Life Cycle Assessment and Economic Aspects of Laterally Integrated Solar Cell

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Dedication

This thesis is dedicated to my mother ***Pushplata Singh***, my father ***Rammurti Singh***, and my brothers who have always been the force driving me towards success in life.

Abstract

Sustainable development requires use of many different methods and tools to measure performance with regards to environmental impact. Environmental impact counts for both the emission from the system and also the emission during the manufacturing of the system. The standards for solar cells are given in the ISO 14000 series. ISO standards can only be used for solar systems that are in service. This paper will try to analyze a system which is in its design phase by combining the ISO 14000 series with a quantitative approach from simplification of process-LCA. At the same time it will also try to compute the economics behind the new design to generate a sustainable design. This study is done to analyze the design phase only and to identify any possibility of improvement. This paper also tries to identify the effect of solar insolation on the output of the solar cell. The design that will be analyzed is called a laterally integrated solar cell. In this design, the semiconductors are laterally assembled. Laterally integrated photovoltaic cell design technology is intended as a substitute for a traditional photovoltaic cell offering higher efficiency, lower cost, minimal maintenance and most importantly sustainability. This paper considers energy flows from cradle to gate starting from silica extraction to the final panel assembly. The after use or recycle phase is not considered because this study is intended to understand the design phase and its environmental impacts. The different semiconductors used for this technology include Indium Gallium Nitride (InGaN), Polycrystalline-Si, Amorphous-Si, and Cadmium Telluride (CdTe). The most critical phase is the transformation of extracted raw material into a 99.999% pure form to be used in the production of solar cells. Maximum power point (P_m) and Energy Payback Time (EPBT) have been evaluated, considering different geographic locations with the use of relevant real time values of solar radiation, latitude, longitude and elevations. Evaluation of an existing solar panel system located at UMD as compared to a laterally integrated PV solar panel is also performed. It was concluded from the study that the energy payback time of the system is comparatively higher than other systems present in the market. Solar insolation also plays a big role in the output of the solar system. The difference between the maximum and minimum EPBT of laterally integrated systems at different locations across the globe was about 7.4years. Levelized cost of energy of the system is around $247/MWh. It is very high compared to other conventional and non-conventional energy sources. The factor that supports the design is the present worth of electric power the system will generate over its entire life of 30 years. System results were promising when compared with the University of Minnesota-Duluth solar panel. A laterally integrated system, if substituted for the panel at UMD, will generate 19438.53kWh of electricity and save 12370.68 kg of CO_2, 48.60 kg of NO_2, and 69.98 kg of SO_2 within 18 months of its service.

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Chapter1: Introduction

Energy is one of the key inputs which improves and drives the life cycle. In other words it’s a gift by Mother Nature to all living forms on planet earth. Direct and indirect consumption of this energy is directly proportional to the development of life. With rising population and increased standard of living backed by growing industrialization of countries, the demand for energy is expected to increase by many folds in coming years. The primary source of energy used today is conventional energy (fossil fuels), mainly coal [Sidhu, 2007]. At present, most countries depend on coal for their electric power generation.

However, switching to non-conventional, renewable and green energy is recommended, as the use of limited resources cause large environmental degradation leading to global warming, air and water pollution

There are many kinds of non conventional sources of energy; most of them come directly from sun like solar energy, hydro energy, and wind energy. Geothermal and tidal energy are not directly related to sun. Most types of energy are ultimately related to sun energy; as a result, there has been focus on this form of energy recently. Solar rays are electromagnetic waves; when reaching the earth it consists of about 8% ultraviolet radiation, 46% visible light and 46 % infrared radiations [Sidhu, 2007].

The Photovoltaic (PV) process, the direct conversion of sunlight to electricity by solar cells, is a demonstrated and attractive “alternative energy” technology. The potential contribution of this technology can be understood by noting that the average solar radiation incident in a year on the contiguous 48 states of the United States is approximately 1.47x10^{15} watts. This is approximately 500 times the power consumption of United States in a year; that includes electricity, heat, transportation and other uses [Sidhu, 2007].

Most forms of solar energy initially faced problems of storage, but today it can stored as thermal energy, chemical energy, and electromagnetic energy as illustrated in Figure 1.

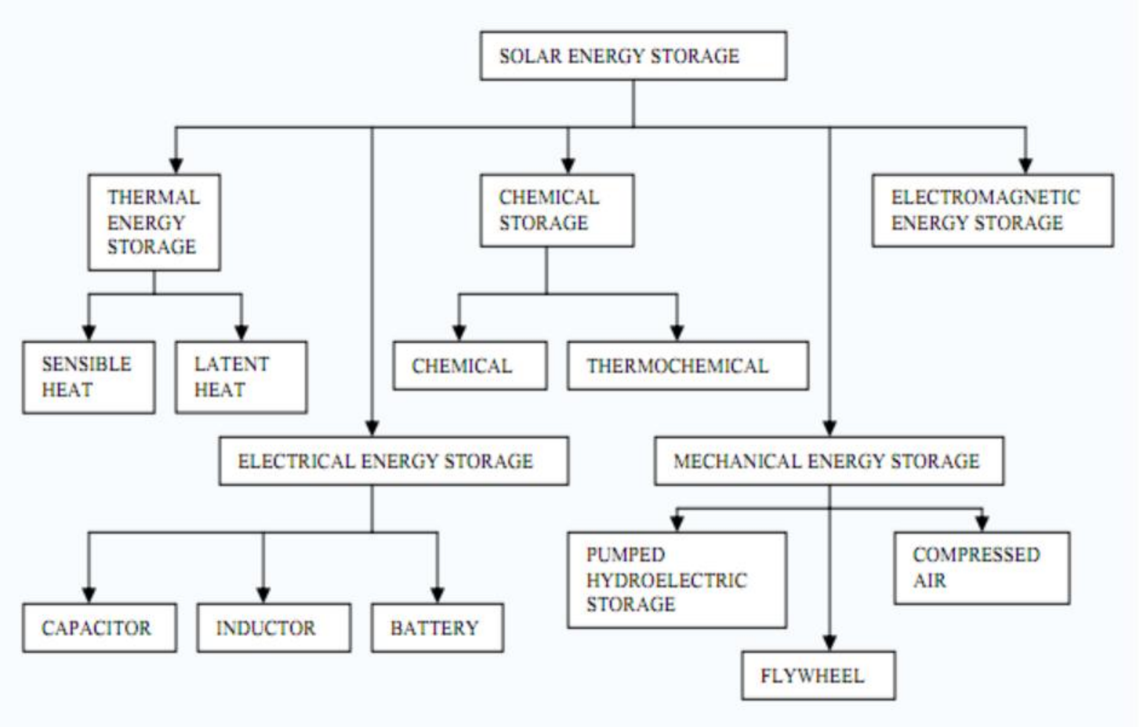


Figure 1: Solar energy storage [Sidhu, 2007]

Solar energy: Solar energy is the energy received by the earth from the sun. This energy is in the form of solar radiation, which makes the production of solar electricity possible.

Solar cell: A solar cell is a device that converts the energy of sunlight directly into electrical energy (electricity) by the photovoltaic effect.

Solar module: Solar module is an assembly of solar cells also known as solar panels.

Solar array: A single solar panel can only generate a small amount of energy so many solar panels are assembled together to generate the desired amount of energy. This assembly of solar panels is called a solar array.

Solar electric power generation has gone through many changes throughout the years. Initially solar cells were made of crystalline materials, with the most common being polycrystalline-Si. It has gradually improved through research to thin film PV cells. Regardless of type, all solar cells still work on the same principles.

The operation of a solar cell is simple and can be easily explained in three steps. 1. Sunlight hits the solar panel. Photons present in the sunlight get absorbed by the semiconducting material (all solar cells are made of semiconducting materials). 2. Negatively charged electrons get separated from their atoms and flow through the material producing electricity. Electrons are only allowed to move in a single direction in a solar cell. 3. The array of solar cells converts this solar energy into usable direct current (DC) electricity.

The current laterally integrated design combines the past with the present to create the future for solar cells as illustrated in Figure 2. As the name indicates the semiconductors will be laterally assembled to absorb the entire incident light of different wave lengths to have highest efficiency possible.

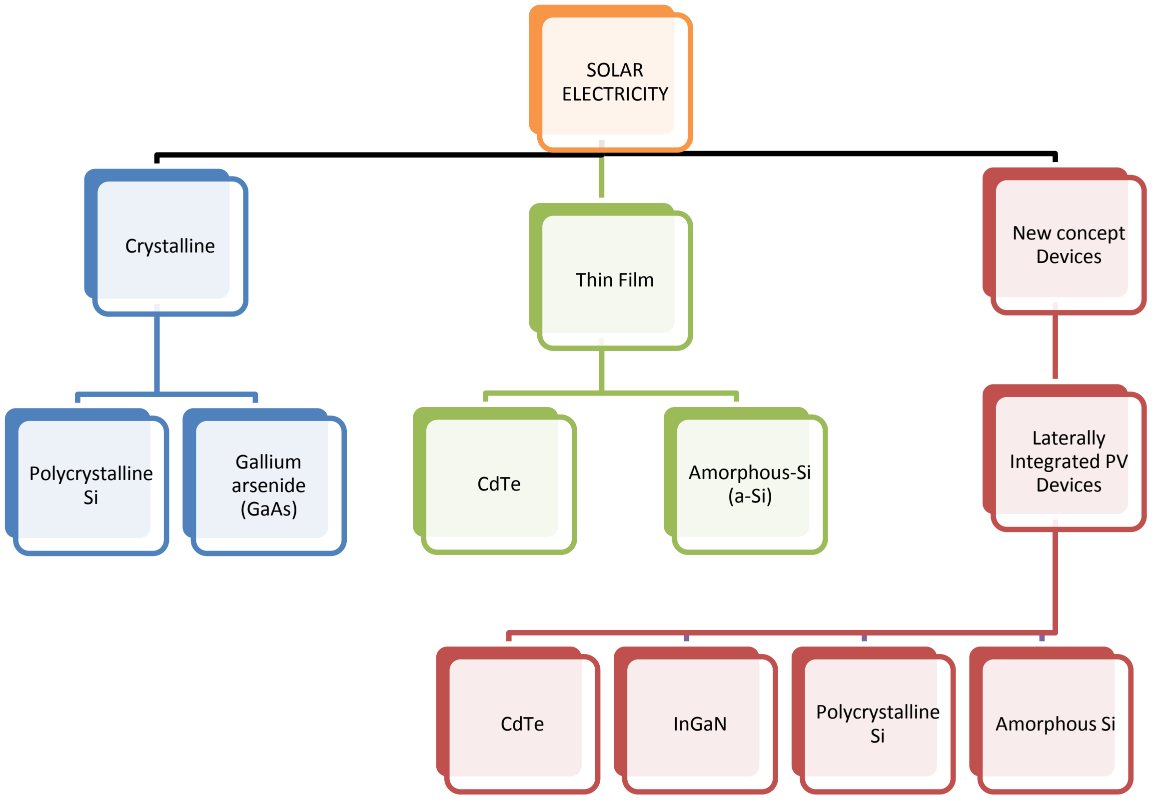


Figure 2: Taxonomy of solar cells

From the four elements suggested in the design, Cadmium Telluride and amorphous-Si will be provided by National Renewable Energy Laboratory (NREL) and polycrystalline-Si and Indium Gallium Nitride will be manufactured in a laboratory at the University of Minnesota (as the manufacturing is not yet started, it is speculated that it will be made somewhere in the Electrical Engineering department).

