Topten Technology Paper on Photovoltaic Modules

Freiburg, den 17.11.2014

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List of abbreviations

ADP	abiotic depletion potential
AP	acidification potential
a-Si	amorphous silicon
CdTe	cadmium telluride
CED	cumulative energy demand
CIGS	copper indium gallium diselenide
CIS	copper-indium delenide / sulfide cells
CML	Institute of Environmental Sciences, Leiden University
CO_2e	carbon dioxide equivalent
c-Si	crystalline silicon cells
CTU	comparitive toxic units
EP	eutrophication potential
EPBT	energy payback time
GWP	Global warming potential
GPBT	greenhouse gas payback time
IEC	International Electrotechnical Commission
kWh	Kilowatthour
kWp	Kilowatt(peak)
LCA	Life Cycle Analysis
MJ	Megajoule
sc-Si	Single-crystalline silicon
PCF	Product Carbon Footprint
PO_4e	phosphate equivalents
mc-SI	multicrystalline silicon
PR	Performance Ratio
PV	photovoltaic
ribbon-Si	String Ribbon silicon cells
RoHS	Restriction of the Use of Certain Hazardous Substances
Sbe	antimony equivalent
SO_2e	sulphur dioxide equivalent

UCTE	Union for the Co-ordination of Transmission of Electricity
WEEE	Waste Electrical and Electronic Equipment

1 Product definition

1.1 Definitions

A **solar cell** is an electrical device made of a semiconductor material that converts the energy of the sun into electricity by a photovoltaic effect.

Solar cells are often electrically connected to form a photovoltaic arrangement called a **module**. A module consists of several connected solar cells which are usually encapsulated between glass or plastic panes and inserted into a metal frame. Modules are installed on the roof or on an open area, using a mounting system.

A **photovoltaic system** is an arrangement of modules, wiring, rechargeable batteries, inverters and so on, designed to produce electricity, convert it into usable forms, and feed it into the grid or supply energy-using appliances. The British Solar Trade Association describes the usual components of a photovoltaic system as follows:

- Solar cells and modules
- Power inverters (necessary if: the system is connected to the public power supply system or the electricity is intended to be used in a system for conventional alternating current which runs electrical appliances)
- Solar photovoltaic mounting system (will be needed to accommodate the photovoltaic system)
- Isolators (enabling the separation from and within the photovoltaic system for safety reasons when carrying out installations, upgrades and maintenance work)
- Cables and connectors (used to connect the various components of the photovoltaic system and selected based on the size and characteristics of each system)
- System monitoring (required to monitor the quantity of electricity produced, exported to the grid and used by the property. This can be carried out by most commercially available inverters and can be integrated into PC and web applications)
- Junction box (These are used to allow the parallel connection of several strings of photovoltaic modules)
- Rechargeable batteries (necessary if the system is off-grid) (Solar Trade Association UK 2013

1.2 Technologies

There are various solar cell technologies on the market. They can be classified with respect to material, material thickness (thin-film solar cells or cells from bulk materials), or crystal structure.

Materials used for photovoltaic cells include single crystalline silicon (sc-Si), multicrystalline silicon (mc-Si), amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium selenide/sulfide (CIS). Materials differ with respect to the characteristics of the light they are able to use, e.g. CIS cells generate energy with direct as well as with diffuse light, mono- and polycrystalline cells have losses when light is diffuse (DAA 2014).

Silicon remains the only material that is commonly used in both *bulk* and *thin-film* forms. Solar cells from bulk materials are manufactured by cutting the material into thin slices, so-called *wafers* (180 to 200 micrometers). These are then processed like any other semiconductor. In *thin film* solar cells, which can be made from silicon or other materials, the material is deposited in the form of thin films layers, organic dyes, or organic polymers on supporting substrates.

Figure 1 gives an overview.

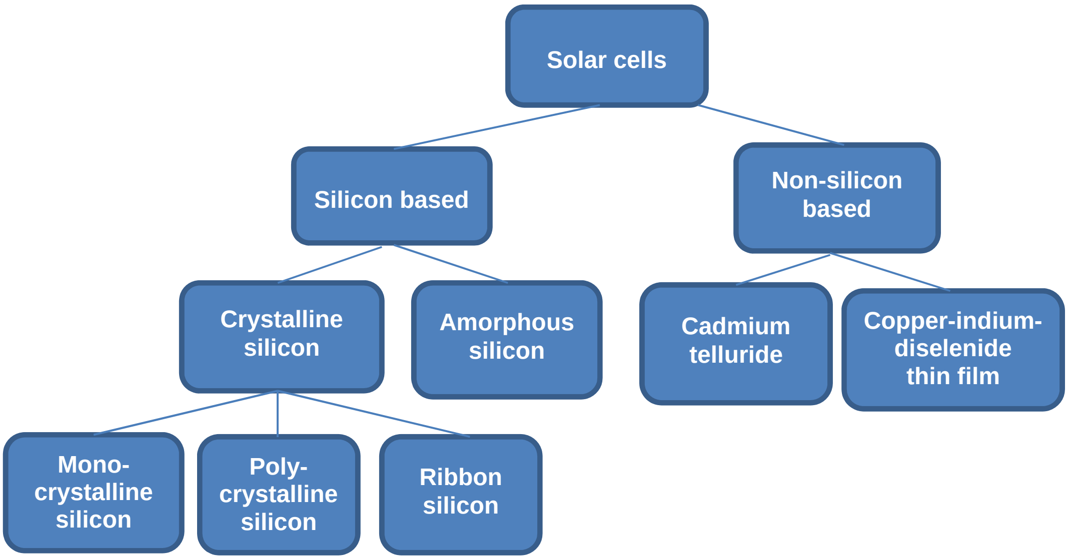

Figure 1: Solar cell types. Source: Authors.

The market share of different photovoltaics technologies is pictured in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

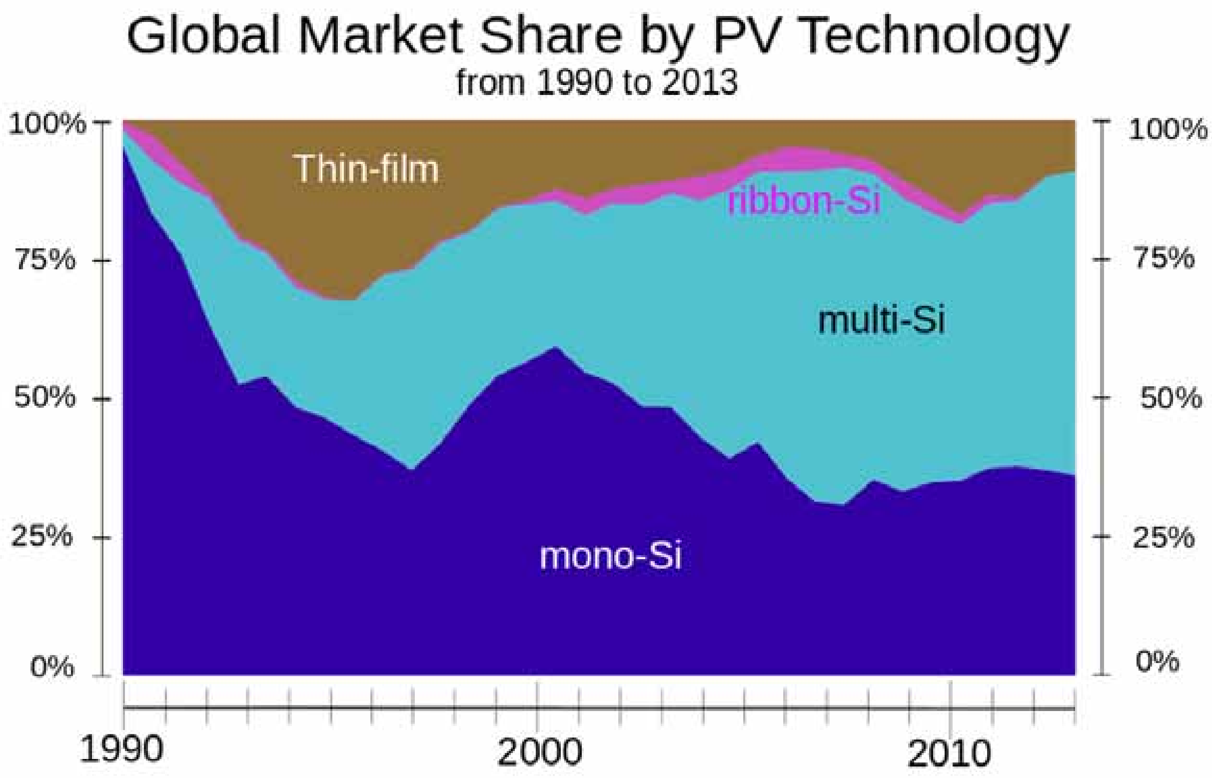

Figure 2 Global market-share by photovoltaic technology from 1990 to 2013, in terms of annual worldwide production. Technologies include as follows, crystalline silicon (c-Si) encompassing monocrystalline silicon (mono-Si), polysilicon (multi-Si) and ribbon silicon (ribbon-Si), as well as thin-film technology, including amorphous silicon, CdTe and CIGS. Source: Fraunhofer ISE, Report, current edition data from archived edition, July 28, 2014, page 18 via Wikipedia 2014

The composition of crystalline and amorphous silicon, copper-indium selenide / sulfide and cadmium telluride cell technologies is illustrated in Table 1. Because of the different composition, the different technologies imply different availability of the material and different environmental impact during manufacturing and end-of-life phases (see for details chapter 8).

