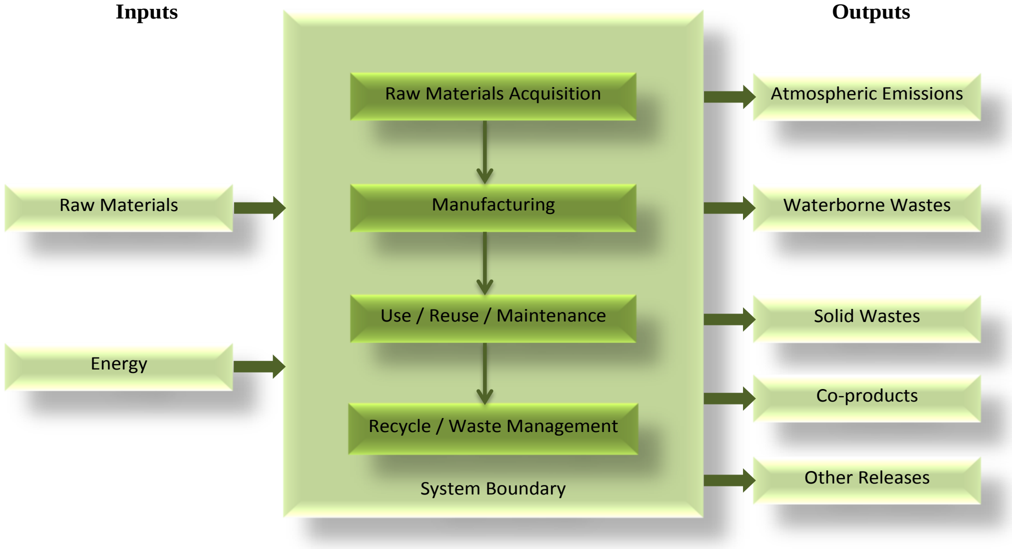

Figure 3: Life cycle stages (EPA, 2006)

The LCA is a methodical step by step procedure. The four main components of the LCA are summarized in Table 2 below:

Life Cycle Assessment components	
Goal Definition and Scoping	The product/service or the process and the context in which the environmental assessment is to be made are identified.
Inventory Analysis	The amount of water, energy and materials consumption as well as the environmental releases such as water pollution, air emissions and other solid waste disposals would be analyzed.
Impact Assessment	The potential ecological and human effects of water, energy and material defined in the "Inventory Analysis" phase would be assessed.
Interpretation	The results of the "Inventory Analysis" and "Impact Assessment" phases would be carefully evaluated and the preferred product/service or process with the least impact on environment is defined.

Table 2: Four main steps of the LCA (Alting & Brabech Legarth, 1995)

There are some complexities in running the different steps of the LCA. The plenty of information that is required in the different phases is either unavailable or unreliable. Moreover, in some phases judgments could be rather subjective. In order to deal with these complexities, a number of computer based LCA software programs has been developed by researchers; such as Ishii et al. (1994), Rosen et al. (1996) and Hooks et al. (1997) (Alting & Brabech Legarth, 1995).

As for the different types of industries, life cycle assessment is also a necessity for the PV industry. By 2030 there would be about 130,000 tons of PV panels at the end of their life cycle in Europe (REN21, 2011).

5.2. Life Cycle Management (LCM)

In order to be compatible with new innovative ever-growing technologies that lead to new generations of products and services, it is necessary to create a comprehensive analysis of the different stages of the product/process creation.

Life Cycle Management is a strategy that provides a comprehensive information on a product through its conception, design, manufacture, service and finally end of the product life.

5.3. End-of-Life Management

Through ever increasing concern for product end-of-life systems, companies in various industries are forced to establish systems to take back their products. There are plenty of similar definitions for the product end-of-life. Two examples are:

- End-of-life is the point at which the product no longer performs the intended functions due to failure or wear-out.
- End-of-life is the point in time when the product no longer satisfies the initial purchaser or first user.

In general, these different definitions lead to the same result. Therefore, this topic is not discussed in more detail here. End-of-Life management is describing the systems and processes that take place at the end of the life cycle of a product, i.e. after a product is used as initially proposed. Due to economic and ecologic reasons, these old products are no longer seen as a useless amount of waste that has to be disposed as cheap as possible. Instead, old products represent interesting resources that can be used for various new products. Additionally, the awareness of ecological questions is rising. According to various regulations, hazardous materials have to be collected and treated in a special way in order to minimize the negative effects on the environment.

In EoL management, basically four different strategies can be chosen. These are (the 4-R): Reduce, Reuse, Recycle and Recover. These strategies are presented together with the least favorable strategy, landfilling, in Fig. 4. In this EoL pyramid, the various strategies are order in a way, that a strategy is more preferred due to economic and ecologic reasons the closer it is situated to the top. That implies that it is a goal of EoL management to use the most preferred strategy out of the pool of available strategies in a specific situation.

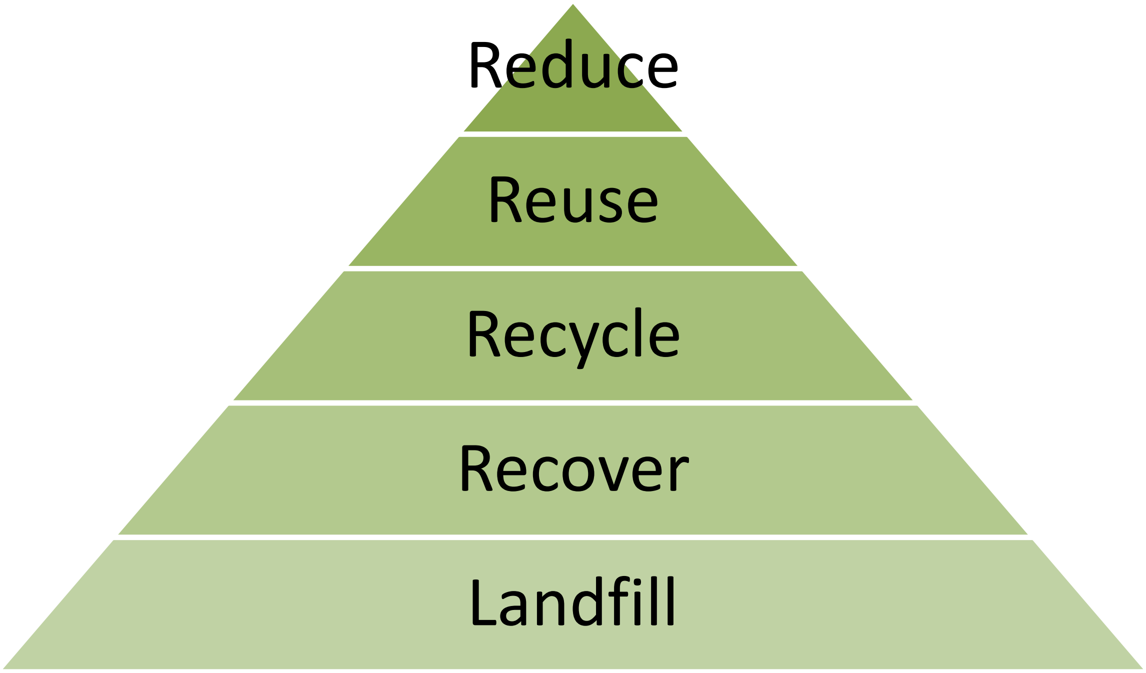

Figure 4: End-of-Life pyramid (European Union, 2008)

Reduce: The first and most favorable strategy is the reducing of the amount of material that is used for a product during the production process. Therefore, this strategy is located at the beginning of the product life-cycle. This includes that this strategy has to be taken during the design phase of the product and not after the life-cycle of the product, which makes it outstanding within the EoL strategies.

Reuse: The second best option is reusing the whole product, modules or single parts of it. In this case, the produced value can be won for a second life-cycle, without (significant) modifications of the device that is reused. If not the whole product, but just some modules or parts can be reused, the device has to be disassembled in a way, that at least the parts, which are envisaged for reusing, are not destroyed during the process. Additionally, it might be necessary to repair or clean the parts that should be reused.

Recycle: The third best alternative is the recycling of the material that can be extracted from a device. These materials can be used as starting material for new products. When the new products are of a better quality than the origin device, the process is called “upcycling”, while “downcycling” describes the process of producing new products of a lower quality than the origin device. For an efficient recycling strategy it is important, that the output material of the disassembly process is as pure as necessary for the following production steps.

Recover: The forth “R” used in this model stands for the energy recovery of the waste devices. During this process, non-hazardous materials are combusted, which has two goals. The first one is that the generated heat can be used to produce e.g. electric power, which can be used or sold. The second advantage is that the material is reduced and the amount of waste that has to be combusted in landfills is therefore much smaller than it would have been without prior combustion.

Landfill: The least preferred strategy is landfilling, where devices are deposited at landfills after their life-cycle. This alternative is costly due to several reasons. A high amount of ground is necessary, that could be used for something else, and a lot of resources are needed for maintaining a landfill. On the other side, there are no positive returns coming from a landfill.

Therefore, it has to be a goal for the present and future developments to reduce the waste amounts that are landing on a landfill down to zero.

6. Materials used for PV cells

Photovoltaic is consisted of the word “photo”, from Greek roots, which means “light” and the word “voltaic” from “volt” which is the unit used to measure electric potential at a given point.

Photovoltaics converse the sunlight into the electricity with the use of layers of semiconductors. When the light shines on a PV cell, an electric field across the layers is created. This electric field causes the electricity to flow. The higher the intensity of the light rays is, the higher is the flow of electricity.

The most common semiconductor material used in the construction of photovoltaics is silicon. Silicon can be extracted from quartz and there is no limitation to its availability. The materials that are used in photovoltaic cells are listed below.

6.1. Glass

Glass is used in most of the available PV technologies to provide a package for the thin layers of semiconductor and protect them. Furthermore, glass is practical as a cover that can be mounted on the roofs or could be installed on the floor as well. Approximately 80% to 90% of a PV module’s weight is glass, depending on the type.

6.2. Metals

PV modules are also including ferrous and non-ferrous metals. Aluminum and copper are especially currently used in the production of PV modules. Approximately 10% of a PV module’s weight is from these metals. Due to the high impact and scarcity of some metals, they are analysed below in detail.

6.2.1. Aluminum (Al)

Aluminum is a metal that can be found all over the world. It is not scarce, because it is the most abundant metal worldwide. It usually extracted from ore bauxite. Main bauxite producers are countries like Australia, China, Brazil, India and Guinea. The deposits of bauxite are therefore distributed all over the world. According to this, the risks of shortages due to political or ecological changes in single countries or regions are low.

One disadvantage of the use of aluminum is the high energy consumption during the production process due to the natural occurrence of aluminum and its physical characteristics. Therefore, the production is just economic in areas where the producing companies can purchase cheap energy, e.g. in Brazil or Iceland.

One advantage of aluminum is the usability for material recycling. During the aluminum recycling process, just around 5% of the energy needed for primary aluminum is needed. This offers huge economic and ecological advantages.

Other advantages of aluminum are the comparable low weight, the resistance against corrosion, the good processability and the good electrical and thermal conductivity. Aluminum is therefore used in various fields, e.g. in the frames of cars and ships, in packaging industries as foil or cans, in buildings for frames of windows and doors, in cooking utensils or as conductive material inside of cables. Aluminum is nowadays one of the most important materials for the humanity.

In PV cells, aluminum is usually used for frames and for the cells themselves, where the back surface contact is made of an aluminum paste, which is produced from fine aluminum powder.

6.2.2. Indium (In)

Indium is a scarce metal that is produced primary in East-Asian countries. The main producer of indium is China, which is responsible for about 60% of the worldwide output of this metal and owns the highest amounts of known deposits. Other main production mines are located in Japan, South Korea and Canada. This unequal distribution of indium is the source of a high risk in means of security of supply. Unstable political situations in the main production areas are the reason for that. Additionally, the governments of the most important production countries are aware of their power in terms of reducing or cutting important supply lines of several scarce materials, like indium.

One disadvantage of Indium is the above mentioned scarcity, which leads to high prices. This is one reason for the high recycling rate of indium. The amount of secondary raw material is already higher than the amount of primary produced indium. Especially in Japan, the recycling of this scarce metal is an important source for producers. As the indium deposits are estimated to last for just 20 years, the topic of recycling gets more and more important for this resource.

Indium can be used for many different applications in a wide range of technical fields. For example, indium is used in LED screens as a basis for compound semiconductors, in control rods of nuclear reactors or as a component in lead-free solders.

In PV cells, indium is especially used in a-Si cells and CIS/CIGS cells. In CIS/CIGS cells, Indium is used as a part of the semiconductor material, together with copper, selenium and gallium. In a-Si cells, indium is used e.g. within transparent conducting films, which help to reduce the internal resistance of the PV cells.

6.2.3. Germanium (Ge)

Germanium is a scarce metal that can be found in many areas, but usually in small concentrations. The main production countries are China, with around 70% of the worldwide production, Russian and the United States, which follow with a respectable distance. Similar to indium, the germanium deposits are distributed unequally and therefore the risk of a shortage of the production and consequently, availability of germanium due to political reasons or environmental disasters is high.

In the past, germanium used to be the most important semiconductor material, until it got more and more replaced by silicon. The reason therefore is mainly the high price and low availability of germanium compared to silicon. Another property of germanium is that it is transparent in the infrared light spectrum.

Nowadays, the applications of germanium are mainly based in fiber optics and infrared optics due to the high index of refraction and the low optical dispersion. For example, germanium is used for optical fibers, camera lenses or night vision systems. Other important fields of use are in the electronic sector, where germanium is used as a semiconductor material, sometimes in an alloy together with silicon.

6.2.4. Silver (Ag)

Silver is produced in many areas all over the world, especially in the southern hemisphere. The most important producing countries are Mexico, Peru and China. Large mines can also be found in Bolivia, Australia and Chile. As a result of this distribution, silver as a resource is not scarce and the risk of a shortage is very low.

One characteristic of silver is that it provides the highest electrical conductivity and the highest thermal conductivity of all metals. Additionally, it has a high optical reflectivity. These reasons are responsible for the usage of metal in different industries.

One disadvantage of silver is the wide use in other areas. Silver is one of the oldest known metals and very popular as a basis material for jewelry and other decorative things, like mirrors. Additionally, it is used for coins, as an investment good or as a material for dental fillings. These applications are responsible for higher prices compared to a situation where silver is just used for industrial applications.

In the producing industry, silver is used for many different applications. Important applications are situated in photography in photographic films, in electronics as a conductive material, where a high conductivity is more important than a low price or in optics, where it is used in the production of mirrors.

In PV cells, silver is used in monocrystalline and polycrystalline PV cells as a paste on the cells that is responsible for the collection and transport of the produced electrical current. Additionally, this silver paste has positive effects on the reflectivity of the PV cell.

6.3. Plastics

The plastics needed in the construction of PV cells are used for example for connections, wires, frames or laminates.

An important plastic used in PV cells is EVA (Ethylene Vinyl Acetate). This material is used e.g. for foils in various applications and for sports equipment like shoes or boots. In PV cells, it is used as an encapsulation material especially for silicon cells.

6.4. Semiconductors

As mentioned before the most commonly used semiconductor material for the construction of photovoltaic cells is silicon. Silicon can be used in several different types (monocrystalline, multicrystalline and amorphous). More detail on this topic, is provided in part 7.1.

It is worth to mention that solar cells need highly purified silicon. Silicon sources are also limited; one solution that the PV industry has already used is to use the reject material from the semiconductor industry that was available at low cost. But this only works if both sectors grow at the same rate. It means that this solution is not very efficient. Another solution is to reduce the amount of silicon in solar modules. For example, PV industry has already used the approach of reduction of kerf loss by wire sawing and use of thinner wafers.

Other materials used in the construction of PV cells are polycrystalline thin films (copper indium selenide and cadmium telluride). More details on this topic are provided in part 7.2.

7. Different types of PV cells

There are two main technologies involved in producing PV cells; crystalline silicon technology, which is known as the “first generation” technology and thin-film technology as a “second generation” technology.

7.1. Crystalline Silicon PV cells

Crystalline silicon cells represent about 90% of the market. Crystalline Silicon cells can be categorized into three main categories as follows:

- Monocrystalline silicon (mono c-Si)
- Multicrystalline/Polycrystalline silicon (multi c-Si)
- Ribbon- technology (ribbon sheet c-Si)

What makes distinguishes between these three types is mainly related to the characteristics of the silicon, which has been used and also the process of producing.

7.1.1. Monocrystalline silicon (mono c-Si)

Monocrystalline silicon PV cells are quite easily recognizable by an external even coloring and uniform look, indicating high-purity silicon. An example of such a module is presented in Fig. 5.

The process of producing a “monocrystalline silicon” wafer is consisting of several steps; the first step is the extraction of quartz (SiO_2) from the earth. It is worth to mention that quartz is a common substance on earth, which is easy to mine and the energy that is needed to extract quartz is rather small and can be omitted from the calculations.

Figure 5: Monocrystalline silicon PV cells (Energy Informative, 2014)

After silicon extraction from quartz, silicon is refined to higher level of purity and then melted in a furnace. During this step the Metallurgical grade silicon (MG-Si) is converted into trichlorosilane ($SiHCl_3$) through a method called the "Siemens method", which reacts with H_2 in a large electric furnace producing electronic grade (EG-Si) polycrystalline silicon. According to the literature, no losses are estimated for the Siemens method (Jester, 2002).

In the next step, a monocrystalline seed is planted from the molten electronic grade polycrystalline silicon. A large cylindrical single crystal, known as “ingot”, with a diameter of 10-15 cm and a length of 1 m or more is drawn from the melt. This cylindrical crystal weights several tens of kilograms. The material losses estimated at this level add up to 28%. Then the crystal is sliced into circular wafers with the thickness of less than half a millimeter (Fig. 6). Further 10% losses are assumed in wafer forming (Green, 2000).

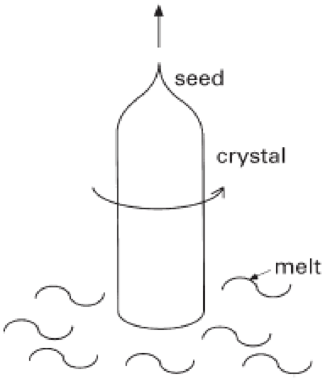

Figure 6: Growth of a cylindrical silicon crystal (Green, 2000)

The molecular structure of monocrystalline silicon is uniform. This uniformity helps that the electrons from the sun ray are transformed efficiently through the cell. However, in order to make an effective photovoltaic cell, silicon needs to be "doped" with other elements.

7.1.2. Multicrystalline/Polycrystalline silicon (multi c-Si)

A good way to distinguish monocrystalline and multicrystalline/polycrystalline solar modules is that polycrystalline solar cells look perfectly rectangular with no rounded edges.