The research is comprised of five complimentary teams. Four teams are from the University of Minnesota-Twin Cities campus which includes Dr. Phil Cohen and his team working on device testing and material growth. Dr. James Leger and his team are concentrating on a holographic concentrator/tracker. Dr. Joseph Talghader and his team are focusing on device design and fabrication. Dr. Paul Ruden and his team are looking into epitaxial growth apparatus and numerical device simulator SCAPS. At the University of Minnesota-Duluth campus, Dr. Emmanuel Enemuoh and his team are concentrating on life cycle assessment and economic aspects of the project. Dr. Emmanuel Enemuoh and his team are looking into each process and every component selected so that they can evaluate the entire project based on the inflow (embodied energy) and later on the outflow from the system (emission). The economics of photovoltaic, solar cell technology is determined by the balance between light gathering cost and sustainability (because it is supposed to be “green energy or alternative energy”). LCA performed during the design phase will give rough results according to which changes in process and materials might be done to make it more sustainable.

Chapter 2: Literature Review

Literature is partitioned into sections as follows: Life Cycle Analysis and types; extraction of materials; and methods of system evaluation. While there is a need to harness the green energy, there should be a way to evaluate how green the energy is. Initially it was considered that any system that produces energy without emitting harmful toxins to the environment is called green energy. This later was deemed as not true. Systems should be studied in detail to determine if it is environment friendly. The word sustainability was introduced to determine if the system is environmentally friendly or not.

Sustainability: According to the Brundtland Commission of the United Nations on March 20, 1987 “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” It’s that gray area where social, economic, and environmental considerations come together to make a balance.

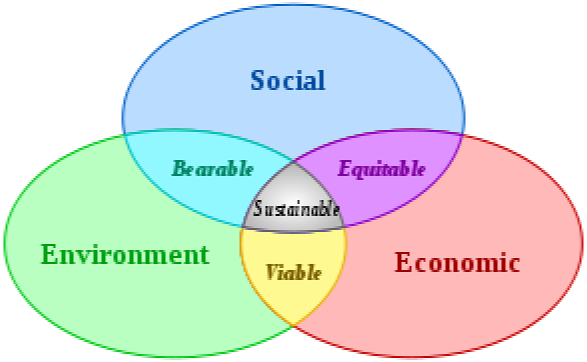


Figure 3 : Sustainability Framework

The question was how can sustainability be achieved and how can we measure it?

The term Life Cycle Analysis (LCA) came into existence in the 1960's. This was further supported by many firms due to the scarcity of resources; one of them was Coca-Cola Company in the year 1969. LCA saw many changes before establishing a standard procedure to perform LCA by the International Standard Organization (ISO).

Life Cycle Analysis: Life Cycle Analysis (LCA) is a "cradle-to-grave" approach for assessing any particular system. Cradle implies gathering or acquiring materials from earth to create a final product and grave implies when all the gathered material are returned to the earth in different forms [Kazuhiko Kota, 2001].

2.1. Life Cycle Analysis

Life cycle assessment (LCA) analyzes the environmental impacts of products and services. The International Organization for Standardization (ISO) has developed a standard basic principle for the computation of LCA. Advancement continues in LCA but the standards given in the ISO 14000 series [G. Rebitzer, 2004] provide a framework that is generally accepted worldwide.

> International Standards ISO 14040 (1997) on principles and framework [G. Rebitzer, 2004]
>
> International Standards ISO 14041 (1998) on goal and scope definition and inventory analysis [G. Rebitzer, 2004]

International Standards ISO 14042 (2000) on life cycle impact assessment [G. Rebitzer, 2004]

International Standards ISO 14043 (2000) on life cycle interpretation [G. Rebitzer, 2004]

According to ISO standard 14000 series, the framework consists of four steps: goal and scope definition, inventory analysis, impact assessment, and interpretations. The frame work is illustrated in Figure 4.

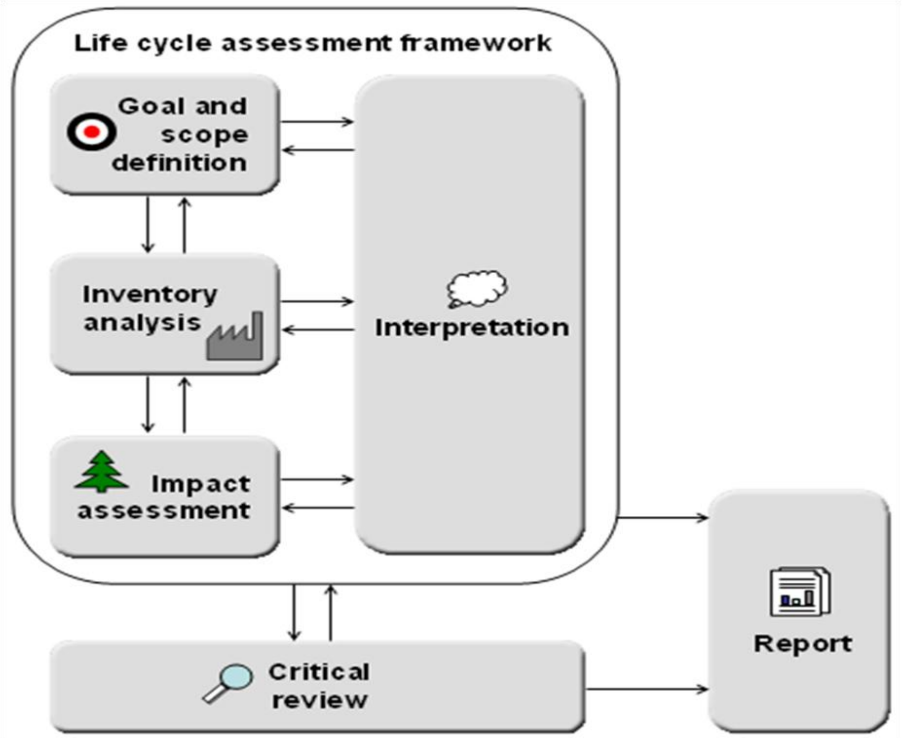


Figure 4: Life Cycle Assessment Framework (source: ISO, 1997)

The different subsystems of the life cycle framework are explained according to the standard ISO 14000 series.

2.1.1 Goal, Scope and Background

This subsystem practically defines the final system (product) by different components, process and activities. At the same time, it establishes a system boundary within which the assessment is to be made considering system inputs and outputs from the system. A typical system boundary is illustrated in Figure 5.

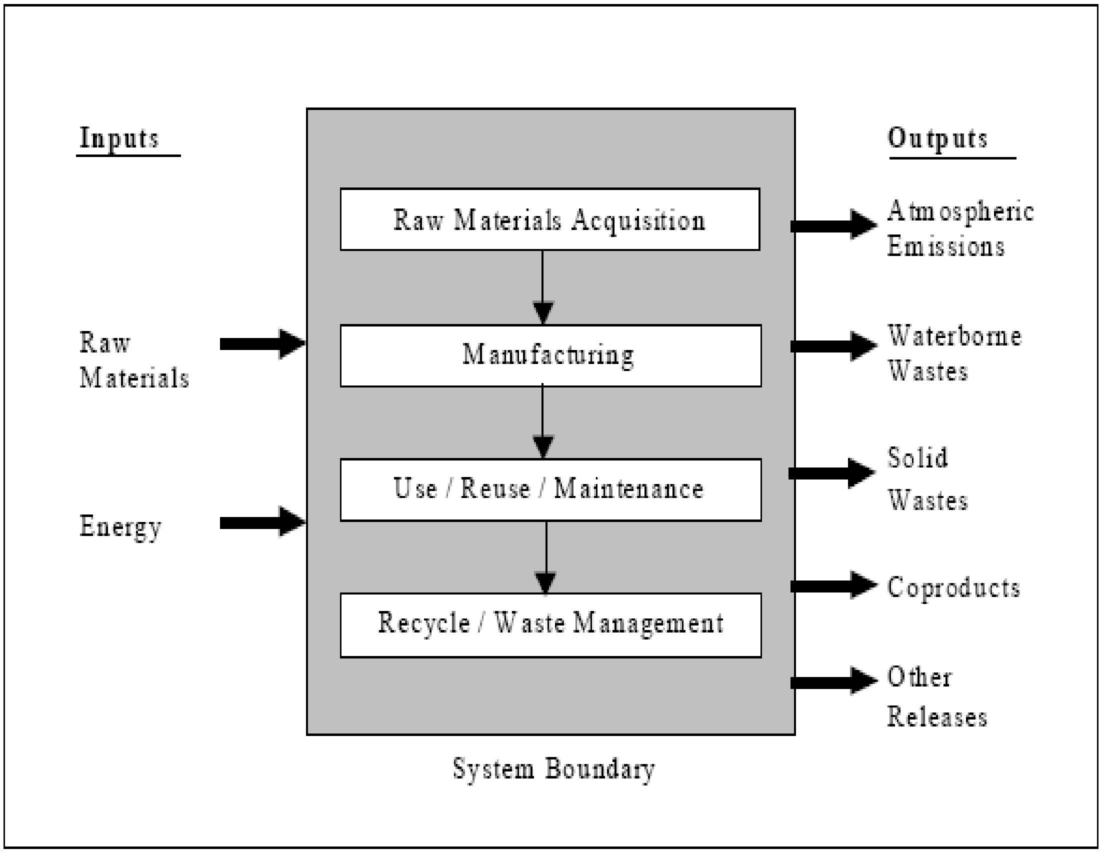


Figure 5: Typical System Boundary [source: ISO, 1997]

2.1.2 Inventory Analysis

After defining a well known system, boundary life cycle inventory (LCI) is performed. LCI includes gathering, compiling, and tabulating all the emissions and resource consumption, in other words environmental exchanges made by the product, and carefully analyzing it.