Table 1 Composition of various photovoltaic technologies (Source: BINE 2007)

	c-Si (crystalline silicon cells)	a-Si (amorphous silicon cells)	CIS (copper-indium delenide / sulfide cells)	CdTe (cadmium telluride cells)
	Percentage [%]			
Glass	74	90	85	95
Aluminium	10	10	12	<0.01
Silicon	~ 3	<0.1		
Polymers	~ 6.5	10	6	3.5
Zinc	0.12	<0.1	0.12	0.01
lead	<0.1	<0.1	<0.1	<0.01
Copper (cable)	0.6		0.85	1
Indium			0.02	
Selenium			0.03	
Tellurium				0.07
Cadmium				0.07
Silver	<0.006			<0.01

Furthermore, cell technologies vary with respect to efficiency. It is difficult to arrive at unambiguous conclusions in this respect. First, information from different sources varies greatly. Secondly, efficiency is often higher in prototypes than in mass production, higher in the laboratory than in practice, and higher in individual cells than in a module. They also vary with the temperature of the cells. Sources usually do not give sufficient information on the conditions under which cell efficiency has been determined. Table 2 gives a rough overview of different sources that shows broad trends.

Table 2: Efficiency of different cell technologies (Gröger et al. 2013)

Cell technology	**Efficiency [%]***
Crystalline silicon (c-Si)	
Single-crystalline silicon (sc-Si)	14-20 (Lab: up to 24)
Multicrystalline silicon (mc-Si)	12-16 (Lab: up to 18)
Amorphous Silicon (a-Si)	5-8 (Lab: up to 13)
Cadmium telluride (CdTe)	6-10
Copper-indium-diselenide-thin film (CIS)	6-13 (Lab: up to 20)

* *Includes laboratory and field values as well as values for cells and modules. Laboratory values and cell-related values are higher. Sources: http://www.solarserver.de/wissen/basiswissen/photovoltaik.html (from 2010); ZSW Baden-Württemberg www.zsw-bw.de (from 2011), Fraunhofer ISE 2011, Fraunhofer ISE 2013, http://www.photovoltaik.org/wissen/photovoltaik-wirkungsgrad (undated), http://www.solaranlagen-portal.com/photovoltaik/vergleich (undated)*

In the following chapters, the individual technologies are described.

1.2.1 Crystalline silicon cells

The main advantage of silicon cells is that there is no shortage of material: silicon is the second-most frequent element of the earth`s crust and available in nearly unlimited quantities. But the process of producing high-purity silicon is very energy-intensive and could result in production bottlenecks. Mono- (mono-Si) and polycrystalline (poly-Si) cells are both produced by cutting silicon crystals into thin discs (wafers). Mono-crystalline cells are produced from one single silicon crystal. This procedure avoids losses caused by cracks and impurities of the material, and therefore guarantees a relatively high efficiency of 14 to 20 percent, but it is quite expensive and energy-intensive. For polycrystalline cells, liquid silicon is poured into blocks which are sawn afterwards. When moulding the silicon, crystals in different sizes form. At the edges of the crystals, impurities and cracks occur. Hence they have a lower efficiency of 12 to 16 percent. This technology represents about 85% of the market today (EPIA 2013_a))

In both processes, losses of material occur when blocks are cut and contaminated sections are removed.

1.2.2 String Ribbon silicon cells (Ribbon-Si)

In the string ribbon process, two thin wires are moved through the liquid molten silicon. Between them, a thin silicon film forms which solidifies into a wafer when cooling. This method produces less loss of material than the cutting of the blocks.

1.2.3 Thin film cells made from amorphous or microcrystalline silicon (a-Si)

Thin film cells are produced by (vapour-)depositing the semiconductor material on supporting substrates. Their thickness ranges from less than 1 µm to 10 µm. Therefore, very little material is needed.

In amorphous silicon cells, the semiconductor material is silicon. Production costs are very low because of the low material cost and the simple manufacturing method. However, their efficiency is also quite low, ranging from 5 – 8%. Besides, they degrade quickly during the first period of use and their efficiency decreases fast. On the other hand, amorphous silicon cells have the advantage that they generate energy also from diffuse light. They are applied primarily in the low power range (e.g. watches, calculators) or integrated in façades.

1.2.4 Copper-indium diselenide / sulfide cells

Copper-indium diselenide / sulfide cells have the highest efficiency of all thin film cells (6-13%). They are however also the most expensive. A problem is the use of rare metals like indium or gallium which are also needed for other products like white LEDs (gallium) or for flat panel displays (indium).

1.2.5 Cadmium telluride cells

Cadmium telluride cells have an efficiency of 6-10% and are relatively inexpensive. Cadmium is a co-product of the zinc production and can be recovered, for example, from used batteries. Prices for cadmium have fallen during the last few years, maybe because of the cadmium ban in electronics products by the EU directive 2011/65/EU (ROHS-directive). The ROHS-directive is not valid for photovoltaic modules, but the toxicity of cadmium can be still be viewed as problematic. As the cadmium telluride compound is chemically stable, it poses no risk for health or environment during regular use. However, in case of fire or if broken by accident or during disposal, cadmium can leak. Therefore, the professional disposal of CdTe cells is indispensable. Up to now CdTe cells have not yet reached the end of their life cycle, so that no experience with the disposal exists so far.

1.3 Emerging technologies

Several other types of PV technologies are being developed today or are starting to be commercialised, including concentrated photovoltaics or **“concentrator cells”** (operates with concentrated sunlight, using a lens to focus the sunlight onto the cells) and **flexible cells** (similar production process to thin film cells, their flexibility opening up the range of applications) (EPIA 2013).

A number of other cell technologies exist, which are however not relevant for photovoltaic systems up to now. They are either used for special purposes (e.g. astronautics; functional clothes, small uses …) or they are still in a developmental stage.

- Thin layer cells with high efficiency can be produced using gallium arsenide (GaAs); they are used in astronautics.
- With tandem cells, different materials are piled up to achieve better efficiencies.
- Organic solar cells are made from thin films of organic semiconductors, including polymers, and promise low prices and easy use.
- Dye sensitized solar cells (Grätzel cells) imitate the mechanism of photosynthesis.
- Quantum dot solar cells are made from nanocrystals of semiconductor material. The interesting aspect about them is that they can be adjusted to harvest different sections of the solar spectrum by adjusting particle size.

1.4 Global market trends

During the next few years, the USA and Asia (in particular India and China) could reach the highest annual growth rates of all countries and become the growth markets of the future, while growth will weaken in Europe. In the long term, the photovoltaic sector expects high growth rates particularly in the very sunny regions of the world, called "Sun Belt".

In the nearer future, a consolidation of the market is expected, caused by existing overcapacities in module production, which implies a high pressure on module prices. In the sector, the opinion prevails that in foreseeable future only a handful of manufacturers will dominate the photovoltaic module market worldwide (Gröger et al. 2013).

2 Quality and environmental aspects

2.1 Conversion Efficiency

The energy conversion efficiency of a solar cell is the percentage of the solar energy to which the cell is exposed that is converted into electrical energy (Office of Energy Efficiency & Renewable Energy 2013). The efficiency of the modules is generally about 10-15% lower than the efficiency of the individual cells, and the efficiency of the whole photovoltaic system is again lower, being also influenced by the wiring of the modules as well as the inverter.

2.2 Performance ratio

The **performance Ratio (PR)** describes the ability of a module to maintain its output as continuously as possible under different conditions (e.g. weak light, warming). It is defined as the ratio of the actual yield – taking into account the efficiency – to the theoretically possible yield. Thus a module with an efficiency of 15% which produces 150 kWh per year with an annual solar irradiation of 1000 kWh would have a PR of 100%. The same is true for a module with an efficiency of 10% which produces 100 kWh under the same amount of irradiation. In reality, maximum PRs of approx. 90% are achieved.

2.3 Durability

Durability issues include both the degradation of the performance over time, as described above, and the physical durability, for example resistance against corrosion, overvoltage, UV light, and breaking. Durability issues are covered by various European standards (see chapter 4.2.2).

2.4 Hazardous substances

A much-debated issue is the cadmium content in CdTe cells. Cadmium is a heavy metal that is emitted to the environment mainly by combustion processes and the dumping of sewage sludges. Cadmium is absorbed and accumulated by plants and ends up in the human body via the food chain. It is accumulated mainly in the kidneys and may contribute to kidney malfunction and osteoporosis.

In CdTe cells, Cadmium is used in the form of the stable compound cadmium telluride. However, it may leak into the environment in case of a fire or unsafe disposal methods at the end of life of CdTe cells.

2.5 Results from LCAs

2.5.1 Literature review

A literature search shows that during the last years numerous LCA-or PCF-studies to the subject photovoltaic have been published.

In general, a comparison of the results of various LCAs is difficult, because core parameters such as goals of the study, temporal and geographical scope, system boundaries etc. vary. Furthermore, LCAs usually do not refer to the modules alone but to the complete photovoltaic system (including the modules, the electronic and if necessary mechanical components).

Still, some meta-analyses are available that offer some guidance to the question of the environmental effects of the different module technologies. Gröger et al. (2013) report results from several meta-analyses with respect to total greenhouse gas emissions, greenhouse gas emissions as a function of the electricity mix in production countries, pollutants such as cadmium, and material consumption. They are completed by the results of another recent meta-analysis (Turconi et al. 2013) and presented in the following chapters.