Figure 7: Multicrystalline/Polycrystalline silicon PV cells (Energy Informative, 2014)

In the process of “multicrystalline silicon” wafer production, the molten silicon is let to get solid slowly in its container. This starting crystal or known as “ingot” is weighting several hundreds of kilograms (Fig. 8 (a)). At the next step, this massive ingot is sawn into smaller pieces (Fig. 8(b)) and is finally sliced into wafers (Green, 2000).

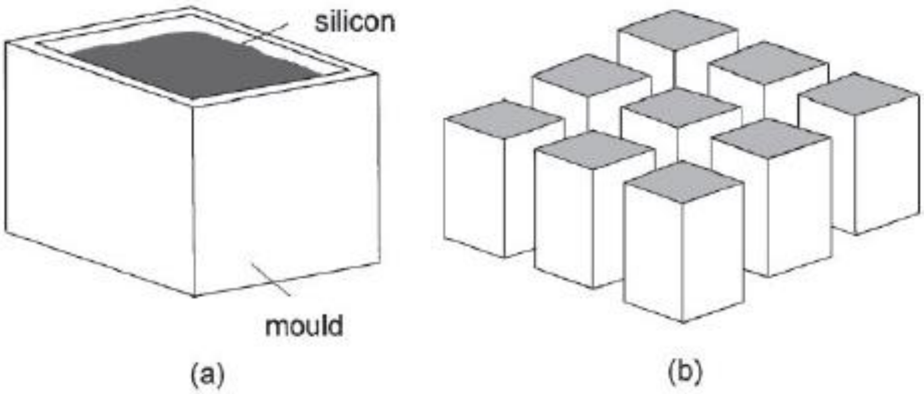

Figure 8: (a) Ingot, (b) Sawn Ingot
(Green, 2000)

Multicrystalline silicon is normally considered less efficient than monocrystalline silicon. However, multicrystalline silicon devices are less expensive to produce. This casting process is the most common means of producing multicrystalline silicon on a commercial scale.

It is worth to mention that cast silicon, which is also called polycrystal silicon, is only used for solar cells and not for any other semiconductor devices.

7.1.3. Ribbon- technology (ribbon sheet c-Si)

The third group of silicon based wafers is the Ribbon- technology based wafers. The advantage of Ribbon- technology is the reduction of costs by eliminating the costly sawing process as well as minimizing the amount of silicon used due to the reduced layer thickness. The resulting ribbons can be directly used as wafers.

New techniques of growing silicon in the shape of ribbons from the molten mass of silicon have been tremendously developed. Among those there are mainly five methods which are under the development and are described in the following section that is based on Goetzberger et al (Goetzberger et al., 2000).

Edge defined film fed growth process (EFG)

During this process, a special shaper is used to pull a tubular crystal, usually with an octagonal shape, out from a melt, using capillary channels. The resulting tubes are separated to produce the final wafers.

String ribbon process

This method was developed in the 1970s. Temperature resistant strings or wires are used to pull out ribbons from a silicon melt. Subsequently, the resulting ribbon is cut into the desired length. Even this process is very simple, it has several disadvantages, e.g. the thickness of the produced ribbon is having a high variance. Therefore, the resulting wafers cannot always be directly used for the assembly of a PV cell.

Ribbon growth on substrate (RGS)

A cooled substrate is pulled along the bottom of a crucible of liquid silicon. As a result, grains grow vertically to the pulling direction of the cooled substrate. This method allows a high rate of production.

Silicon sheets from powder (SSP)

The primary material for this method is silicon powder or granular silicon. This material is placed onto temporary plates and heated. The powder or granular melts and forms silicon wafers.

Dendritic web

This method aims to produce monocrystalline ribbons instead of polycrystalline ribbons. A dendrite seed is brought into contact with the surface of a silicon melt, causing the seed to grow.

7.2. Thin film PV cells

Photovoltaic (PV) technology is undergoing a transition to a new generation of efficient, low-cost products based on thin film of photoactive materials. In this method, thin layers of semi-conductor material are deposited on a substrate.

One typical type of thin film PV cells is c-Si TFC (thin film cells). These cells are using a thin monocrystalline silicon layer (typically 5 to 50 mm) as the active layer. Due to this reduced thinness these approaches contain an underlying carrier, which serves as a mechanical support. Materials used for this carrier layer include low quality silicon like SSP ribbons and foreign materials, e.g. glass, ceramics or graphite.

This substrate could be a large sheet of glass (Fig. 9). Afterwards, the film is structured into cells. Thin film modules are manufactured in a single step.

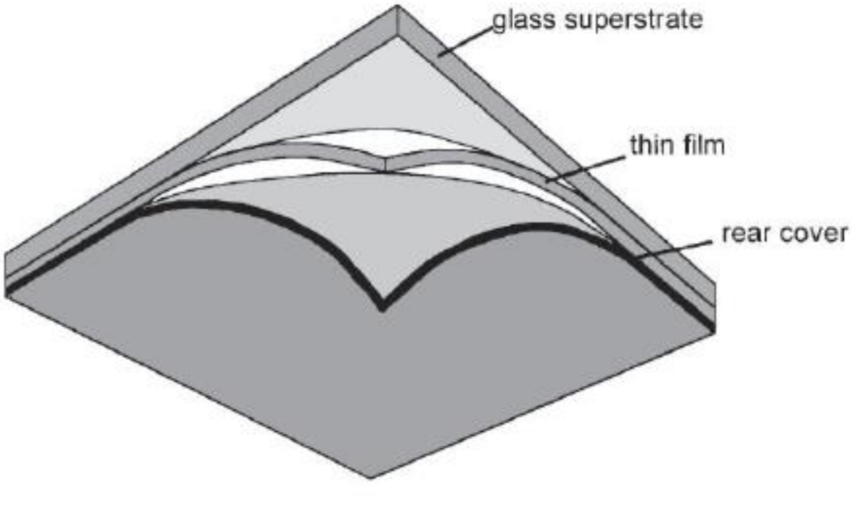

Figure 9: Thin film technology (Green, 2000)

In this approach the amount of semiconductor material is 100-1000 times less than the thickness of the semiconductor used in a silicon wafer (Green, 2000). In comparison with Crystalline Technology, the efficiency of the thin film cells is lower (5% - 13%). But it is worth to mention that this lower efficiency can be compensated through the lower production costs.

One of the key advantages of thin film cells is a reduced amount of material in their construction, which leads to reduced manufacturing costs. Furthermore, the unit of production is larger than the silicon wafers, which also lead to less manufacturing costs. The semiconductor in thin film technology can be chosen from a variety of semiconductors. Although silicon is a rather cheap semiconductor to use, but as mentioned, in the thin film technology, the amount of material needed is reduced, so that there is no limitation in choosing a different semiconductor than silicon (Green, 2000).

Currently, there exist several different categories of thin film solar cells. These modules, which are described below, can be distinguished according to their type of semiconductors.

7.2.1. Amorphous silicon (a-Si)

In amorphous silicon cells, the atoms have the same structure as in the crystalline silicon cells, however the electronic quality of amorphous is much lower and it is mentioned that amorphous silicon was not originally considered as a suitable material for solar cells. It was found that producing amorphous silicon with decomposing silane gas (SiH4), at a low temperature, would improve the electronic quality of the amorphous silicon. These hydrogenated amorphous silicon cells have been used in consumer products such as solar calculators and digital watches (Green, 2000).

As mentioned above amorphous silicon cells have a poorer electronic quality than the crystalline silicon cells, so that the design structure of these cells is different. In order to optimize the efficiency, amorphous silicon can be alloyed by germanium. Germanium is a material, which is chemically similar to silicon, but it is much scarcer. The best commercial amorphous silicon cells, which are currently in the market, contain three cells stacked on top of one another, with more germanium in the bottom two. Each cell is 100-200 nm thick, which ensures a reasonable stability. However, according to the data from best commercial amorphous silicon modules, the efficiency of these cells is just 6-7%, which is quite low (Green, 2000).

To summarize, amorphous silicon cells have a complicated design process, which makes it difficult to be competitive in the long term. In the other side of view, the low temperature needed to produce these cells let them to be deposited on substrates such as plastics, which make them attractive for consumer products (Green, 2000).

7.2.2. Cadmium telluride (CdTe)

Many semiconductors made from compounds have a higher potentiality in absorbing the light than the elemental semiconductors like silicon and germanium. Cadmium Telluride (CdTe) is one of these compound semiconductors, which its structure provides a technically ideal material suitable for making solar cells (Green, 2000).

The main concern with Cadmium Telluride (CdTe) cells is the toxicity of the materials involved, even though very small amounts are used in the modules. This creates the demand to carefully designed processes to dispose or recycle these cells at the end of their life cycle. Furthermore, the amount of tellurium resources is limited. According to Zweibel and Green, by the use of all the existing tellurium resources, just 10% of the world’s electricity use could be generated (Green, 2000).

To summarize, modules with this technology are now available in small quantities with efficiencies demonstrated up to 12% in pilot production. It is mentioned that one of the limitations of this method is the manufacturability, which means it is difficult to distinguish between a bad and a good material at the production level. So that, the control factors at the production level are hard to define (Green, 2000).

7.2.3. CIS/CIGS

Copper indium gallium selenide (CIGS) cells are consisted of various kinds of elements, which make their production complicated. The difficulty is either in complex process technology in co-evaporation of the elements or in controlling processes such as the salinisation of metal films.

Figure 10: CIGS PV cells (Energy Informative, 2014)

Furthermore, special equipment for the deposition has to be developed. In the beginning, CIGS solar cells were based on pure $CuInSe2$ single crystals with an n-type window layer deposited by the evaporation of CdS. One of the disadvantages of this method is that the control of the deposition process in this method is difficult, therefore in large production processes, a two stage process was used. At this so-called two stage process the deposition of metal films is followed by a selinisation step in $H2Se$.

In order to increase the efficiency of CIGS cells, elements like gallium or sulphur were added to the absorber layer. Therefore, a five-component alloy $Cu(In,Ga)(S,Se)$ was formed. As a result, together with the development of compound elements and also with the use of new technologies, co-evaporation of the elements was taken as flexible method for large-production of the CIGS films.

These kinds of CGIS cells, which have been produced through the co-evaporation of the elements, have automated control systems, which reduce the complexity of the production. CIGS cells have the highest quality potential of all thin-film materials.

In order to produce low-cost CIGS cells, the amount of materials used should be reduced. Regarding the availability of indium (In) and considering the fact that it is an expensive material, it is advisable to reduce the amount of indium in the absorber layer of the CIGS cells (Dimmler, Powalla and Schock, 2002).

The total production of CIGS modules in 2011 has been around 1 GW/annum (Dimmler, Powalla and Schock, 2002).

7.3. Other types of PV cells

In addition to the before mentioned main types of PV cells, there are some other types of PV cells available in the market. These cells are shortly presented in this chapter, with the aim of providing an overview over the solutions that are available in the market or in research. It is important to mention that, due to the marginal market shares and lack of enough information on these types of cells, they are not explained in detail in the evaluation in chapter 12 and 13.

7.3.1. Nano a-Si PV cells

As described before, one category of thin film cells are a-Si PV cells, which among other types of thin film cells are a less efficient type. In order to increase the efficiency of this type of cells, new designs with nano-scale materials are under the research. These nano-crystalline (nc) materials include small grains of crystalline materials. The aim of adding a scale of about 100 nm for a-Si device is either to improve existing systems, or develop new systems like dye-sensitized cells. These cells are also called micro crystalline cells.

Typically, nc-cells are made of silicon, but other materials, e.g. CdTe, can be used too. Although these cells are more efficient, they have potential risks to humans and ecosystems. Furthermore, the life-cycle of nano-technology-based PV cells is not completely understood because of the lack of data since they are not yet in commercial production.

7.3.2. Nano-crystalline dye PV cells

This method is rather a different method which involves the use of ruthenium-based organic dyes. In this approach, dye molecules are coated into a porous network to titanium dioxide particles which is immersed into an electrolyte.

The construction of a dye sensitized PV cell consists of two glass plates on the outside. Starting from the light entry, a coating layer, which works as a transparent anode, is placed on the outside layer. The next layer is a TiO_2-layer, with a porous structure in order to provide a large surface area. This TiO_2-layer is sensitized by absorption of a dye. The next layer contains an electrolyte solution, followed by a Pt-layer that serves as a catalyst. Subsequently, another TCO-layer and a final glass layer are situated. This configuration is shown in Fig. 11.

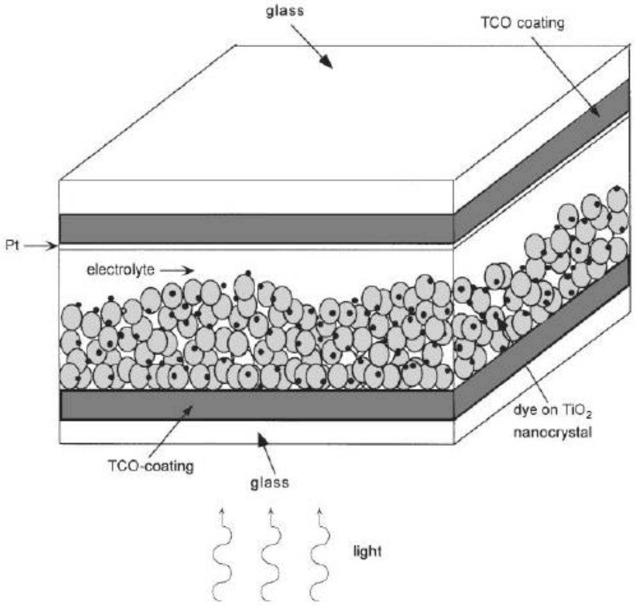

Figure 11: Nano-crystalline dye sensitized solar cell (Green, 2000)

Rather than all photons of energy, the dye only absorbs a band of photon energies. In normal cells, the absorption is different and the cells absorb all the photons and not just a band of them. This property of Nano-crystalline dye cells make them suitable for transparent windows that convert the infrared wave, while letting the visible light passing through.

7.3.3. Concentrated PV cells

Concentrated solar cells are designed in a way that they can focus the sunlight to the cells' surface through a lens or other types of concentrators. The main idea is to use as less semiconductor material as possible, while absorbing as much sunlight as possible. Concentrated PV modules have efficiency ranges of 20 to 30% (EPIA, 2012).

Rondine© is one example for a concentrated module, which has been presented for the first time during the conference and exhibition of the 22nd " European Photovoltaic Solar Energy Conference" in Milan and has reached its first commercial configuration in September 2008 in Valencia.

Rondine© is consisted of mono-crystalline silicon solar cells with a concentration factor of 25x zoom and with an optical efficiency of 80%. The module is made of many cell- concentrator elementary units, where the concentrators are based on reflective structures with a geometry system.

One driver behind the development of the Rondine© module are the production costs. These should be reduced, compared to modules currently available on the market. Rondine© modules are designed with concentrating optics that feature wide acceptance angles, which allow pointing precision characteristics that are comparable to traditional PV modules that are equipped with two-axis trackers.

The modules can be placed on standard movers for flat plate PV modules, which are cost-effective and also avoid reliability problems related to the accuracy in sun tracking. Furthermore, almost all the components of the module (Aluminum, glass and plastics) can be made from recycled materials, and can be recycled as well.

A study on the calculation of the energy pay-back time of a Rondine© system with non- recycled materials for an installation of 5 kWp in south of Italy shows that the energy pay-back time of such a system is less than about two years. According to this calculation more than 50% of the energy consumed is for the tracker fabrication. Another advantage of Rondine© cells is the high resistance against soiling.

Testing a Rondine© cell, wherein each module has four bypass diodes (usually, two bypass diodes are used in comparable silicon panels), an average efficiency of 17.5% was measured. The increased number of diodes is to ensure a higher energy production if parts of the modules are shaded because of dirt or any other reason. The electrical components are soldered during automated or semi-automated processes (Antonini et al, 2009).

7.3.4. Flexible PV cells

Flexible PV cells are modules, where the active material is deposited on a flexible substance, e.g. a thin plastic or paper layer. Due to this construction, the cell as a whole is flexible and can be deformed to a certain degree. This flexibility offers the possibility of special applications, especially for the integration in buildings (e.g. roof tiles) and end consumer applications (e.g. foldable cells for outdoor use). Another possible application are clothes with integrated PV cells, e.g. to power a portable music player or a mobile phone.

Researchers of the Massachusetts Institute of Technology (MIT) have developed a process to print organic photovoltaic circuits on a paper substrate. These PV cells are flexible and can be folded without a loss of conductivity (Barr et al, 2011).

The PV cells comprise five layers, which can be printed on untreated paper, e.g. ordinary copy paper, tissue paper or even newsprint, inside a vacuum chamber. Additionally, it was shown that this process works with PET plastic layers as a base material instead of paper. This printing process uses vapor deposition temperatures of less than 120 °C, which is rather cold compared to other photovoltaic manufacturing processes. That circumstance makes it possible to use ordinary paper as a base layer. The production costs of this printing process are about the same as for common inkjet printing. Additionally, the materials used are cheaper than for common PV cells.

One challenge is the efficiency of these cells, which lies around 1%. Nonetheless, compared to the production cost, it might be possible to implement these cells to power small things, like mobile phones. The researchers are positive to improve the efficiency due to fine-tuning the materials.

8. PV value chain

This chapter aims to provide basic knowledge of the production processes required to produce a PV cell. The value chain of a silicon PV cell, a thin-film PV cell and a concentrated PV cell is shown and described in detail. In order to understand a product as a PV cell and to be able to think about EoL regarding such a product, it is important to understand the manufacturing steps.

In Fig. 12, an exemplary PV value chain of a crystalline silicon PV cell, a thin-film PV cell and a concentrated PV cell is presented. The different value chains of these types of cells are marked. On the very left side of the diagram, the input resources for the silicon and the thin film cells are shown. In case of a silicon cell, the primary resource is sand, while for thin films the primary resources are the various materials, e.g. GaAs (Gallium arsenide), InSb (Indium antimonide) and others. The primary inputs for concentrated modules are shown in the center of the diagram. These resources are mainly a concentrator, a cooling and a tracking.

The first step in the manufacturing of a crystalline PV cell is the production of raw silicon out of sand. On one hand, this raw silicon is the input for high purity silicon, which is used for mono-crystalline and poly-crystalline PV cells and on the other hand, for silane, which is used for amorphous silicon that is an input for the production of amorphous thin-film cells.