2.1.3 Impact Assessment

Once all the required data is collected from LCI, assessment of its impact is analyzed; this is also known as life cycle impact assessment (LCIA). Assessment includes evaluation of all the potential human and ecological effects of all the data collected in LCI.

2.1.4 Interpretation

Interpretation occurs at every stage of LCA. It includes closely evaluating the results from impact assessment to select a sustainable product or process. It is said that ISO 14043 (2000) is a standard process for interpretation but in reality it is up to the analyst to generate conclusions from the total life cycle.

2.2 Types of LCA Approaches

One objective behind performing LCA is to provide insights into the potential environmental effects of the entire system in detail [G. Rebitzer, 2003]. The detailed system includes goods and services that go in the system and also the output coming out of the system. This type of robust methodological framework, which looks into every aspects of the system in detail, can also be described as a “Detailed LCA” [DE Beaufort-Langeveld et al., 1997]. Performing detailed LCA is both time and cost consuming. There is a rise in concern about “whether the LCA community has established a methodology that is, in fact, beyond the reach of most potential users” [Todd and Curran, 1999]. In addition to ISO standards, there are few other LCA performing methods and approaches. Some of these other methods are listed below:

2.2.1 Simplification of Process-LCA

The U.S. Environmental Protection Agency (EPA) and the Research Triangle Institute (RTI) came together to study various LCA simplification techniques [Hunt et al., 1998]. Due to lack of process knowledge and other scarce data, Hunt et al (1998) concluded that a vertical cut can be assumed in the entire process. This vertical cut helps in focusing on major components and cutting off the unknowns. These vertical cuts were differentiated by different approaches called screening. The following concepts were established for screening purpose.

2.2.1.1 Qualitative approaches: Selecting and screening specific process and cutting out rest of the process and materials [Fleischer and Schmidt, 1997], according to this a matrix is generated which represents the life cycle stages [Graedel et al., 1995; Tood, 1999; Hunkeler et., 1998a,b].

2.2.1.2 Semiquanitative methods: Statistical weighted processes and materials are considered and the rest are not considered in the system [Fleischer et al. 2001; environmental-FEMA].

2.2.1.3 Quantitative approaches: Input-Output LCA of the key substance based on the calculation of the cumulative energy demand on publically available data. These are particularly accurate where decisions regarding design are required [Berzet and van Hemel 1997, p.200; De Beaufort-Langeveld et al., 1997, p. 10] or in other words they are useful as a design tool. It provides a good overview of systems impacts. In a brief period of time, it provides an efficient and reliable decision support.

2.2.2 Input/output-LCA

The input/output-LCA approach takes into account the material or energy that goes into and comes out of the system. “In input/output-LCA modeling the product stream, which is based on supply chains, is modeled using the economic flow databases” [G. Rebitzer, 2003]. These databases are collected and supplied by the national government agencies. This approach cannot be used for LCA of a new design as the data will not be available.

2.2.3 Hybrid LCA

Both simplification of process-LCA and input/output-LCA have their specific limitations. Simplification of process-LCA does not have well defined system boundaries but does have detailed unit processes. On the other hand input/output-LCA has well defined system boundaries but lacks specifications for unit processes. Hybrid-LCA is a combination of both of these LCA approaches with an attempt to combine their advantages to overcome their weakness [Suh and Huppes, 2001]. This technique requires huge databases as it looks into detailed unit processes. At the same time, hybrid LCA requires a team of specialists from the design department and environmental agencies to specify the well defined system boundary.

2.2.4 Types of Levels

LCA can be performed for different levels. These levels are specified as,

***2.2.4.1 Cradle-to-Grave*:** Cradle to grave is a complete life cycle assessment from manufacturing (cradle) to use phase and then finally disposal phase (grave).

***2.2.4.2 Cradle-to-Gate*:** Cradle to gate is a partial life cycle assessment of a product from manufacturing phase (cradle) to use phase (gate).

***2.2.4.3 Cradle-to-Cradle*:** Cradle to cradle is a unique LCA process specially done to the system which is assumed to have a recycling phase for all its components. This method is designed to have minimum environmental effects. For assuming a perfect recycle phase the sustainability methodology is implemented at every level of production, operation, and disposal [Ecomii, 2010]

***2.2.4.4 Gate-to-Gate*:** Gate to gate is also a partial LCA concentrating only on the production phase. This LCA can be later combined with cradle analysis for a complete cradle to gate LCA [Jiménez-González, C.; Kim, S.; Overcash. 2000]

2.3 Extraction and Refining

Before analyzing any system it is essential to know the key components of the system, materials, and processes used. Without complete knowledge of the materials and processes, a comprehensive LCA of a system cannot be analyzed. In this section, all the major components of the proposed solar panel and their manufacturing processes are studied.

2.3.1 Silica

The extraction of silica from sand, found abundantly on earth, is a very mature process [Hagedorn G, 1992]. This process of extraction is expensive and requires a huge amount of energy [Hagedorn G, 1992]. The result of this process is metallurgic grade silicon (mg-Si). The purity after this process is about 98%, which is not enough for solar cells and has a market price ranging from 0.77-1.45cents/pound [Sollmann, Feb 2009]. This leaves mg-Si to be further processed to get 99.9999% purity. The purity of solar cell is called solar-grade silicon Pure silicon of about 99.99% purity can also be extracted from silica using a process developed at the University of Cambridge by George Z. Chen, Derek J. Fray and Tom W. Farthing between 1996 and 1997 called the FFC Cambridge process. The process allows high purity solar grade-Si with low energy input and low CO_2 emissions [George Z. Chen, 1997].

2.3.2 Cadmium (Cd)

Residue during the production of zinc from electrolysis, fumes, and dust collected in bag houses from emission during pyrometallurgical processing of zinc and lead smelting are the feed inputs for the production of cadmium. The feed from electrolysis is about 95% pure cadmium which is then sent to a cadmium plant where it is oxidized for two days to give out cadmium oxide with other impurities. Around 10% of cadmium is produced by treating fumes and dust collected in bag houses with sulfuric acid which produces cadmium sulfate. Cadmium sulfate is roasted and leached with water and then filtered to remove dissolved cadmium. Cadmium is passed through electrolytic separation to produce 99.995% pure cadmium. About 95% is converted to metallurgical grade which requires cadmium to be purified in vacuum distillation to get the 99.9999% pure cadmium essential for cell manufacturing [MetSco, accessed: 2010]

2.3.3 Indium (In)

Indium is recovered as a by-product of zinc production from the fumes, dusts, slag’s, and residues in zinc smelting [Chagnon MJ. 4ed, 2000]. Zinc oxide is leached with dilute sulfuric acid and then again treated with dilute hydrochloric acid. During the leaching and purification of zinc oxide, indium is produced. The residue from the leaching contains only 0.2% of indium [Felix N. 2002]. Adding soda to the remaining filtrate results in precipitate of indium. This precipitate contains 6g/liter of cadmium [G. Rebitzer, 2004]. The solution still contains about 10% of cadmium which is removed by processing it with sodium hydroxide and then with dilutes of hydrochloric acid. Cadmium still needs to be processed to metallurgical grade (99.999%).

Figure 6 is an illustration of the recovery of indium and cadmium from zinc processing at Cominco's Trail Operations at southeastern British Columbia.