See also the work of the International Energy Agency (task 12)[1] on Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems and Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity. Both studies were published in 2011.

Greenhouse gas emissions

Hsu et al. (2012) have evaluated 397 existing environmental impact studies for **crystalline silicon cells**, and thereof selected 13 studies meeting certain minimum requirements, for example, regarding a good documentation of the main parameters and the quality of results. Then, the GWP results obtained under different framework conditions were broken down to uniform conditions. The harmonized parameters are listed in Table 3.

[1] See: http://www.iea-pvps.org/index.php?id=9&tx_damfetools_pi1[setCatList]=61-79

Table 3: List of parameters for silicon PV technologies, on the basis of which harmonized results were obtained in the study by Hsu et al. (2012)

Parameter	Amount
Service life	30 years
Performance Ratio (PR)	
-Ground-mounted plants	0.80
-Roof systems	0.75
Efficiency (average across service life)	
- Single crystalline silicon	13.0%
- Multicrystalline silicon	12.3%
Solar radiation	1,700 kWh/m²/a

Similar to the analysis undertaken by Hsu et al. (2012), H.C., Kim et al. (2012) evaluated 109 existing environmental impact studies examining **thin-film silicon cells**. Five of them were selected, meeting minimum requirements, e.g. in terms of good documentation of key parameters as well as of quality of results. Then, the GWP results obtained under different framework conditions were broken down to uniform conditions. The harmonized parameters are listed in Table 4.

Table 4: List of parameters for thin-film PV technologies, on the basis of which harmonized results were obtained in the study from H.C. Kim et al. (2012)

Parameter	Amount
Service life	30 years
Performance Ratio (PR)	
-Ground-mounted plants	0.80
-Roof systems	0.75
Efficiency (average across service life)	
-a-Si	6.3%
-CdTe	10.9%
-CIGS	11.5%
Solar radiation	1,700 kWh/m²/a[2]
Degradation of performance	0.5% per year

The harmonized results of both studies, relating to GWP, are summarized in Table 5.

[2] 1,700 kWh/m²/a describes the irradiation conditions prevailing in Southern Europe. In the states of Southern USA, 2,400 kWh/m²/a were assumed for the harmonization of results.

Table 5: Comparison of harmonized GWP values of different technologies (data from Hsu et al. 2012, H.C.Kim et al. 2012)

PV module/system	Module		System	
Installation type	**Ground-mounted plants**	**Roof systems**	**Ground-mounted plants**	**Roof systems**
a-Si (2004)	20 g CO_2e/kWh	21 g CO_2e/kWh	28 g CO_2e/kWh	29 g CO_2e/kWh
CdTe (2005)	17 g CO_2e/kWh	18 g CO_2e/kWh	23 g CO_2e/kWh	24 g CO_2e/kWh
CdTe (2008)	13 g CO_2e/kWh	14 g CO_2e/kWh	20 g CO_2e/kWh	20 g CO_2e/kWh
CIGS (2004)	45 g CO_2e/kWh	48 g CO_2e/kWh	51 g CO_2e/kWh	54 g CO_2e/kWh
CIGS (2003-2006)	30 g CO_2e/kWh	32 g CO_2e/kWh	37 g CO_2e/kWh	38 g CO_2e/kWh
sc-Si (average) mc-Si (average)	45 g CO_2e/kWh 55 g CO_2e/kWh		—	
sc-Si (minimum) mc-Si (minimum)	27 g CO_2e/kWh 26 g CO_2e/kWh			
sc-Si (median) mc-Si (median)	40 g CO_2e/kWh 47 g CO_2e/kWh			
sc-Si (maximum) mc-Si (maximum)	109 g CO_2e/kWh 183 g CO_2e/kWh			

The results of both studies relating to PV modules are summarized in Figure 3. It can be seen that thin-film technologies in principle have a lower global warming potential than traditional (crystalline) silicon technologies. This is due to the fact that the silicon wafer manufacture generally entails higher energy input. When compared to other PV technologies, CdTe, in terms of the greenhouse effect, performs the best.

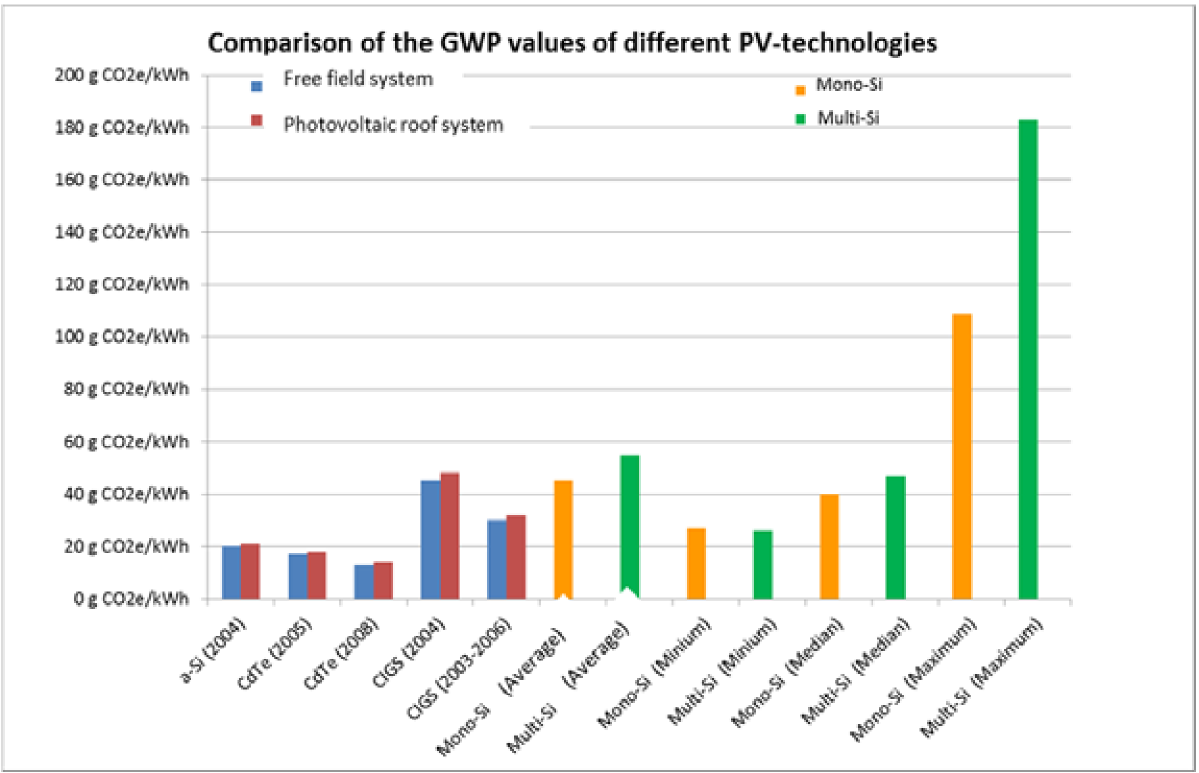

Figure 3: Comparison of harmonized GWP values of different PV modules (data from Hsu et al. 2012, H.C. Kim et al. 2012) Note: mono-SI = sc-SI; multi-SI = mc-SI

Turconi et al. (2013) conducted a meta-analysis of LCAs of various electricity generation technologies across different life cycle phases (fuel provision, use phase, and infrastructure) and environmental indicators (GHG, NO_x and SO_2 emissions). The following selection criteria were applied: the studies should be no more than 15 years old, they should differentiate either between the different life cycle phases or the different environmental indicators, and the functional unit should relate to electricity generation. They identified 22 studies that related to PV. All of them considered GHG emissions. All but one study related them to the manufacturing phase while the latter study also considered maintenance. GHG emission factors varied greatly, between 13 and 130kg CO2-eq/MWh (as becomes also clear in Figure 3). The authors ascribe the differences “to local conditions, such as the source of the electricity used during manufacturing, the typology of panels and the climate conditions where the panels were installed.” (Turconi et al., p. 561).

Electricity mix in the production phase

For a greenhouse gas balance, the country-specific electricity mix is crucial. Jungbluth et al. (2012) conducted a comparison, assuming the European and the Chinese electricity mix as the basis for their calculations. Figure 4 has been directly sourced from the study of Jungbluth et al. (2012). It can be seen that the greenhouse gas emissions of PV modules produced in China are approximately 70 percent higher than that of PV modules manufactured in Europe. The reason is that in China, the share of coal for the supply of electricity is currently at quite a high level (over 70 %).