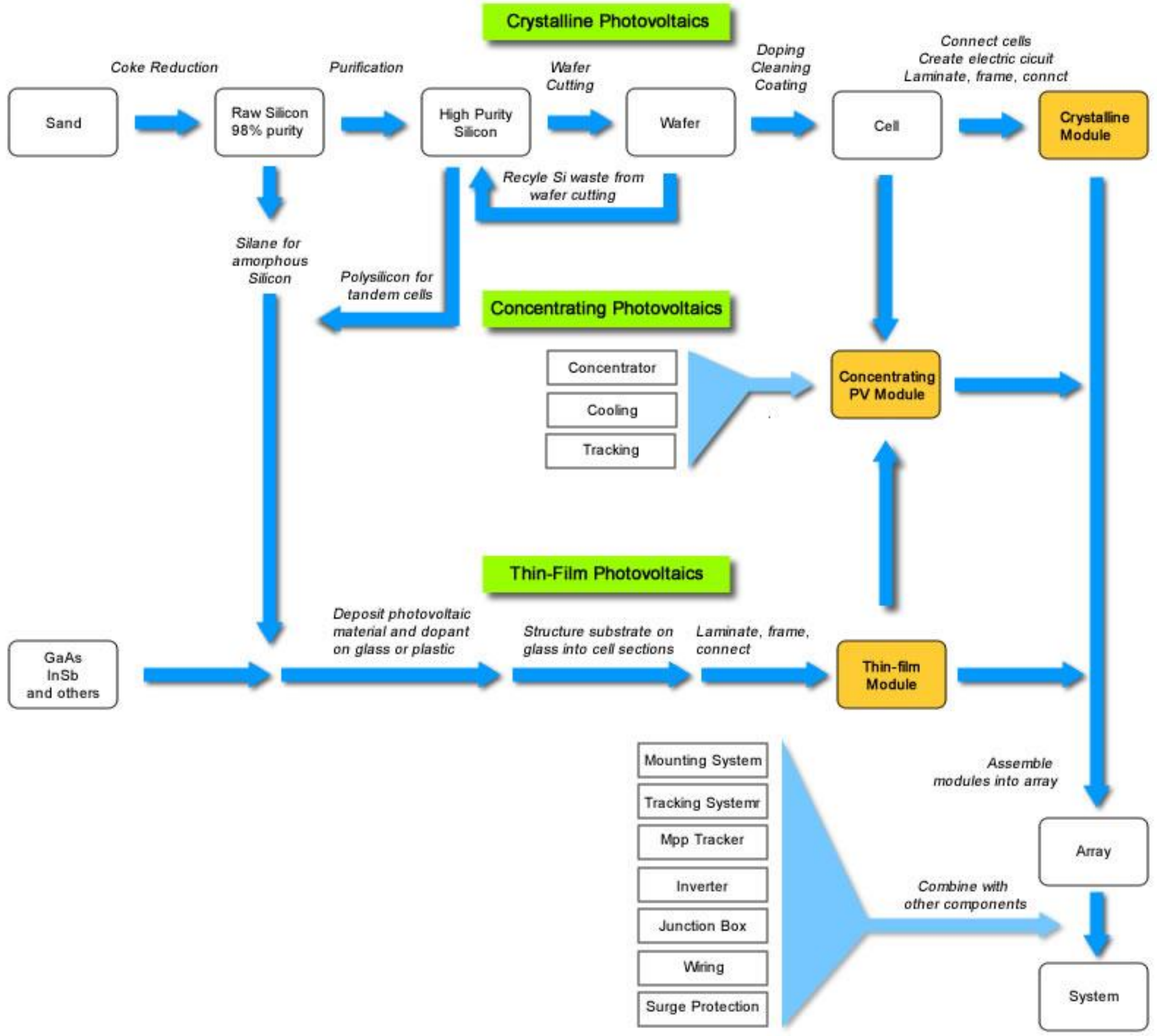

Figure 12: PV value chain (Green Rhino Energy, 2014)

9. Current End-of-Life Management of Photovoltaic Modules

The PV industry has an environmental friendly nature; as the production of PV systems does not create any noise pollution and no toxic-gas emissions nor green-house emissions. Furthermore, the PV systems would prevent the environmental costs of burning fossil fuels.

At the time of decommissioning of PV cells, they may be reused, recycled or disposed. The PV cells may contain small amounts of materials like Cd, Pb and Se, which make their disposal in landfills questionable and additionally, landfill is the least optimal treatment of EoL in any kind of industry. That means, based on the five EoL strategies, which have been described in the EoL pyramid in Fig. 4, chapter 5.3, the author found out that there are just two (reused and recycled) of the strategies applicable for photovoltaic. Further discussion of these EoL strategies is provided below.

Beside aluminum, glass, and semiconductor materials, photovoltaic modules contain other materials for reuse. In Table 3 below a list of valuable materials that photovoltaic modules contain is presented:

Material	Material
Silicon Cadmium	Silicon wafers
Selenium	Indium
Tetrachloride	Tin
Sulfur Hexafluoride	Silver
Aluminum	Nickel
Plastics	Zinc
Glass	Copper
CIGS filter cake	CdTe filter cake

Table 3: Materials within PV cells

9.1. Reuse

Reuse relates to the further use of a worn out or damaged PV module or parts of it. The reasonability of such a reuse is strongly bounded to the (expected) life time of a module or a part of a module. If for example a house with a roof including PV cells should be destroyed for any reason, it might be reasonable to reuse the PV cells as a whole, depending on their age. As usual, a cost-benefit calculation is necessary to answer this question.

In case that the reuse of the whole PV cell is not reasonable anymore, because it is too old already, it might be reasonable to reuse parts of the modules, which have a longer (expected) life time than the module as a whole.

9.2. Recycle

As the recycling of PV cells would add benefits to the environment, recycling methods in this industry are getting high attention from the public and the market.

Europe recycling strategies- PV CYCLE

Throughout Europe, PV CYCLE (a not-for-profit association) is managing a voluntary collection and recycling program for end-of-life PV cells. PV CYCLE is launched by the European PV industry in 2007. Over 90 percent of the PV organizations within the EU are members of PV CYCLE. PV CYCLE has around 105 collection locations in Europe, including Spain, Italy, Germany, France, the UK, and Switzerland.

US recycling strategies- SVTC

It is worth to mention that, in contrast to Europe, US does not have any formal plan regarding PV cells recycling programs. The Silicon Valley Toxics Coalition (SVTC) is an environmental organization from California, which believes that the US needs a national mandate to address the issues related to photovoltaic recycling. This organization is aiming to provide some standardized recycling processes in the whole US, in order to reduce the environmental damages associated with solar cells.

The SVTC has created a scorecard to rank solar manufacturers. This ranking is based on various aspects, such as chemical materials in use, energy take back, life cycle analysis and recycling. The companies that scored well include Trina Solar, SunPower, First Solar and Solar World. Among these companies, the recycling processes from First Solar and Solar World are discussed in chapter 11.4.

It is worth to mention that the first research question, which is; “What are the existing EoL strategies for photovoltaic around the world?” has been covered at this part.

Current developments within the recycling industry

Even the recycling industry is traditionally dominated by SMEs (Small and Medium Enterprises); there exists a current shifting of the industry structure from SMEs to large, multinational companies. One interesting example of a current research path is described in (B. Kopacek, 2013). A mobile recycling plant has been developed, to increase the operating grade within companies. The advantage of such a mobile recycling plant compared to a few stationary recycling plants is that it can be moved from one company to the other in order to recycle the amounts of waste that are available at the moment. This reduces the investment costs for each single company and increases the operating grade, as recycling companies face a highly fluctuating stream of incoming raw materials, i.e. waste materials.

The described mobile recycling plant is highly automated to decrease the personnel costs. It aims to extract materials like yttrium, indium, lithium, cobalt, zinc, copper, gold, silver, nickel, lead or tin in a high purity of above 95%. The recycling process itself is based on hydrometallurgical processes, i.e. the gain of materials from waste by processes based on the material-specific differences in the solubility and the wettability.

A workable EoL program for PV cells will require careful attention to the experiences of comparable industries (chapter 10), recycling processes of currently existing PV cells (chapter 11) and finally materials economics (chapter 12).

10. Experiences of Comparable Industries

As mentioned before, there is a long-distance between the installation and recycling of PV cells (the life-cycle of PV cells is approximately 30 years). Furthermore, recycling of PV cells is complicated, due to the fact that the concentration of the valuable material in PV cells is low and also modules are dispersed in various geographical places, which makes their collection difficult.

In order to define a feasible recycling program for PV modules, a careful attention to the experiences of comparable industries is necessary. Therefore, in this section of this dissertation a discussion on “Recycling of electronic and telecommunication devices” and “Recycling of NiCd batteries” is provided.

In electronics and telecommunications industries a wide range of used products at the end of their life cycle is collected, consolidated and finally shipped to a service center. That is basically the first phase of recycling. At the service center the used products are categorized and they are either, refurbished for resale or disassembled for the spare parts or dismantled for reclaiming the materials. It is necessary to mention that the recycling of electronics and telecommunications products, due to their precious metals content is valuable. The question that rises here is that, how this recycling method would match for PV industry? Is the amount of valuable metals in PV modules interesting enough to get reclaimed?

In battery industry, recycling is done collectively. That means there are plenty of institutions and associations that have agreed to return the NiCd batteries to designated consolidation facilities.

Furthermore, in the United States city municipals have also provided some collection centers to gather the NiCd batteries at the end of their life. These collected batteries are sent to consolidation centers which, in turn, send them to the International Metals Reclamation Company, Inc. (INMETCO). In INMETCO, they recover nickel and iron from NiCd batteries and use them in the Fe-Ni-Cr alloy, which is used in the stainless steel industry; also cadmium is recovered from NiCd batteries at a high level of purity, which is returned to the NiCd industry.

10.1. PV cells Recycling Options

Considering the recycling methods mentioned above for electronic industry and NiCd batteries, the author explores the recycling options for PV cells in this section.

First point to consider is the widely dispersion of PV cells, which make their collection a challenge. Second point to consider is the low concentration of valuable materials in PV cells.

10.1.1. Discussion on PV cells collection

According to Reaven et al. (1996), there are three paradigms to collect solar panels:

- Utilities
- Electronics
- Batteries

These paradigms are explained in the following:

Utilities

In the utility paradigm, for example electric utilities would be the large end-users and primarily, they would be responsible to get the PV cells at the end-of-life to the recyclers. Furthermore, in the utility paradigm, the recycling model would be integrated with other utility programs, such as off-grid service tariffs, conservation and demand-side management.

Costs of recycling, as well as costs of decommissioning of gas, oil and nuclear power plants would be imbedded in the rates charged by the utility.

Electronics

In the Electronics paradigm, manufacturers would be individually responsible to get the PV cells at the end-of-life to the recyclers. They are responsible for all the tasks dealing with collecting, consolidating and transporting the modules to the recyclers. Furthermore, in the electronics paradigm, the recycling model is involved with reverse-logistics companies. In this paradigm, the recycling is done by integrated dismantlers, (which are not exclusive to solar panels) and also by materials recyclers. The costs of recycling services are paid by the manufacturer or the generator.

Batteries

In the battery paradigm, manufacturers are collectively responsible for collecting and transporting modules to recyclers. It is likely that recycling companies that are operated or controlled by manufacturers fulfill this task. The collection, consolidation and transport are done by reverse retail channels and consolidation entities. Reverse retail channels could send goods directly to smelters, while consolidation entities collect goods from municipal recycling centers and players providing large amounts of goods.

10.2. End-of-Life management of automation devices

One interesting approach to describe the EoL-options available within the sector of automation devices was presented by Haas (Haas 2012). In this paper, various important devices used in automation industries have been analyzed and ranked according to their value for EoL management. This ranking can be used to determine the value of specific products within the EoL stage.

Some structural, basic concepts from this paper have been used within the present dissertation, e.g. the structure of the evaluation and the concept of EoL-Value. It is worth to mention that, although this paper describes an interesting general model and valid solutions for many fields within automation devices, this paper does not provide substantial input to the special field of PV cells.

11. Recycling Processes of currently existing PV cells

In this section the author provides a discussion on existing recycling processes that are provided by the “PV Cycle Association”.

11.1. Recycling of silicon based PV cells

The recycling process that the PV CYCLE Association is currently using, is consisted of three main steps:

- Preparation; removing of the junction box and the frame
- Shredding
- Processing in the flat glass recycling line

The outputs from these steps are silicon, glass, ferrous and non-ferrous metals and plastics with a recycling average quota between 80 to 90%. The glass, which is recycled from the PV modules, is mixed with standard glass cullet and part of it is reintroduced into the glass fiber and the rest could be used in glass packaging products. The rest of the recycled materials, such as recycled metals, silicon and plastics can be used for the production of new raw materials (PV CYCLE, 2014).

11.2. Recycling of non-silicon based PV cells

For CI(G)S and CdTe PV modules, three companies within Europe, which are all located in Germany, are deploying their own specific recycling methods. Among these, two of them are focusing on the usage of a chemical bath to separate the components of the PV modules. The main steps of this method are showed below:

Saperatechnology:

- Shredding
- Solubilising
- Detaching
- Sorting of the materials

Tenside bath:

- Chemical bath
- Sorting of the materials
- Further processing in dedicated glass and semiconductor recycling facilities

11.3. Recycling of crystalline silicon cells

A study (de Wild-Scholten & Alsema, 2005) that has been done during September 2004 until November 2005 has provided the “life cycle inventory” list for crystalline silicon modules. The aim of this study has been to explore the material and energy consumption data during the production of crystalline silicon modules. In order to create a reliable list of life cycle inventory data, the study has got the data (material- and energy consumption data) from real measured cases from production lines.

The production process for crystalline silicon modules has been aggregated into four main process steps:

I. Silicon feedstock
II. Crystallization and wafering
III. Cell processing
IV. Module assembly

The study has calculated the amount of energy consumption in each single step.

11.4. Recycling of thin-film cells

Thin film modules contain hazardous substances that may harm the environment if they are not recycled properly. For example, heavy metals that can be found in these modules can be toxic as well as carcinogenic or teratogenic. The energy payback time for such modules is relatively low. On the other hand, the prices for the rare materials such as indium and tellurium will probably continue to increase. Further data about the World production and TMR for elements used for thin film PV cells is provided in Table I in the Appendices.

Currently there exist few recycling strategies for thin film PV modules based on (wet) mechanical processing, and combined thermal and mechanical methods for end-of-life modules.

The investigation of the environmental impacts of these recycling strategies has shown that the (wet) mechanical separation process has advantages in comparison to the thermal treatment or disposal on landfills.

An advanced method for recycling of CdTe thin film modules is the method introduced by “First Solar”. First Solar is the largest thin-film manufacturer, which has developed a process for recycling CdTe thin film modules. This recycling process has been scaled to full production at manufacturing facilities in the US and also in Frankfurt, Germany. The company claims it recycles 90 percent of the material used to build its modules. This recycling method includes the following process steps (First Solar, 2014):

- Size reduction: In this step, at first with the use of a shredder the glass is broken into large pieces and next with the use of a hammer mill these broken pieces of glass are crushed into 4–5mm pieces.
- Semiconductor film removal: In this phase with the use of sulphuric acid and hydrogen peroxide in a slowly rotating leach drum, the semiconductor film is removed.
- Solid–liquid separation: the content of the leach drum is emptied into a classifier, in which the liquids are getting separated from the glass.
- Glass laminate separation: with the use of a vibrating screen the glass is separated from larger pieces of Ethylene Vinyl Acetate (EVA).
- Glass rinsing: In this step, in order to remove any impurities or residual semiconductor material, which may physically remain on the glass, the glass is rinsed.
- Precipitation of the separated metal components: with the means of sodium hydroxide and concentration in a thickening tank, the separated metal components are deposited.

As a conclusion, the First Solar recycling process can recover 90% of the glass for use in new products and also 95% of the semiconductor materials for use in new solar modules.

Furthermore, referring to part 3.5 of this dissertation, different research projects such as SENSE (Sustainability Evaluation of Solar Energy systems) and RESOLVED funded by the European Union have been performed to study alternative recycling strategies of PV modules. More information on these projects is provided below:

11.4.1. Project SENSE and Project RESOLVED

Project SENSE

In the project SENSE the recycling of various thin film modules based on CdTe, copper indium germanium diselenide (CIGS) and amorphous silicon (a-Si) has been investigated. In this project a method, which is a combination of mechanical and chemical treatment steps for photovoltaic, has been developed. As a result, depending on the different module types, the project SENSE has developed three main recycling strategies as below:

- Thermal (pyrolysis) and chemical treatment for CdTe and CIGS modules.
- Waterjet cutting and chemical treatment for CIGS modules.
- Grinding and pneumatic separation of the polymer frame for a-Si modules.

Project RESOLVED

In the project RESOLVED the recycling of CdTe and CIS thin film modules has been investigated. The RESOLVED project aims to introduce sustainable recycling strategies for photovoltaic thin film modules. The methods developed by the RESOLVED project based on (wet) mechanical processes use less chemicals than are used for conventional recycling and also show a reduced amount of waste as a result, depending on module types (modules with firstly intact carrier glass (RS1) and secondly broken modules (RS2)). The project RESOLVED has developed two main recycling strategies with the main steps as below:

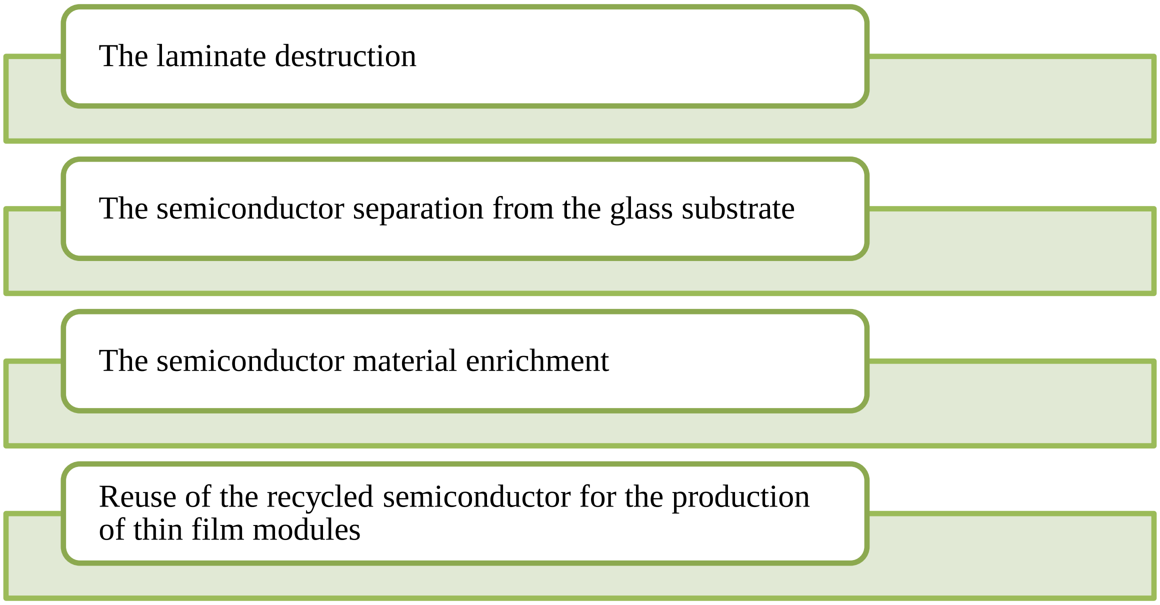

Figure 13: Recycling steps in RESOLVED project

The two recycling strategies developed in the project are summarized in Fig. 14. Due to the fact that semiconductors contain hazardous materials; strategies are defined in closed loops in two directions. On the one hand, complete modules are considered (Left-hand loop RS-1), and on the other hand, broken modules and production residues are examined (Right-hand loop RS-1).

