Universitat de Barcelona

Energy Life Cycle Assessment (LCA) of silicon-based photovoltaic technologies and the influence of where it is manufactured and installed.

Author: Alejandro Calderón Díaz

Tutor: Dr. Jordi Andreu Batalle

Academic course: 2013- 2014

Master of renewable energy and energy sustainability

Acknowledgments

I want to thank my wife Karla and my parents Mario and Rosa María, who have supported me throughout the entire process of achieving this important goal, both by keeping me harmonious and helping me putting pieces together. I will be grateful forever for your love. I want to express my gratitude to my tutor Dr. Jordi Andreu for his guidance, useful comments and commitment through the elaboration of this work. Finally I want to thank the *Consejo Nacional de Ciencia y Tecnología (CONACYT)* for the support and the special interest on developing high qualified professionals.

Universitat de Barcelona

Index

1. Introduction

Todays need for more energy that can also can be clean energy and that provide energetic security is becoming more and more valuable. There are global, regional and national goals for achieve either one or all of this energy challenges. There are emerging economies claiming for their right for industrialization using fossil fuels, regions and countries claiming for energetic independence and also others claiming for clean energies that don't compromise world sustainability on the long term.

There are worldwide efforts to get to clean and cheap energy sources. One of this initiatives is International Energy Agency goal to reduce by 50% Greenhouse effect Gases (GHG) on 2050.

Solar energy is the most abundant form of energy in the world. In one hour the earth receives more energy than the one used by human activity. There are three main forms developed for harvesting energy from the sun. Solar Heating and Cooling (SCH), Concentrating Solar Power (CSP) and solar Photovoltaics (PV). Solar PV is a clean energy harvesting technology that also provides energy security. Also in the following years it is expected that solar PV prices will drop down enough to offer cheap energy as well.

Today it's true that when solar PV technology is manufactured produces GHG emissions. These emissions are mainly associated with the electricity needed for manufacture process, so if while clean energy develops also PV manufacture produce lower quantity of GHG emissions.

PV industry is growing almost exponentially. Today's residential PV prices are competitive with electricity retail prices and in the mid-term utility PV will became competitive without special policies. On PV industry silicon related technologies have the challenge to reduce their energy intensity during the manufacture process and to increase the conversion efficiency of turning solar energy into electricity. Other PV technologies that are not based on silicon use scarce materials, making them not viable for wide world extended use.

Efficiency, embedded energy and GHG emissions are the most important variables for PV manufacture and therefore will be the ones treated on this study. In order to understand embedded energy, the PV technologies manufacture process must be understood. GHG on PV industry are closely related to the embedded energy and to the energy mix of where it is manufactured.

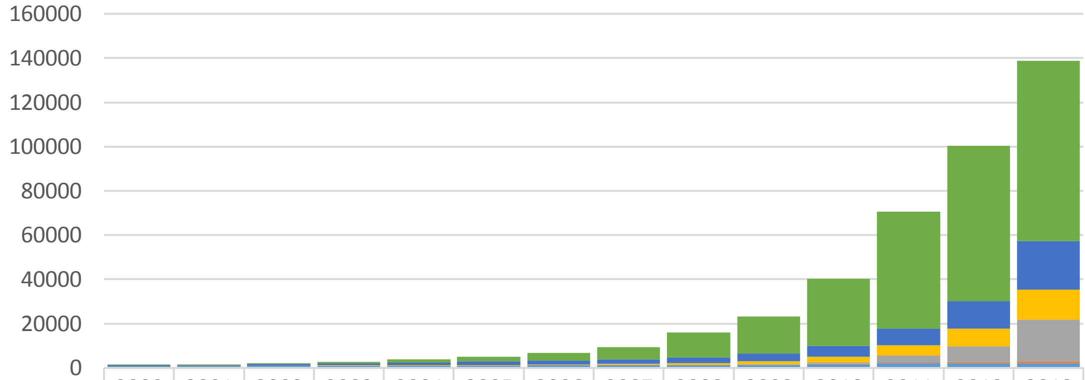
Life Cycle Assessment (LCA) can help us to evaluate the sustainability of silicon-based PV industry. We can understand better embodied energy and energy payback times on a common baseline. It is important to establish a common methodology so the different LCAs can be integrated and/or compared. For this study we will focus of manufacture and transport LCA analysis. Also we will evaluate how the irradiance and temperature according to each geographical location can affect payback times.

We will finally evaluate GHG emissions associated to the energy use during the manufacture process. We will evaluate if we can save energy and therefore CO_2 emissions transporting only solar cells from the main suppliers and building the module on suppliers region.

2. Solar Photovoltaic Outlook

PV has experienced a constant growth in the last decades at an average rate of more than 40% since 2000. At 2013 it provided 0.1% of total global electricity generation and it is expected to provide 5% in 2030 and 11% in 2050 (International Energy Agency, 2010). On *Figure 1* world growth per region is presented, Europe remains as the main region for PV installed capacity, however China and APAC (Asia Pacific) regions has almost tripled and doubled their capacity respectively.

Figure 1. Evolution of global PV cumulative installed capacity 2000-2013 on Megawatts



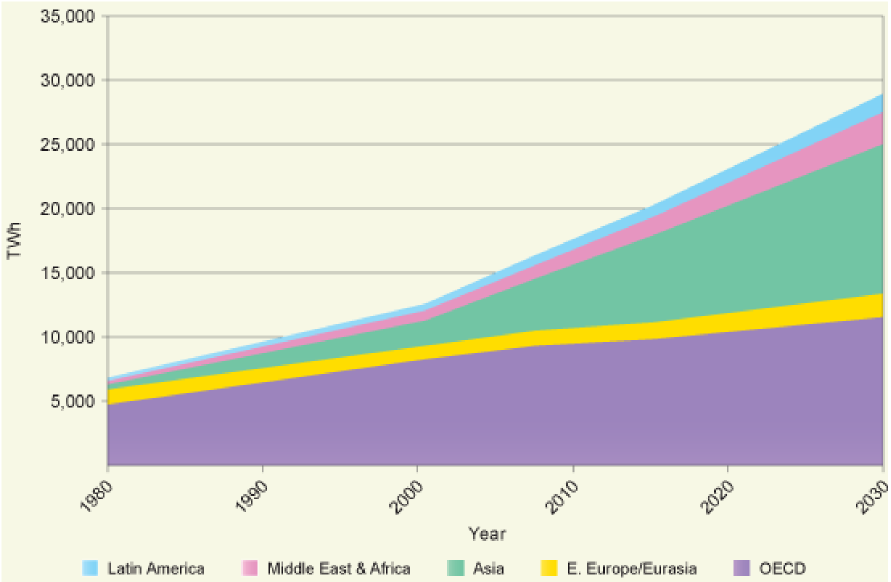
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Europe	129	265	399	601	1306	2291	3289	5312	11020	16854	30505	52764	70513	81488
APAC	368	496	686	916	1198	1502	1827	2098	2628	3373	4951	7513	12159	21992
Americas	21	24	54	102	163	246	355	522	828	1328	2410	4590	8365	13727
China	19	24	42	52	62	70	80	100	140	300	800	3300	6800	18600
MEA	0	0	0	0	1	1	1	2	3	25	80	205	570	953
RoW	751	807	887	964	993	1003	1108	1150	1226	1306	1590	2098	2098	2098

RoW: Rest of the World, MEA: Middle East and Africa, APAC: Asia Pacific.
Source: EPIA – Global Market Outlook for Photovoltaics 2014-2018 (2014).

Nevertheless, this important increase of PV worldwide capacity is insufficient to meet the power needs for the next decades. As shown if *Figure 2*, the increase of energy needs by emerging economies are so intense that will increase use fossil energy sources for the next decades. Even tough, developed countries will have the opportunity to grow renewable energy production and more particular PV solar energy, which is the one with the best rate of increment of use (EPIA - European Photovoltaic Industry Association, 2014). Also in countries like the United States of America, that are looking for stop depending of foreign oil using their own shale gas reserves, will increase their PV electricity participation in the long term (Jones & Martin, 2014). Therefore, PV electricity generation and other renewable energy sources should be developed enough in order for them to be more viable options for emerging economies.

Even with the emerging economies effect, if the 11% of worldwide electricity production for 2050 is achieved, PV generation will reach 3 TW of installed capacity. This will produce 4500 TWh from PV and will avoid 2.3 Gigatonnes of CO_2 emissions per year (International Energy Agency, 2010).

Figure 2. World Energy Consumption per Region.



Source: OECD / IEA World energy Outlook 2009 – Reference Scenario.
From: World Nuclear Association. World Energy Needs and Nuclear Power.

PV market divides on residential systems and utility systems. Residential systems have a higher cost than utility systems. Nevertheless, residential systems compete with the retail prices of distribution grid, rather than utility systems that compete with the generation grid prices (International Energy Agency, 2010).