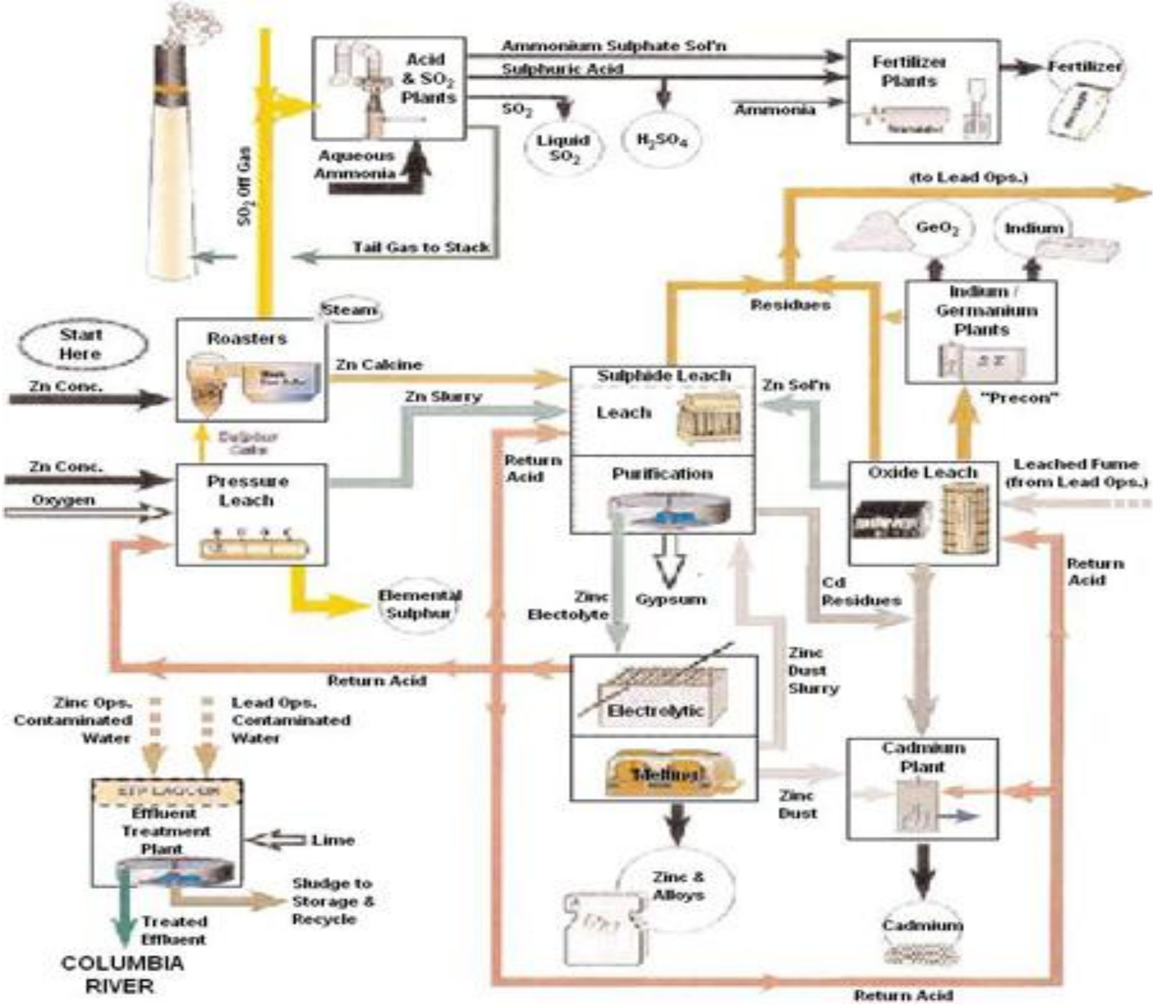


Figure 6: Cominco's Trail Operations - Zinc Flow-Sheet [MetSco, accessed: 2010]

2.3.4 Gallium Production

Gallium, being a weak metal, occurs in very small concentration in the ores of many other metals. Gallium is found most commonly in ores of aluminum, germanium and zinc. Around 5% of the global production of gallium is obtained from residues in zinc-processing; 95% of the global supply is obtained as a byproduct of alumina production from bauxite [Vasilis M. Fthenakis, 2008].

In Zn facilities, as discussed earlier, the zinc ore is leached with sulfuric acid, and the removed impurities include gallium, aluminum and iron. Hydrochloric acid is used to extract gallium and aluminum from the metal hydroxides [Kramer, 2003]. Solvent extraction with ether is used to separate gallium from aluminum. Distillation results in highly concentrated gallium residue but it still contains iron. Iron is removed by the use of caustic solution. Finally, gallium is recovered by electrolysis in crude form.

This crude gallium still needs to be processed to 99.999%. As illustrated in Figure 7.

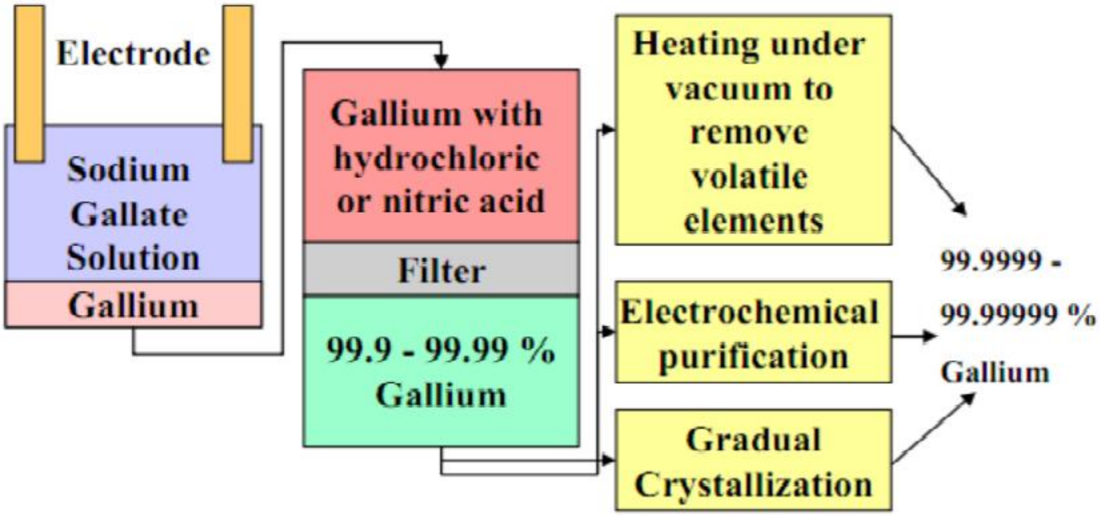


Figure 7: Gallium Purification – Electrolytic Refining [Kramer, Deborah, 2003]

2.3.5 Tellurium

Tellurium (Te) is considered as rare metal that can be extracted as by-product from gold, copper, lead, and bismuth ores. Tellurium is removed by electrolytic refining of copper. Copper is typically removed via oxidative pressure leaching (percolating) with dilute sulfuric acid at 80-160°C. This removes around 80-90% of the tellurium [Vasilis M. Fthenakis, 2008]. It is further processed with caustic soda and air to produce sodium telluride solution. Both sodium Te and extracted Te are used for production of commercial grade Te [Vasilis M. Fthenakis, 2008].

Tellurium can also be extracted from residue dust from steel refining that contains a large amount of lead oxide, and small amounts of tellurium oxide and iron oxide. Figure 8 illustrates the recovery of metallic tellurium from the residue dust.

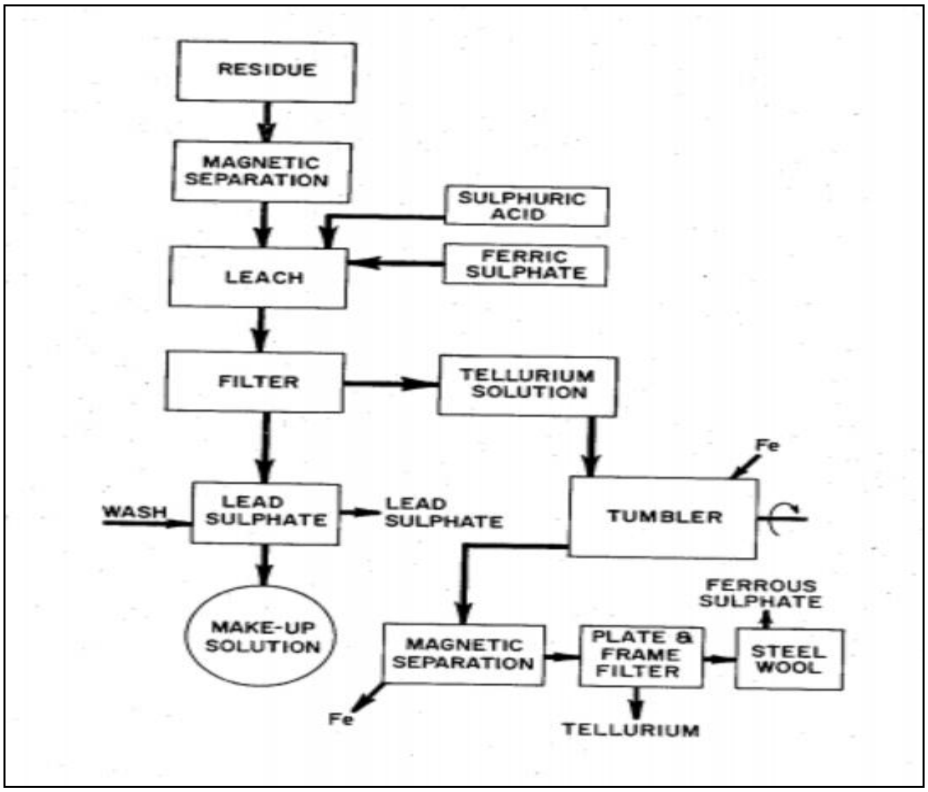


Figure 8: Recovery Process of Tellurium

2.4 Embodied Energy Calculations

The total embodied energy for a material or process is estimated from many sources. Depending on the source of data available, there are four main methods that can be used to calculate the embodied energy of any material or process.

These four methods are

1. Energy per economic activity (EIO)
2. Embodied Energy Density (ED)
3. Nameplate (NP)
    - Active power
    - Reactive power
    - Apparent (or Complex) power
4. Publicly Available Data (PAD)
5. Placeholder Data (PH)

2.4.1 Energy per Economic Activity (EIO)

The EIO-LCA database uses industry-level economic input-output data tables provided by the U.S. Department of Commerce and environmental data provided by the U.S. Environmental Protection Agency to determine an amount per dollar of environmental metrics such as energy use, global warming emissions, and toxic waste [Rasmussen, 1980; Artin Der Minassians, 2006].

2.4.2 Embodied Energy Density(ED)

From previous life-cycle analyses embodied energy per unit mass of specific materials is available, although is questionable how they are determined [Artin Der Minassians, 2006].

2.4.3 Nameplate (NP)

Nameplate is the total energy or power that a machine draws during the manufacturing of any material and throughput time. This energy or power is indicated on the machinery that is processing this material [Artin Der Minassians, 2006].

NOTE: According to this if we know the input current (power) and the through put time for the process we can calculate the energy that goes into the system in manufacturing of a particular material.

2.4.4 Publicly Available Data (PAD)

If the energy or power used by the process and the through put time is not available then we can use publicly available data (PAD) to estimate embodied energy [Artin Der Minassians, 2006].

2.4.5 Placeholder Data (PH)

This requires direct information collection from processing plant which in many cases is not possible [Artin Der Minassians, 2006].