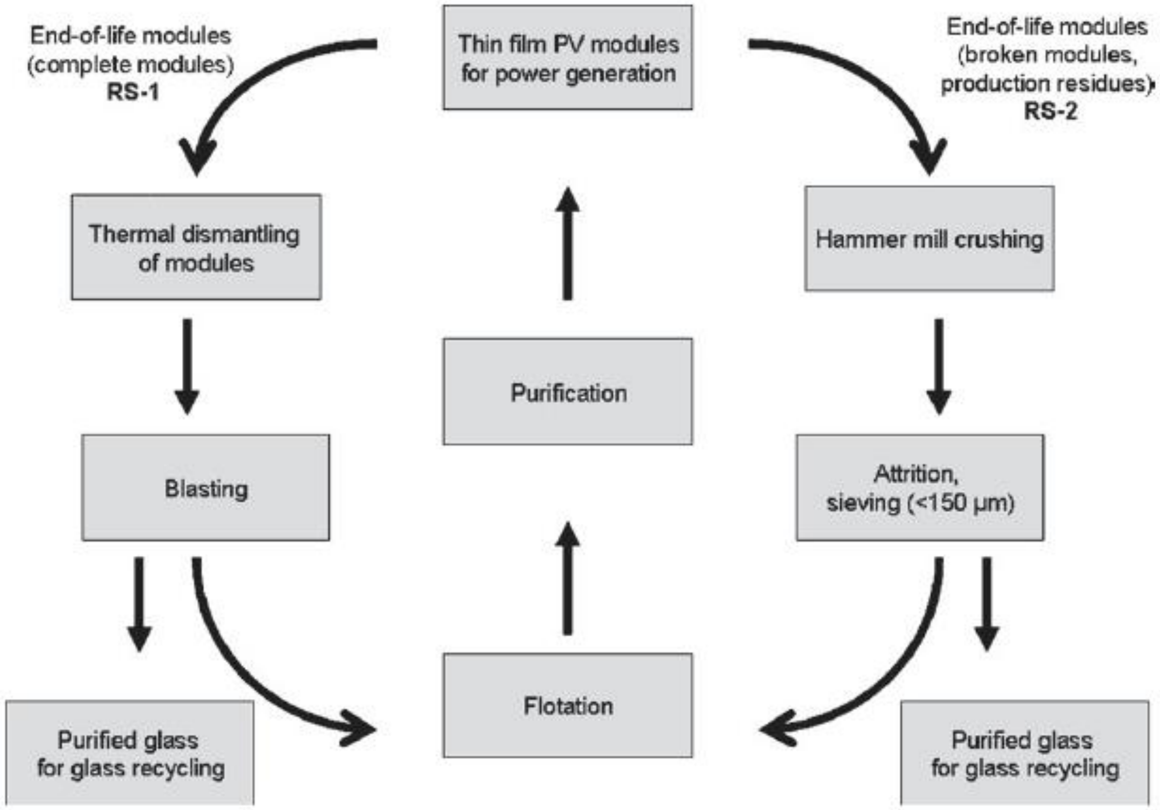

Figure 14: Recycling strategies in RESOLVED project ((Berger, Simon, Weimann & Alsema, 2010).

<u>The left-hand loop RS-1</u>

- Model pre-treatment: Thermal dismantling

As it can be seen in Fig. 14, the left-hand loop RS-1 describes the recycling method for complete PV modules with intact carrier glass. These modules can be dismantled thermally. Investigations were carried out with pieces of modules in a lab-scale furnace. The PV module (Pieces of 30cm×30cm and 10cm×10 cm) got heated at temperatures of approximately 500 °C (Berger, Simon, Weimann & Alsema, 2010).

Through this heat the module composite gets divided into two single glass plates; a carrier glass, which contains the semiconductor that is removed in the next phase (blasting phase) and a protection glass, which contains no semiconductor and can directly go to the glass recycling process without any further treatment.

- Separation of the semiconductor layer: Vacuum blasting

In this method instead of air pressure a vacuum is created to make a blasting. The vacuum, which is created on a limited part of a surface, gets hit with the blast medium at high level of energy. Next, the blast medium together with the thin-film material gets evacuated through the suction created by an industrial vacuum cleaner. In this study different materials were tested as blasting abrasive; such as iron powder, aluminum oxide and glass beads.

- Pre-concentration

At this step, in order to separate the semiconductor material from residues the “flotation” method was used. The flotation is used in the ore processing of gold or platinum tellurides and sulphide minerals.

The following formulas and parameters were defined:
R_M = the mass yield
m_K = mass of concentrate
m_A = mass of input material

$$R_M\ (\%) = \frac{m_K}{m_A} \times 100 \qquad (1)$$

R_C = the valuables yield
C_K = valuable concentration in the flotate
$\mathrm{C_A}$ = valuable concentration in the feed of flotation

$$R_C = R_M \times \frac{c_K}{c_A} \tag{2}$$

$$i = \frac{c_K}{c_A} \tag{3}$$

i= the enrichment factors for the elements tellurium and indium.

- Purification and reuse

CdTe PV cells can be produced through a lot of different deposition techniques such as; vapor transport deposition, close space sublimation, sputter deposition, physical and chemical vapor deposition, electro deposition (using a solution of Cd_2+ and $HTeO_3+$), screen print deposition and spray deposition (using CdC_2 and elemental Te) (McCandless & Sites, 2003).

It is worth to mention that all of these processes (except from electro deposition and spray deposition), which have been mentioned here, are based on CdTe as raw material for which high purity (>99.999%) is required for the production of PV cells.

<u>The right- hand loop RS-2</u>

- Module pre-treatment: Particle size reduction

As you can see in Fig. 14, right- hand loop RS-2 refers to the recycling strategy for broken PV modules. Through this method, at first the broken modules are crushed or milled in order to reduce their sizes. In the next phase, the semiconductor layers are removed through a wet mechanical attrition process with the use of frictional forces (e.g. Eirich intensive batch mixer).

Crushing/milling of the modules leads to particles with a size of ≤20mm, as well as, partial destruction of the laminate compound. In the crushed material as an output of this level following compounds are recognized; glass particles of different size with the semiconductor layer on its surface and large pieces of the EVA foil.

- Separation of the semiconductor layer: Attrition

Attrition is a process that uses shear and friction forces to separate the semiconductor layer from the carrier glass, without any chemical addition. During the attrition, at first crushed material from the previous step is treated in intensive batch mixers with different vessel sizes (25 L, 50 L, and 150 L) and stirring units. Second, parameters such as the rotating speed of the stirring unit and the vessel, the water content and also the treatment duration are tested and respectively optimized.

According to Berger, Simon, Weimann & Alsema (Berger, Simon, Weimann & Alsema, 2010), attrition process has worked for CIS and CdTe layers successfully. The rinsed and sieved material <150 µm has been used for the pre-concentration by flotation.

- Pre-concentration & Purification and reuse

With reference to Fig. 14; these phases for the RS-2 have been done totally the same as for the RS-1. Therefore, the author would like the reader to refer back to the description of this part in RS-1.

More details on these recycling methods provided by project RESOLVED are as below:

The investigated CdTe PV modules in the project RESOLVED are composed of four layers:

- A Transparent Conducting Oxide (TCO) layer, which is consisted of SnO_2 which acts as a front contact on glass substrate.
- A cadmium sulphide (CdS) film, which serves as a n-type layer.
- A CdTe film which serves as an absorber layer.
- A back contact, which is consisted of a copper layer

12. Materials' Economics

In order to create the optimal EoL strategy for PV modules, the materials' economics have to be also taken into account. The principle of defining various categories and evaluating the devices according to these categories, such that a single, comparable value can be calculated for each device, is based on the work of Haas (Haas, 2012), where such a model has been presented for the evaluation of EoL values of automation devices. In this section, PV modules are evaluated from different point of views. The evaluation categories are:

1. Valuable material
2. Hazardous material
3. Weight
4. Market share
5. Energy efficiency
6. Life duration
7. Production costs
8. Light absorption range
9. Energy payback time
10. Greenhouse gas emissions

The categories are explained in detail in the following.

Valuable material

PV cells are categorized according to the materials that are used as the semiconductor material. It is worth to mention that these semiconductor materials do not represent a high share of the whole cell construction; in contrast, the surrounding materials like glass are determining the material composition of PV cells to a high degree. For EoL purposes, the materials available within devices are very important, as this information determines the worth of a device crucially.

Value	<€0.1 Price/kg	€0.1- €0.2 Price/kg	€0.2- €0.3 Price/kg	€0.3- €0.4 Price/kg	€0.4- €0.5 Price/kg	>€0.5 Price/kg
Points	0	1	2	3	4	5

Table 4: Point allocation criterion 1- valuable material

<u>Hazardous material</u>

Another category that is based on the material composition is the possible presence of hazardous materials. These materials, e.g. lead or cadmium, have to be disposed separately from the other, non-hazardous materials, due to legal restrictions in order to protect the environment from unwanted effects. This results in the necessity to provide special process steps when hazardous materials are involved in the photovoltaic cells and subsequently in higher costs for the EoL management. The specific amount of hazardous materials is subordinate, because the important question is if a part is containing hazardous material and needs special treatment during the EoL phase or if it is free of hazardous material and can be treated like other cells.

Value	Yes	Yes/No	No
Points	0	3	5

Table 5: Point allocation criterion 2- hazardous material

<u>Weight</u>

Another important factor that influences the EoL value of PV cells is the weight of a PV cell. In this context, to create comparable values, the weight is defined as a relative number relating on the surface, i.e. weight per square meter. This gives a measure for the value of material included in the PV cells. Another advantage of this definition is that, together with the efficiency, a value for kg/kw can be calculated.

Value	<12 kg	12-14 kg	14-16 kg	16-18 kg	18-20 kg	>20kg
Points	0	1	2	3	4	5

Table 6: Point allocation criterion 3- weight

Market share

One important factor for the design of an efficient EoL management is the amount of cells that can be processed through the EoL stage. The more cells of a specific type are delivered as an input, the more the machinery can be specialized on this type of cells. This allows a higher efficiency during the EoL stage and therefore lower costs and higher benefits during the whole life-cycle. Additionally, higher amounts of input cells lead to other scale effects. One advantage is that higher amounts of one type imply higher outputs, e.g. modules or recycled materials and therefore a better market situation.

Value	<3%	3-7%	7-11%	11-15%	15-19%	>19%
Points	0	1	2	3	4	5

Table 7: Point allocation criterion 4- market share

Energy efficiency

The energy efficiency is an important factor that influences the energy payback time. It is calculated as the ratio between the amounts of energy won by a solar module divided by the theoretical amount of energy supplied by the sun.

Value	<10%	10-11%	11-12%	12-13%	13-14%	>14%
Points	0	1	2	3	4	5

Table 8: Point allocation criterion 5- energy efficiency

Life duration

This category is regarding the expected life-time of a PV cell. As the cells that are produced today are not in the market for a reasonable time, these numbers can just be estimations. Additionally, the life duration does not necessarily have implications on the efficiency that the specific cells provide after the life time has been reached. Nonetheless, these values are crucial for the overall efficiency of PV cells. In this paper, the life duration of a PV cell is defined as the time span that a PV cell is working with at least 80% of the efficiency it had after the installation.

Value	<20yr	21-23yr	24-26yr	27-29yr	30-32yr	>32yr
Points	0	1	2	3	4	5

Table 9: Point allocation criterion 6- life duration

Production costs

In order to minimize costs, it is necessary to take a look on the occurring costs during the production of PV cells and also during the EoL phase. This category gives a rough estimation of the money needed for the production of a PV cell and is therefore measured in €.

Value	>€200	€170-€200	€140-€170	€110-€140	€80-€110	<€80
Points	0	1	2	3	4	5

Table 10: Point allocation criterion 7- production costs

Light absorption

This criterion gives a hint about the potential of PV cells to absorb the sunlight. Considering the fact that different kinds of PV cells contain different kind of materials with various potential to absorb the light. A large light absorption spectrum is an indicator for a high potential, showing that a large amount of light rays can be used for converting light to electrical energy. The spectrum of sunlight provides light with reasonable energy approximately between 300 and 1200 nm, wherein the energy density is unstable. This criterion is considering the amount of the available energy from the sunlight.

Value	<10%	10%-20%	20%-30%	30%-40%	40%-50%	≥50%
Points	0	1	2	3	4	5

Table 11: Point allocation criterion 8- light absorption

Energy payback time

This criterion shows the relationship between the energy needed for the production of PV cells and the energy gained during the use. The relationship is expressed in years needed to produce the energy needed to manufacture the specific type of PV cells. As this value is highly dependent on the location of a specific module and on the construction details, the numbers provided in this section are average values, assuming an average location (approximately 1700 kWh/m^2/year) and an average modern module.

Value	>2.4 years	2-2.4 years	1.6-2 years	1.2-1.6 years	0.8-1.2 years	<0.8 years
Points	0	1	2	3	4	5

Table 12: Point allocation criterion 9- energy payback time

Greenhouse gas emissions

This category considers the impacts of the production of PV cells on the environment. Therefore, the emissions of greenhouse gases (GHG), e.g. water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) or ozone ($O_3(\mu\text{-}O)$), are evaluated. Obviously, lower amounts of greenhouse emissions are better for the environment. The greenhouse gas emission values that are presented in this part are based on a study presented by Peng, Lu, Yang (Peng, Lu, Yang, 2012). Greenhouse gas emissions are usually described in their global warming potential (GWP) factor, which is relative to the amount of CO_2. Additionally, in order to enable a comparison between different types of PV cells, the emissions are related to the output of the PV cells. Accordingly, the greenhouse gas emissions are measured in CO_2-equivalents per kWh output.

Value	>40 g CO_2-eq/kWh	35-40 g CO_2-eq/kWh	30-35 g CO_2-eq/kWh	25-30 g CO_2-eq/kWh	20-25 g CO_2-eq/kWh	<25 g CO_2-eq/kWh
Points	0	1	2	3	4	5

Table 13: Point allocation criterion 10– greenhouse gas emissions

In this dissertation, as the author has not found any specific data showing the importance of one criterion relative to the others, it has been decided to consider that all of the ten evaluation criteria have the same effect on the whole evaluation. The weight factors sum up to one or 100%. That means that each criterion has an equal weight factor of 0.1.

$$q_1 = q_2 \dots = q_{10} = \frac{1}{10} = 0.1 \qquad (4)$$

In order to make the study more specific, the author has also provided a case study in chapter 14, which considers that all of the ten criteria are not at the same level of importance and therefore, they have different weight factors.

As a result, the EoLV_i value is calculated through the following formula:

$$EoLV_i = q_i * w_i \qquad (5)$$

i=1, 2, 3…10
q_i = Weight of the criterion i
w_i = Evaluation points of the criterion i

The final EoLV of each type of PV cell is finally normalized to increase the readability. It is calculated by the formula

$$EoLV = \frac{\sum_{i=1}^{10} EoLV_i}{P_{max}} \qquad (6)$$

P_{max} denotes the maximal amount of points, which can be reached. In this case, P_{max} adds up to 5, as can be seen easily.

12.1. Recycling of silicon based PV cells

As it is obvious from the name of this category of PV cells, the main material in this group is silicon. Silicon is used in two forms, which are called; type-p and type-n. Type-p silicon can be obtained through doping of crystalline silicon structure with three bonds elements such as, Al, B, Ga, In. Type-n silicon uses elements with five bonds, such as As, P, Sb.

For the evaluation of the resource efficiency, the three main groups of crystalline silicon cells, namely monocrystalline, multicrystalline/polycrystalline and ribbon-based PV cells are examined separately. This is necessary due to significant variations between production processes and energy payback times of these groups.

12.1.1. Monocrystalline silicon based PV cells

Valuable material

On average, monocrystalline based PV cells contain the following amounts of materials (European Commission DG ENV, 2011):

Material	Percentage	Price
Glass	74-80%	€ 0,05/kg
Aluminum	10%	€ 1,6/kg
Other components (including silver, EVA, Tedlar backing film, silicon, adhesive)	16%	€ 0,90/kg
	Total Price per kg:	€ 0,341/kg

Table 14: Monocrystalline valuable material

Approximately 80% of a module's weight is glass. The frame is primarily made of aluminum. About 10% of a PV module's total weight comes from metals. Especially aluminum and copper are currently used in the production of PV modules.

Summing up the value of the materials contained in this type of PV cells on average, one kilogram has a worth of around €0,341. Therefore, the point for the evaluation in this category is 3.

Hazardous material

This kind of PV cells contains lead, which is a hazardous material that has to be separated before subsequent EoL steps can be performed. This lead is usually used for the solder. Therefore, the point for the evaluation in this category is 0.

Average weight

An average weight of a monocrystalline silicon module can be estimated according to Table 15:

Company	Module output(W)	Weight
BP solar	175 W	15.4 kg
Sunpower	230 W	15 kg
Trina	210 W	15.6 kg

Table 15: Monocrystalline average weight

According to the data above the average weight for a monocrystalline silicon module is 15.33 kg. Therefore, the point for the evaluation in this category is 2.

Market share

Refering to Fig. I in appendices II, the market share of monocrystalline PV cells in 2011 is around 40% worldwide. These types of PV cells are therefore the most important type of cells. As a result, the point for the evaluation in this category is 5.

Energy efficiency

The energy efficiency for monocrystalline modules can be estimated from the data that is provided in Table 16 below:

Company	Energy efficiency
BP Solar	13.51 %
Sunpower	17.28 %
Trina	16.4%

Table 16: Monocrystalline energy efficiency

According to the data above the average energy efficiency for monocrystalline modules is 15.73%. Therefore, the point for the evaluation in this category is 5.

Life duration

Warranty: BP solar, 175 Watt
Amount of time that the cell’s power rating is guaranteed not to decrease;

- Free from defects in materials and workmanship for 5 years
- 93 percent power output over 12 years
- 85 percent power output over 25 years

Warranty: Sunpower, 230 Watt

- 25 year linear power warranty
- 25 year limited product warranty.
-

Warranty: Trina, 210 Watt
Amount of time that the cell’s power rating is guaranteed not to decrease;

- 10 year workmanship warranty
- 25 year linear performance warranty

Based on the above listed warranty guaranties, the average decrease of power output can be estimated to be around 0, 6% per year. Therefore, the life duration, as defined in this paper, can be calculated to be on average around 33 years. Therefore, the point for the evaluation in this category is 5.

Production costs

These kinds of PV cells have rather high production costs. As it is mentioned before, such cells are sawn from large single crystals of silicon and these large single crystals are grown through a high-precision process, which consumes a significant amount of energy.