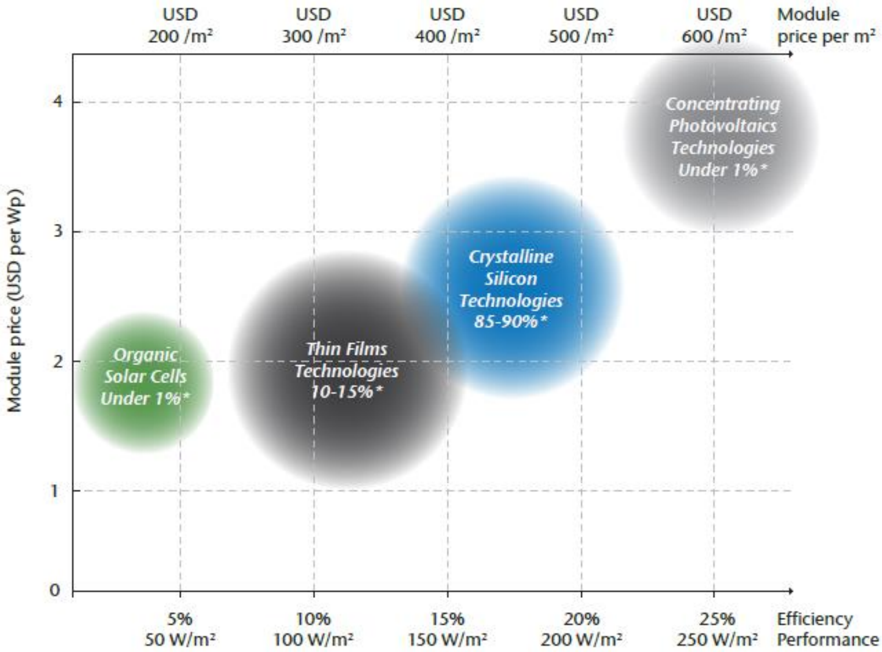
Investment cost on PV systems is still relatively high, although they are decreasing constantly because of the technology improvements and economies of volume and scale. Therefore, the viability of the systems depend on interest/discount rate and the sunlight irradiation. Residential and utility systems are more viable in countries with high electricity costs and with better sunlight irradiation (IEA-ETSAP and IRENA, 2013).

Many countries and world regions are looking to increase R&D (Research and Development) and to stimulate economies of volume and scale by implementing different programs, such as Solar Europe Industry Initiative, the Solar America Initiative (SAI), Japan's PV roadmaps towards 2030 (PV2030) and Australia's Solar Flagships. Also emerging economies like India and China are pursuing an aggressive solar PV growth strategy. Latin America and Africa are considered as a high potential for generation but have no expectations for rapid growth in an immediate stage (International Energy Agency, 2010).

By 2020 PV generation costs at residential and commercial applications are expected to be lower than the electricity retail prices in many countries and utility PV systems are expected to arrive at the edge of competitiveness with wholesale electricity costs (International Energy Agency, 2010) & (IEA-ETSAP and IRENA, 2013).

In PV Industry, Crystalline silicon (c-Si) modules represent more than 80% of the global market today with the best commercial module efficiency of 19-20% and more than 25-year lifetime. C-Si modules are subdivided in two main categories: i) single crystalline (sc-Si) and ii) multi-crystalline (mc-Si). Meanwhile, thin film modules have 10-15% of global PV module sales with an efficiency of 6-12% (International Energy Agency, 2010) & (IEA-ETSAP and IRENA, 2013). PV film technologies are subdivided into three main families: i) amorphous (a-Si) and micromorph silicon (a-Si/µc-Si), ii) Cadmium-Telluride (CdTe), and iii) Copper-Indium-Diselenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS). On *Figure 3* different types of PV technologies are illustrated according to their efficiency, price and market share.

Figure 3. Current performance and price of different PV module technologies.



** Percentage share of 2008 market*

Source: IEA International Energy Agency - Solar photovoltaic energy, 2010.

On crystalline silicon modules it is single crystalline the one that has reached best efficiency compared with multi-crystalline or other thin film technologies, as shown on table 1.

Table 1. Current efficiencies of different PV technology comercial modules.

Wafer-based c-Si		Thin films		
sc-Si	mc-Si	a-Si; a-Si/µc-Si	CdTe	CIS/CIGS
14-20%	13-15%	6-9%	9-11%	10-12%

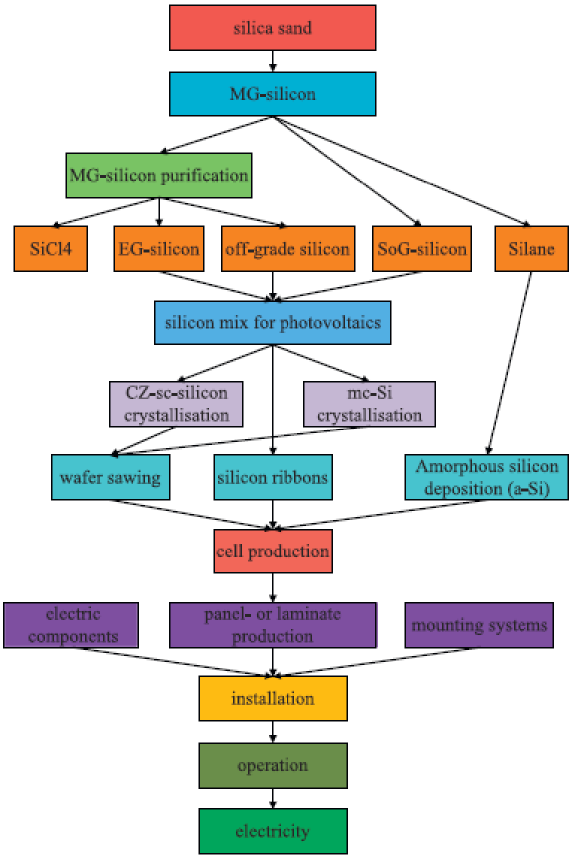
Source: IEA International Energy Agency - Solar photovoltaic energy, 2010.

Each technology has their own challenges to reach major development. For c-Si modules, the main concern is to improve the efficiency and effectiveness of resource consumption through materials reduction and improved cell concepts and automation of manufacturing. Meanwhile, thin film must be developed for obtaining higher efficiency. (International Energy Agency, 2010). Particularly for CdTe and CIS/CIGS technologies today's production of necessary materials is not enough for meeting PV industry needs. Also mineral reserves are concentrated in only few countries (EPIA - European Photovoltaic Industry Association, 2014).

3. Silicon PV Technologies

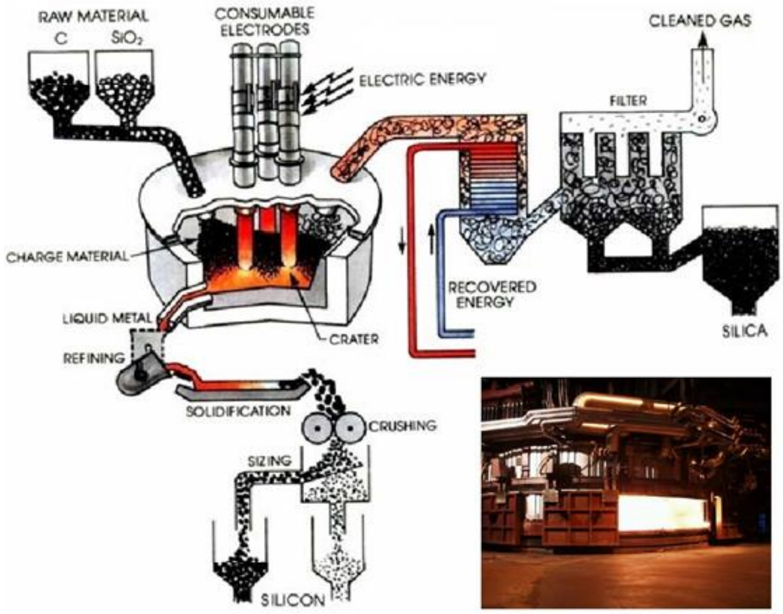
Silicon is the second element on abundance in the Earth´s crust with 28.2% by weight (Lide, 1996). It´s distributed in all regions of the world (U.S. Geological Survey, 2008) and is found in different forms of silicon oxide or silicates. Quartz and quartzite are the minerals in which crystal silicon dioxide is found in a relatively pure form. In order to get silicon for use in PV industry this raw materials must be transformed into purified form of silicon. *Figure 4* illustrates the manufacturing process of silicon-based PV modules. Transformation from silica sand to silicon requires high temperatures and a pure form of carbon in order to reduce dioxide silicon into silicon metal and CO_2 (Lifton, 2008). This silicon metal is called Metallurgic Grade Silicon (MG-silicon) which is the base product for manufacturing amorphous silicon (a-si) and crystal silicon (c-si), both single and multi-crystalline (Peng, Lu, & Yang, 2013). Once the MG-silicon is produced it follows different processes according to the type of solar cell that will be produced (a-Si, mono-Si or multi-Si).

Figure 5. Manufacturing processes of Si based PV modules.



Source: Peng, Lu, & Yang, 2013

Figure 4. Carbothermic Arc Reduction for MG-silicon manufacture.

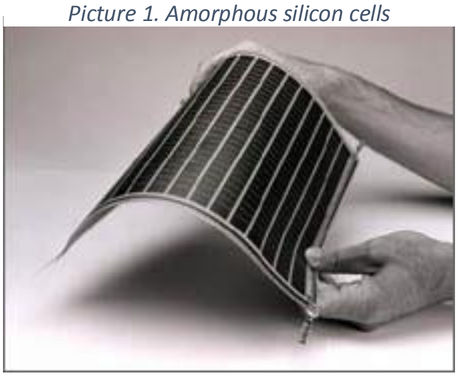


Source: Wendman, 2006. Picture from Elkem Silicon of Norway.

3.1 Amorphous Silicon

Amorphous silicon (a-si) have the lowest ecological impact of PV materials (Kreiger, Shonnard, & Pearce, 2013). It has a lower efficiency compared to crystalline-based PV or even to other thin film PV technologies like CdTe or CIS/CIGS (International Energy Agency, 2010). The main advantages of a-si PV are their low cost, availability of raw materials, lower negative effect of high temperatures compared c-Si and the wide range of possible applications due to their possibility to take different shapes and sizes (Panasonic Corporation, 2014).