Chapter 3: Problem Statement

The utility of solar photovoltaic systems as a mass-market energy source must be determined by a balance between cost and performance. Current technologies that can produce inexpensive solar panels over large areas, such as those using organic materials, have efficiencies that are too low to be practical. Technologies providing high performance, such as those using multi-gap materials or concentrators, are extremely expensive and have overly complicated device structures with massive light gathering units. No current technology has been able to reach efficiencies needed to balance total costs and bring solar energy in line with fossil fuels. However, recent advances in volume holography including theory, materials, and sources make possible the creation of holographic concentrators that can track the sun without moving parts. In addition, advances in surface passivation and atomic thin film deposition by the integrated circuit industry can be utilized to create high-performance and inexpensive polycrystalline thin films. It is proposed to develop an inexpensive, integrated package using holographic concentrator optics to split the solar spectrum into multiple spectral bands and direct each towards a polycrystalline solar cell optimized for that specific range of photon energies. This system eliminates the expense and complication of multi-junction cells, mechanical tracking, and concentrator optics.

To accomplish this, this Initiative for Renewable Energy and Environment (IREE) funded research program has five groups focusing on the five different aspects of the research: cell modeling, optical design, optical testing, device fabrication, and sustainability/economic analysis.

This thesis is focused on the sustainability and economic analysis of the new proposed lateral integrated cells. This will be accomplished by use of Life Cycle Assessment methodology to conduct comparative analysis of the system’s sustainability. Also economic models will be developed to estimate cost of electricity with the proposed cell design. Finally, the effect of solar insolation on the output electricity of the new design is evaluated.

Chapter: 4 Methodology

The sole purpose of alternative energy is to provide the same standard of life that a conventional source of energy does without adversely effecting the environment. To fulfill this purpose a standard measurement technique should be followed during the design phase of any solar panel manufacturing. This will not only evaluate the entire system from the point of sustainability but at the same time will provide means for finding substitute for the materials and process used in the system.

Laterally integrated PV system is analyzed based on the techniques like life cycle analysis (ISO 14000 series framework), embodied energy, energy payback time, maximum power point, present worth of the energy generated from the system, and levelized cost of energy.

4.1 Defining Parameters

Before calculating and analyzing any of the methodologies it is important to define the parameters used in calculations and analysis.

4.1.1 Embodied Energy

Embodied energy is "the total energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e. direct energy plus indirect energy."[M. K. Dixit, 2009]. Embodied energy is used as a basis for most of the calculations in this paper. Embodied energy gives a rough idea of how much energy goes in the making of the system. According to embodied energy, estimation of energy payback period and economic aspects of the design are calculated by levelized cost of energy.

4.1.2 Solar Insolation

"Solar insolation is the incident radiant energy emitted by the Sun, which reaches a unit horizontal area of Earth's surface" [Kazuhiko Kota, 2001]. In simple terms, it is solar radiation received at the earth's surface. The unit of solar insolation is W/m^2 or kWh/m^2. Solar insolation is different across the world.

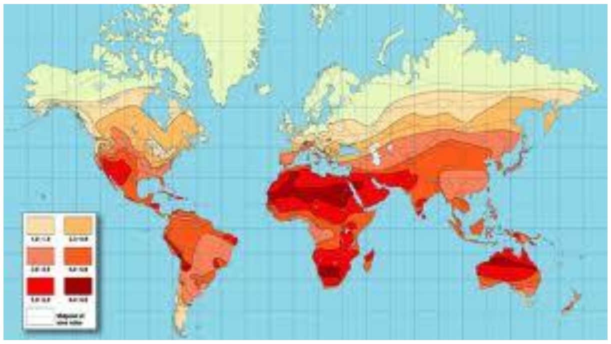


Figure 9: solar insolation across the world (source: oynot solar)

4.1.3 Maximum Power Point

A solar cell delivers maximum power (Pm) when operated at a point where production is maximized. A graphical representation of maximum power point is illustrated in Figure 10. The Pm is represented by the rectangle are under the curve. It helps in understanding the maximum output from the system if operated at full efficiency.

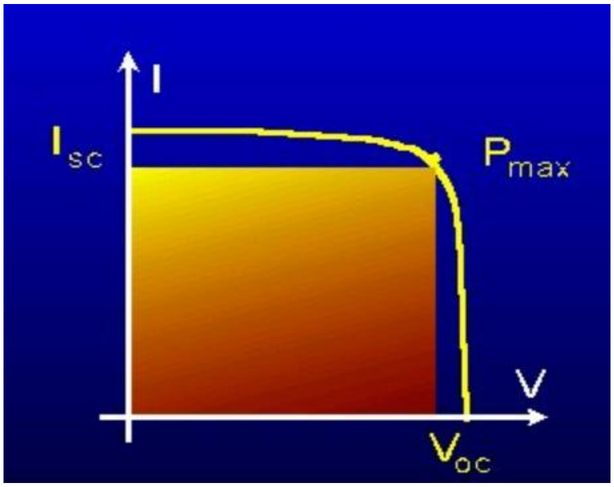


Figure 10: Maximum power point (source: Wright, 2006)

4.1.4 Levelized Cost of Energy (LCOE)

Levelized cost of energy is considered one of the best metrics for decision making in solar industry. LCOE is defined as "the average cost of every unit of energy produced by a generator across its entire lifetime, brought back to the value of that unit of energy determined at the time of the analysis"[Warren Nishikawa, 2000]. According to Warren Nishikawa [2000], it is the best method for estimating the true cost of manufacturing and operating a PV solar panel.

4.1.5 Energy Payback Time (EPBT)

Solar energy is produces electricity without using fossil fuels and without emitting CO_2, or any other green house gases. In this profitable equation there is still something missing. There is a saying that "*money makes money*". Similarly, there is a saying "*energy makes energy*". Energy payback is the term that denotes the time taken by the new system to generate the same amount of energy that goes in the making of the system. It can also be called the time to reach the breakeven point in terms of energy.

Chapter: 5 Performing LCA

LCA was performed following the framework of ISO 14000 series. All components of the framework were performed on laterally integrated PV design. Certain assumptions are made and properly reasoned without affecting the ISO standards.

5.1 Goal, Scope and Background

The focus of the PV design is on how to simplify the concentrator structure so that it will be most cost effective, and at the same time achieving the efficiency that will keep the overall cost ($/kWh) low. An inexpensive holographic concentrator will enable thin film devices to work together to make efficient use of the entire solar spectrum. All analysis was conducted from raw materials production to manufacturing, as working systems are not yet at the working model stage (Cradle to Gate i.e. from acquisition of material to use).

Typical system boundaries consist of four different sub systems: Material Production (material acquisition), Product Manufacturing, and Product Use, Reuse (recycle) or Disposal. The current study concentrates only on the design phase; grave, or end use, is not given much importance and it is assumed that all the components might be recycled. Figure 11 illustrates the system boundary considered in this research; recycle phase is not included.

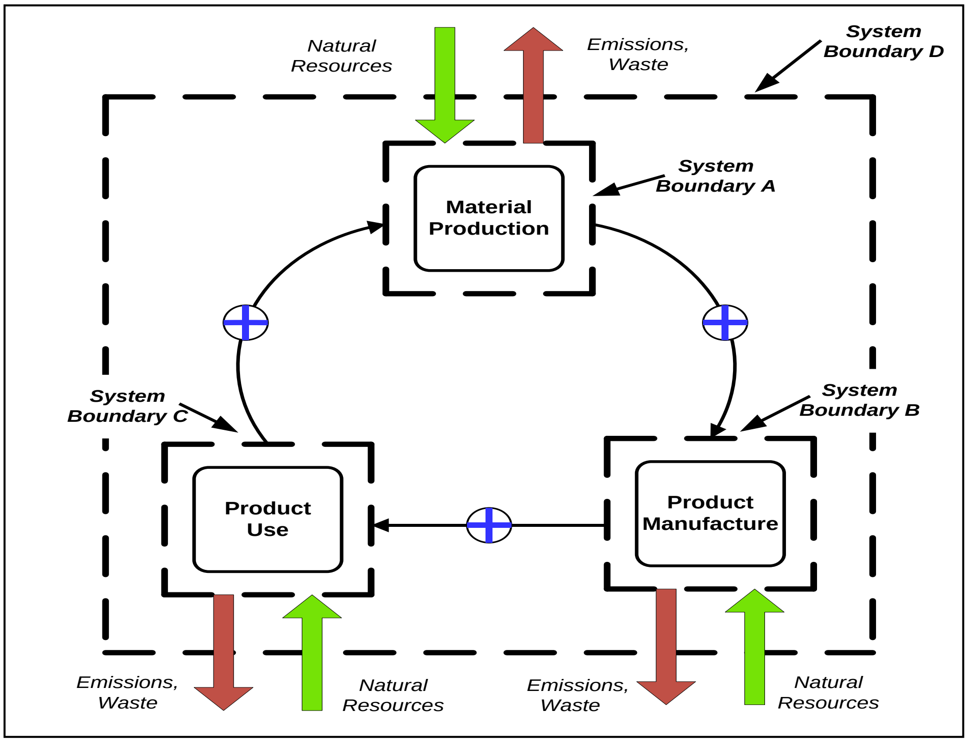


Figure 11: System Boundary

These subsystems can be studied individually as system boundary A, system boundary B, or we can consider them as one single system as system boundary D.

According to ISO 14041 every system should be broken down to several subsystems so that energy and emission data can be carefully analyzed. Following this, all the subsystems shown in Figure 11 are further described within the system boundary for the proposed PV panel. These subsystems are described by all inputs like semiconductor metals, holographic materials, panel materials and auxiliary materials for the production of a PV panel as illustrated in Figure 12.