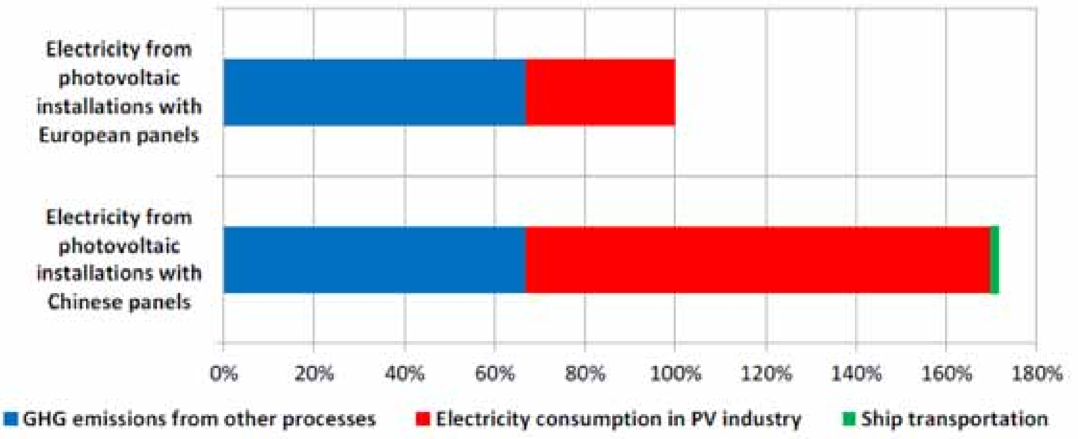

Fig. 17.4: Greenhouse gas (GHG) emissions from photovoltaic electricity produced with a European 3kWp installation on a slanted roof using multi-Si panels produced in Europe and China respectively.

Figure 4: Greenhouse gas emissions from multi-Si modules installed on a slanted roof, based on the assumption that a European and a Chinese electricity mix, respectively, will be used for production (figure directly sourced from Jungbluth et al. 2012)

The result is confirmed by Turconi et al. (2013) who don't give details though.

EPBT (Energy payback time) and GPBT (GHG payback time)

The energy payback time (EPBT) corresponds to the time duration it takes until the renewable energy produced by means of a photovoltaic system in the use phase will counterbalance the energy required for production, transportation, installation and disposal of the system. The "greenhouse gas payback time" (GPBT) is calculated in a similar way, however, taking greenhouse gas emissions instead of energy expenses as a basis for the calculations. There are numerous studies on and calculations of the EPBT and GPBT of different photovoltaic systems.

In their analysis of 2012, Jungbluth et al. depict the energy payback time differentiated according to installation types and module technologies. Figure 5 has been directly sourced from the study. In the study by Jungbluth et al. (2012), the EPBT varies between 1.5 and 4.8 years, the CdTe technology having the shortest energy payback time, which is in accordance with its low greenhouse gas emission value. Basically, the energy payback time of the façade-integrated installation type is approximately 1.5 years longer than that of the other types.

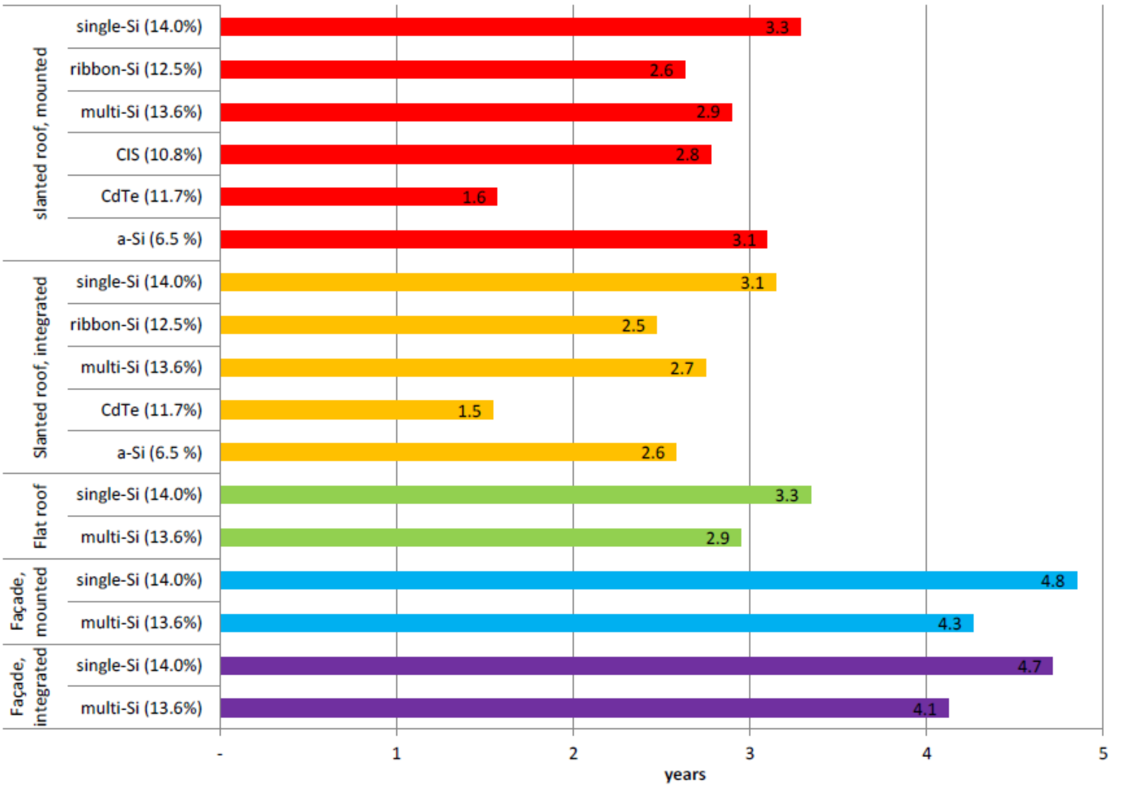

Fig. 17.5: Non-renewable Energy Pay-back Time of 3 kW_p photovoltaic power plants operated in Switzerland in relation to the UCTE electricity mix. Annual yield: 922 kWh/kW_p. The life cycle includes module production, installation, cabling, inverter, maintenance, and disposal.

Figure 5: Comparative evaluation of PV systems with different module types in terms of their energy payback time (EPBT) (figure directly sourced from Jungbluth et al. 2012). Note: single-SI = sc-SI; multi-SI = mc-SI

Fehler! Verweisquelle konnte nicht gefunden werden. and Figure 6 summarize various sources relating to different geographical locations. The results refer to southern Europe and the United States and, over the bandwidth, are in line with the values obtained by Jungbluth et al. (2012). In another interesting study on mono-silicon technology, the geographical location of Hong Kong was investigated. Due to the higher proportion of coal in the energy mix for production, the overall energy payback time in this location exceeds that of other sites. It amounts to at least seven and a maximum duration of 20 years, depending on the direction and the angle of the installation. Another interesting aspect is the calculation of the GPBT (greenhouse gas payback time) in the study of Lu Yang (2010). The greenhouse gas-related payback time varies according to the electricity mix used as a reference for calculation (see Table 6). It amounts to between 3.6 and 5.2 years.

Table 6 Compilation of energy payback times from different sources (Gröger et al. 2013)

	Alsema et al. 2006	**Fthenakis et al. 2008**	**Pacca et al. 2006**	**Lu & Yang 2010**
Installation type	Roof-mounted	Ground-mounted	Roof-mounted	Rooftop installation
Geographical reference	Southern Europe	Southern Europe	USA	Hong Kong
EPBT (energy payback time)	-sc-Si: 2,7a -mc-Si: 2,2a -Ribbon-Si: 1,7a	-sc-Si: 2,7a -mc-Si: 2,2a -Ribbon-Si: 1,7a -CdTe: 1,1a	-a-Si: 3,5a	Mono-Si South-Facing 22.5° (Base Case): 7,3a South-Facing 0°: 9.8a South-Facing 30°: 7.1a South-Facing 90°: 13.3a East-Facing 90°: 18.8a West-Facing 90°: 20.0a
GPBT (greenhouse gas payback time)	no data available	no data available	no data available	Electricity mix assumption 671g CO_2e/kWh: 5.2a (base case; in the other cases, variations as above) Electricity mix assumption 980g CO_2e/kWh: 3.6a (base case; in the other cases, variations as above)

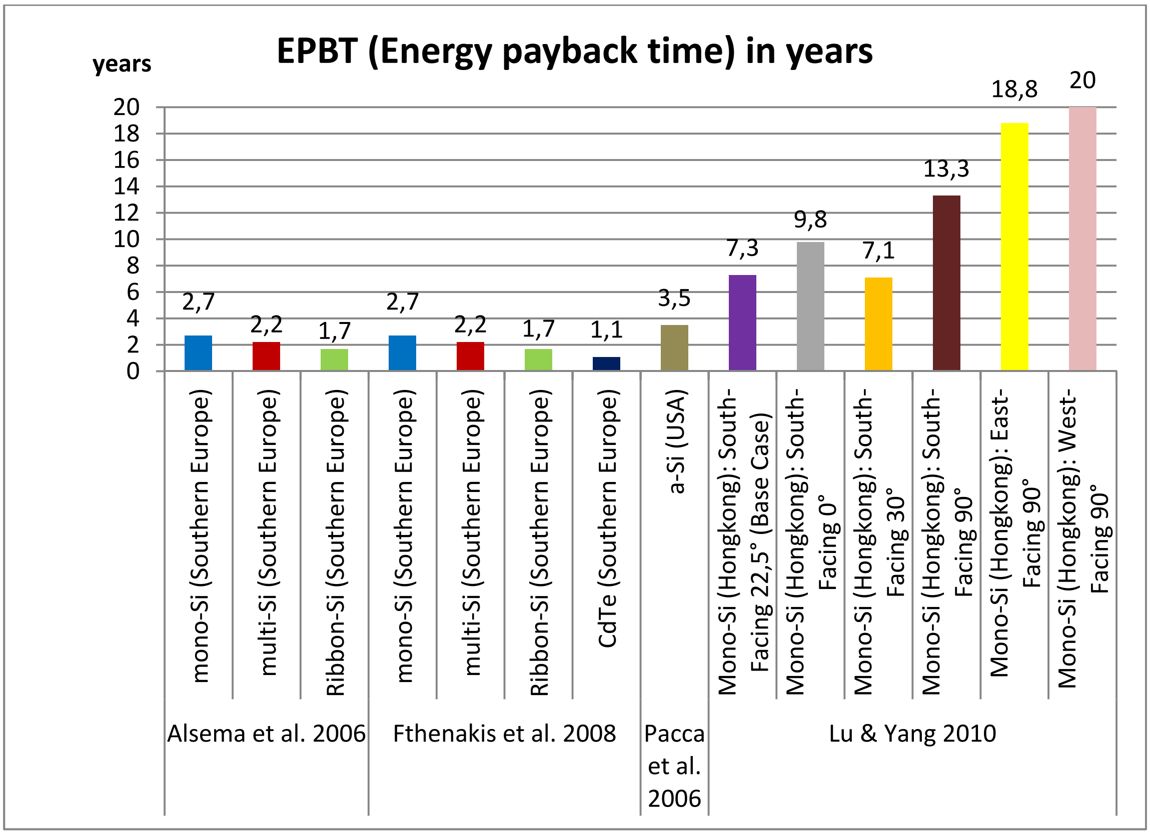

Figure 6: Compilation of EPBT calculation from different sources (author`s own diagram based on Gröger et al. 2013) Pollutants – Cadmium (Cd). Note: mono-SI = sc-SI; multi-SI = mc-SI