Picture 1. Amorphous silicon cells



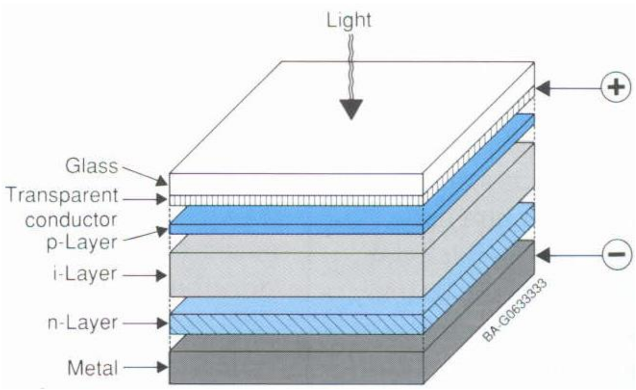
Source: www.wifinotes.com

As shown on *Figure 4*, the MG-silicon is transformed into silane. This process take two steps, first a reaction is needed between MG-silicon powders with hydrogen chloride at about 300 °C in order to get trichlorosilane combined with hydrogen. Then the trichlorosilane is boiled in a bed with a special catalyst in order to transform trichlorosilane into silane and silicon tetrachloride (O'Lenick, 1999).

Deposition of a-Si layers are made by running a substrate through a set of chambers and exposing it to a mix of silane and hydrogen using plasma enhanced chemical vapor deposition (PECVD). Once PECVD is made a-Si layers get deposited in solid state on the substrate. PECVD process get place at low temperatures (about 65 °C) so the deposition can be made in a wide range of substrates, even on plastic (Kreiger, Shonnard, & Pearce, 2013).

A-Si layer are constructed in a p-i-n and n-i-p device structure as shown on *Figure 6*. P-i-n- or n-i-p diodes consist on classic P and N material doped regions and an intrinsic (I) region between them. This I region makes the diode more suitable for photo-electronic applications (Doherty, 1997). P-layer is usually doped with boron, it is followed by I-layer which is either undoped or doped with germanium. Finally n-layer is doped with phosphorous. Once the doping is done the substrate is ready for cell production.

Figure 6. The structure of amorphous silicon.



Source: University of New South Wales, 2008.

3.2 Crystalline silicon.

The embodied energy represents the quantity of energy used on all the life cycle of a product, from cradle (raw materials) to grave (disposal) or even to recycling (Costanza, 1980). The main concern on crystalline silicon for PV is the amount of embodied energy accumulated during the manufacture process. Greenhouse effect gas emissions have a wide variation depending on the energetic mix of each country or region in which the cells are manufactured (Blakers & Weber, 2000).

In order to produce either mono-crystalline silicon (also called single-crystalline silicon) or multi-crystalline silicon (or poly-crystalline silicon) the MG-silicon must be processed. MG-silicon has a purity of 98% which is too low for PV needs and needs to be purified to electronic grade silicon (EG-silicon) with a purity of 99.9999999%. This is achieved via the Siemens process, in which silicon is reacted with HCl to produce trichlorosilane, which is then decomposed with the aid of hydrogen at 1200ºC in order to produce EG-silicon and silicon tetrachloride ($SiCl_4$) in a proportion of 2:7 respectively. $SiCl_4$ is used in other industries so it can account its own embodied energy (Blakers & Weber, 2000).

Picture 2. MG-silicon.

Source: Qatar Solar Technologies

Since solar PV does not require so much high silicon purification, there has been developed a modified Siemens process in which silane and hydrogen are only heated to about 800ºC. Therefore, Siemens modified process allows to save large amount of energy during the process of producing solar grade silicon (SoG-silicon). Also off-grade silicon, that is a by-product from the original Siemens process to produce EG-silicon, can meet the requirements of SoG-silicon (Peng, Lu, & Yang, 2013).

Initially scale economy make more viable to produce crystalline silicon from EG-silicon or from off-grade silicon. With the increase of the PV industry it has become more viable to produce SoG-silicon so that important energy saves (and therefore reduce embodied energy) can be achieved. On 2006 off-grade silicon was reduced to 5% of total PV supply (Peng, Lu, & Yang, 2013).

3.2.1 Multi-crystalline silicon.

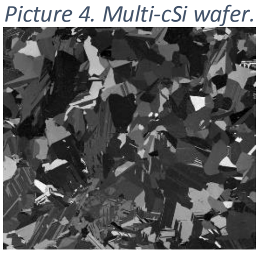
For multi-cSi manufacture SoG-silicon, EG-silicon or off-grade silicon is melted and crystalized by casting process to make a large grained multi-crystalline ingot (Blakers & Weber, 2000). Compared with single-crystalline silicon, multi-cSi production is more simple and cheaper. Wafers are directly produced from the ingot with no additional process (Peng, Lu, & Yang, 2013). Multi-cSi have lower efficiency than single-cSi. Grain boundaries reduce solar cell performance because the carrier flows is blocked, creating shunting paths of the current flow on the semiconductor n-p junction. Also overall minority carrier lifetime is reduced due to extra defect energy level on the band gap, caused because grain boundaries introduce high localized regions of recombination (Card & Yang, 1977).

Picture 3. Polysilicon ingot.

Source: Dow Corning Corporation.

Multi-cSi silicon crystals can be observed at simple sight of grain boundaries noted in the wafer. This kind of PV technology has being experiencing important growth in the last years, by 2013 there are over 100 manufacturers compared with only twelve on 2006 (ENF Solar, 2014). Multi-cSi PV is expected to dominate solar industry on 2014 with more of the 60% of the PV market (Solarbuzz, 2013).

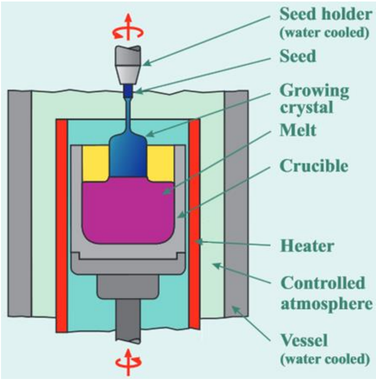
Picture 4. Multi-cSi wafer.



Source: Card & Yang,

3.2.2 Mono-crystalline silicon.

Figure 7. Czochralski crystal growth.



Source: N Cheung, Berkeley, 2006.

Mono-crystalline silicon, or single-crystalline silicon, is the most energy intensive and efficient PV technology. This because while having a single crystal there are no problems with grain boundaries presented on multi-cSi. Because of this energy intensive process the current share market for multi-cSi is in a slow declination (29.6% on 2013 to 29.3% projected to 2014) (Solarbuzz, 2013). The main difference compared to multi-cSi is that SoG-silicon, EG-silicon or off-grade silicon melted to form multiple crystals must be transformed into one single crystal ingot. The process most used for this to happen is the Czochralski (CZ) method (Blakers & Weber, 2000). CZ process was invented in 1916 by Polish chemist Jay Czochralski. This method for crystal growth consists on pulling fibers of different metals from their melts and get a product composed by a single crystal.

Picture 5. Single crystal ingot.

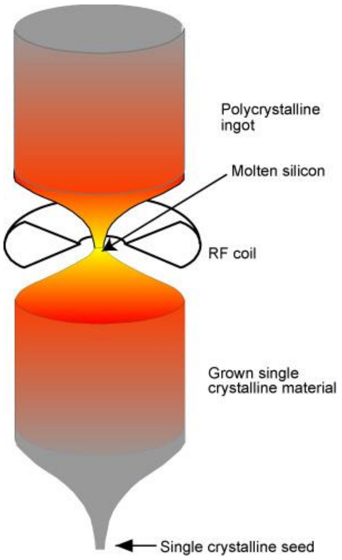
Source: N Cheung, Berkeley, 2006.

High-purity silicon is melted at 1400ºC in an inert atmosphere on a chamber usually made of quartz. Then dopant can be added (typically boron or phosphorous) to make a p-type or n-type silicon. Then a rod seed crystal is inserted into de molten silicon. The rod seed starts rotating while it is slowly pulled upwards. Having an adequate control of temperature, speed rotation and pulling upward speed makes possible to produce a cylindrical ingot (Talik & Oboz, 2013). *Figure 7* illustrates CZ process in which rotation and principal variables can be observed. *Picture 5* shows a single crystal ingot produced by CZ process. At this point to produce 1.6 kg of CZ silicon requires 5.8 kg of MG-silicon (2.4 kg if silicon incorporated into $SiCl_4$ is excluded) (Blakers & Weber, 2000).

CZ process is commonly used for commercial substrates, but it has several disadvantages for high efficiency cell market because of the oxygen impurities in the silicon wafer. This impurities reduce the carrier lifetime in the solar cell reducing voltage, current and efficiency. It also makes solar cell more sensitive to heat, reducing its efficiency under high heat conditions. (Honsberg & Bowden, Float Zone Silicon, 2013).

An alternative for CZ method is Float-zone (FZ) method. FZ use an EG-Si ingot placed vertically, which is passed along back and forward with a circular magnetic heater (RF coil) melting only one zone of the ingot. The ingot have a seed rod in it. In this process the ingot impurities are removed from the ingot at the time it grows single crystal ingot. At the end of the process high purity mono-cS is produced. Principal difficulties are growing large diameter mono-cSi ingot (because it has to be enough surface tension in order to and the elevated price of the process). FZ wafers are commonly used on laboratory cells and high efficiency cell applications rather than common cell commercial production (Green, 2009).