The production costs of one square meter of monocrystalline PV cells ranges between €150 and €300. For the evaluation, an average value of €200 is used. Therefore, the point for the evaluation in this category is 1.

Light absorption

If you try to plot a diagram of solar cell's output energy against the wavelength of incoming light, the plot looks like below (Fig. 15). The available light absorption spectrum of monocrystalline PV cells ranges from about 300- 350 nanometers (nm) to 1100 nm. That means the graph will show a response curve that begins at about 300-350 nm. It arrives at a maximum at about 900 nm, then it makes a series of peaks and dips, and falls abruptly at 1100 nm (Seattle PI 2014).

It is worth to mention that the maximum peak of this kind of PV cells is far away from the peak of sunlight at about 600 nm. As a result, this kind of PV cells covers about 50% of the available sunlight spectrum. Therefore, the point for the evaluation in this category is 5.

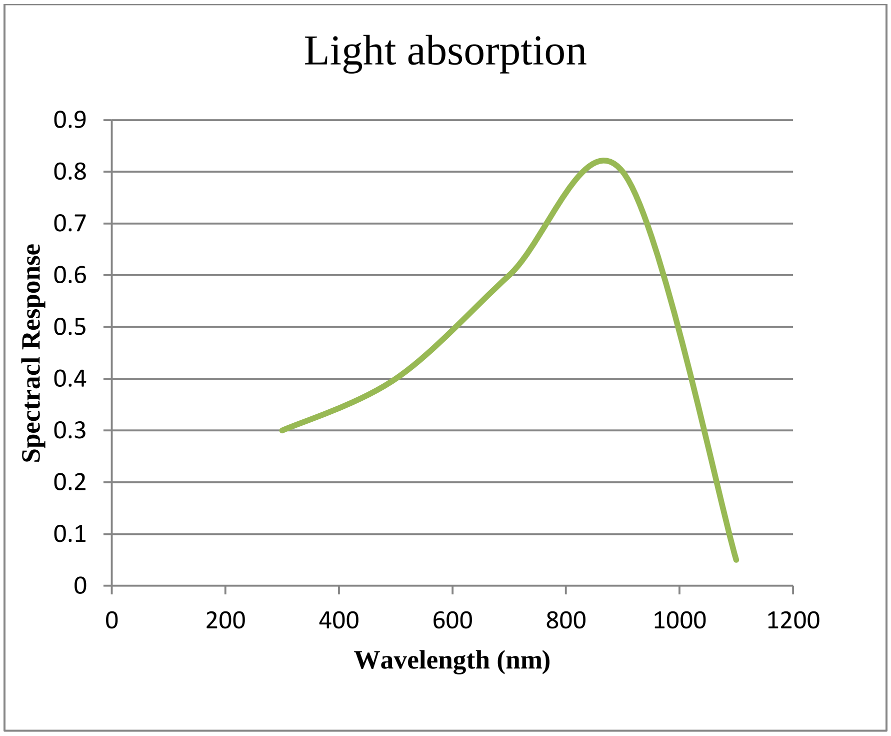

Figure 15: Light absorption in monocrystalline PV cells

Energy payback time

Considering Fig. II provided in appendices III, the energy payback time of monocrystalline PV cells sums up to around 2 years. Most of the energy needed for the production is used for the wafer and for the silicon feedstock (de Wild-Scholten, 2013). Therefore, the point for the evaluation in this category is 1.

Greenhouse gas emissions

The greenhouse gas emissions of monocrystalline PV cells are on average approximately 37 g CO_2-eq/kWh. On the one hand, monocrystalline PV cells provide high conversion rates, but on the other hand, the production costs for this type of PV cells are also high. The costs substitute the effects of the high efficiency compared to other types of PV cells. Therefore, the point for the evaluation in this category is 1.

Summary

The ten evaluation criteria (valuable material, hazardous material, average weight, market share, energy efficiency, life duration, light absorption, energy payback time and greenhouse gas emissions) are weighted by a factor, called weight factor (q_i). Weighted points show the importance of each criterion in EoL evaluation.

It is worth to mention that the weight factor is considered to be 0.1, because it has been considered that all of the ten criteria are at the same level of importance, therefore, the weight factor is one divided by ten and therefore 0.1. In Table 17, a summary of the evaluation criteria for monocrystalline PV cells is provided.

No.	Evaluation Criteria	Average Value	Points w_i	Weight Factor q_i	Weighted Points $EoLV_i$
1	Valuable material	€ 0,341	3	0.1	0.3
2	Hazardous material	Yes	0	0.1	0.0
3	Average weight	15,33 kg	2	0.1	0.2
4	Market share	40%	5	0.1	0.5
5	Energy efficiency	15,73 %	5	0.1	0.5
6	Life duration	33 years	5	0.1	0.5
7	Production costs	€ 200	1	0.1	0.1
8	Light absorption	50%	5	0.1	0.5
9	Energy payback time	2 years	1	0.1	0.1
10	Greenhouse gas emissions	37 g CO_2-eq/kWh	1	0.1	0.1
Total points:			28		2.8
Normalized Total Points (EoLV):					0.56

Table 17: Monocrystalline silicon summary

12.1.2. Multicrystalline/ polycrystalline silicon based PV cells

Valuable material

Material	Percentage	Price per kg
Glass	74-80%	€ 0.05
Aluminum	10%	€ 1.60
Other components (including silver, Tedlar backing film, silicon, adhesive)	16%	€ 0.90
	Total Price per kg	€ 0.341

Table 18: Multicrystalline valuable material

The material composition of multicrystalline/polycrystalline PV cells is similar to the material composition of monocrystalline PV cells, with the important difference, that multicrystalline/ polycrystalline silicon is used instead of monocrystalline silicon.

As monocrystalline silicon is more expensive than multicrystalline/polycrystalline PV cells, the average total price for one kg multicrystalline/polycrystalline PV cell is lower than for the same amount of monocrystalline silicon PV cells. Therefore, the point for the evaluation in this category is 3.

Hazardous material

Similar to monocrystalline PV cells, multicrystalline/polycrystalline PV cells contain lead, a hazardous material that increases the EoL costs. It is usually used for the solder. Therefore, the point for the evaluation in this category is 0.

Market share

The market share of multicrystalline/polycrystalline PV cells in 2011 is around 40% worldwide. Therefore, the point for the evaluation in this category is 5.

Energy efficiency

The energy efficiency for multicrystalline/polycrystalline modules can be estimated from the data that is provided in Table 19 below:

Company	Energy efficiency
Q-Cells	14.11 %
BP Solar	13.11 %
Sungrid	14.4 %
Evergreen	13.1 %
REC	15.5 %

Table 19: Multicrystalline energy efficiency

According to the data above the average energy efficiency for multicrystalline/polycrystalline modules is 14.04%. Therefore, the point for the evaluation in this category is 5.

Life duration

The life duration of this type of PV cells is expected to be around 30 years, but due to the construction, the energy efficiency is shrinking more rapidly than the energy efficiency of other PV cells, e.g. monocrystalline PV cells.

Warranty: BP Solar; 175-215-230 Watt

- Free from defects in materials and workmanship for 5 years
- 93 percent power output over 12 years
- 85 percent power output over 25 years

Based on the above listed warranty guaranties, the average decrease of power output can be estimated to be around 0.6% per year. Therefore, the life duration, as defined in this paper, can be calculated to be on average around 33 years. Therefore, the point for the evaluation in this category is 5.

Production costs

The manufacturing processes for multycrystalline/polycrystalline modules are simpler and therefore cheaper than the manufacturing processes of monocrystalline modules. In order to produce multycrystalline/polycrystalline modules, smaller silicon crystals are grown in a cluster, which is sawn into solar cell wafers.

The production costs of one square meter of polycrystalline PV cells ranges between €100 and €180. Based on this range, the average costs can be estimated to be around €140. Therefore, the point for the evaluation in this category is 2. Furthermore, the multycrystalline/polycrystalline modules, produced by Evergreen are manufactured through a cost effective process, which is called StringRibbonTM. This process reduced the amount of raw materials and therefore leads to a less expensive manufacturing process.

Light absorption

The available light absorption spectrums of multicrystalline PV cells ranges are similar to monocrystalline cells, from about 350 nm to 1100 nm (Seattle PI, 2014). The peak of the sensitivity can be seen at about 700 nm and rather close to the peak of sunlight at about 600 nm, but the whole curve is lower compared to monocrystalline cells (Fig. 16). Multicrystalline cells cover about 40% of the light absorption spectrum available; therefore, the point for the evaluation in this category is 4.

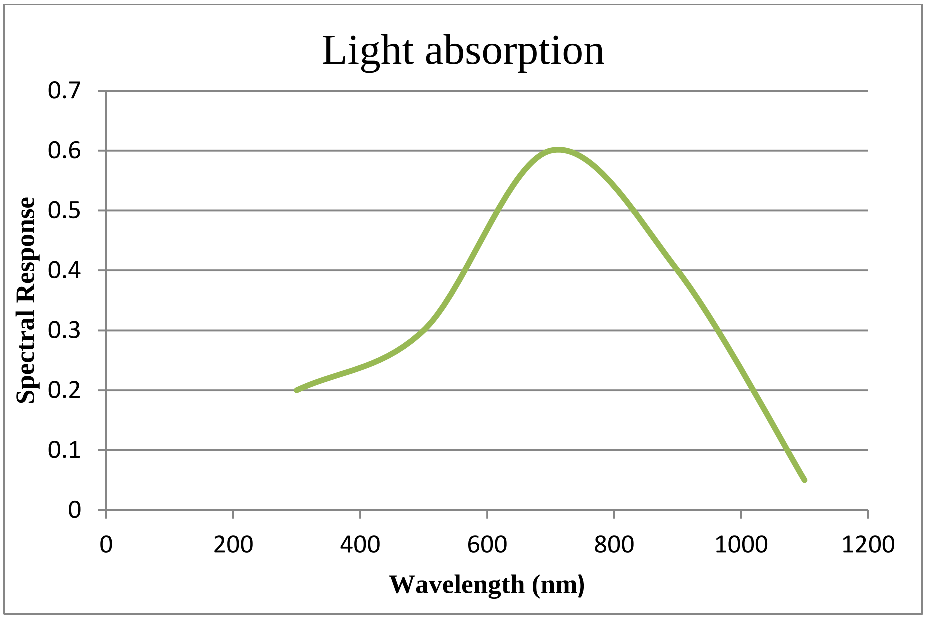

Figure 16: Light absorption in multicrystalline PV cells

Energy payback time

Considering Fig. II provided in appendices III, multicrystalline PV cells provide an energy payback time of about 1.6 years (de Wild-Scholten, 2013). The production steps consuming the largest amounts of energy are the silicon feedstock and the wafer. Compared to monocrystalline PV cells, the energy needed for the silicon feedstock is higher, while the energy needed for the wafer is lower. Therefore, the point for the evaluation in this category is 2.

Greenhouse gas emissions

The efficiency of multicrystalline PV cells is slightly smaller than the efficiency of monocrystalline PV cells, but the emissions during production are significantly smaller. This is also expressed in the average greenhouse gas emission of about 33 g CO_2-eq/kWh. Therefore, the point for the evaluation in this category is 2.

Summary

No.	Evaluation Criteria	Average Value	Points w_i	Weight Factor q_i	Weighted Points $EoLV_i$
1	Valuable material	€ 0,341	3	0.1	0.3
2	Hazardous material	Yes	0	0.1	0.0
3	Average weight	16,8 kg	3	0.1	0.3
4	Market share	45%	5	0.1	0.5
5	Energy efficiency	14,04 %	5	0.1	0.5
6	Life duration	33 years	5	0.1	0.5
7	Production costs	€ 140	2	0.1	0.2
8	Light absorption	40%	4	0.1	0.4
9	Energy payback time	1,6 years	2	0.1	0.2
10	Greenhouse gas emissions	33 g CO_2-eq/kWh	2	0.1	0.2
Total points:			31		3.1
Normalized Total Points (EoLV):					0.62

Table 20: Multicrystalline summary

12.2. Recycling of thin film PV cells

12.2.1. Amorphous silicon (a-Si)

Valuable material

Material	Percentage	Price per kg
Glass	86%	€ 0,05
Aluminum	< 1%	€ 1,60
Other components (including Indium, Germanium, Polyol and MDI)	14%	€ 6,00
	Total price per kg	€ 0,899

Table 21: Amorphous silicon valuable material

These modules include amorphous silicon and plastic for the substrate. It is also worth to mention that germanium is scarcer than silicon.

It can be seen that a-Si solar cells are containing 86% glass, which is higher than the amount of glass in other silicon based PV cells. Additionally, this type contains less aluminum than other silicon based cells. Considering Table 21, these cells contain less than 1% aluminum and around 14% are other components. Therefore, the point for the evaluation in this category is 5.

The most valuable materials that are used within a-Si solar cells are Indium and Germanium, which are both scarce, and therefore expensive, metals.

Hazardous material

In contrast to other PV cells, this type usually does not contain any hazardous materials and therefore, the point for the evaluation in this category is 5.

Average weight

An average weight of an amorphous silicon module can be estimated according to Table 22 below (Greentechmedia, 2014):

Company	Module output(W)	Weight
Anwell Sollar	105 W	26 kg
HQRP	110 W	18.3 kg
Sharp	115 W	19.1 kg
Solar Frontier	150-155-160 W	20 kg
Kaneka	105-110-115-120 W	18.3 kg

Table 22: Amorphous silicon average weight

According to the data above the average weight of an amorphous silicon module silicon module is 20.34 kg. Therefore, the point for the evaluation in this category is 5.

Market share

Referring to Fig. I in appendices II, the market share of a-Si PV cells in 2011 is around 2.4% worldwide. Therefore, the point for the evaluation in this category is 0.

Energy efficiency

The energy efficiency for of an amorphous silicon module can be estimated from the data that is provided in Table 23:

Company	Energy efficiency
Sharp	9.6 %-10%
Solar Frontier	11.4%-13%
Kaneka	8.6%-9.8%

Table 23: Amorphous silicon energy efficiency

According to the data above the average energy efficiency of an amorphous silicon module is 10.4%. Therefore, the point for the evaluation in this category is 1.

Life duration

Warranty: Anwell 95-100-105 Watt

- Free from defects in material for 10 years
- Workmanship for 10 years
- Maintain more than 90 percent minimum rated power for 10 years
- 80 percent minimum rated power for 25 years

It can be seen, that the life duration (as defined in this work) is at least 25 years, which can be used for the evaluation. Therefore, the point for the evaluation in this category is 2.

Production costs

Amorphous silicon modules contain less silicon than crystalline modules, which means lower costs. Amorphous silicon cells use around 1% of the silicon that is necessary for a traditional silicon PV cell. Another advantage compared to silicon cells of the first generation is the possibility to deposit amorphous silicon onto a substrate easily. The production costs per square-meter are between €30 and €90, resulting in an average of €60 per square-meter. Therefore, the point for the evaluation in this category is 5.

Light absorption spectrum

The available light absorption spectrum of amorphous silicon PV cells ranges from about 350 nm to 800 nm and is rather limited, compared to other PV cells (Seattle PI, 2014). The peak of the sensitivity is at about 600 nm, almost identical with the peak of sunlight. As a result, this kind of cells covers the sunlight at a high degree within the range of visible light (400-800 nm), but poorly in the UV-range (<400nm) and very poorly in the infrared range (>800nm) (Seattle PI, 2014). The overall relative amount of the light absorption spectrum can be assumed to be around 25%. Therefore, the point for the evaluation in this category is 2.

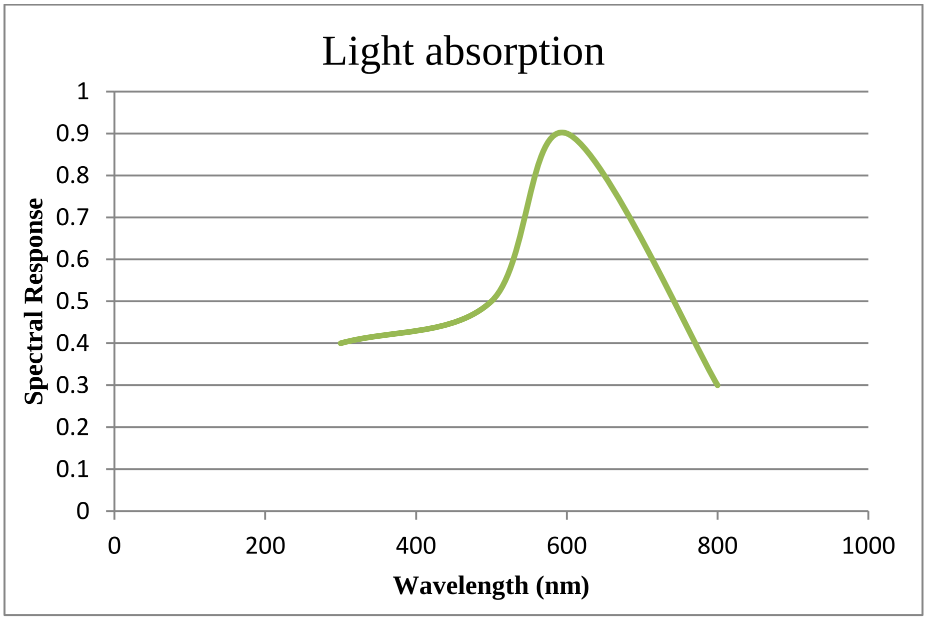

Figure 17: Light absorption in a-Si PV cells

Energy payback time

The energy needed for the production of a-Si PV cells is mainly used for the silicon feedstock and the wafer, wherein the energy needed for the silicon feedstock is lower compared to multicrystalline PV cells. Considering Fig. II provided in appendices III, a-Si PV cells have an energy payback time of about 1.3 years (de Wild-Scholten, 2013). Therefore, the point for the evaluation in this category is 3.

Greenhouse gas emissions

The efficiency of a-Si PV cells is, similar to other thin-film PV cells, significantly smaller than the efficiency of crystalline PV cells. During the production, fewer emissions occur. On average, a-Si cells are responsible for about 33 g CO_2-eq/kWh, similar to multicrystalline PV cells. For the evaluation, 2 points are given.

Summary

No.	Evaluation Criteria	Average Value	Points w_i	Weight Factor q_i	Weighted Points $EoLV_i$
1	Valuable material	€ 0,899	5	0.1	0.5
2	Hazardous material	No	5	0.1	0.5
3	Average weight	20.34 kg	5	0.1	0.5
4	Market share	2.4	0	0.1	0.0
5	Energy efficiency	10.4%.	1	0.1	0.1
6	Life duration	25 years	2	0.1	0.2
7	Production costs	€ 60	5	0.1	0.5
8	Light absorption	25%	2	0.1	0.2
9	Energy payback time	1,3 years	3	0.1	0.3
10	Greenhouse gas emissions	33 g CO_2-eq/kWh	2	0.1	0.2
Total points:			30		3.0
Normalized Total Points (EoLV):					0.60

Table 24: Amorphous silicon overview

12.2.2. Cadmium Telluride (CdTe)

Valuable material

It is important to mention that tellurium resources are limited.