A problem encountered with CdTe lies in the fact that one of the raw materials used for CdTe, the heavy metal cadmium, is highly toxic. Hence, there are numerous investigations and discussions on the issue with regard to a possible emission of cadmium during production, use and disposal, and on its potentially dangerous effects on the environment, especially in the event of unexpected situations such as a house fire or inadequate disposal. On its website, the CdTe manufacturing enterprise First Solar has published independent studies as well as reviews carried out by expert commissions concerning the toxicity of CdTe modules.[3] The studies show that the CD in the CdTe compound is very stable. In the event of unexpected incidents such as a house fire or an uncontrolled disposal resulting in the leaching to groundwater, the emitted quantities of CD are negligible according to these studies.

The Fraunhofer Center for silicon photovoltaics CSP has published a scientific comment on several studies[4] containing a toxicity evaluation of CdTe modules and risk assessments. Accordingly, the CdTe compound should not be governed by the regulations concerning metallic cadmium or $CaCl_2$, but must be classified on an individual basis, since CdTe has a lower toxicity than Cd or $CaCl_2$. However, the CSP recommends companies starting with the new production of CdTe to conduct their own LCA studies and to develop their own disposal or recycling approaches in order to obtain more data and to create a sound database.

Figure 7 illustrates the results of the Cd emissions of PV electricity published in the study of Fthenakis et al. (2008) in comparison to other sources of energy, Cd emissions from CdTe modules turning out to be lower than that of silicon technologies, the reason being that CdTe technology in the manufacturing phase is less energy-intensive compared to the silicon technology. Provided that the electricity consumed in the manufacture of the modules comes from energy sources such as coal and oil, the lower energy demand is reflected in lower CD emissions throughout the life cycle.

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3 http://www.firstsolar.com/en/Innovation/CdTe-Technology

4 http://www.csp.fraunhofer.de/presse-und-veranstaltungen/details/id/47/

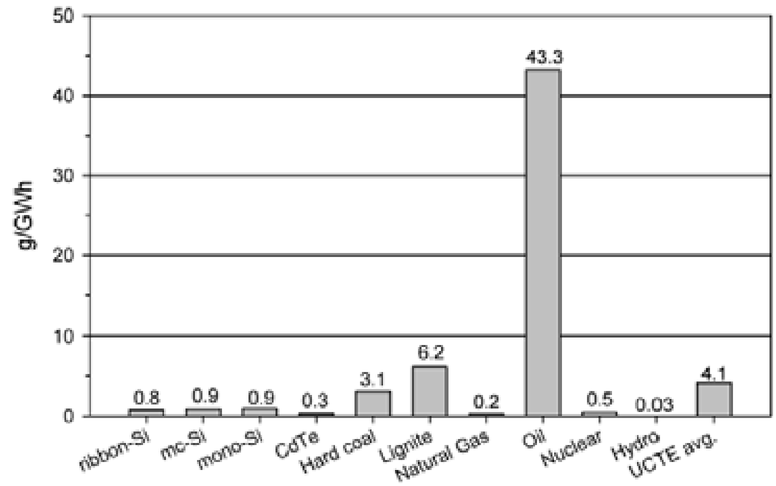

FIGURE 3. Life-cycle atmospheric Cd emissions for PV systems from electricity and fuel consumption, normalized for a Southern Europe average insolation of 1700 kWh/m²/yr, performance ratio of 0.8, and lifetime of 30 yrs. Ground-mounted BOS (*18*) is assumed for all PV systems; comparisons with other electricity generation options.

Figure 7: Comparison of life cycle emissions of the different forms of electricity generation. For the production of solar cells, the UCTE electricity mix is taken as reference (directly sourced from Fthenakis et al. 2008)

The studies carried out up until now, however, have only been looking at the regular operation of the modules, as well as at individual risk events such as house fires. The question on how cadmium emissions will develop, if, on a larger scale, CdTe modules have reached the end of their service life and need to be recycled, has not been investigated yet. Experiences gained in practice as well as further investigations are broadly missing here(first PV modules are expected to have reached the end of their service life in the year 2020). Except for special cases (such as a house fire) the question arises as to whether widely dispersed, small amounts of cadmium telluride can be recycled at all.

Material Consumption of PV Modules

Analysing four PV technologies, J. Kim et al. (2012) have examined the material consumption with regard to metals on the basis of 1 m^2 of a PV module. The totals of each category are presented in the following Table 7, the categories being subdivided into ferrous and non-ferrous metals, rare metals and rare earths. While in the original source uranium was shown along with the rare earth elements, it is presented separately in the table below, since it does not belong to the group of rare earth. Besides, the results of other PV technologies were related to the monocrystalline silicon (mono-SI). The results show that CdTe modules, in comparison to the other modules, account for the greatest demand of rare metals (such as gallium, indium, cadmium), followed by the polycrystalline silicon modules, while CI(G)S modules have the lowest material consumption. With regard to uranium, the monocrystalline silicon module has the highest material requirements.

However, it has to be kept in mind that the reference based on m² is not suitable as a basis for comparison of the different PV technologies, since the efficiency factor and performance ratio (PR) differ between the various technologies. The sole purpose of the summary is therefore to provide an overview of the material consumption of the different PV modules. The critical metals such as the rare earths are particularly interesting in this respect.

Table 7 Total material consumption of different PV modules broken down by material categories (calculated on the basis of data from J.Kim et al. 2012) and comparison with the result of the monocrystalline silicon in percent (mono-Si)

Categories	sc-Si (single crystalline silicon)	mc-Si (multicrystalline silicon)	CI(G)S[5]	CdTe
Ferrous/non-ferrous metals (kg/ m² PV module)	32	32	25	25
Rare metals (kg/ m² PV module)	1,2	1,3	1,2	1,4
Uranium (kg/ m² PV module)	4,6E-02	4,9E-04	9,2E-04	2,4E-03
Rare earths (kg/ m² PV module)	1,0E-14	1,0E-14	5,9E-15	7,9E-15
Ferrous/non-ferrous metals	100%	100%	78%	78%
Rare metals	100%	108%	96%	116%
Uranium	100%	1%	2%	5%
Rare earths	100%	100%	57%	76%

2.5.2 A recent LCA by Oeko-Institut

Scope

A recent screening LCA of photovoltaic modules has been conducted by the Öko-Institut e.V. (Gröger et al. 2013) on the basis of Ecoinvent data. It defines as its **functional unit** the amount of energy generated (in kWh). The **system boundaries** are as follows: The Ecoinvent data relate to 3kWp-PV systems. They include the production of the PV panels (including water use for cleaning, heat loss, and transmission losses of electricity in the system) as well as the installation for different roof types. The production data are based on the Swiss electricity mix. The use phase and disposal phase are not analysed: For the use phase, no data is available in Ecoinvent; furthermore, the impacts are expected to be

[5] Copper indium diselenide (CIS) and copper indium gallium diselenide (CIGS)

negligible. For the disposal phase, there are to date no practical experiences, because the first solar panels are expected to reach the end of their lifetime by 2020 only.