Figure 8. Float Zone wafer growth

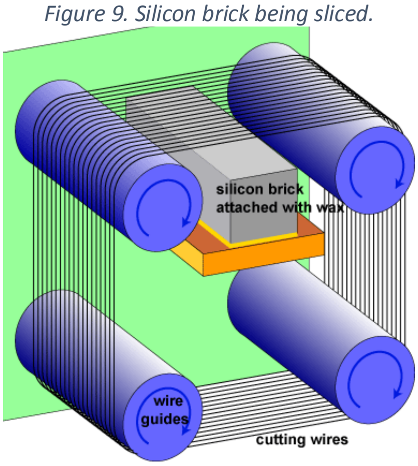


Source: Honsberg & Bowden, 2013.

3.3 Cell and module production.

After production of Ingots from mono-cSi or multi-cSi, they need to be sliced into wafers losing the top and the tail of the ingot. This is made using a multiwire saw and abrasive slurry. The ingot is sliced with a pitch of 0.5 to 1 mm to produce wafers of 0.3 to 0.5 mm, thus 40-50% of the ingot is lost as dust. This dust can be recovered to make a new ingot, but it has to be processed again in order to produce an ingot. (Blakers & Weber, 2000). Any way energy from upgrading silicon from MG-silicon to EG-silicon could be avoided in some fraction. This process dominates the PV ingot market, but there are other processes under development that try to grow wafers so that the cutting process could be avoided. Edge Defined Film Fed Growth (EFG) is a technique that permits to crystalize silicon wafers with large grains (Honsberg & Bowden, Float Zone Silicon, 2013).

Figure 9. Silicon brick being sliced.



Source: Honsberg & Bowden, 2013.

Si solar cell processing starting substrates are uniformly doped with boron giving a p-type base. The n-type emitter layer is formed through phosphorous doping. This is achieved by Solid state diffusion method for introducing dopant atoms into semiconductors (Honsberg & Bowden, Float Zone Silicon, 2013). Once either the doped wafer of c-Si or the doped substrate of a-Si is produced a step of a sequence of high temperature diffusion, oxidation, deposition and annealing are made on the cells. Then, after metallization, cells are connected with copper tabs. Up to 9% of the area is lost due to spaces leaved between cells (Blakers & Weber, 2000).

Then cells are encapsulated into a module behind glass with Ethylene-Vinyl Acetate (EVA) and Polyvinyl Fluoride film (PVF or Tedlar) using only heat and pressure. Depending on the Si technology and application the modules are mounted on different type of frames with different type of front materials.

4. Life Cycle Assessment

PV is recognized as one of the cleanest technologies for electricity generation. In order to be sustainable, energy consumed on its lifetime has to be lower than the one generated by the PV appliance. Life Cycle Assessment (LCA) allows to know how sustainable a PV technology is (Peng, Lu, & Yang, 2013). On this analysis we will consider only embedded energy and CO_2 equivalent emissions to determine sustainability. It is clear that other factors could be of great importance for determine an absolute sustainability but for the present analysis the other factors will not be considered. There will be no possible sustainability if embedded energy is greater than the energy generated by the PV appliance, either if the CO_2 emissions are greater than the ones generated by conventional fossil electricity generation technologies.

4.1 Methodologies

There is a methodology guidelines for developing LCA for PV electricity made by the International Energy Agency (IEA). Having a standard methodology allows to make comparisons or homologations on different LCA studies (Alsema, et al., 2009). Methodology guidelines establish that all PV LCA studies must be elaborated according to the ISO standards 14040 and 14044. It also structures the guidelines into three main areas: recommendations for technical characteristics related to PV systems, aspects regarding modeling in both LCA inventory and impact approaches and aspects about reporting and communication (Alsema, et al., 2009). Guidelines will be presented in a resumed way showing the relevant facts for the present analysis and that are followed by LCA reports analyzed.

- Photovoltaics-specific aspects.
    - Recommended life expectancy.
        - Modules: 30 years on mature module technologies (EVA-Tedlar encapsulation)
        - Inverters: 15 years for residential PV and 30 years for large plants with 10% of part replacement each 10 years.
        - Structure: 30 years for roof-top al facades and 30 to 60 years for ground mount.
        - Cabling: 30 years.
        - Manufacturing plants: less than 30 years because technology development.
    - Irradiation. It depends on the location and orientation of the modules.
        - Analysis of industry average and best case. Assume optimal orientation of the array plane. Case specific irradiation for façade installations.
        - For analyzing the average of installed systems in a grid use actual orientation and irradiation.
    - Performance ratio (PR). Depends on the kind of installation. Well controlled temperature installations and large installations will have a better performance.
        - For roof-top installations use a default value of 75%.
        - For ground-mount installations use 80% for default PR.
        - Use performance data when is available or use assumptions accord grid data.
    - Degradation. Results on reduction of efficiency over the life time. Mature technologies assume 80% of degradation at the end of 30 years. Assume lineal degradation over the life time.
    - Back-up systems. For PV LCA analysis is not necessary to include even if it's present.

- LCA modelling aspects.
  - System modelling
    - Define and distinguish the following goals of the LCA:
      - Report environmental impacts.
      - PV systems comparison or comparison vs. other technologies.
      - Long-term energy policies based of future PV systems.
    - Recommendations:
      - An attributional, decisional or consequential approach should be chosen.
      - Product system shall be divided into foreground and background processes.
      - Use the present average mix when modelling future PV production.
      - Use specific electricity mix when the analysis is bounded to a certain country.
      - Identify clearly country o company specific cases.
      - For long-term use an average future mix and adapt performance of power plants contributing for this future mix.
      - On long-term analysis adapt the efficiency of material supply, transport and waste management.
  - Functional unit and reference flow. Use ISO definitions of functional unit and reference flow. Functional unit is quantified with the reference flow as KWh electricity or m^2 laminate. Location, module type, voltage and how the transmission and distribution loses are accounted must be specified.
    - PV Comparison. Use kWh of electricity fed into the grid
    - For quantify environmental impacts of buildings or for quantifying energy gains on roofs use m^2 of PV module.
  - System Boundaries. It is important to define what to include and what to exclude from the analysis.
    - Product system must include the panel, the mounting system, the cabling, the inverter and all components since generation until injection to the grid.
    - Include energy and material flows of manufacturing process like climate control, ventilation, lighting, emissions control or waste treatment.
    - Exclude transportation of human resources.
    - If administration, sales and distribution, and research and development are included in the analysis try to keep separated from manufacturing inventory.
- Reporting and communication.
  - Key parameters to be reported:
    - Explicit goal of the study, name of the commissioner and intended purpose and audience.
    - Module efficiency, Irradiation, performance data (including PR) and define the region / location of the PV plant.
    - Assumptions for production of major input materials, for system type, method of module mounting and Balance of System components (BOS).
  - Reporting results:
    - Adapt category indicators to audience.
    - Describe Cumulative Energy Demand (CED) method used for Energy Pay-Back time (EPBT)

- Give clear reference to the impact assessment method applied and separate “background” and “foreground” contributions to the impact.

4.2 Objectives and Scope.

The main goal of this study is to analyze different LCA for a-Si, mono-cSi and multi-cSi PV technologies and focus on embedded energy and EPBT, as well as GHG emissions. The scope of this analysis is limited to recent LCA studies in order to use information of the most recent technology available. The range of years in which LCA results were published goes from 2005 to 2011.

Even though each of LCA studies have its own objective and scope, the total embedded energy an EPBT are similar in the order of magnitude and allows to have a good idea of the magnitude and effect on each PV technology.

GHG emissions have a big variation between different LCA studies, but have a similar order of magnitude. This variation can be caused by a very wide range of reasons (different electricity mix of the country where it was manufactured, kind of process used, etc.). This effect will be analyzed in *Chapter 5* in which it will be considered the geographical influence. Balance of System (BOS) will not be considered because it’s the same for all the silicon-based PV technologies studied.

The functional unit is one square meter of PV module. EPBT will be expressed in years and will be independent of functional unit because is also function of the irradiance received per square meter. GHG emissions will be expressed on grams of CO_2 equivalent per kWh, but will also be related to the kWh produced per square meter of module.

4.3 Parameter Inventory.

Inputs and outputs considered are not always presented in the same way on all the LCA analysis. Sometimes are integrated on other inputs. *Table 2* shows the input and output parameters that will be considered.

Table 2. LCA Parameter Inventory.

PV Tech	Inputs	Units
mono-cSi	Energy for produce MG-silicon	MJ/m^2
multi-cSi	Si feedstock production energy	MJ/m^2
mono-cSi	CZ Process	MJ/m^2
mono-cSi	Wafer slice	MJ/m^2
multi-cSi	Casting and cutting	MJ/m^2
cSi & aSi	Cell production	MJ/m^2
cSi & aSi	Module assembly	MJ/m^2
cSi & aSi	Frame	MJ/m^2
multi-cSi	Other manufacture parameters	MJ/m^2
a-Si	Capital Equipment	MJ/m^2

PV Tech	Inputs	Units
a-Si	Cell Material	MJ/m^2
a-Si	Process Energy	MJ/m^2
cSi & aSi	Irradation	$kWh/m^2/yr$
cSi & aSi	Module efficiency	
cSi & aSi	Lifetime	Years
cSi & aSi	Performance Ratio (PR)	
PV Tech	**Outputs**	**Units**
cSi & aSi	Total Embedded Energy	MJ/m^2
cSi & aSi	EPBT	Years
cSi & aSi	GHG emissions rate	g of $CO_{2\text{-eq}}$ /kWh

4.4 Results.

Data was collected from different LCA analysis and is presented in comparative tables. At the end averages for each silicon-based PV technology are compared. On reference section the detail of each LCA publication can be found.

Table 3. Embedded energy from mono-cSi manufacture.