Material	Percentage	Price per kg
Glass	95%	€ 0.05
Aluminum	< 1%	€ 1.60
Other components (including EVA)	4%	€ 0.30
	Total price per kg	€ 0.0755

Table 25: CdTe valuable material

It can be seen that Cadmium Telluride solar cells contain 95% glass, less than 1% aluminum and around 4% other components. The amount of valuable materials, in this kind of cells is very low; therefore, the point for the evaluation in this category is 0.

Hazardous material

As the name of this type of PV cells already indicates, it contains a portion of cadmium in the semiconductor layer. Cadmium is a hazardous material that increases the EoL costs due to the necessary presorting step. Therefore, the point for the evaluation in this category is 0.

Average weight

Company	Module output(W)	Weight
Calyxo	75	12 kg
First Solar	70-75-77.5 W	12 kg

Table 26: CdTe average weight

According to the data above the average weight of a cadmium telluride silicon module is 12 kg. Therefore, the point for the evaluation in this category is 1.

Market share

Referring to Fig. I in appendices II, the market share of CdTe PV cells in 2011 is around 8% worldwide. Therefore, the point for the evaluation in this category is 2.

Energy efficiency

Company	Energy efficiency
Calyxo	6.94 %
FS2	10.69 %
First Solar	14.4 %

Table 27: CdTe energy efficiency

According to the data above the average energy efficiency of a cadmium telluride silicon module is 10.68%. Therefore, the point for the evaluation in this category is 1.

Life duration

The CdTe thin film PV cells produced by Calyxo have the following warranties:

- 10 years on material and workmanship
- performance guarantee on 90% of rated power in the first 10 years; on 80% over 25 years

This data shows that the expected life duration of CdTe PV cells is at least 25 years. Therefore, the point for the evaluation in this category is 2.

Production costs

CdTe modules can be produced in high-volume with a low-cost production system. The manufacturing process is simpler than for other thin-film cells. For example “First Solar” makes a complete solar panel from a sheet of glass in less than 2.5 hours through a continuous, automated process. Also, Calyxo has a fully automated production system requiring less manufacturing costs. Furthermore, the Calyxo's production process guarantees that no cadmium telluride can harm humans or the environment.

CdTe responds to sunlight differently than typical crystalline silicon technologies, which would lead to a better temperature coefficient and therefore implies less temperature-related losses. Furthermore, CdTe performs well in hot conditions.

It is also worth to mention that "First Solar" has a recycling process that can recover up to 95% of the semiconductor materials, which is reusable in a new solar module. According to the calculation, the production cost per square-meter is €110. Therefore, the point for the evaluation in this category are 3.

<u>Light absorption</u>

The available light absorption spectrum of CdTe PV cells ranges from about 350 nm to 850 nm, with a peak of the sensitivity at about 800 nm and a sharp decline between 800 nm and 850 nm (Fig. 18).

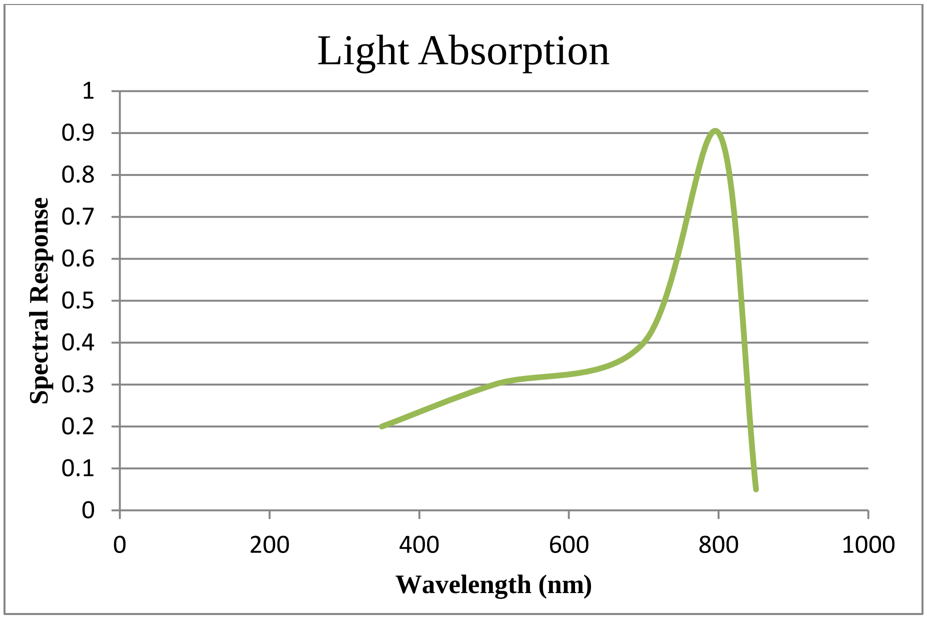

Figure 18: Light absorption in CdTe PV cells

Similar to a-Si PV cells, CdTe PV cells provide a good covering of the sunlight within the range of visible light (400-800 nm), but poorly in the UV-range (<400nm) and very poorly in the infrared range (>800nm). Summarizing, the relative amount of the light absorption spectrum can be assumed to be around 30% (Seattle PI, 2014). Therefore, the point for the evaluation in this category is 3.

Energy payback time

The energy payback time of CdTe PV cells comprises mainly energy for the production of the cell and the module. Additionally, energy is needed for the frame, the inverter and the BOS (Balance of System) components. Summed up, the energy payback time for CdTe PV cells amount to approximately 1 year. Therefore, the point for the evaluation in this category is 4.

Greenhouse gas emissions

Similar to other thin-film PV cells the emissions of CdTe PV cells are relatively low, going in hand with a comparable low efficiency. For CdTe PV cells, this results in an average greenhouse gas emission value of 24 CO_2-eq/kWh, equivalent to 4 point for the evaluation.

Summary

No.	Evaluation Criteria	Average Value	Points w_i	Weight Factor q_i	Weighted Points $EoLV_i$
1	Valuable material	€ 0,0755	0	0.1	0.0
2	Hazardous material	Yes	0	0.1	0.0
3	Average weight	12 kg	1	0.1	0.1
4	Market share	8%	2	0.1	0.2
5	Energy efficiency	10.68%	1	0.1	0.1
6	Life duration	25 years	2	0.1	0.2
7	Production costs	€110	3	0.1	0.3
8	Light absorption	30%	3	0.1	0.3
9	Energy payback time	1 year	4	0.1	0.4
10	Greenhouse gas emissions	24 g CO_2-eq/kWh	4	0.1	0.4
Total points:			20		2.0
Normalized Total Points (EoLV):					0.40

Table 28: CdTe overview

CdTe modules have a lower efficiency than some Silicon based technologies; therefore, in order to reach to the given output more panels would be needed.

Calyxo CdTe modules have some benefits as follow (Calyxo, 2014):

- Better performance than crystalline silicon at high temperatures and low light
- Lower output voltage; which allows longer strings and lower system cost
- Recycling program through PV cycle
- 100% collection and recycling of the modules at the end of their service life

First Solar CdTe modules have some benefits as follow (First Solar, 2014):

- Holder of world-record in terms of CdTe thin film efficiency; efficiency of 14.4% for each module and 18.7% for each cell,

- Having the fastest energy payback time of any other type of PV modules,
- Having the smallest amount of carbon footprint of any other type of PV modules,
- Manufacturing cost leader at $.68/watt (Q4 2012) ,
- Holder of global proven recycling service

12.2.3. CIS/CIGS

Valuable material

Material	Percentage	Price per kg
Glass	84%	€ 0.05
Aluminum	12%	€ 1.60
Other components (including Indium, Gallium and EVA)	4%	€ 2.00
	Total price per kg	€ 0.314

Table 29: CIS/CIGS valuable material

Considering Table 29 above, it can be seen that CIS/CIGS solar cells contain 84% glass, 12% aluminum and around 4% other components. The amount of valuable materials, in this kind of cells is €0,314. Therefore, the point for the evaluation in this category is 3.

Hazardous material

State-of-the-art CIS/CIGS cells contain a buffer layer made of cadmium sulfide. Cadmium as a hazardous material has to be preselected and raises the EoL costs.

In order to prevent the use of cadmium, buffer layers made from other materials have been proposed, e.g. materials based on zinc. As a result, cadmium is still used in a high portion of CIS/CIGS cells, but not in all of them anymore. Therefore, the point for the evaluation in this category is 3.

Average weight

Company	Panel output(W)	Weight
Q-Cells	75-80-85-90 W	13.2 kg / 14.5 kg
Solyndra	157 W	31 kg

Table 30: CIS/CIGS average weight

According to the data above the average weight of a CIS/CIGS silicon module is 19.56 kg. Therefore, the point for the evaluation in this category is 4.

Market share

Referring to Fig. I in appendices II, the market share of CIGS PV cells in 2011 is around 3.6% worldwide. Therefore, the point for the evaluation in this category is 1.

Energy efficiency

Company	Energy efficiency
Q-Cells (75-80-85-90 W)	10%-10.7%-11.3%-12%
Solco Choice Electric	6.9 %

Table 31: CIS/CIGS energy efficiency

According to the data above the average energy efficiency of a CIS/CIGS silicon module is 10.18%.

In the laboratory, CIGS modules have reached high efficiencies, which are comparable to crystalline silicon modules. Q-Smart CIGS modules produced by the company Q-Cells have one of the highest conversion efficiencies of thin film modules on a commercial scale. Therefore, the point for the evaluation in this category is 1.

Life duration

Warranty: Solyndra 157 Watt

- 5 year workmanship
- 25 year 80% efficiency

From this warranty can be seen, that the life duration (as defined in this work) is at least 25 years, which can be used for the evaluation. Therefore, the point for the evaluation in this category is 2.

Production costs

The production costs of CIS/CIGS cells are much lower than of silicon based PV cells. Due to several reasons, the costs for a square meter of this type of cells range between about €40 to €80. For the evaluation, an average value of €60 is used. Therefore, the point for the evaluation in this category is 5.

Light absorption

The available light absorption spectrum of CIS/CIGS PV cells ranges from about 350 nm to 950 nm. The peak of the sensitivity can be found at about 900 nm and the shape of the curve is similar to the one characteristic for CdTe PV cells, providing a sharp decline between about 900 nm and 950 nm (Fig. 19).

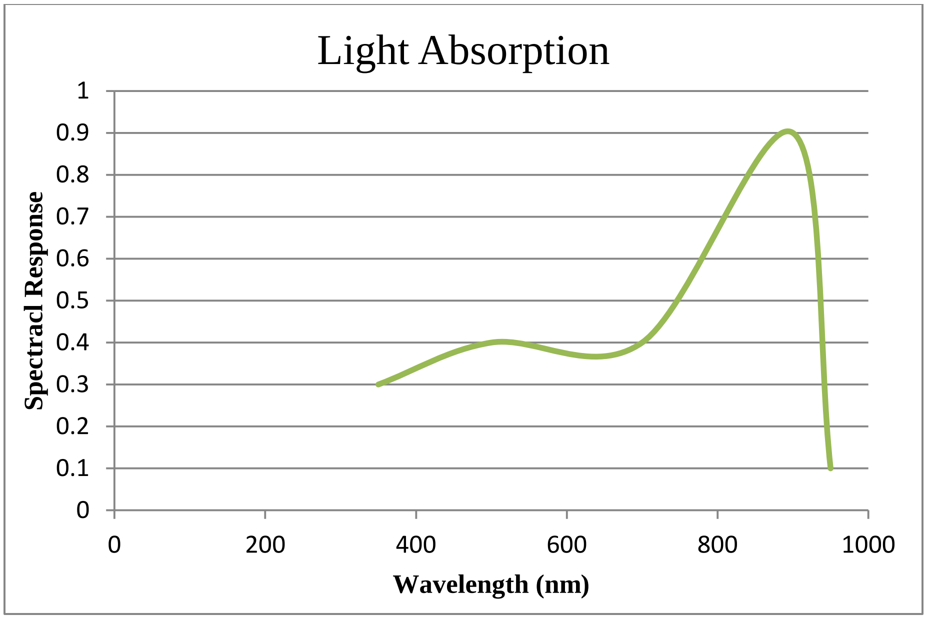

Figure 19: Light absorption in CIS/CIGS PV cells

Also similar to CdTe PV cells, the visible light range between 400 nm and 800 nm is covered well, while the UV-range (<400 nm) and especially the infrared range (>800 nm) are covered poorly. As a result, the relative amount of CIS/CIGS PV cells of the light absorption spectrum can be assumed to be around 40%. Therefore, the point for the evaluation in this category is 4.

<u>Energy payback time</u>

CIS/CIGS PV cells provide an energy payback time of about 0.9 years. Similar to CdTe PV cells (and other thin film PV cells), the energy is mainly necessary for the production of the cell and the modules. Overall, the energy payback time for CIS/CIGS PV cells sums up to approximately 0.9 years. Therefore, the point for the evaluation in this category is 4.

<u>Greenhouse gas emissions</u>

The average greenhouse gas emissions of CIS/CIGS PV cells sum up to about 28 g CO_2-eq/kWh. This value is based on relative low emissions and a relative low efficiency. As a result, 3 points are given for the evaluation.

Summary

No.	Evaluation Criteria	Average Value	Points w_i	Weight Factor q_i	Weighted Points $EoLV_i$
1	Valuable material	€ 0,314	3	0.1	0.3
2	Hazardous material	Yes/No	3	0.1	0.3
3	Average weight	19.56 kg	4	0.1	0.4
4	Market share	3.6	1	0.1	0.1
5	Energy efficiency	10.18%	1	0.1	0.1
6	Life duration	25 years	2	0.1	0.2
7	Production costs	€ 60	5	0.1	0.5
8	Light absorption	40%	4	0.1	0.4
9	Energy payback time	0,9 years	4	0.1	0.4
10	Greenhouse gas emissions	28 g CO_2-eq/kWh	3	0.1	0.3
Total points:			30		3.0
Normalized Total Points (EoLV):					0.60

Table 32: CIS/CIGS overview

CIGS material can be used with a variety of substrates, allowing it to be incorporated into building materials such as roof tiles, windows and commercial building panels. This makes their installation very versatile.

13. Summary of the evaluation

The final results of the evaluation of the various photovoltaic are presented in Table 33 and Table 34. Each value is weighted and normalized. Additionally, the values are multiplied by 1000 to increase the readability. That means the points are calculated with the following formula:

$$w_{inorm} = EoL\mathrm{V_i} * \frac{1}{5} * 1000 \qquad (7)$$

w_{inorm} = Normalized evaluation points of the criterion i

EOL_{Vi} = Weighted points of the criterion i

As a result given points are numbers from 0 to 100 and respectively EoL points are numbers from 0 to 1000.

Criterion 1: Valuable material
Criterion 2: Hazardous material
Criterion 3: Average weight
Criterion 4: Market share
Criterion 5: Energy efficiency
Criterion 6: Life duration
Criterion 7: Production costs
Criterion 8: Light absorption
Criterion 9: Energy payback time
Criterion 10: Greenhouse gas emissions

Criteria PV Cells	1 w_i	2 w_i	3 w_i	4 w_i	5 w_i	6 w_i	7 w_i	8 w_i	9 w_i	10 w_i	EoL V
Monocrystalline	3	0	2	5	5	5	1	5	1	1	28
Multicrystalline	3	0	3	5	5	5	2	4	2	2	31
a-Si	5	5	5	0	1	2	5	2	3	2	30
CdTe	0	0	1	2	1	2	3	3	4	4	20
CIS/CIGS	3	3	4	1	1	2	5	4	4	3	30
Sum per Criterion	14	8	15	13	13	16	16	18	14	12	

Table 33: Summary of the evaluation I

Criteria PV Cells	1 w_{inorm}	2 w_{inorm}	3 w_{inorm}	4 w_{inorm}	5 w_{inorm}	6 w_{inorm}	7 w_{inorm}	8 w_{inorm}	9 w_{inorm}	10 w_{inorm}	EoLV
Monocrystalline	60	0	40	100	100	100	20	100	20	20	560
Multicrystalline	60	0	60	100	100	100	40	80	40	40	620
a-Si	100	100	100	0	20	40	100	40	60	40	600
CdTe	0	0	20	40	20	40	60	60	80	80	400
CIS/CIGS	60	60	80	20	20	40	100	80	80	60	600
Sum per Criterion	280	160	300	260	260	320	320	360	280	240	

Table 34: Summary of the evaluation II

As mentioned before in this dissertation, the optimal EoL treatment for PV cells is recycling. Considering the Tables 33 and 34, the high EoLVs of PV cells indicate a reasonable possibility for recycling; which means the higher the EoLVs, the higher the efficiency of recycling.

According to the data, multycrystalline PV cells have the highest points (31/620). The second highest points goes to a-Si and CIS/CIGS PV cells (30/600). Monocrystalline PV cells with (28/560) EoLV points are at the next group with the high potential to be recycled and finally CdTe PV cells with the least EoLV points (20/400) have the smallest worth as an input for a recycling process

13.1. Advantages and Disadvantages of the evaluated PV cells

Multicrystalline PV cells

Advantages of multicrystalline PV cells

- Multicrystalline PV cells have a high amount of market share.
- Multicrystalline PV cells are rather efficient.
- Multicrystalline PV cells have a long life duration.

Disadvantages of multicrystalline PV cells

- High production costs.

a-Si PV cells

Advantages of a-Si cells

a-Si cells, in comparison with crystalline based cells, need a smaller amount of silicon. Only 1% of the silicon used in crystalline silicon solar cells is required for the production of amorphous silicon solar cells.

Disadvantages of a-Si cells

In order to manufacture a-Si cells applicable for large-scale usages, a special process, called stacking is necessary. With this manufacturing technique several layers of amorphous silicon solar cells can be combined but this process is expensive.

CIS/CIGS PV cells

Advantages of CIS/CIGS PV cells

- CIS/CIGS PV cells contain a smaller amount of hazardous material (cadmium) than e.g. CdTe PV cells.
- CIS/CIGS PV cells have the highest efficiency of all thin film cells.

Disadvantages of CIS/CIGS PV cells

- CIS/CIGS PV cells have a lower efficiency than crystalline cells.
- The manufacture of CIS/CIGS PV cells is rather difficult and the production costs are high.

Monocrystalline PV cells

Advantages of monocrystalline PV cells

- Monocrystalline PV cells have the highest efficiency rates of all evaluated PV cells. Considering Table 33 and 34 above they have the highest amount of points in this category.
- Monocrystalline silicon PV cells are material-efficient. According to the analysis in this dissertation, monocrystalline PV cells have an average weight of 15.33kg, which is, except from CdTe PV cells that have an average weight of 12, the smallest value.
- Monocrystalline PV cells have a longer life-span than e.g. thin film PV cells.