Results

The following Table 8 shows the results of the records from Ecoinvent for the functional unit of 1 kWh of solar electricity and the production and installation of the modules. It distinguishes between installations mounted later on an existing roof with the help of a mounting system, and installations directly integrated into the roof. Data from the Institute of Environmental Sciences, Leiden University (CML) and from the UseTox model[6] are compared. The fields marked in green show the minimum value, the fields marked in red the maximum value of the respective environmental impacts. It becomes clear that, in most respects, the environmental impacts of the different cell technologies differ only slightly. With regard to the cumulated energy demand (CED) and the greenhouse gas potential (GHP), all technologies are about the same. The abiotic depletion potential (ADP) is an exception: here, the impact of CIS- and CdTe-cells is ten times higher than that of the other technologies. With respect to human toxicity and the ecotoxicity, the amorphous silicon cells (with roof-mounted panel) stand out, exhibiting up to 56% higher values

Table 8 Results of the Data from Ecoinvent v2.2 (with regard to 1 kWh) (Gröger et al. 2013). Abbreviations used: ADP = Abiotic Depletion Potential, CED = Cumulative Energy Demand, GHP = Greenhouse Potential, AP = Acidification Potential, EP = Eutrophication Potential, CTU = Comparative Toxic Units,

Installation		**By CML (2010)**					**By USEtox**	
	Cell type	ADP (kg Sbe/kWh)	CED (MJ/kWh)	GHP (kg CO_2e/ kWh)	AP (kg SO_2e/ kWh)	EP (kg PO_4e/ kWh)	Human toxicity (CTU)	Ecotoxicity (CTU)
Panel, roof-mounted	a-Si	3,6E-06	5,03	0,069	4,2E-04	2,5E-05	3,2E-08	1,2E-01
	CIS	4,5E-05	4,92	0,063	2,7E-04	2,5E-05	2,4E-08	8,2E-02
	mono-Si	8,5E-06	5,03	0,062	3,0E-04	2,9E-05	2,8E-08	9,1E-02
	ribbon-Si	9,1E-06	4,93	0,058	3,0E-04	2,9E-05	2,8E-08	9,1E-02
	poly-si	8,1E-06	5,18	0,069	3,3E-04	3,3E-05	2,8E-08	9,5E-02
Panel laminated, roof-integrated	a-Si	3,6E-06	4,80	0,054	3,5E-04	2,0E-05	2,1E-08	7,8E-02
	CdTe	5,0E-05	4,76	0,054	3,7E-04	2,7E-05	2,1E-08	7,7E-02
	mono-Si	8,5E-06	4,96	0,057	2,8E-04	2,8E-05	2,5E-08	7,9E-02
	ribbon-Si	9,1E-06	4,85	0,053	2,8E-04	2,7E-05	2,5E-08	7,8E-02
	poly-Si	8,1E-06	5,11	0,064	3,1E-04	3,2E-05	2,5E-08	8,3E-02

[6] http://www.usetox.org/

3 Economic aspects

The economic viability of photovoltaic systems expressed as their payback time, depends mostly on the cost for purchase and installation on the one hand, and energy prices on the other (as the operation costs are negligible). Furthermore, in most European countries, schemes are in place that support either the production of renewable energy and / or the purchase and installation of PV systems, thereby influencing the economic viability for the individual operator. As energy prices and support schemes differ between European countries, no general conclusion can be drawn. However, the following sections collect some information on PV panel prices and support schemes in various countries.

3.1 Prices

Module prices vary according to technology and may be subject to major changes. Production costs for thin film solar cells are still quite high. However, analysts assume that, because of the smaller amounts of material needed, the costs for thin film cells will fall considerably below those of crystalline cells when produced in mass production. Table 9 gives a compilation of various sources and maps price against efficiency.

Table 9: Price and efficiency for different cell technologies. Prices refer to modules and do not include taxes whereas efficiency refers to cells (higher value) and modules (Gröger et al. 2013)

Cell technology	Price [€ per W_p]	Efficiency [%]
Crystalline silicon (c-Si)		
Single crystalline silicon (sc-SI)	0,99-1,34	14-20 (Lab: up to 24)
Multicrystalline silicon (mc-SI)	0,99-1,34	12-16 (Lab: up to 18)
Amorphous Silicon (a-Si)	Ca. 0,84	5-8 (Lab: up to 13)
Cadmium telluride (CdTe)	Ca. 0,98	6-10
Copper-indium-diselenide-thin film (CIS)		6-13 (Lab: up to 20)

Technology improvements and economies of scale have advanced cost reductions, which will continue in the coming years. The price development for photovoltaic modules till September 2013 is illustrated in the following table (Table 10). These are average wholesale prices on the European market (incl. Chinese custom duties)[7]. The end consumer price for an average ready-to-use photovoltaic system is much higher, e.g. in Germany it must be multiplied by 2-2.5. (pvXchange GmbH 2014).

[7] Since September 2013, prices for thin film cells were no longer determined. Therefore the price trend is shown until September 2013 only.

Table 10 Price barometer for crystalline modules and thin film modules on the European market since December 2014 resp. September 2013 (pvXchange GmbH 2015)

Type of module, origin	€ / Wp in December 2014	Trend since November 2014	Trend since January 2014
Crystalline modules			
Deutschland	0.59	-1,67 %	-14,49 %
Japan, Korea	0.62	0,00 %	-11,43 %
China	0.53	-1,85 %	-8,62 %
Südostasien, Taiwan	0.45	-2,17 %	-15,09 %
Type of module, origin	**€ / Wp in September 2013**	**Trend since August 2013**	**Trend since January 2013**
Thin film modules			
CdS/CdTe	0.58	0.00%	+ 3.57%
a-Si	0.35	- 2.78%	- 16.67%
a-Si/µ-Si	0.45	- 2.17%	- 13.46%

The system price decline, as expected by the European Photovoltaic Industry Association (EPIA 2013_b) is illustrated in Figure 8.

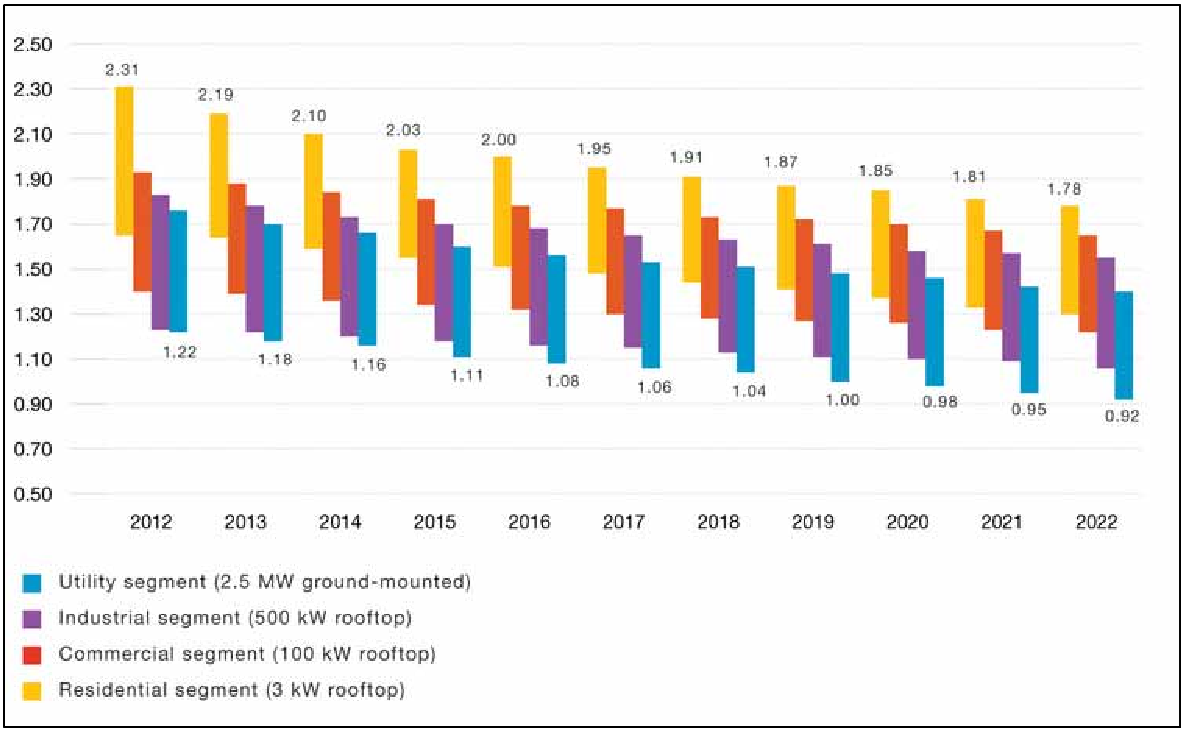

Figure 8 Scenarios for future photovoltaic system prices evolution (€/W) (EPIA 2013_b)

3.2 Support schemes

The actual end consumer price massively depends on the availability of support schemes. The following support schemes are in place in European countries (European Commission 2013).

Table 11 Support schemes for renewable energies in European countries (European Commission 2013)

Country	Main instruments		Further information
Austria	Feed-in tariff for renewable energies Subsidies for PV systems on buildings		http://www.res-legal.eu/search-by-country/austria/tools-list/c/austria/s/res-e/t/promotion/sum/91/lpid/94/
Belgium	Quota system based on renewable energy certificates	Responsibility of the regions; regional differences	http://www.res-legal.eu/search-by-country/belgium/tools-list/c/belgium/s/res-e/t/promotion/sum/108/lpid/107/
Bulgaria	Feed-in tariff for renewable energies subsidies and BEERECL grants loans for renewable energy projects		http://www.res-legal.eu/search-by-country/bulgaria/tools-list/c/bulgaria/s/res-e/t/promotion/sum/112/lpid/111/
Croatia	feed-in tariff for certain producers (“qualified producers”) for renewable energies		http://www.res-legal.eu/search-by-country/croatia/tools-list/c/croatia/s/res-e/t/promotion/sum/358/lpid/359/
Cyprus	subsidies and a premium tariff scheme for electricity from renewable sources		http://www.res-legal.eu/search-by-country/cyprus/tools-list/c/cyprus/s/res-e/t/promotion/sum/116/lpid/115/
Czech Republic	guaranteed feed-in tariff or a green bonus paid on top of the market price for renewable energy; and support of renewable energies through several subsidies		http://www.res-legal.eu/search-by-country/czech-republic/tools-list/c/czech-republic/s/res-e/t/promotion/sum/120/lpid/119/
Denmark	premium tariff and net-metering for electricity from renewable sources; local initiatives for the construction of wind energy plants are supported through loan guarantees; subsidies for strategic important small renewable electricity generation systems		http://www.res-legal.eu/search-by-country/denmark/tools-list/c/denmark/s/res-e/t/promotion/sum/95/lpid/96/
Estonia	Premium tariff for renewable energy; investments supports are available for certain types of renewable energy production technologies		http://www.res-legal.eu/search-by-country/estonia/tools-list/c/estonia/s/res-e/t/promotion/sum/124/lpid/123/
Finland	No support scheme for photovoltaic.		