Authors	Year	MG-silicon (MJ/m_2)	CZ process (MJ/m2)	Wafer (MJ/m2)	Cell production (MJ/m2)	Module assembly (MJ/m2)	Frame (MJ/m2)	Total (MJ/m2)
Alsema and Wild-Scholten	2005	1759	2391		473	394	236	5253
Jungbluth and Stucki	2009	1029	1208	562	595	466		3860
Wild-Scholten	2009	728	1266		389	477		2860
Laleman	2011	2397	432			684		3513

On *Table 3* embedded energy from manufacture process of mono-cSi is presented collected from 4 LCA analysis. In the total energy there is a clear difference between 2005 compared with 2009 and 2011 studies. The best improvement is noted on CZ process which was importantly reduced on that period. Other stages remain almost in the same quantity on energy use. In some LCA separated energy data for wafer or frame was given.

Table 4. Embedded energy from multi-cSi manufacture.

Authors	Year	Si feedstock production (MJ/m_2)	Wafer (MJ/m2)	Cell production (MJ/m2)	Module assembly (MJ/m2)	Frame (MJ/m2)	Others (MJ/m2)	Total (MJ/m2)
Alsema and Wild-Scholten	2005	1759	1078	473	276	236	118	3940
Pacca and Sivaraman	2007	1075		3247				4322
Alsema and Wild-Scholten	2007	1400	550	400	500	270		3120
Jungbluth and Stucki	2009	1030	968	544	523			3065
Wild-Scholten	2009	1110	744	378	467			2699

Embedded energy analysis for multi-cSi manufacture process is shown on *Table 4*. There is a more attenuated reduction tendency (compared to mono-cSi) on total energy, mostly caused by improvements on Si feedstock production. For Pacca and Sivaraman study cell production groups several stages of the manufacture process so no individual analysis can be studied.

Table 5. Embedded energy from amorphous-Si manufacture.

Authors	Year	Cell Material (MJ/m_2)	Substrate, encapsulation, materials and cell production (MJ/m2)	Process energy (MJ/m2)	Capital equimpment (MJ/m2)	Total (MJ/m2)
Pacca and Sivaraman	2007	172	690			862
Wild-Scholten	2009	50	350	400	189	989

On *Table 5* energy consumption for a square meter of amorphous-Si module is evaluated on two LCA analysis. There is no tendency to reduce energy consumption, even it appears to be increasing. But if we compare these results with 1998 LCA analysis we can see a clear reduction of more than a half of energy use (Peng, Lu, & Yang, 2013).

Table 6. LCA Results of mono-cSi, multi-cSi and aSi PV systems.

PV Tech.	Authors	Year	Location	Irradiation ($kWh/m^2/yr$)	Module Efficeincy	Lifetime (yr)	Performance Ratio	EPBT (yr)	GHG emissions rate (g CO_2-eq/kW h_e)
mono-cSi	Alsema and Wild-Scholten	2005	South Europe	1700	13.7%	30	0.75	2.6	41
mono-cSi	Alsema and Wild-Scholten	2006	South Europe	1700	14.0%	30	0.75	2.1	35
mono-cSi	Jungbluth and Dones	2007	Switzerland	1117	14.0%	30	0.75	3.3	
mono-cSi	Wild-Scholten	2009	South Europe	1700	14.0%	30	0.75	1.8	30
mono-cSi	Ito and Komoto	2010	China	1702			0.78	2.5	50
multi-cSi	Alsema and Wild-Scholten	2006	South Europe	1700	13.2%	30	0.75	1.9	32
multi-cSi	Pacca and Sivaraman	2007	U.S.	1359	12.9%	20		2.1	72.4
multi-cSi	Jungbluth and Dones	2007	Switzerland	1117	13.2%	30	0.75	2.9	
multi-cSi	Raugei and Bargigli	2007	South Europe	1700	14.0%	20	0.75	2.4	72
multi-cSi	Wild-Scholten	2009	South Europe	1700	13.2%	30	0.75	1.8	29
multi-cSi	Ito and Komoto	2010	China	1702			0.78	2.0	43
aSi	Jungbluth and Dones	2007	Switzerland	1117	6.5%	30	0.75	3.1	
aSi	Pacca and Sivaraman	2007	U.S.	1359	6.3%	20		3.2	34.3
aSi	Ito and Kato	2008	China	2017	6.9%	30	0.81	2.5	15.6
aSi	Wild-Scholten	2009	South Europe	1700	6.6%	30	0.75	1.4	24

Table 6 shows EPBT and GHG emissions for 15 different LCA studies since 2005 until 2010. EPBT depends on irradiation available where the PV panel is allocated. On Switzerland analysis of all PV technologies show an increase on EPBT because low irradiation. Also too much irradiation like shown on Ito and Kato LCA on China, does not necessarily reflects on an EPBT improvement. High irradiation can increase module temperature and decrease efficiency and therefore EPBT.

Figure 10. Average embedded energy

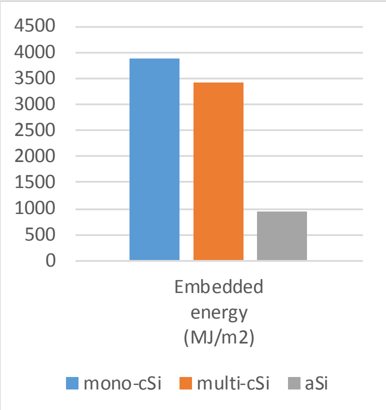


Figure 11. Average module efficiency

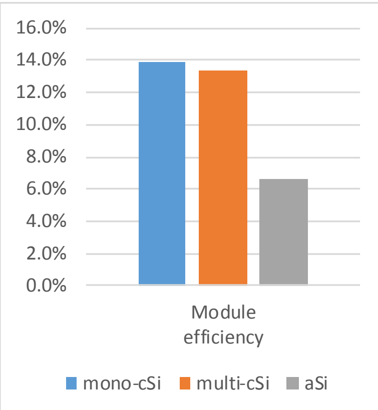


Figure 12. Average EPBT

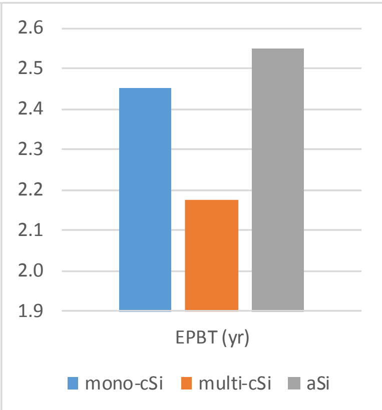


Figure 13. Average GHG emissions rate

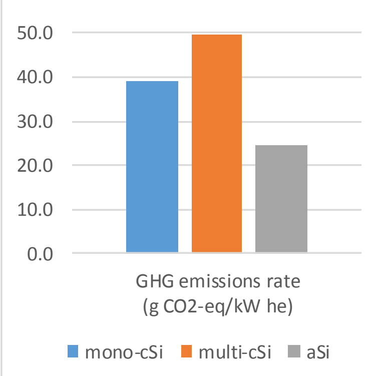


Table 7. Average values of LCA results.

PV Tech	Embedded energy (MJ/m2)	Module efficiency	EPBT (yr)	GHG emissions rate (g CO2-eq/kW he)
mono-cSi	3871.5	13.9%	2.5	39.0
multi-cSi	3429.2	13.3%	2.2	49.7
aSi	925.5	6.6%	2.6	24.6

High temperatures cause silicon semiconductors become a more resistant conductive material, reducing the band gap of the semiconductor affecting its efficiency (Honsberg & Bowden, Effect of Temperature, 2013). On *Table 6* a-Si shows a better performance at high temperatures, while mono-cSi and multi-cSi have better performance on low temperature locations.

Table 7 shows the average values of LCA results for all the three PV technologies on total embedded energy from manufacture, module efficiency, EPBT and GHG emissions. *Figures 10, 11, 12 and 13* shows the data on *Table 7* for comparison.

Figures 10 and 11 shows that mono-cSi is the most energy intensive and more efficient of the three type of modules, followed closely by multi-cSi. Amorphous silicon shows very low energy consumption on the manufacture process, but it also have less than half efficiency of the crystalline technologies. Neither the most efficient nor the more low energy consume module is the ideal for achieving the best EPBT. As shown on *Figure 12* the best EPBT is presented by multi-cSi. We have to look for the correct balance in order to have a most sustainable technology. This doesn´t mean than multi-cS is the ideal in all cases, each project must be evaluated individually. For this analysis it only show a possible market tendency, which is true as analyzed at the end of Chapter 3.2.1 of this study. One important consideration is that the most developed countries on use of PV technology are not the ones with best irradiation and high temperatures. The best PV technology can change for regions with high temperatures and irradiation.

On *Figure 13* average GHG emissions is presented. There is no relation between GHG emissions and embedded energy or module efficiency. This is because GHG emissions reported are the ones generated directly by the different steps on manufacture process. GHG emissions related to electricity and therefore to the energy mix of the network used are not reported con LCA analysis. Even though, later we will take this factor under consideration.

5. Geographic Influence.

After analyzing the Si PV technologies it's clear that embodied energy is a very important factor on determining technologies viability. Embodied energy accumulated during the manufacture process of Si-based PV have a direct relationship with the CO_2 footprint but the scale depends on the energetic mix of electricity used during the different manufacture processes. It is important to consider that, even that the majority of embedded energy comes for electricity, there are some processes that may use other energy sources. Also there is the possibility that some part of materials manufacture can had taken place in a different country that the one where the solar cell is produced.