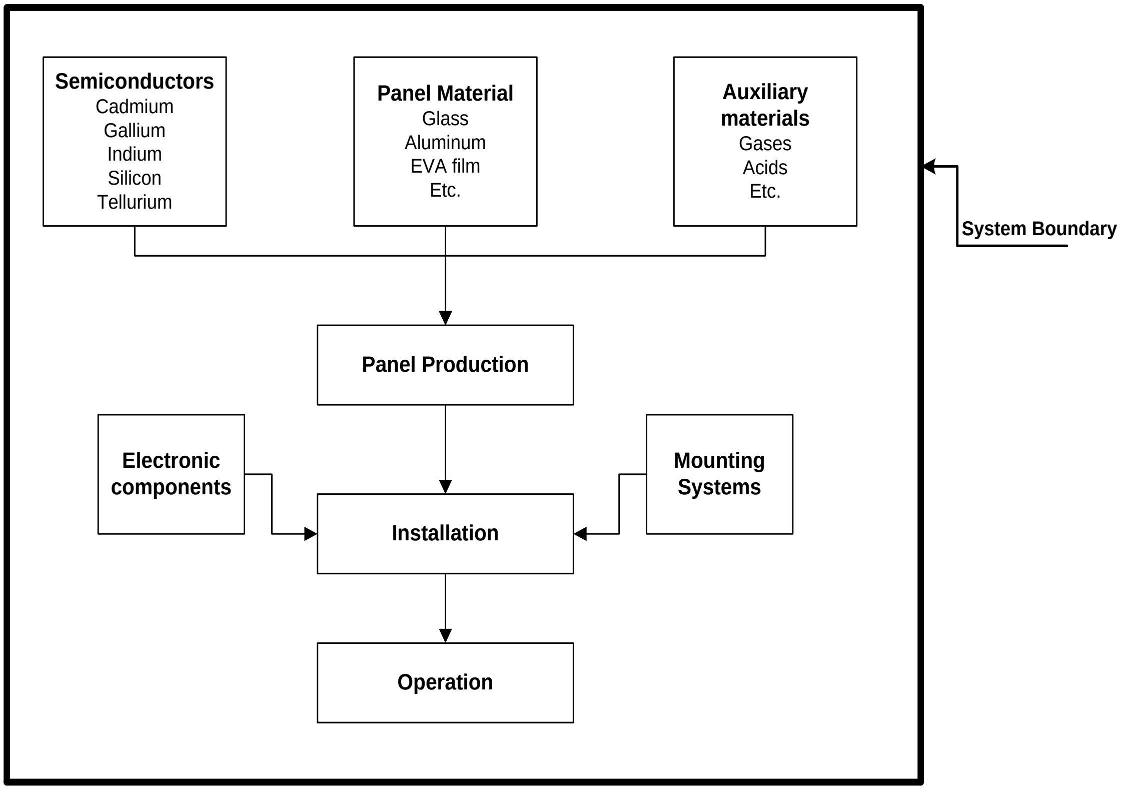


Figure 12: Different Sub System within system boundaries [Rasmussen, Jul, 1980]

5.2 Life Cycle Inventory Analysis

The different methods used to extract minor metals are described in Chapter 2. According to the first rule of ISO 14041, "the emission from the mining of the metal ores to the recovery of scalable zinc are allocated to zinc and the emissions during the purification of the waste stream to extract a by-product, are assigned to the by-product"[Vasilis Fthenakis, 2007].

All the information was gathered about various methods of extracting minor metals, as well as emissions within the system boundary. Purification of the semiconductors is the stage where most of the environmental effects occur during the production of photovoltaic cells. In the life cycle analysis of any proposed photovoltaic cell, indium, gallium, tellurium and cadmium are mined as by-products of major metals as explained in detail in Chapter 2.

According to ISO 14041 standards, before analyzing any system, the system should be well defined and understood to assess the environmental impact of the system. Before starting data collection and primary computation of inventory data, design and specification of the system is defined. A schematic diagram of the design and its components is illustrated in Figure 13.

5.2.1 Design and Specifications: Material Inventory

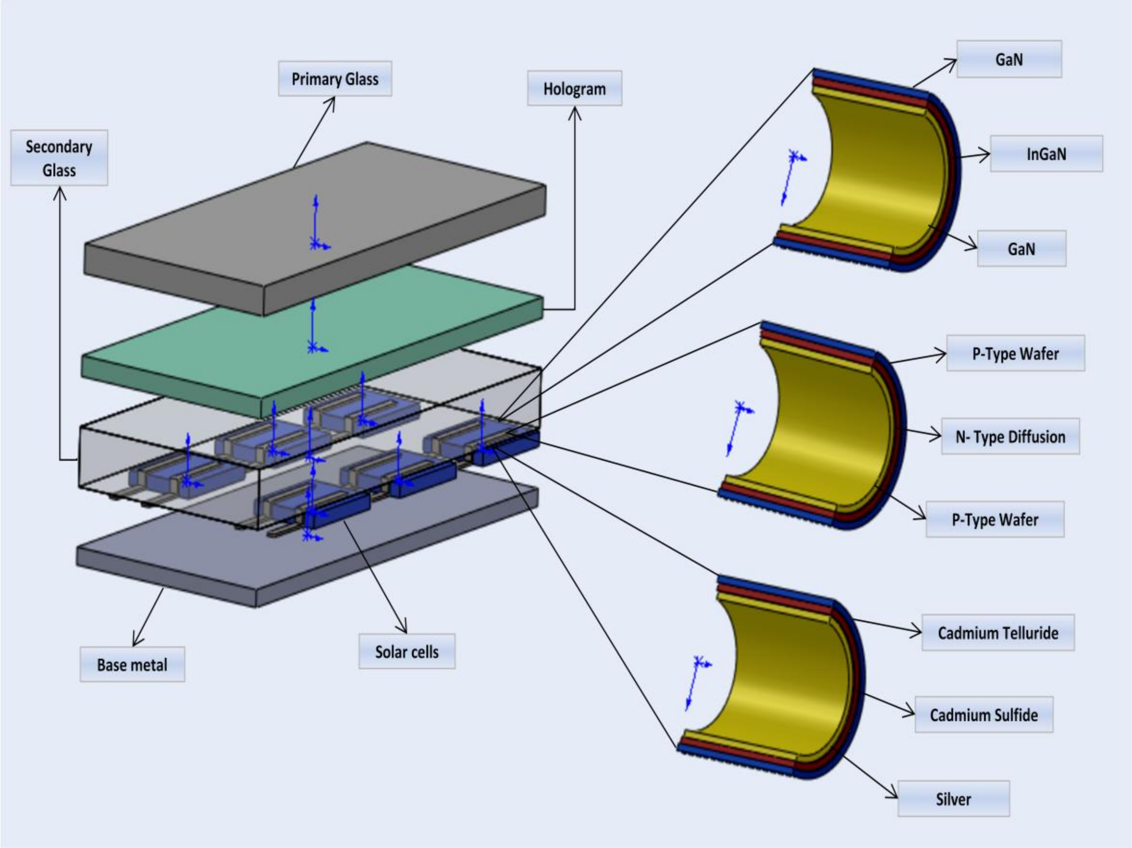


Figure 13: Solar Cell Array Architecture

Specifications of the design and materials considered

Wafer area	2.5mm X 2.5mm
Wafer thickness	200 µm
EVA sheet thickness	0.5 mm
Module area	1m^2
Operation life	30 years

Module efficiency	20%, 25%, and 30%

5.2.1.1 Energy Conversion Efficiency

Cadmium Telluride	13 % [Kazuhiko Kota, 2001]
Indium Gallium Nitrite	27.5% [M.A. Stan, Feb 2001]

Note: The work of manufacturing of InGaN is still in its mid phase. Dr. Phil Cohen (P.I. of the project) recommended use of the efficiency and embodied energy of InGaP/InGaAs as a substitute for InGaN for calculations as InGaP/InGaAs will have almost same embodied energy and efficiency as that of InGaN.

Amorphous-Si	7% -10% [Lau, accessed: Dec, 2010]
Polycrystalline- Si	14% -15 % [Lau, accessed: Dec, 2010]

5.2.1.2 Primary Glass

Primary glass is made of float glass. It works as a concave mirror and acts as the input aperture for the hologram. As it is directly exposed to the atmosphere it works as a protecting shield against the different weather conditions. The glass needs to be cleaned at regular intervals as dust or any other particles collected on it will reduce the efficiency of the PV module.

5.2.1.3 Hologram

The hologram in the design acts as separator and concentrator. The suggested material for a volume hologram is Dichromate Gelatin.

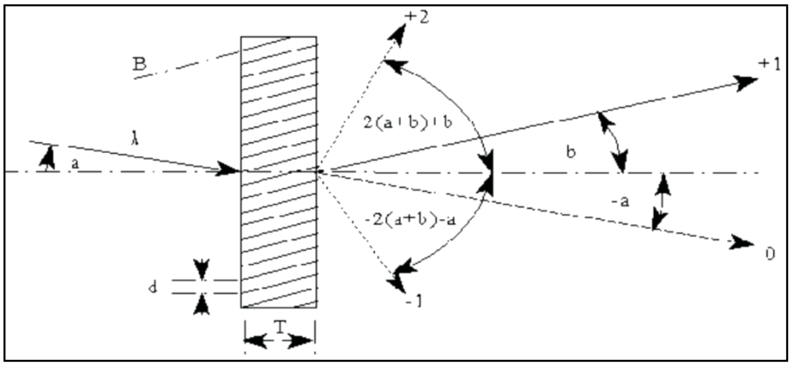


Figure 14: Volume Hologram Separator (source: IREE project report).

An incident plane wave can be converted into another plane wave at a different angle via diffraction gratings in a volume hologram. Diffraction efficiency in volume gratings is dictated by the Bragg condition relating the incident wave with the diffracted wave through a vector that describes the grating [IREE project report]**.**

***5.2.1.3.1 Separator*:** Volume hologram separates the incident sunlight into distinct wave length bands. This is possible by the use of multiplexed gratings in the volume hologram. By applying the Bragg condition the sunlight will be separated according to the wavelength of different semiconductors or cells used in the design. For example: 2.5 eV for InGaN.

***5.2.1.3.2 Motionless Tracking*:** Use of volume hologram will also allow us to track the motion of the sun throughout the day without the use of any mechanical tracking device. This will not only simplify the design but at the same time will avoid the high maintenance cost of a mechanical device.

5.2.1.4 Secondary Glass

Secondary glass is made of soda lime glass. It is comparatively thicker then primary glass.

5.2.1.5 Solar Cell

There are four different materials that are proposed for the design but from these four semiconductors, only three will be used in the final design. One of the reasons for doing the LCA is to find a sustainable combination of three semiconductors out of four suggested semiconductors. To find a sustainable design three models has been derived which is explained in the later part of the paper.