France	feed-in tariff and call for tenders		http://www.res-legal.eu/search-by-country/france/tools-list/c/france/s/res-e/t/promotion/sum/132/lpid/131/
Germany	Feed-in tariff for electricity from renewable sources; low interest loans for investments in new plants are provided for by different KfW-programmes		http://www.res-legal.eu/search-by-country/germany/tools-list/c/germany/s/res-e/t/promotion/sum/136/lpid/135/
Greece	feed-in tariff for electricity from renewable sources; and subsidy combined with tax exemption are possible for renewable energies		http://www.res-legal.eu/search-by-country/greece/tools-list/c/greece/s/res-e/t/promotion/sum/140/lpid/139/
Hungary	feed-in tariff for electricity from renewable sources; subsidy programme for pilot projects on the use of renewable energy sources		http://www.res-legal.eu/search-by-country/hungary/tools-list/c/hungary/s/res-e/t/promotion/sum/144/lpid/143/
Ireland	feed-in-tariff scheme for electricity from renewable sources; Additionally a tax relief scheme for corporate investments in projects generating electricity from renewable sources exists		http://www.res-legal.eu/search-by-country/ireland/tools-list/c/ireland/s/res-e/t/promotion/sum/148/lpid/147/
Italy	feed-in and premium tariffs and a tendering system for electricity from renewable sources		http://www.res-legal.eu/search-by-country/italy/tools-list/c/italy/s/res-e/t/promotion/sum/152/lpid/151/
Latvia	feed-in tariff for electricity from renewable sources		http://www.res-legal.eu/search-by-country/latvia/tools-list/c/latvia/s/res-e/t/promotion/sum/156/lpid/155/
Lithuania	feed-in tariff for electricity from renewable sources; possibility for grants and exemption from excise tax for the producers of renewable electricity		http://www.res-legal.eu/search-by-country/lithuania/tools-list/c/lithuania/s/res-e/t/promotion/sum/160/lpid/159/
Luxembourg	feed-in tariff for electricity from renewable sources; subsidies for renewable energy plants; Private individuals operating small solar systems are entitled to tax benefits		http://www.res-legal.eu/search-by-country/luxembourg/tools-list/c/luxembourg/s/res-e/t/promotion/sum/164/lpid/163/
Malta	feed-in tariff for electricity from		http://www.res-legal.eu/search-

	renewable sources		by-country/malta/tools-list/c/malta/s/res-e/t/promotion/sum/168/lpid/167/
Netherlands	feed-in tariff for electricity from renewable sources; and subsidies for PV-systems, net-metering and tax benefits		http://www.res-legal.eu/search-by-country/netherlands/tools-list/c/netherlands/s/res-e/t/promotion/sum/172/lpid/171/
Poland	quota system for electricity from renewable sources (electricity suppliers are obliged to acquire a certain number of so-called "certificates of origin", which are issued to the producers of electricity from renewable sources.); support through tax relief		http://www.res-legal.eu/search-by-country/poland/tools-list/c/poland/s/res-e/t/promotion/sum/176/lpid/175/
Portugal	feed-in tariff for electricity from renewable sources		http://www.res-legal.eu/search-by-country/portugal/tools-list/c/portugal/s/res-e/t/promotion/sum/180/lpid/179/
Romania	quota system for electricity from renewable sources (electricity suppliers and producers are obliged to present a certain number of so-called "green certificates", which are issued for electricity from renewable sources)		http://www.res-legal.eu/search-by-country/romania/tools-list/c/romania/s/res-e/t/promotion/sum/184/lpid/183/
Slovakia	feed-in tariff for electricity from renewable sources; excise tax and several subsidies for the use of renewable energy sources		http://www.res-legal.eu/search-by-country/slovakia/tools-list/c/slovakia/s/res-e/t/promotion/sum/188/lpid/187/
Slovenia	feed-in tariff and a premium tariff for electricity from renewable sources; subsidies for projects in the field of renewable energy		http://www.res-legal.eu/search-by-country/slovenia/tools-list/c/slovenia/s/res-e/t/promotion/sum/192/lpid/191/
Spain	a guaranteed feed-in tariff or a guaranteed bonus (premium) paid on top of the electricity price achieved on the wholesale market		http://www.res-legal.eu/search-by-country/slovenia/tools-list/c/slovenia/s/res-e/t/promotion/sum/192/lpid/191/
Sweden	Various incentives, e.g. a quota system, which is based on a certificate trading system; tax regulation mechanisms; subsidy schemes		http://www.res-legal.eu/search-by-country/sweden/tools-list/c/sweden/s/res-e/t/promotion/sum/200/lpid/199/
United Kingdom	combination of a feed-in tariff system and a quota system in		http://www.res-legal.eu/search-by-country/united-

	terms of a quota obligation and a certificate system		kingdom/tools-list/c/united-kingdom/s/res-e/t/promotion/sum/204/lpid/203/

4 Overview of legislation, labels and benchmarks

This chapter gives a short overview of the relevant legislation, labels and benchmarks for photovoltaic modules.

4.1 European Legislation

4.1.1 RoHS

The RoHS Directive (EU Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment) sets limit values for lead, mercury, cadmium, hexavalent chromium (chromium VI), polybrominated biphenyl (PBB) as well as polybrominated diphenylether (PBDE) in electrical and electronic equipment. Although photovoltaic panels may contain some of these substances such as lead, flame retardants (polybrominated biphenyl (PBB), polybrominated diphenylether (PBDE)) and cadmium, they are currently exempted from RoHS directive. They can, however, be provided with a voluntary "RoHS Compliant" marking. The voluntary marking confirms that the amounts of the regulated substances in the panel are within the limit values set by the RoHS Directive. It is applied by manufacturer self-declaration. For the next amendment of the Directive (in 2014), no changes are planned with regard to the photovoltaic modules.

4.1.2 Ecodesign

The Eco-Design Framework Directive (Directive 2009/125/EC) sets a framework for defining product-specific minimum requirements for energy efficiency and sometimes other environmental impacts, as well as mandatory consumer information, for energy-related products. The Directive is implemented via individual Implementing Measures for various product groups. The product groups are defined by three-year Working Plans. The current Working Plan covers the period from 2012-2014, while the Working Plan for the period 2015-2017 is currently being developed.

The current understanding of the meaning of “energy related products” is that PV panels are not covered, because the term describes products that have an impact on energy *consumption* in the use phase. However, a review of the Ecodesign Directive is currently under way and the European Commission is conducting studies about modifying the scope to cover, among other things, power generating devices such as solar panels. Therefore, they may become subject of a future Working Plan (probably not yet for 2015-2017).

4.1.3 WEEE

Photovoltaic modules are subject to the Waste Electrical and Electronic Equipment (WEEE) Directive (Dir 2012/19/EU). This European directive regulates the disposal and the recycling of electric and electronic devices. Its purpose is to promote, first, the prevention of WEEE and, in addition, by the re-use, recycling and other forms of recovery of such waste. Member States are required to collect PV panels separately and report to the Commission on the collection rate by 14 Aug 2015. Furthermore, they need to ensure proper treatment. Annex V states that 75% shall be recovered and 65% shall be recycled. From August 15, 2015 on, it is 80% and 70%, respectively. Furthermore, systems must be installed that allow the end user to return the used equipment free of charge.

4.2 European labels, standards and benchmarks

4.2.1 European Ecolabel

Currently it is not possible to label photovoltaic modules with the European Ecolabel.

4.2.2 Standards

The relevant CENELEC committee is the Technical Committee 82, Working Group 1 (wafers, cells and modules). It cooperates with IEC TC82, WG2 (Modules, non-concentrating), and WG7 (Concentrator modules). (CENELEC 2013). There are some 40 European standards that relate, in one way or the other, to PV modules. They regulate aspects such as

- design qualifications and type approval (EN 61215 for crystal silicone modules, EN 61646 for thin film modules EN 62108 for concentrator modules)
- safety (general: EN 61730-1 and EN 61730-2; overvoltage: EN 61173; lightning protection: EN 62305 series, concentrator modules: 62688)
- integration of PV in buildings (prEN 50583);
- test standards, general or for specific aspects or technologies
  - performance: EN 60904 series, EN 61853 series;
  - durability: durability during transport EN 62759, resistance to UV radiation EN 61345 corrosion testing EN 61701, EN 62716, system voltage durability: EN 62804 etc.
  - specific types: for concentrator modules: EN 62670 series; for crystalline silicon modules: EN 61829
- datasheet information for various module types (EN 50830, EN 50461, EN 50513)
- collection, logistics, and treatment requirements for WEEE (EN 50625 series)
- terminology: CLC/TS 61836.

The most basic and comprehensive standards are those for design qualification and type approval and the general safety standards listed above.