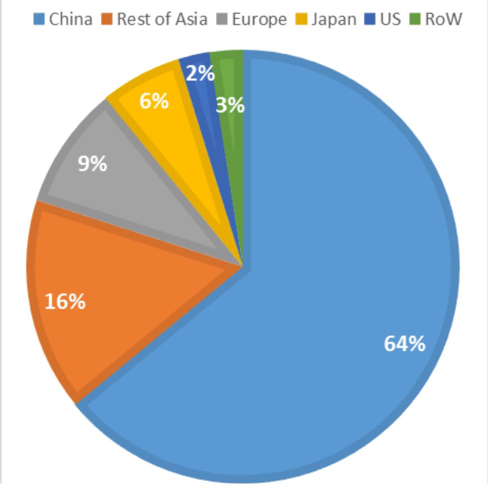
Other important factor on embedded energy and CO_2 footprint is the transportation of the cells or modules from the manufacturer to the facilities where is installed. On many cases the distances between them can be very large and therefore accumulate more embedded energy and CO_2 footprint.

In order to determine how these parameters influence on CO_2 footprint an embodied energy we will study which countries are the main suppliers and buyers and energy mix for each of these countries. We will make a comparison between transporting solar cells and build modules on the country of final use or sending modules from the supplier country. For calculating embedded energy and CO_2 footprint for transport and manufacture we will use *Granta CES Edupack 2012* from *Granta Design Limited*. *CES Edupack* is a software program for materials analysis with a database of most common materials.

5.1 Main Suppliers and main buyers

When analyzing main PV suppliers it is important to consider where the cells and modules are made, rather than where are based the companies that make them. On *Figure 8* global PV production by region is presented, it's calculated on percentage of MW of capacity produced. If we consider all Asia in concentrates up to 86% of worldwide production, followed by Europe and U.S. with 11% of market share. This is a big difference compared with recent years ago. On 2007 Europe and U.S. held 40% of market share (Mehta, 2014). It doesn`t mean that if they are losing market share they also are decreasing their MW produced. Market has been growing constantly (*Figure 1*). The difference in market share shows which countries are expanding more their production.

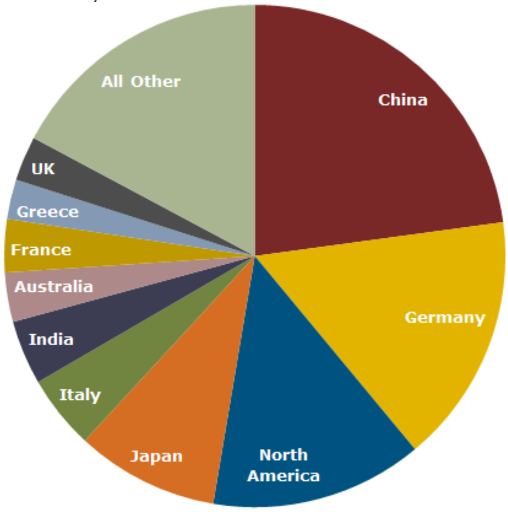
Figure 14. Global PV Production by region, 2013.



Source: Metha, 2014.
Rest of Asian nations refer primarily to Malaysia, South Korea and Taiwan.

Main world buyers have significant differences with main suppliers. On *Figure 11* it can be seen that the main markets for PV demand are China, Germany, North America, Japan, Italy, India, Australia, France, Greece and United Kingdom. China has the mayor growth also as a consumer of PV, not because a renewable energy policy or tendency, but because their big energy growing needs. China electricity needs are growing faster than renewable energy production (Solarbuzz, 2013). China is the biggest consumer but they export almost double quantity of the PV modules they consume. Germany an U.S. are big importers because their demand is far greater than their production.

Figure 15. Global PV Demand in 2013.



Source: Marketbuzz, 2013.

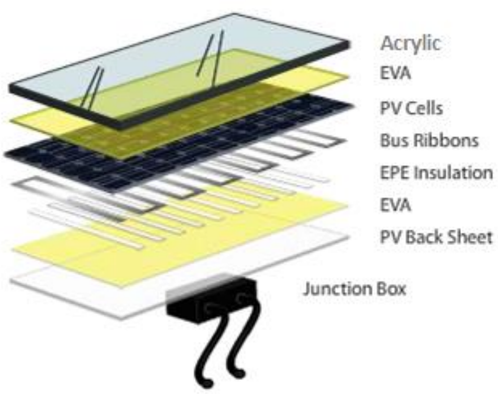
5.2 Transporting modules vs. transporting cells.

As analyzed on previous chapters, embedded energy from PV cell manufacture represents the main energy concern. As shown on Chapter 5.1, there is a lot of PV modules commerce between Asia and Europe - U.S. markets. On this and the next chapter embedded energy from transporting will be evaluated. For this evaluation we will assume several characteristics of a PV solar cell and module. The most important parameter to obtain is the weight of solar cells on a module and the complete module. Also different route scenarios will be created in order to analyze the distances between suppliers and buyers.

A one square meter of mono-cSi PV Panel is assumed for transport evaluation. As suggested by Blakers and Webber a square meter of PV Panel will require 90 solar cells with a total mass of 725 grams of mono-cSi (Blakers & Weber, 2000). For module and encapsulation we will assume the following elements (Dunmore Corporation) with a total weight of 13.12 kg (including solar cells)

- One acrylic Layer for protecting PV cells and electronic on the exposed to sunlight face of the panel. Weight according to density and thickness: 3.6 Kg
- Two Ethylene Vinyl Acetate (EVA) layers for cell encapsulation. Weight: 0.095kg x 2 = 0.19kg.
- Copper wire. Weight 0.13 kg estimated to interconnect all cells.
- Polyethylene for insulation. Weight: 1.4 Kg
- Polyester base and frame. Weight: 7 kg
- Bakelite electrical contacts. Weight: 0.07 kg

Figure 16. Solar Module Exploded View



Source: Dunmore Corporation.

Two options of transportation will be evaluated. The first considering only solar cells with a mass of 725 grams and the second considering a complete module of 13.12 Kg. The next step is to establish what routes will be analyzed.

Since Asia is the main PV cell al module producer we will consider that the supplier will be China and Japan. For the transport embedded energy we will not expect be relevant, but when analyzing electricity mix we expect to see considerable differences on GHG emissions.

The main buyers worldwide are China, Europe (mainly Germany), U.S. and Japan. Since China and Japan are also big suppliers they can meet their own PV needs and don´t have to import PV modules or cells, thus we will consider Germany and U.S. as the main buyers.

The Chinese port that will be considered for distance calculations will be Beijiao Terminal, while for Japan will be Fukuyama terminal. The port considered for importing on U.S. will be San Francisco Terminal, while for Germany will be Hamburg Terminal. Route distances will be calculated using SeaRates.com port distance calculator (SeaRates.com, 2014).

5.3 Embedded Energy and GHG emissions from transport.

Distances, module and cells weight have been entered into *CES Edupack 2012* software considering that the distances will be covered by sea freight transportation. Distances and results are showed on *Table 8*.

Table 8. Transport embedded energy and GHG emissions for sea transportation.

Supplier Port	Buyer Port	Distance (km)	Mass transported (kg)	Transport Emboddied Energy (MJ)	$CO_{2\text{-eq}}$ Footprint (kg $CO_{2\text{-eq}}$)
Beijiao, China	San Francisco, U.S.	11330	0.725	1.3	0.093
Fukuyama, Japan	San Francisco, U.S.	8995	0.725	1	0.074
Beijiao, China	Hamburg, Germany	18600	0.725	2.2	0.15
Fukuyama, Japan	Hamburg, Germany	20748	0.725	2.4	0.17
Beijiao, China	San Francisco, U.S.	11330	13.12	24	1.7
Fukuyama, Japan	San Francisco, U.S.	8995	13.12	19	1.3
Beijiao, China	Hamburg, Germany	18600	13.12	39	2.8
Fukuyama, Japan	Hamburg, Germany	20748	13.12	44	3.1

Source: Data from SeaRates.com and CES Edupack 2012.

When comparing *Table 8* embedded energy from transportation with manufacture embedded energy on *Table 7* we can see that there is a small but significant reduction on total embedded energy when solar cells are transported to be assembled on the buyers region. The greatest save will be the case on which Japan sells solar cells to Germany, in that scenario the reduction will be equivalent of a 4.5% reduction on manufacture embedded energy. The complete set of possible saving on this scenario are shown on *Table 9*.

Table 9. Possible savings compared to manufacture embedded energy.

PV Tech	Supplier Port	Buyer Port	Energy Savings (MJ)	Manufacture embedded energy (MJ)	Savings / Manufacture energy
mono-cSi	Beijiao, China	San Francisco, U.S.	22.7	3871.5	0.59%
mono-cSi	Fukuyama, Japan	San Francisco, U.S.	18	3871.5	0.46%
mono-cSi	Beijiao, China	Hamburg, Germany	36.8	3871.5	0.95%
mono-cSi	Fukuyama, Japan	Hamburg, Germany	41.6	3871.5	1.07%
multi-cSi	Beijiao, China	San Francisco, U.S.	22.7	3429.2	0.66%
multi-cSi	Fukuyama, Japan	San Francisco, U.S.	18	3429.2	0.52%
multi-cSi	Beijiao, China	Hamburg, Germany	36.8	3429.2	1.07%
multi-cSi	Fukuyama, Japan	Hamburg, Germany	41.6	3429.2	1.21%
a-Si	Beijiao, China	San Francisco, U.S.	22.7	925.5	2.45%
a-Si	Fukuyama, Japan	San Francisco, U.S.	18	925.5	1.94%
a-Si	Beijiao, China	Hamburg, Germany	36.8	925.5	3.98%
a-Si	Fukuyama, Japan	Hamburg, Germany	41.6	925.5	4.49%

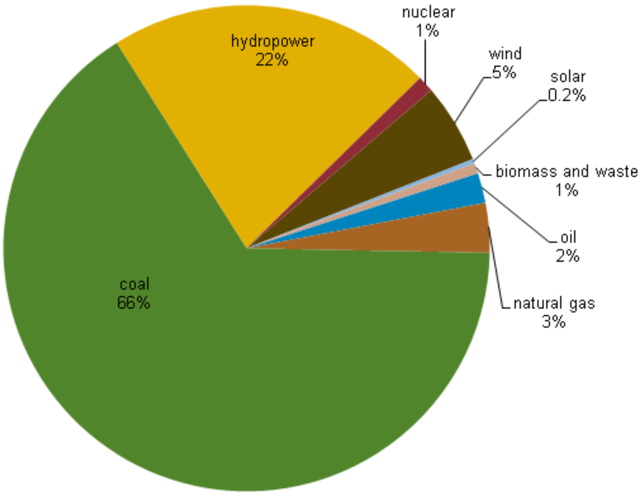
The savings described are considering energy only. Differences could appear when building the rest of the module on the buyer region. Assuming that the energy saving are absolute real is to assume that supplier and buyer regions can gather resources and build in the same conditions as supplier region.