5.2.1.5.1 Indium Gallium Nitride

Its high manufacturing cost and the complexity related to its deposition on a substrate narrows its use in concentrator systems where only a small cell area is needed. Not much data is available as it is still in the experimental phase.

5.2.1.5.2 Amorphous-Si

Amorphous-Si has dominated the thin film market since it was first discovered. It has low production cost and a low primary energy requirement but has low conversion efficiency [Johansson, Thomas B., 1993].

5.2.1.5.3 Polycrystalline-Si

It is the most common type of PV cell used. Production of polycrystalline-Si is the most energy consuming stage of the silicon module’s life cycle and it accounts for 45% of the total primary energy usage in the multi-Si module life cycle [Alsema, E, 2005].

5.2.1.5.4 Cadmium Telluride

Film deposition of CdTe accounts for the maximum primary energy in the CdTe module life and that is around 54% [Fthenakis, V. M, 2005].

5.2.1.6 Base Metal

It is the metal sheet on which the entire assembly is located. It provides the strength and firm base for the different layers.

5.2.2. Energy Inventory

The first total cost model created gave a rough idea of how much energy is used from raw materials to manufacturing of the PV cell (cradle to gate). Energy from cradle implies cumulative energy from mining, processing, manufacturing of raw material, and producing the proposed PV cell. The total cost of energy consumption during manufacturing of PV cells is dominated by the cost of transforming from the raw materials to the PV grade materials; this is about 55% of the total cost. The remaining cost attributions are from the paneling materials, and other miscellaneous costs like electrical wires and installations. In the first attempt to estimate the total cost, only the major cost of transforming from raw to PV grade material will be estimated as shown in Table 1. The cost of making the primary materials: aluminum, zinc, and silicon are estimated based on data from literature. It can be deduced from the table that the cost of designing the cell with Indium Gallium Nitrate will be much more expensive than Cadmium Telluride.

Table 1: Summary of Energy and Cost at Different Levels

Primary Elements	Mined Elements	Processed Elements	Total Utilized (MJ/kg)	Total Cost ($/kg)
Gallium	Bauxite	Aluminum	600	146
Cadmium	Zinc Ore	Zinc	8.8	2.15
Tellurium	Ore	Steel	150	36.72
Indium	Zinc ore	Zinc	3155	771
Amorphous-Si	Sand	Silicon	50	12.14
Polycrystalline-Si	Sand	Silicon	500	121.4
Air	Air	Nitrate	25	6.07

Total cost model shown in Table 1 is not considered for the LCA assessment as scalability of the design is much more difficult since the data for materials used in specific processes and amounts per m^2 is not available. The idea behind the model is to break the myth that solar cells cannot harvest the energy required to manufacture them.

Note: According to the ISO 14000 series standards interpretation occurs at every stage of the project, that includes during LCI, so there will be some interpretation at every LCI and methodology. Final interpretation will be in Chapter 6

5.2.3 Embodied Energy

Embodied energy, which was defined in Chapter 4, forms the base of the inventory analysis as it can be scalable and accurate data of the process and material used in the process is available. Inventory analysis follows the flow of all materials from cradle to gate i.e. right from the mining to use. Embodied energy used at different levels of mining, extraction from other metals, production, etc. is illustrated in Table 2.

Table 2: Embodied Energy of Semiconductors

Semiconductors	**Embodied Energy MJ/m^2**	**Reference**
Polycrystalline- Si	1465.2	Joshua Pearce, AndrewLau
Amorphous-Si	417.6	Joshua Pearce, AndrewLau
CdTe	639	Kazuhiko Kota, 2001
InGaN	9612	S.P. Philippsa, May 2010
Total	**12133.8**	

The embodied energy shown in Table 2 is for $1m^2$ of each individual material (semiconductors). The wafer size is just 2.5mm X 2.5mm and they are laterally assembled in the PV panel. In other words, we can make a $3.2667m^2$ PV panel from this amount of material (see appendix A). Embodied energy for an individual material used in a $1m^2$ size solar panel is calculated and illustrated in Table 3.

Table 3: Embodied Energy for $1m^2$ Size Panel

Semiconductors	**Embodied Energy in MJ for individual semiconductors.**
Polycrystalline- Si	448.53
Amorphous-Si	127.84
CdTe	195.61
InGaN	2942.42
Total	**3714.39**

5.2.4 Flow of Materials from Cradle to Gate

The LCA is performed from cradle to gate, therefore every input that goes in the making of the system should be considered from its cradle; this is difficult to do without a clear picture of how the flow of material takes place at different stages. To understand and simplify this complexity, a flow chart of different components from cradle to gate (use) was constructed. At the same time a rough idea of different combinations of semiconductors laterally integrated in the PV panel was also suggested.

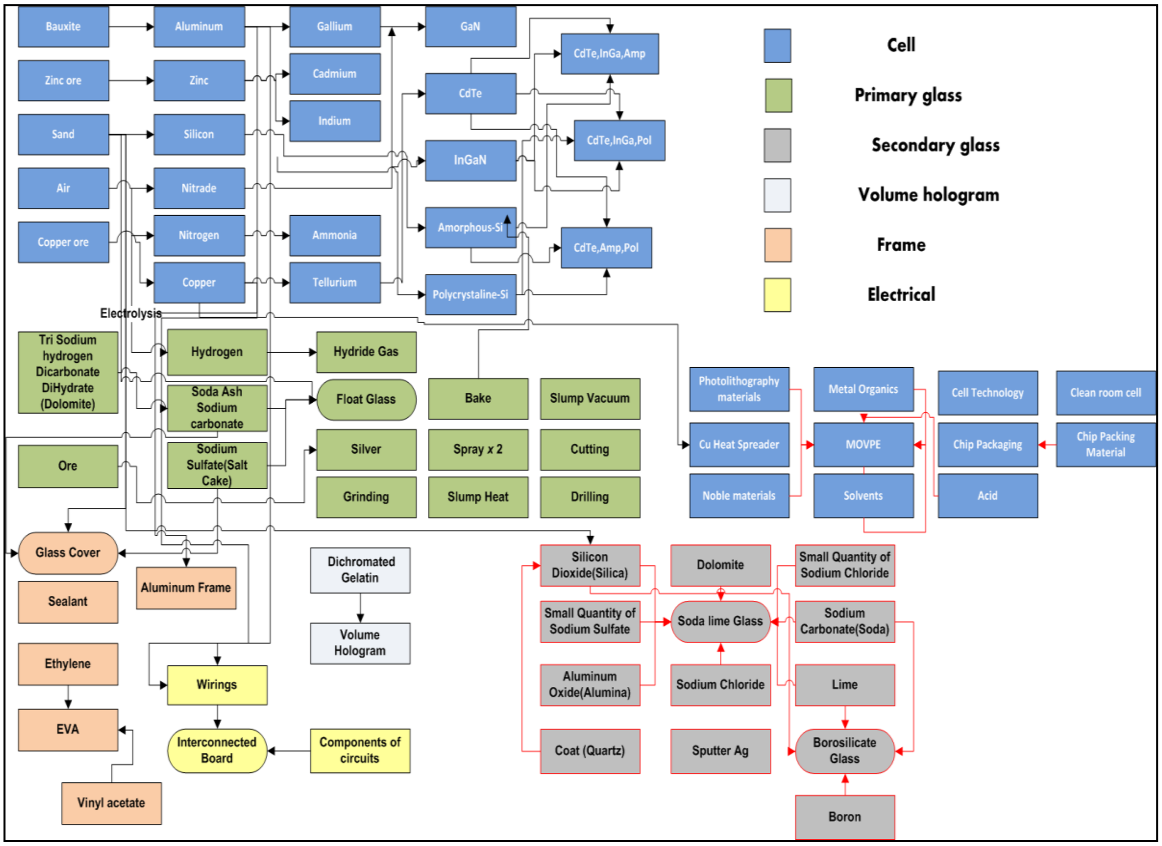


Figure 15: Flow of Material from Cradle to Gate

Flow of material from cradle to gate at different levels of cell and body of structure manufacturing; different colors are used in the flow chart to indicate different components of the PV cell as illustrated in Figure 15.

5.2.5. Three Alternative Designs of Lateral Integrated Architecture

The three designs are also illustrated in Figure 15 flow of material from cradle to gate.

5.2.5.1 Design 1

Design 1 consists of Indium Gallium Nitride (InGaN), Cadmium Telluride (CdTe), and Amorphous-Si semiconductors laterally integrated. The total embodied energy required to manufacture model 1 PV module of dimensions 1m x 1m is estimated at 36283.66 MJ.

5.2.5.2 Design 2

Design 2 consists of Indium Gallium Nitride (InGaN), Cadmium Telluride (CdTe), and Polycrystalline-Si semiconductors laterally integrated. The total embodied energy required to manufacture model 1 PV module of dimensions 1m x 1m is estimated at 36604.36 MJ.

5.2.5.3 Design 3

Design 3 consists of Cadmium Telluride (CdTe), Amorphous-Si, and Polycrystalline-Si semiconductors laterally integrated. The total embodied energy required to manufacture model 1 PV module of dimensions 1m x 1m is estimated at 33789.77 MJ.

Table 4 Illustrates the total embodied energy required to make a solar cell of 1m^2 and the Energy Pay Back Time (EPBT) to recover the initial energy that goes into the making of the system. The EPBT is based on the solar insolation of Duluth, Minnesota which is around 1390 kWh/m^2 with a Maximum power point of 4.17 kWh and electricity generated is 333.6 kWh/m^2.