4.3 International labels, standards, and benchmarks

For almost all of the European standards, there are corresponding IEC standards. No other relevant international labels, standards, and benchmarks have been identified.

4.4 Relevant national labels, standards, and benchmarks

In Germany, a preparatory study developing possible criteria for awarding the Ecolabel Blue Angel to photovoltaic panels has been conducted by Oeko-Institut (Gröger et al. 2013). However, scheme owners did not decide in favor of labeling PV panels and the study remains unpublished. Parts of the results have been used as a basis for the existing paper.

4.5 Informal benchmarks, tests, comparisons

4.5.1 Quality seals

RAL solar is a German "quality association", bringing together interested industry participants who develop quality criteria for various products. RAL solar has developed the quality seal "Gütezeichen 966" for solar systems which includes requirements for modules.[8] The requirements refer to data sheets, documentation of performance data, safety requirements, requirements for the measurement and declaration of the durability, and requirements for connecting elements and module framework. PV system providers can be certified according to the seal. Unfortunately, criteria are available in German only.

A more international approach is applied by the renowned German **VDE institute** who has, together with Fraunhofer ISE, developed the seal of approval. "VDE quality tested". According to the institute, requirements "go above and beyond the well-known standards IEC 61215[9] (…) design qualification and type approval of crystalline silicon terrestrial photovoltaic modules; IEC 61730-1 and IEC 61730-2[10] (…) photovoltaic module safety qualification, include, for example:

- Performance of tests with a higher number of samples
- Thermal-cycling test with higher number of cycles

[8] www.ralsolar.de

[9] Identical to EN 61215 discussed above.

[10] Identical to EN 61730-1 and 61730-2, discussed above

- Damp-heat test with longer test time
- Dynamic mechanical load test
- In all tests, the maximum power degradation may not exceed 5 percent over the entire test sequence
- Continual, monitored tests during production
- Continual monitoring of modules taken from production." (VDE 2011).

Certisolis (France)[11]: Solar photovoltaic module performance testing and certification laboratory: Certisolis conducts various tests on solar photovoltaic modules and certifies their performance according to international standards. It performs weather, mechanical, and photo-electric tests – overall 24 different test procedures[12]. Testing is done according to EN 61215, NF EN 61646, and NF EN 61730 standards.

All the tests are conducted as part of the photovoltaic product qualification process. They are performed singly or in sequence. After each test, power variation is checked to ensure it is not greater than 5% or 8% after each sequence.

4.5.2 PV tests and benchmarking

The **PHOTON Laboratory GmbH** has been testing solar modules since its establishment in 2009. Until now the company has focused its activities on performing yield measurements under standard conditions (STC), evaluating weak light behavior and determining temperature coefficients. (Gröger et al. 2013)

Since 2010, PHOTON Laboratory GmbH is conducting long-term yield measurements on an outdoor test field (Gröger et al. 2013). The test field, as of December 2012, contained over 170 different types of modules from 90 national and international manufacturers, 46 of them are in use since 2010 (PHOTON Holding GmbH 2013; http://www.photon.info/photon_home_en.photon, 26.09.2013

). The magazine "PHOTON" regularly publishes rankings and assigns a label highlighting Performance ratio, yield, rank of the respective module and total number of tested modules. The next yield measurement in Germany is starting in 2014. (Gröger et al. 2013);

The **CalLab PV Cells at Fraunhofer ISE**, an independent accredited test laboratory, compiles information on tested PV cells and publishes it in "PV Charts" in graphical and tabular form, summarized on its website, and disseminated at photovoltaic conferences. The publication is dependent on the manufacturer's agreement. (Fraunhofer ISE 2013).

[11] See: http://certisolis.com/?lang=en

[12] See: http://certisolis.com/-Test-laboratory-

Also, the German company Solarpraxis AG, who provides services to is running, in cooperation with TÜV Rheinland, the **PV+ test,** which "assesses products based on performance criteria, but also in terms of durability, electrical safety, workmanship, the quality of documentation provided, warranty terms and ease of installation." (PV magazine o.J.) The new 2013 criteria "include a strict aging examination, a test for Potential Induced Degradation (PID) and a more accurate determination of low-light and temperature behaviors in comparison to the previously valid test conditions from February 2011. " (PV test 2013). The module manufacturers bear the cost of the tests but do not have an influence on the test process. Results are published in form of a "best of" list in the PV magazine; however, the manufacturer may choose to remain anonymous, so usually only the best perfoming modules are identified. The modules may receive a test seal.

4.5.3 Industry standards

SEMI is a global industry association for the micro- and nano-electronics industries, including: Semiconductors, Photovoltaics (PV), High-Brightness LED, Flat Panel Display (FPD), Micro-electromechanical systems (MEMS), Printed and flexible electronics, Related micro- and nano-electronics.[13]

They have created a library of about 850 SEMI Standards and Safety Guidelines. At present there are 51 SEMI standards regarding to photovoltaic. The development process of the standards includes only the expertise of industry representatives.

5 Existing Buyer's Guides

A number of buyer's guides for PV equipment are already in place in various countries. The main parts of most guides deal with checking general issues in the establishment of a PV system, not with choosing the individual product (planning the system, grid connection, legal framework (permits), contractual issues, insurance, cost etc.) With respect to panel choice, most guides emphasize the need to choose panel size in line with the needs and budget. Some of them also give hints for the optimal orientation of the panel and some point to existing national standards. The general recommendation is to discuss the optimal choice of product with a trusted retailer, designer or installer, who, in some countries, may bear a seal of approval or be listed in a national list of approved partners. Most guides also highlight the necessary training of the installer, and almost all recommend a 25 year warranty. Table 12 sums up core recommendations.

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[13] www.semi.org

Table 12 Buyer's guides

	USA	Australia - Household	Australia – Business and industry	Canada	UK
Source	http://www.nrel.gov/docs/fy04osti/35297.pdf	http://www.solaraccreditation.com.au/dam/cec-solar-accreditation-shared/guides/Consumer-Guide-to-Buying-Household-Solar-Panels-December-2012.pdf	http://www.solaraccreditation.com.au/dam/cec-solar-accreditation-shared/guides/Guide-to-Installing-Solar-PV-for-Business-and-Industry-September-2013/Guide-to-Installing-Solar-PV-for-Business-and-Industry-February-2014.pdf	http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/canmetenergy/files/pubs/PhotovoltaicSystemsBuyerGuide.pdf (2002 edition, not updated)	http://www.peterborough.gov.uk/pdf/env-cc-estsolarguide.pdf
General	Information on technology ("how does it work"?), costs and benefits, funding sources, legal framework (permits), grid connection designing a contract, insurance, maintenance etc.				
Size	Depends on the needs, 50% of the needed electricity could be delivered by the pv system	depends on the budget, the physical unshaded area available, the amount of electricity that should be generated), e.g. 1-2 people 2kW system	must suit electrical loads, discuss with designer	panel should suit the needs and budget; calculation examples and tables are given	-
Place	Best: south-facing roof	orientation, tilting, shading, mounting	consider angles, available sunlight, shading and temperature; discuss with designer	-	-
Type of panels		No recommendation; different types described with their pros and cons	no specific recommendation, discuss with designer		no specific recommendations; different types described with pros and cons
Material/Quality	-	No defined recommendations, but the consumer should ensure how the panel is manufactured and which material is used	check degradation factor	-	-

	USA	**Australia - Household**	**Australia – Business and industry**	**Canada**	**UK**
Standards / seals of approval		List of panels that meet Australian standards provided	Products must meet Australian standards		
Installer / provider	The installer or the subcontractor should have an electrical contractor`s license; also check years of experience, and certificates	Should be trained; follow the industry practice; adhere to Australian standards; regularly update their skills and product knowledge	choose Clean Energy Council approved retailer	Check design/sales experience, knowledge of energy efficiency, area of expertise, product quality, warranty, installation service, follow-up service, price	Microgeneration certification scheme (MCS) certified installer; Energy Saving Trust Recommended; check assurances
Guarantee/Warranty	-	25 years	check financial strength of the company providing the warranty / guarantee	25 years	25 years

6 Guidelines for procurement

The following general recommendations can be given, based on the above considerations:

- It is of prime importance to find a **trusted dealer / installer** who can help choosing the appropriate system for your needs and provide appropriate service for installation and maintenance as acceptable cost. Size, type of panel, and orientation need to be adapted and it is difficult for a layperson to make these choices on his / her own. Therefore, an installer should be chosen considering the following issues:
  - Years of experience in the respective field
  - Warranties and guarantees provided
  - Financial strength of the company
  - licenses.

  Often, national industry associations or public institutions (such as energy agencies) issue certificates or provide lists of approved retailers or installers. These can offer a convenient way to identify reliable partners without having to research all the necessary information.
- When choosing solar panels, consider **test results** and **seals of approval**. Some possible sources have been sketched above. It is important though to check both the experience and reputation of the issuing company and the questions which issues are covered by the seal or test. Some may only consider conversion efficiency, some may include performance ratio, some other aspects such as durability or recyclability.
- Take note of relevant **European standards**. The most basic and comprehensive standards are those for design qualification and type approval and the general safety standards listed above in chapter 4.2.2.
- Take note of the following **list of environmental and quality aspects** to consider. Among the possibly relevant issues for your specific case are:
  - Conversion efficiency
  - Performance ratio
  - Energy payback time
  - Durability
  - Hazardous substances.

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8 Annex

Overview of LCA-or PCF-studies to the subject photovoltaic

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