5.4 Regional energy mix

Energy mix is very important when referring to GHG emissions. Manufacture embedded energy can come from more than one country. For the purpose of this study we will consider that all the solar cell and all the raw materials used are made in the same country. There are three scenarios that we will study:

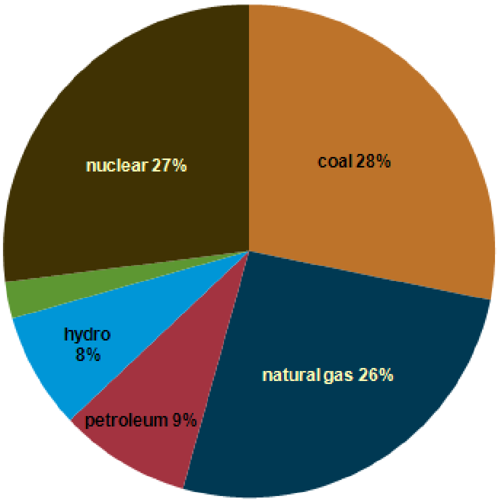
- **China** has an energy mix dominated by the use of coal. 2/3 of electricity generation comes from coal, followed by 22% of hydropower (U.S. Energy Information Administration, 2014). This mix make China one of the countries with higher emission of GHG per MWh with a factor of 920 kg CO_2 per MWh (CO2Benchmark Ltd, 2013). *Figure 17* shows China energy mix on 2012.
- **Japan** is one of the countries that invest more on renewable energies, and until 2009 it also had an important energy share of nuclear energy. Since 2009 Fukushima disaster Japan have gradually reduced nuclear generation. For purpose of getting the effect of nuclear and renewable energy on energy mix we will consider values of 2009 before Fukushima disaster. By 2009 Japan had 27% percent of nuclear energy on their mix, also 26% with gas and only 28% with coal (U.S. Energy Information Administration, 2011). That energy mix let them to have GHG emissions of 436 kg CO_2 per MWh (International Energy Agency, 2009). *Figure 18* show Japan energy mix on 2009.
- **Germany** is a country that has bet for renewable energy sources not only above fossil fuel generation, also above nuclear energy. On 2013 coal generation is in around 46% of energy mix, while renewable energy represents 24% of energy mix (Morris, 2014). *Figure 19* illustrates Germany energy mix. With high participation of renewable energy but with half of their production on coal, Germany has a GHG emission rate of 670 kg CO_2 per MWh (CO2Benchmark Ltd, 2013).

Figure 18. China Energy mix on 2012.



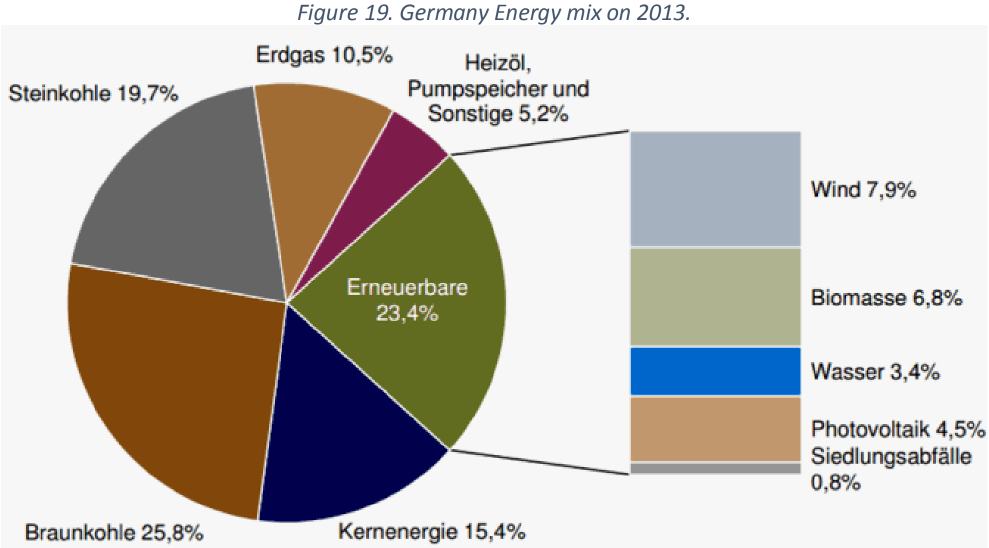
Source: U.S. Energy Information Administration, 2014.

Figure 17. Japan Energy mix on 2009.



Source: U.S. Energy Information Administration, 2011)

Figure 19. Germany Energy mix on 2013.



Source: Morris, 2014.

5.5 CO2 Emissions.

Considering GHG emissions rate for China, Japan and Germany on *Table 10* shows an example of $CO_{2\text{-eq}}$ produced by the use of electricity on Si-based PV technologies.

Table 10. CO_2 emissions from manufacture on Si-based PV based on LCA for China, Japan and Germany

PV Tech	Manufacture embedded energy (MJ)	Manufacture embedded energy (MWh)	CO_2 Emission on China (kg $CO_{2\text{-eq}}$)	CO_2 Emission on Japan (kg $CO_{2\text{-eq}}$)	CO_2 Emission on Germany (kg $CO_{2\text{-eq}}$)
mono-cSi	3871.5	1.075	989	469	721
multi-cSi	3429.2	0.953	876	415	638
a-Si	925.5	0.257	237	112	172

Japan GHG emissions prove to be low when considering 2009 energy mix. Considering that manufacture embedded energy given is calculated for a PV module of one square meter we can estimate that buying it in Japan instead of China will save over 50% of the GHG emissions.

It is important to notice that this GHG emissions study considers that all the embedded energy comes from electricity. Of course we know that not all the embedded energy come from electricity, but the majority does. Exact data cannot be used because of the lack of access to the complete LCA studies. The purpose is to highlight the influence of the energy mix on GHG emissions, not to get exact emission calculations.

Also transportation prove to have small influence on CO_2 emissions when transporting on freight. In the best case with a-Si saves could reach up to 2% of CO_2 emissions saving.

6. Conclusions.

Silicon-based PV industry is growing and it is expected to continue growing on the mid and long term. The effect on emerging economies is that energy needs are growing faster that PV industry and therefore more Research and Development must be made on the next years.

Crystal silicon have the biggest market share and it´s expected to continue that way, with a tendency for growth on multi-cSi PV. Also the LCA analysis is consequent with this assumption, providing bases that multi-cSi PV hast the best EPBT.

In the last decade energy needed for PV manufacture has decrease but it is still too intensive in order to compete with conventional energy sources. Different technologies offer different advantages and the best technology to use must be evaluated individually for each project.

LCA is a fundamental tool to understand and evaluate sustainability of PV technologies, but also to identify the areas that have more impact on sustainability in all their variables (EPBT, GHG, embedded energy). Also for correctly understand LCA analysis main manufacture process and PV fundamentals must be understood and evaluated. Geographic irradiance and temperature are very important, and can make one or another PV technology better for a specific project. Mono-cSi and multi-cSi prove to work better under low temperature conditions. A-Si increase its PR on high temperature conditions, making it more viable on regions with high irradiance and temperature.

LCA cannot account GHG emissions from electricity use because it varies from country to country and even from time of the day or day of the year. Therefore it is fundamental to establish some guidelines for evaluating the effect of the energy mix on PV technologies. The risk is that high GHG emission technology can be disguised using PV clean energy or any other intensive clean energy. Within this guidelines, it should be important to differentiate embedded energy according to the primary energy source and country where the particular process has been made.

Transporting solar cells from suppliers instead of modules must be carefully evaluated in order to have energy, CO_2 and price saves. Today will not make great difference on the embedded energy of the PV modules, but as the manufacture process use less energy transport will become more relevant.

7. References

Alsema, E., Fraile, D., Frischknecht, R., Fthenakis, V., Held, M., Kim, H. C., . . . Scholten, M. d. (2009). *Methodology Guidelines of Life Cycle Assessment of Photovoltaic Electricity.* International Energy Agency. Photovoltaic Power Systems Programme.

Azonano.com. A to Z of Nanotechnology. (2009, May 27). *Hemlock Semiconductor Begins Operation of New 8,500 Metric Tons Polysilicon Production Facility*. Retrieved August 05, 2014, from Azonano.com. A to Z of Nanotechnology: http://www.azonano.com/news.aspx?newsID=11715

Blakers, A., & Weber, K. (2000). *The Energy Intensity of Photovoltaic Systems.* Canberra: Engineering Department, Australian National University.