Disadvantages of monocrystalline PV cells

- Monocrystalline PV cells have the highest production costs and respectively the highest price.
- Monocrystalline PV cells are more efficient in warm weather. That means they are not intolerant to the weather and their performance suffers as temperature decreases.

CdTe PV cells

Advantages of CdTe PV cells

CdTe cells can be produced easily and with low costs.

Disadvantages of CdTe PV cells

- CdTe PV cells have a lower efficiency than crystalline cells.
- Cadmium, an important material for CdTe cells, is toxic.

Summary

From the above described advantages and disadvantages of the evaluated cells can be seen, that in general, crystalline PV cells are more efficient, but more costly than thin film PV cells.

13.2. Examination of the criteria

In this chapter, the ten evaluation criteria are categorized in two main groups:

1) Criteria which have an impact on the efficiency of the EoL-stage;
    a) Valuable material
    b) Hazardous material
    c) Average weight
    d) Market share
2) Criteria which have an impact on the life-cycle of a PV cell;
    a) Energy efficiency
    b) Life duration
    c) Production costs
    d) Light absorption
    e) Energy payback time
    f) Greenhouse gas emissions

The first group of criteria helps to answer the question about the EoL management at the current stage, wherein the input, the PV cells, can be seen as fixed. They have been produced, used and now they have to be processed through the EoL-stage in the most efficient way.

The second group of criteria helps to answer the question, which type of PV cells should be further developed and produced, seen from a view concerning the whole life-cycle. The criteria efficiency, production costs and life duration are not important when we consider the PV cells as a given input, but they play an important role within the decision which PV cells are worth to produce nowadays.

This categorization implies that the first group of criteria is more limited regarding the scope, while the second group of criteria is broader in respect to the scope, wherein the first group of criteria is also included in the consideration of the whole life-cycle.

In Table 35 below, the various ten criteria are ranked according to their total weighted points.

Rank	Criterion	Weighted Points	Proposed Action
1	Light absorption	360	Increase
2	Production cost	320	Decrease
2	Life duration	320	Increase
4	Average weight	300	Decrease
5	Valuable material	280	Increase
5	Energy payback time	280	Decrease
7	Energy efficiency	260	Increase
7	Market share	260	Increase
9	Greenhouse gas emissions	240	Decrease
10	Hazardous material	160	Decrease

Table 35: Criteria ranking

Considering the first category of criteria, in order to create an efficient EoL stage, the amount of valuable materials in relation to other materials in PV cells should increase wherever it is possible. Respectively, to reduce the negative influence on the environment, the amount of hazardous material should decrease, or in the best case, be eliminated and substituted by other, non-hazardous materials, wherever it is possible. If factors like the amount of valuable and hazardous material are considered during the design stage and the manufacturing process, high positive returns can be created at the EoL stage. Furthermore, two other criteria in this category are average weight and market share. The proposed action plans are to decrease the average weight, which make the process of EoL management more efficient and also to increase the amount of market share.

Considering the second category of criteria, presented in Table 35 above, the highest rank is for the criterion light absorption and then followed by the criteria production costs and life duration. All of these are categorized as criteria, which have an impact on the life-cycle of a PV cell. If a look at the proposed action column is taken, it can be seen that the light absorption and life duration are marked to be increased, while production costs is marked to be increased.

Another criterion in this group is energy payback time, which obviously has a direct negative impact on the life-cycle of a PV cell and is marked to be decreased. The criterion energy efficiency, which obviously has a direct positive impact on the life-cycle of a PV cell and is marked to be increased and finally the greenhouse gas emissions criterion, which should be definitively decreased.

The PV cells with the highest amount of light absorption, smallest amount of production costs and a longer life cycle should be further developed and produced, seen from a view concerning the whole life-cycle.

To summarize, it can be seen that the largest potential for further improvements lies in the field of criteria in group two, which have an impact on the life-cycle of a PV cell. Especially the criteria in the highest ranks (light absorption, production cost and life duration) provide interesting opportunities.

As a conclusion, the development of new, faster and less energy consuming technologies with smaller production costs for production of PV cells with a long life-cycle is vital for an efficient EoL management.

13.3. Examination of the different types of PV cells

In Table 36 below, the five examined PV cells are ranked according to their total weighted points.

Rank	PV cells	Weighted Points
1	multicrystalline	620
2	a-Si & CIS/CIGS	600
4	monocrystalline	560
5	CdTe	400

Table 36: PV cells ranking

This ranking provides a general answer to the second research question. Referring to chapter 2.1, the second research question is “What kind of PV cells is optimal from the EoL point of view?”. Higher EoL values indicate a higher efficiency of recycling and respectively lower EoL values indicate a lower efficiency of recycling.

In Table 37 below, the weighted points per each PV cell type are divided by the two categories of factors that have been discussed in chapter 13.2 above.

Rank	PV cells	Criteria group 1	Criteria group 2	Weighted Points
1	multicrystalline	220	400	620
2	a-Si & CIS/CIGS	300/220	300/380	600
4	monocrystalline	200	360	560
5	CdTe	60	340	400

Table 37: Weighted points per PV cell per category

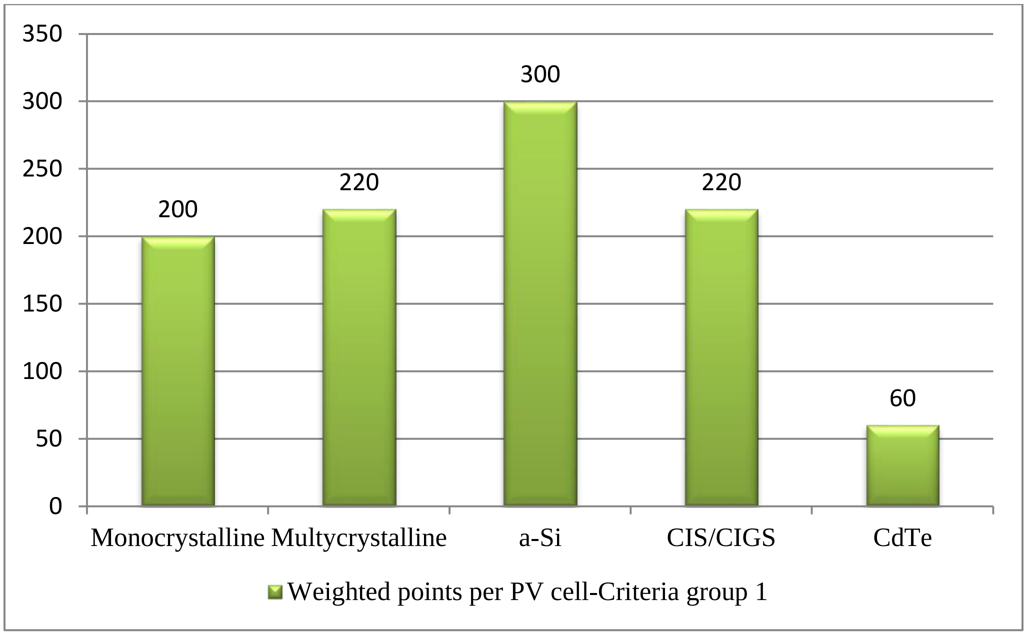

Figure 20: Evaluation Criteria group 1

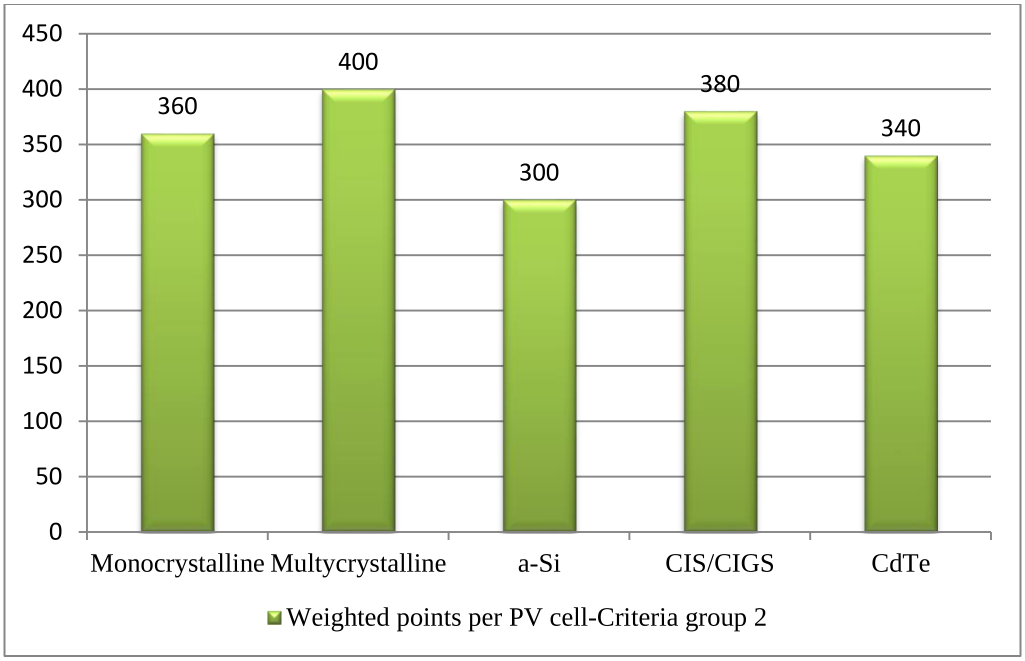

Figure 21: Evaluation Criteria group 2

It can be seen where the strengths and weaknesses of each kind of PV cells are. In the criteria of group 1 (Fig. 20), the relative difference between the highest and the lowest amount of points is relative high (240 points), which could be interpreted that the criteria in this group provide large differences for all of the PV cells. Also, a-Si PV cells have the highest points in this category, which shows that these cells are more optimal seen from a pure EoL view than seen from a whole life-cycle view.

Furthermore, in order to create recycling-friendly PV cells, the manufacturing processes should also be recycling-friendly. That means that criteria like valuable material, hazardous material and average weight in group 1 have an impact on manufacturing processes and should be optimized. Considering these criteria, it should be tried to use as much as possible valuable materials instead of hazardous materials wherever it is possible.

In the criteria of group 2 (Fig. 21), the relative difference between the highest and the lowest amount of points is lower than within the first group (100 points), which could be interpreted that the criteria in these group are more similar for all of the PV cells.

14. Case studies

In the analysis presented in previous chapters, all the various criteria are regarded as being equally important. This is done by using uniformly distributed weight factors. Even this is an easy approach to establish, it is not likely to picture reality in the best possible way. Therefore, this chapter is presenting various case studies, in which the whole problem is viewed from different points of view. To do that, the criteria are weighted by different values, according to the importance they have.

14.1. Society

It can be generally assumed that the view of society is characterized by the goal to improve the total welfare of the people. Some of the common sub-goals to reach this aim are the protection of the environment, the improvement of the efficiency in economics and many others, which do not play an important role within the present analysis. Furthermore, the time horizon of the society goes far beyond the lifetime of a human and therefore, the whole thinking is very long-term oriented.

That means in particular that it is not so important for the society to improve the current efficiency of the whole life-cycle or the EoL management, but it is far more important to improve the efficiency of the life-cycle of upcoming products and devices. As a result, from the point of view of the society, the short-term criteria are not as important as the long-term criteria. The criteria are briefly discussed below.

<u>Valuable material</u>

On the one hand, this criterion is not very important for the society, because it does not influence the total welfare directly; but on the other hand, a reasonable amount of valuable material increases the incentive for companies to establish a reasonable EoL management. Overall, this criterion is average important for society.

Hazardous material

Similar to the first criterion, valuable material, this criterion does not have a direct influence on the welfare of the society, but it is still preferably to produce PV cells comprising low amounts of hazardous materials.

Average weight

For the society, it does not matter if a solar panel is heavy or not, and therefore, the importance of this criterion in this context is very low.

Market share

It is also not important which PV cell is the most used one for the society. As a result, this criterion is not important from the point of view of society.

Energy efficiency

One goal of society is the efficient use of resources, in order to maintain or increase the output while decreasing the input. The efficiency of energy generation plays a crucial role in such considerations. As a consequence, this criterion is considered as one of the most important criteria within this framework.

Life duration

Similar to the energy efficiency, this criterion is important for the efficiency of energy generation, as it describes the time that a PV cell can be used. Therefore, this criterion is very important from the viewpoint of the society.

Production cost

This criterion has an average importance for society, as it is preferably to have low production costs while maintaining or increasing the output value. On the other hand, the production costs are not the most important factor for society, as it is just considering the input and not the output.

Light absorption

The light absorption gives a hint on the potential of a PV cell to increase the efficiency, and therefore, it is an important criterion for the society, as this criterion is future-related.

Energy payback time

This is an important criterion from the viewpoint of society, because it is important to have a good cost/benefit relationship, as this criterion describes the energy efficiency of production in terms of output.

Greenhouse gas emissions

This is another important criterion from the viewpoint of society, as it is favorable to produce as less greenhouse gas as possible to protect the environment.

In Table 38 an exemplary set of weight factors from the society point of view is shown.

Criteria No.	Criterion	Weight Factor
1	Valuable material	0.05
2	Hazardous material	0.05
3	Average weight	0.00
4	Market share	0.00
5	Energy efficiency	0.20
6	Life duration	0.20
7	Production costs	0.05
8	Light absorption	0.10
9	Energy payback time	0.20
10	Greenhouse gas emissions	0.15

Table 38: Weight factors from the society point of view

In Table 39 below, the evaluation result is shown, using the above discussed weighting factors.

Criteria	1	2	3	4	5	6	7	8	9	10	Weighted
Weight factor	0.05	0.05	0.00	0.00	0.20	0.20	0.05	0.10	0.20	0.15	EoLV
PV Cells											
Monocrystalline	3	0	2	5	5	5	1	5	1	1	
Weighted	0.15	0.00	0.00	0.00	1.00	1.00	0.05	0.50	0.20	0.15	3.05
Multicrystalline	3	0	3	5	5	5	2	4	2	2	
Weighted	0.15	0.00	0.00	0.00	1.00	1.00	0.10	0.40	0.40	0.30	3.35
a-Si	5	5	5	0	1	2	5	2	3	2	
Weighted	0.25	0.25	0.00	0.00	0.20	0.40	0.25	0.20	0.60	0.30	2.45
CdTe	0	0	1	2	1	2	3	3	4	4	
Weighted	0.00	0.00	0.00	0.00	0.20	0.40	0.15	0.30	0.80	0.60	2.45
CIS/CIGS	3	3	4	1	1	2	5	4	4	3	
Weighted	0.15	0.15	0.00	0.00	0.20	0.40	0.25	0.40	0.80	0.45	2.80

Table 39: Case study society: Summary of the evaluation

The evaluation from the point of view of society shows interesting results, because the ranking of the different types of PV cells changes compared to the first evaluation, assuming equal importance of all criteria. As can be seen in Table 39, multicrystalline cells are most favorable for society, followed by monocrystalline cells, CIS/CIGS cells and finally, a-Si cells and CdTe cells at the end of the ranking.

14.2. Recycling company

Recycling companies try to maximize their profit, which is based on the value of the incoming PV cells for the EoL management, e.g. the value of the recyclable material that can be sold after the EoL process. Therefore, from the recycling company point of view, the criteria that are providing information on the value of the PV cells during the EoL are important.

Furthermore, other criteria, aiming on the efficiency of the whole economy or on the ecologic impact of these cells are less important, as they do not provide direct positive value to the recycling company. Such a company just takes influences in account, which are important for their own monetary success. These influences vary between different companies, e.g. due to differences in efficiency, between different countries, e.g. due to different legal restrictions and between different points in time, e.g. due to changing frameworks. The criteria are discussed briefly below.

Valuable material

This criterion is the most important criterion for recycling companies, as their business is to sell parts of the PV cells. A high value of the material raises the prices they can obtain and therefore the profits they make.

Hazardous material

For recycling companies, this criterion is important, because hazardous materials have to be taken out during the EoL process and treated in a different way than the rest of the cells. This process step of treating hazardous materials is complex and as a result, costly. Therefore, it is favorable for a recycling company to have PV cells with low or no shares of hazardous materials.

Average weight

Recycling companies try to get the highest possible value out of the incoming material. Under this point of view, it is important to have a high amount of material within a specific PV cell, which can be treated during the EoL stage and sold afterwards.

Market share

Another important criterion for recycling companies is the amount of PV cells they can receive. The differences in design of the various types of PV cells require differences during the treatment in the EoL stage. It is costly to establish a recycling line for a specific PV cell and therefore, it is important to have enough incoming material for using the capacity in an efficient manner. The amount of incoming material from a specific type of PV cells can be expressed by the market share of this specific type.

Energy efficiency

From the recycling company point of view, it does not matter if the PV cells have been not energy efficient during their lifetime.

Life duration

The life duration of PV cells has no influence on the performance of recycling companies and therefore, this criterion is not important under this point of view.

Production cost

For a recycling company, it does not matter how much effort it takes to produce a PV cell, which means that this criterion is not important for a recycling company.

Light absorption

The light absorption is another unimportant criterion from the point of view of a recycling company and will not be considered by such a company.

Energy payback time

Similar to other criteria, this criterion is part of the performance of the PV cells during their use and has no effects on the business of recycling companies.

Greenhouse gas emissions

A recycling company is not related to the emissions of greenhouse gases during the use of the PV cells and will not consider this criterion.

In Table 40, an example of weight factors denoted by a recycling company is provided.

Criteria No.	Criteria	Weight Factor
1	Valuable material	0.35
2	Hazardous material	0.15
3	Average weight	0.25
4	Market share	0.25
5	Energy efficiency	0
6	Life duration	0
7	Production costs	0
8	Light absorption	0
9	Energy payback time	0
10	Greenhouse gas emissions	0

Table 40: Weight factors from the recycling company point of view

Criteria	1	2	3	4	5	6	7	8	9	10	Weighted
Weight Factor	0.35	0.15	0.25	0.25	0.00	0.00	0.00	0.00	0.00	0.00	EoLV
PV Cells											
Monocrystalline	3	0	2	5	5	5	1	5	1	1	
Weighted	1.05	0.00	0.50	1.25	0.00	0.00	0.00	0.00	0.00	0.00	2.80
Multicrystalline	3	0	3	5	5	5	2	4	2	2	
Weighted	1.05	0.00	0.75	1.25	0.00	0.00	0.00	0.00	0.00	0.00	3.05
a-Si	5	5	5	0	1	2	5	2	3	2	
Weighted	1.75	0.75	1.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.75
CdTe	0	0	1	2	1	2	3	3	4	4	
Weighted	0.00	0.00	0.25	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.75
CIS/CIGS	3	3	4	1	1	2	5	4	4	3	
Weighted	1.05	0.45	1.00	0.25	0.00	0.00	0.00	0.00	0.00	0.00	2.75

Table 41: Case study recycling company: Summary of the evaluation

The evaluation presented in Table 41 shows the ranking of the PV cells from the perspective of a recycling company. It can be seen that recycling companies prefer silicon based PV cells, especially a-Si cells, due to their possible high value after the EoL treatment. On the other side, CdTe cells are not very favorable for recycling companies.