Card, H., & Yang, E. (1977). Electronic processes at grain boundaries in polycrystalline semiconductors under optical illumination. *IEEE Transactions on Electron Devices, ED-24*, 397-402.

CO2Benchmark Ltd. (2013). Retrieved 07 25, 2014, from CO2Benchmark Ltd: http://www.co2benchmark.com/co2-per-MWH-per-country

Costanza, R. (1980). Embodied Energy and Economic Valuation. *Science 12. Vol. 210*, 1219-1224.

Doherty, B. (1997, April 25). *PIN Diode Fundamentals.* Retrieved 08 02, 2014, from Microsemi: http://www.microsemi.com/sites/default/files/micnotes/701.pdf

Dunmore Corporation. (n.d.). *Solar Back Sheet.* Retrieved 08 18, 2014, from Dunmore Corporation: http://www.dunmore.com/products/solar-back-sheet.html

ENF Solar. (2014). *Polysilicon Manufacturers - Ingot Process*. Retrieved 08 08, 2014, from ENF Solar - Accelerating the Industry: http://www.enfsolar.com/directory/material/polysilicon

EPIA - European Photovoltaic Industry Association. (2014). Global Market Outlook For Photovoltaics 2014-2018. doi:ISBN: 9789082228403

Green, M. (2009). The path to 25% silicon solar cell efficiency: History of silicon cell evolution. *Progress in Photovoltaics: Research and Application, 17*, 183-189.

Honsberg, C., & Bowden, S. (2013). *Effect of Temperature.* Retrieved 08 28, 2014, from PV Education: http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-temperature

Honsberg, C., & Bowden, S. (2013). *Float Zone Silicon.* Retrieved 08 12, 2014, from PV Education: http://pveducation.org/pvcdrom/manufacturing/float-zone-silicon

IEA-ETSAP and IRENA. (2013). *Solar Photovoltaics. Technology Brief.* IEA-ETSAP and IRENA.

International Energy Agency. (2009). *World Energy Outlook 2010.* International Energy Agency.

International Energy Agency. (2010). Solar photovoltaic energy. *Technology Roadmap*, 5-23.

Jones, J., & Martin, L. (2014, July 16). *EIA projects modest needs for new electric generation capacity*. Retrieved July 21, 2014, from U.S. Energy Information Administration: http://www.eia.gov/todayinenergy/detail.cfm?id=17131

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

Lide, D. R. (1996). *Handbook of Chemistry and Physics, 77th Edition.* CRC Press. doi:ISBN: 978-0849304774

Lifton, J. (2008, March 13). *Materials for Solar Photovoltaic Cells I: Silicon, Very Abundnt, Very Expensive*. Retrieved 07 26, 2014, from Hard Assets. Metals, energy & minning for the serious investor: http://www.resourceinvestor.com/2008/03/13/materials-for-solar-photovoltaic-cells-i-silicon-v

Mehta, S. (2014, April 23). *Technology shares, regional production trends, top suppliers, and the outlook for 2014.* Retrieved from Greentech Media: http://www.greentechmedia.com/articles/read/Global-2013-PV-Module-Production-Hits-39.8-GW-Yingli-Leads-in-Production-a

Morris, C. (2014, April 11). *Reality check: massive overcapacity on German power market.* Retrieved from Energy Transition. German Energy Transition.: http://energytransition.de/2014/04/reality-check-massive-overcapacity-on-german-power-market/

O'Lenick, A. J. (1999, August). *Basic Silicone Chemistry – A Review.* Retrieved 07 29, 2014, from Silicone Spectator: http://www.siliconespectator.com/articles/Silicone_Spectator_January_2009.pdf

Panasonic Corporation. (2014). *Amorphous Si Solar cells*. Retrieved from Panasonic Global: http://panasonic.net/energy/amorton/en/solar_battery/

Peng, J., Lu, L., & Yang, H. (2013). Review of life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and Sustainable Energy Reviews 19*, 255-274.

Qatar Solar Technologies. (n.d.). *Solar Value Chain*. Retrieved 08 05, 2014, from QSTec - Qatar Solar Technologies: http://www.qstec.com/products/solar-value-chain-qstec/solar-value-chain

Riaz, J. A. (n.d.). *Types of solar cells*. Retrieved 08 06, 2014, from WifiNote.com: http://www.wifinotes.com/energy/types-of-solar-cells.html

SeaRates.com. (2014). *Distances and Time*. Retrieved 08 20, 2014, from Transit Time, Distance Calculator & Port to Port distances.: http://www.searates.com/reference/portdistance/

Sherwani, A., Usmanu, J., & Varun. (2010). Life cycle assessment of solar PV based electircity generation systems: a Review. *Renewable and Sustainable Energy Reviews, 14*, 540-544.

Solarbuzz. (2013). *PV Equipment Quarterly .* Santa Clara, California: Solarbuzz - Solar Market Reserach and Analysis.

Solarbuzz. (2013, March 11). *Solar Photovoltaic Demand to Reach 31 Gigawatts in 2013, According to NPD Solarbuzz.* Retrieved from Solarbuzz: http://www.solarbuzz.com/news/recent-findings/solar-photovoltaic-demand-reach-31-gigawatts-2013-according-npd-solarbuzz

Talik, E., & Oboz, M. (2013). Czo chralski Metho d for Crystal Growth of Reactive Intermetallics. *Acta Physica Polonica, 124*, 340-343.

U.S. Energy Information Administration. (2011). *Japan depends significantly on nuclear power to meet its electricity needs.* U.S. Energy Information Administration.

U.S. Energy Information Administration. (2014). *China.* U.S. Energy Information Administration.

U.S. Geological Survey. (2008). *Mineral Commodity Summaries.* U.S. Geological Survey.

Wendman, M. (2006, September 10). *Pictures of Metallurgical Silicon Refining.* Retrieved from Wendmans Views on Nanotech: http://mark-nano.blogspot.com.es/2006/09/pictures-of-metallurgical-silicon.html

World Nuclear Association. (2014, May). *World Energy Needs and Nuclear Power.* Retrieved July 20, 2014, from http://www.world-nuclear.org/info/Current-and-Future-Generation/World-Energy-Needs-and-Nuclear-Power/

ABSTRACT

Energy produced from solar PV (Photovoltaic) have been increasing constantly and is expected to continue growing into the energy market share in the following years. In the last decades the photovoltaic industry had succeeded to make an important decrease on the amount of energy necessary for manufacturing and installing solar panels. Therefore it has decreased the financial and energy payback for new installations. This has allowed to achieve low cost energy from PV systems and to decrease in many cases the amount of greenhouse gas emissions associated to PV manufacturing. So then, it is important to continuously improve PV panel's state of the art manufacturing and installing framework. The silicon based PV technologies dominate today's world market and are expected to continue ruling the PV industry. This because they depend more on the improvement of the manufacturing process requiring less energy, rather than other PV technologies based on scarce materials that are founded only on certain regions. Amorphous, mono-crystalline and poly-crystalline are the main silicon based PV technologies used today and will be the ones studied in this paper. Different LCA (Life Cycle Assessment) will be considered for these PV technologies as also as the transportation influence into the PV panels embedded energy, and, as a consequence of the energy required, the CO_2 emissions associated to the place where the panels or modules are manufactured. Only embedded energy and quantity of CO_2 emissions will be considered (it depends on the electricity mix of where it's manufactured), other possible financial aspects or pollutant matters will not be studied on this paper.

RESUMEN

La energía producida a partir de la energía solar fotovoltaica (PV, por sus siglas en inglés) se ha ido incrementando constantemente y se espera que su participación en el mercado energético siga creciendo durante los próximos años. En las últimas décadas la industria fotovoltaica ha logrado disminuir de manera importante la cantidad de energía necesaria para la fabricación e instalación de paneles solares. Debido a esto, el tiempo de retorno de inversión financiera ha disminuido, así como la energía necesaria para desarrollar nuevas instalaciones. Esto ha permitido alcanzar costos bajos en la producción de energía procedente de sistemas fotovoltaicos; así como también disminuir, en muchos casos, la cantidad de emisiones de gases de efecto invernadero (GHG, por sus siglas en inglés) asociadas a la fabricación de los sistemas fotovoltaicos. Así pues, es importante mejorar continuamente el proceso de fabricación e instalación de sistemas fotovoltaicos utilizando tecnologías de última generación. Las tecnologías fotovoltaicas basadas en silicio dominan el mercado mundial actual, y se espera que continúen siendo la tecnología líder en la industria fotovoltaica. Este comportamiento se debe a que el desarrollo de estas tecnologías depende en gran medida de la mejora del proceso de fabricación en cuanto al menor uso de energía; a diferencia de otras tecnologías fotovoltaicas, que están basadas en materiales escasos, y que se obtienen sólo en ciertos países o regiones. El silicio amorfo, el monocristalino y el policristalino son los principales tipos de tecnologías fotovoltaicas basadas en silicio utilizadas en la actualidad, las cuales serán estudiadas en este trabajo. Diferentes análisis de ciclo de vida (LCA, por sus siglas en inglés) serán considerados para analizar estas tecnologías fotovoltaicas. Además se estudiará la influencia del transporte en la energía incorporada de los paneles fotovoltaicos. Como consecuencia de esta energía incorporada, se analizarán las emisiones de CO_2 asociadas al lugar donde los paneles o módulos fueron fabricados. Sólo la energía incorporada y la cantidad de emisiones de CO_2 serán considerados en este análisis (las emisiones GHG dependen en gran medida del "mix" energético de donde es fabricado). Otros posibles aspectos financieros o de materiales contaminantes no serán estudiados en este trabajo.