14.3. PV cell manufacturing company

Basically, PV cell manufacturing companies try to produce and sell as much PV cells as possible. From the viewpoint of such companies, it is very important to produce at low costs and with a high quality. As a result, criteria that are describing such factors are important for PV cell manufacturing companies, while other criteria are not that important.

Similar to recycling companies, ecologic criteria are not the first priority of PV cell manufacturing companies, as the primary aim of companies is profit making. On the other hand, it might be useful to have products that do not harm the environment, due to gaining a positive image that can be used during marketing the products. Again similar to recycling companies, the importance of the criteria may vary to a high degree between different companies, different countries and different points in time. The criteria are discussed briefly below.

Valuable material

This criterion is not important for PV cell manufacturing companies, as they do not gain profit from the valuable material. In contrast to that, it is advantageous for such companies when the material used in PV cells is not valuable, as this implies that the costs for resources during production are lower.

Hazardous material

Similar to the first criterion, this criterion is not important for PV cell manufacturers, as they do not need to care about the PV cells and especially about the recycling of these cells during the EoL management.

Average weight

This criterion is also not important for PV cell manufacturing companies, because they do not need to think about the EoL stage and do not gain profits from this phase of the life cycle of the cells. As a result, this criterion is not important for these companies.

Market share

This criterion is crucial for manufacturing companies. A high market share of a specific type of PV cells has several advantages for a manufacturer of these PV cells, e.g. higher economies of scale allow lower production costs.

Energy efficiency

On the one hand, PV cell manufacturing companies have no direct value from producing energy efficient PV cells. On the other hand, a higher energy efficiency of the products of a company will probably lead to higher sales and a better image. Therefore, this criterion has an average importance for PV cell manufacturing companies.

Life duration

This criterion has similar characteristics as the criterion “energy efficiency”. It does not have direct positive effects, but higher life duration has several effects providing a competitive advantage comparing to competitors.

Production cost

The production costs are very important for manufacturing companies, as they directly affect the costs and as a result, the profits of a company. The lower the production costs are, the higher are the profits and/or the lower are the prices for the consumer.

Light absorption

This criterion is important for the future development of PV cells. It is therefore not influencing the present profits, but might give a hint showing the future potentials of a specific type of PV cells.

Energy payback time

This criterion is similar to other criterions, which do not have a direct, but an indirect influence on the profits and the performance of PV cell manufacturing companies.

Greenhouse gas emissions

Also this criterion does not have a direct influence on the manufacturing company, but it has indirect effects due to an increase of the brand value.

In Table 42 an exemplary set of weighting factors from the point of view of a PV cell manufacturing company based on the brief discussion above is shown.

Criteria No.	Criteria	Weight Factor
1	Valuable material	0.00
2	Hazardous material	0.00
3	Average weight	0.00
4	Market share	0.20
5	Energy efficiency	0.10
6	Life duration	0.10
7	Production costs	0.30
8	Light absorption	0.10
9	Energy payback time	0.10
10	Greenhouse gas emissions	0.10

Table 42: Weight Factors from the solar cell manufacturing company point of view

Criteria	1	2	3	4	5	6	7	8	9	10	Weighted
Weight Factor	0.00	0.00	0.00	0.20	0.10	0.10	0.30	0.10	0.10	0.10	EoLV
PV Cells											
Monocrystalline	3	0	2	5	5	5	1	5	1	1	
Weighted	0.00	0.00	0.00	1.00	0.50	0.50	0.30	0.50	0.10	0.10	3.00
Multicrystalline	3	0	3	5	5	5	2	4	2	2	
Weighted	0.00	0.00	0.00	1.00	0.50	0.50	0.60	0.40	0.20	0.20	3.40
a-Si	5	5	5	0	1	2	5	2	3	2	
Weighted	0.00	0.00	0.00	0.00	0.10	0.20	1.50	0.20	0.30	0.20	2.50
CdTe	0	0	1	2	1	2	3	3	4	4	
Weighted	0.00	0.00	0.00	0.40	0.10	0.20	0.90	0.30	0.40	0.40	2.60
CIS/CIGS	3	3	4	1	1	2	5	4	4	3	
Weighted	0.00	0.00	0.00	0.20	0.10	0.20	1.50	0.40	0.40	0.30	3.10

Table 43: Case study PV cell manufacturing company: Summary of the evaluation

From the evaluation shown in Table 43 can be seen how the different types of PV cells can be ranked according to the viewpoint of a PV cell manufacturing company. Multicrystalline PV cells are preferred, followed by CIS/CIGS cells, monocrystalline cells, CdTe cells and finally a-Si cells.

14.4. Summary of the case studies

These case studies show how the types of PV cells can be ranked in different ways, according to different points of view, leading to different rankings. The preferences have been expressed by varying the weighting points, showing the preferences of the different points of view.

The various PV cells have different advantages and disadvantages. These differences are the reason for the specific outcomes of the rankings.

15. Discussion and analysis

In this chapter, the results of the presented evaluation are discussed and analysed.

15.1. Topics related to the EoL management of PV cells

The goal of EoL management is to maximize the output that can be obtained from the waste materials that enter the waste cycle. In order to make this process optimal, it is very important to put as less as possible harmful influences on the environment.

As can be seen in the evaluation above, the PV cells with the highest material value are crystalline PV cells, both monocrystalline and multicrystalline/polycrystalline cells. The EoL management has to consider these cells first, in order to waste as less value as possible in this stage.

15.2. Topics related to the production of new PV cells

This chapter is not just about EoL management in a narrow definition, but about a view on the whole life-cycle of a product, starting at the design and production stage, over the use stage to the EoL stage at the end of the life-cycle. For this topic, the consideration does not start with a pre-given amount of waste that has pre-given characteristics and has to be treated in the best possible way. Herein, the design and the production of PV cells are considered too, as these stages have important influences on the whole life-cycle of a product and especially on the EoL management. Solutions that are just considering the production and the use stage of a product are not the best way, as they might create problems in the EoL stage. For example, it might be easier and cheaper for the production of a product to use welded connections instead of screws, but at the EoL stage, these connections might reduce the value of the waste product as the product has to be destroyed to separate different parts. Screws, on the other hand, might be more costly, but have the advantage that the different parts that built-up the product can be separated easily and these parts can be reused independently from each other without being destroyed. For example, in chapter 7.3.1 a-Si PV modules with a nanocrystalline-silicon bottom layer are discussed. These kinds of PV cells have demonstrated a high efficiency in the process of photon-to-electricity conversion, but on the other hand the life-cycle energy and environmental implication of such nano designs has yet to be investigated.

16. Conclusion

This dissertation aimed to develop a new quantitative evaluation model for finding an optimal kind of PV cells from the EoL point of view and additionally, from a whole life-cycle point of view. Considering the model, different kinds of PV cells are analysed and ranked according to various criteria. Additionally, some case studies have been presented, which aim at considering the PV cells from different points of view.

PV cells construction and materials

It is important to know the structure of the PV cells. It is vital to know which materials can be found to which extend in the PV cells and where these materials can be found. This knowledge influences the decision for an EoL strategy to a high degree. It is also necessary to consider the ecological impact and legal restrictions resulting from that. The most important material within PV cells has been and still is silicon. Silicon dominates the present world market especially in crystalline form but a-Si cells are also at the high level of importance. Crystalline silicon cells have a large potential for cost reduction in its conventional form. Taking a look at analysed data provided in this study, it can be seen that the production costs for monocrystalline PV cells and multicrystalline PV cells are high.

There is a great hope with the thin-film materials, which require only small amounts of material; amorphous silicon, cadmium telluride and copper indium gallium selenide are the most hopeful materials herein.

PV cells Market share

Furthermore, a profound knowledge of the market is important. In order to decide on the optimal EoL management strategy, the market situation of the PV cells itself and also on the other hand the market situation of the valuable raw materials that are used in PV cells should be taken into granted. Especially the prices for the materials extracted from the PV cells during the EoL process are important and influence the decision for the most efficient EoL strategy to a high degree.

Characteristics of the presented model

The model has a general scope and is not restricted to a specific group of PV cells or to a specific company or to any specific situation in a specific country. Additionally, the findings can be generalized across other kinds of products. For example, it can be applied across telecommunication and electronics devices. Furthermore, the model fits both old and new data.

The model is simple and user-friendly, because it does not have too many variables and it is not dependent on special circumstances. Further, the variables in this model are easy to understand and intuitive for a person, who is familiar with the topic of EoL management.

The model uses mathematic (equations) rather than verbal descriptions. This characteristic makes the model accurate and trust-worthy as well.

The model is adaptable and flexible**.** The variables and values can be changed, according to the individual cases. Additionally, the values stated in the evaluation are dependent on the new technologies and developments in the future, which mean that the inputs can be changed. As mentioned above the model fits old and new data, which makes it flexible.

17. Learning and outlook

In this chapter the potential for further research around the topic of EoL management of PV cells are discussed. The chapter is divided into two sections, in the first section, the improvement factors for the presented model are discussed and in the second section, general improvement factors around the topic of EoL management of PV cells are provided.

17.1. Improvement of the model

Considering the evaluation model presented in this paper, three main areas of improvement are suggested:

- Improvement of parameters; for example weight factors.
- Implementation of the model for other kinds of PV cells than the mentioned ones. Considering new technologies, as there will be a lot of various PV cells produced in the near future. At the moment, the information available about new PV cells is limited.
- Analyzing the mentioned PV cells in more detail and for special surroundings and environments.

17.2. Improvement of EoL management

One potential field of research is the improvement of the low-cost disassembly processes for PV cells. It is important to mention that one of the essential factors in recycling of PV cells is the separation and concentration of the materials. PV modules are rather difficult in recycling through the glass-recycling process, due the amount of metals that they contain. It is also difficult to grind the laminate to cullet specifications. If PV cells did not contain a laminated system, then it might be possible to have more sufficient recycling processes, which make it possible to separate the glass through glass-recycling processes and the films through the metal recycling processes. Further work on methods for disassembling PV modules will be important.

Another potential field of research is the development of standard recycling processes, which would be fulfilled through specific companies or utilities. As mentioned before there exist already some few recycling processes or companies like PV CYCLE, but that is not enough and there would be a need of more standard processes of EoL management. For example**,** standard processes, which are flexible and give us the opportunity to use any kind of PV cell as an input**,** are desirable.

17.3. Improvement of semiconductors/materials used

With the development of new technologies, the photovoltaic industry faces the challenge to reduce costs whilst at the same time increasing efficiency to be able to compete with other kinds of renewable sources of energy. One of the areas of potential research is the material improvement.

For example, the currently existing crystalline silicon PV cells have a full aluminum back-side field (Al BSF) technology, which does not have the optimal efficiency. There is a research around the next generation of crystalline silicon solar cells, which introduces a semiconductor process toolbox. According to this study, there are plenty of new techniques including implantation, atomic layer deposition, Cu-plating and barrier layer technology that help to produce crystalline silicon PV cells with less cost and higher efficiency.

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19. Appendices

19.1. Appendices I

Element	World production 2007(tons/year)	TMR(tons/ton)
Copper	15,600,000	300
Cadmium	19,900	2,000
Indium	510	200,000
Selenium	1,550	1,000
Tellurium	135	270,000

Table I: World production and TMR for elements used for thin film PV modules

(Berger, Simon, Weimann & Alsema, 2010)

19.2. Appendices II

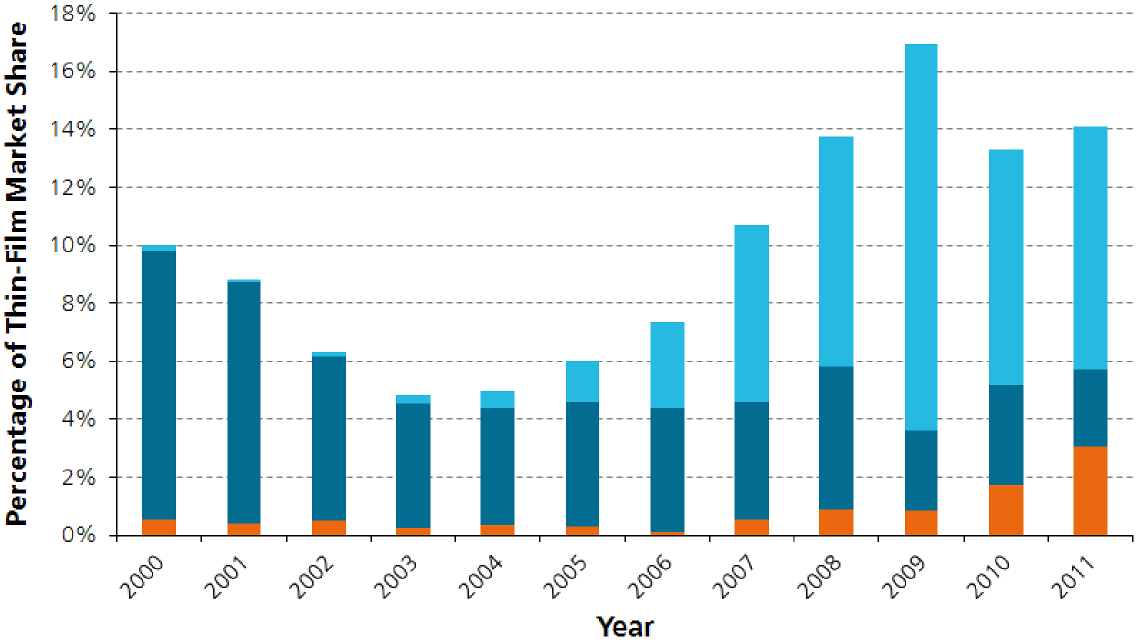

Figure I: Market Share of Thin-Film Technologies Related to Total Worldwide PV Production

(Fraunhofer, 2012)

19.3. Appendices III

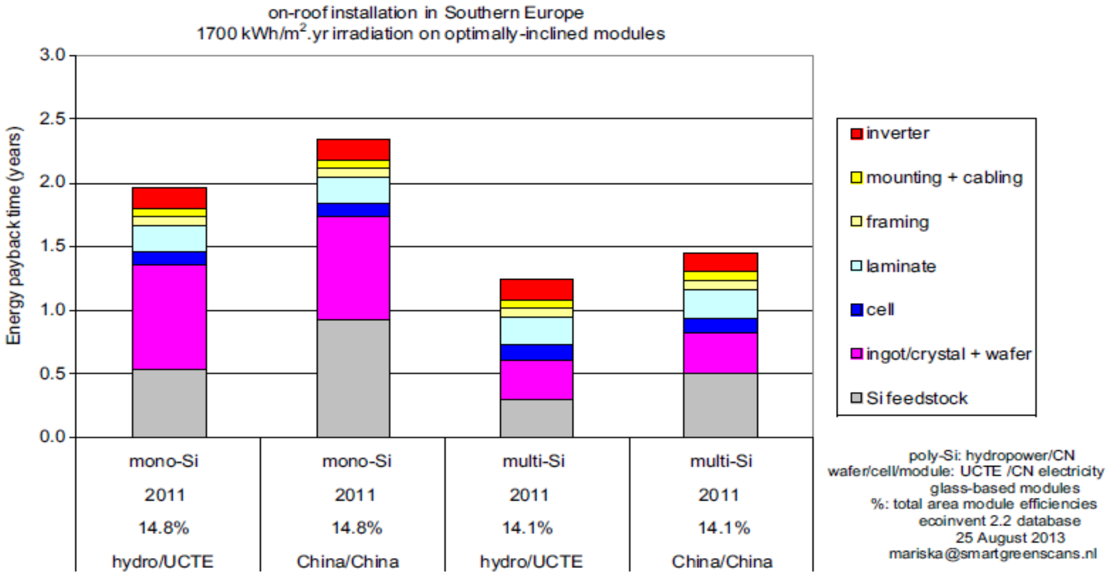

Figure II: Energy Payback Time of Si-cells

(de Wild-Scholten, 2013)

Curriculum vitae

Mahsa Masoumian, MSc, BSc

Weißes Kreuz Gasse 96/29/4
2340 Mödling

Telefon: 02236/367191
Mobil: 0680/1325315
E-mail: mahsa.masoumian@gmail.com

Persönliche Daten

Geburtsdatum	29.11.1982
Geburtsort	Teheran, Iran
Nationalität	Iran

Ausbildung

Seit 2011	Doktoratsstudium: TU Wien Maschinenbau - Recycling
09/2007 - 07/2009	Masterstudium: Chalmers Tekniska Högskola, Göteborg, Schweden Qualitäts- und Prozessmanagement Titel der Diplomarbeit: “Improving Quality Management Systems through Lean concept”
09/2001 - 07/2005	Bakkalaureatsstudium: Universität für Wissenschaft und Kultur, Teheran, Iran Wirtschaftsingenieurwesen Titel der Diplomarbeit: "Industrial Plants Design"

Relevante Berufserfahrung

Seit 06/2012 Ikea Vösendorf

- Kundenservice

01/2011 - 10/2011 Securikett Ulrich & Horn GmbH (http://www.securikett.com), Österreich
Marketingassistentin

- Kundenbetreuung
- Marktanalysen und -auswertungen
- Erstellung von Marketingunterlagen

12/2008 - 06/2009 Åmål Components AB (http://www.acomp.se/en/index.html), Schweden
Internes Consulting

- Gestaltung von Prozessen
- Ausarbeiten eines QM-Handbuches
- Unternehmensrichtlinien zu ISO 9001, ISO/TS 16949 und ISO 14001

02/2008 - 07/2008 Volvo Powertrain (http://www.volvogroup.com), Schweden
Vorstandsassistentin

- Six Sigma Projekt

10/2006 - 08/2007 Peymankhadir Company (http://www.nicsaco.com/index.html), Iran
Projektmanagement

- Projektmanagement und –controlling
- Arbeitspläne, Zeitpläne, Kostenpläne
- Schnittstelle zwischen Kunden und Produktion

08/2005 - 08/2006 Keyfiat Pardaz (http://ir.kompass.com/keyfiat-pardaz-ps.html), Iran
Management-Consulting

- Einführung von
    - ISO 9001
    - ISO 14001
    - OHSAS 18001
- Prozessoptimierung
- Breite Branchenerfahrung

07/2004 - 09/2004 Irankhodro (Automobilhersteller) (http://www.ikco.com/en/), Iran

- Zeitstudie
- Qualitätskontrolle

Sprachkenntnisse

Persisch	Muttersprache
Englisch	Verhandlungsfähig
Deutsch	Gut
Schwedisch	Gut

EDV Kenntnisse

MS Office (ECDL), MSP (Microsoft Office Project), Primavera, Minitab

Sonstiges

Führerschein Klasse B

Freizeitinteressen

Lesen, Fremdsprachen, Kino, Musik