Table 4: EPBT for Different Models

Models	Embodied energy(kWh/m^2)	EPBT (Years)
Model 1	10078.79	11.5
Model 2	10167.88	11.6
Model 3	9386.05	10.7

5.2.6 Embodied Energy for Different Components

Cell

Table 5: Embodied Energy and Method of Estimation [Artin Der Minassians, Dec, 2006]

Material	**Energy**	**Unit**	**Method**
Cell			
Cadmium Telluride	195.61	**MJ**	ED/PAD
Indium Gallium Nitride	2942.42	MJ	ED/PAD
Amorphous-Si	127.84	MJ	ED/PAD
Polycrystalline- Si	448.53	MJ	ED/PAD
Hydrogen	11	MJ	PAD
Hydride gases	13	MJ	PAD
Metal organics	1	MJ	PAD
MOVPE process	478	MJ	PAD
Clean room – Cell	1173	MJ	PAD
Solvents	39	MJ	PAD
Acids	3	MJ	PAD
Photolithography materials	45	MJ	PAD
Evaporation noble metals	321	MJ	PAD
Cell technology	146	MJ	PAD

Chip packaging materials	450	MJ	PAD
Chip packaging	366	MJ	PAD
Copper Heat Spreader	422	MJ	PAD
Total	**7182.40**	**MJ**	
Concentrator			
Primary Mirror			
Float Glass	639	**MJ**	ED
Silver	9612	MJ	EIO
Cut	417.6	MJ	PAD
Slump heat	1465.2	MJ	PAD
Slump vacuum	11	MJ	PH
Cut	13	MJ	PH
Drill	1	MJ	PAD
Grind	478	MJ	NP
Spray x2	1173	MJ	PAD
Bake	39	MJ	PAD
Total	**6688**	**MJ**	
Secondary Mirror			
Soda Lime glass	59	MJ	ED
Sputter(Ag)	846	MJ	PAD
Coat(Quartz)	69	MJ	PH
Borosilicate glass	526	MJ	EIO
Total	**3178**	**MJ**	
Frame			
Aluminum Frame	1739	MJ	EIO
Glass cover	1305	MJ	ED
Sealant	134	MJ	EIO
Total	**3178**	**MJ**	
Electrical			
AC and DC Wiring	525	MJ	PAD
Interconnected Board	750	MJ	PAD
Total	**1275**	**MJ**	
Installation			
Installation	144	MJ	PAD
Total	**24598**	**MJ/m2**	

Table 5 illustrates the total embodied energy that goes into the making of different components of the photovoltaic device.

Table 5 illustrates the embodied energy of different components of the system used from the system installed in Berkeley, CA [Artin Der Minassians, Dec, 2006]. The unit used for this is Mega joules and the method used to find this total embodied energy is abbreviated as Energy per economic activity (EIO), Embodied energy density (ED), Nameplate (NP), Publicity available data (PAD), and Placeholder value (PH)

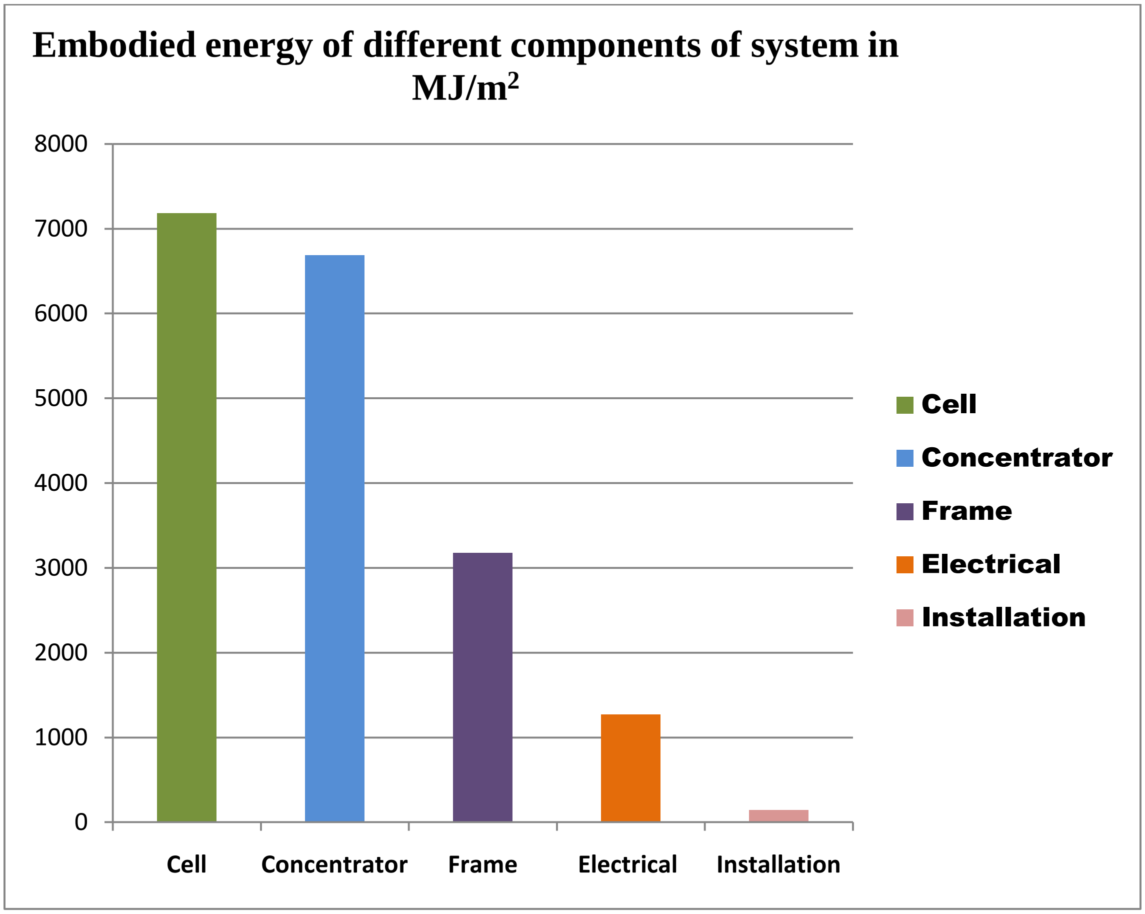


Figure 16: Embodied energy of different components of system in MJ/m^2

Embodied energy of cell, concentrator, frame, electrical, and installation that goes into the making of solar panel is illustrated in Figure 16.

Previous studies showed that cell manufacturing will contribute the highest amount of energy that goes into the making of the system, but after our analysis and evaluation of embodied energy for every individual component in the design, it was concluded that there is not a huge difference between the embodied energy of cell and concentrator. The percentage of embodied energy by different parts is illustrated in Figure 17.

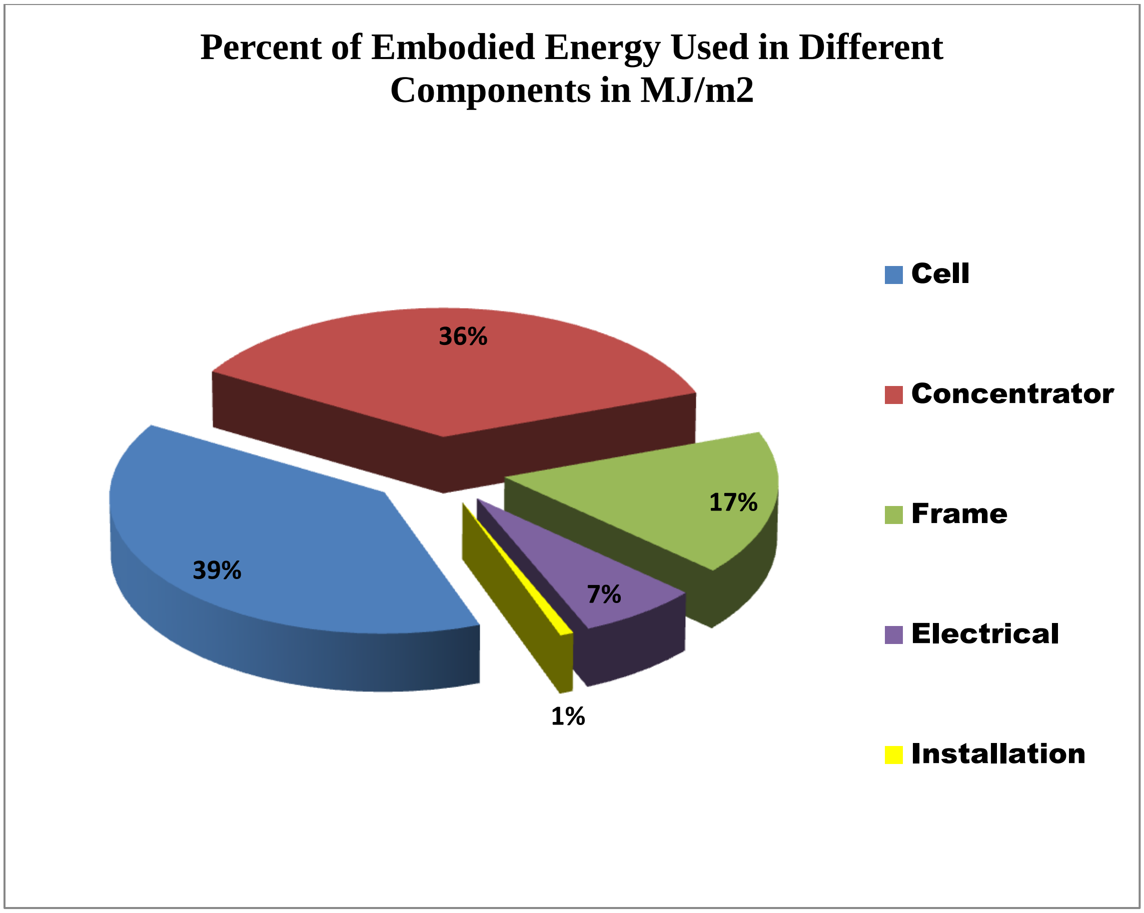


Figure 17: Percent of Embodied Energy Used in Different Components

5.2.7. Maximum Power Point (Pm)

As the design is in its initial stage it is really difficult to predict the overall efficiency of the PV device. Once this total efficiency is known, the energy output from a solar cell, depending on the dimensions of that particular cell, can be calculated.

$$\eta = \frac{Pm}{E*Ac} \qquad \text{[S.P.Philippsa,May 2010]} \quad (1)$$

Where,

η= Conversion efficiency (%)

P_m = Maximum power point

E = Input light irradiance (E, in kWh/m2)

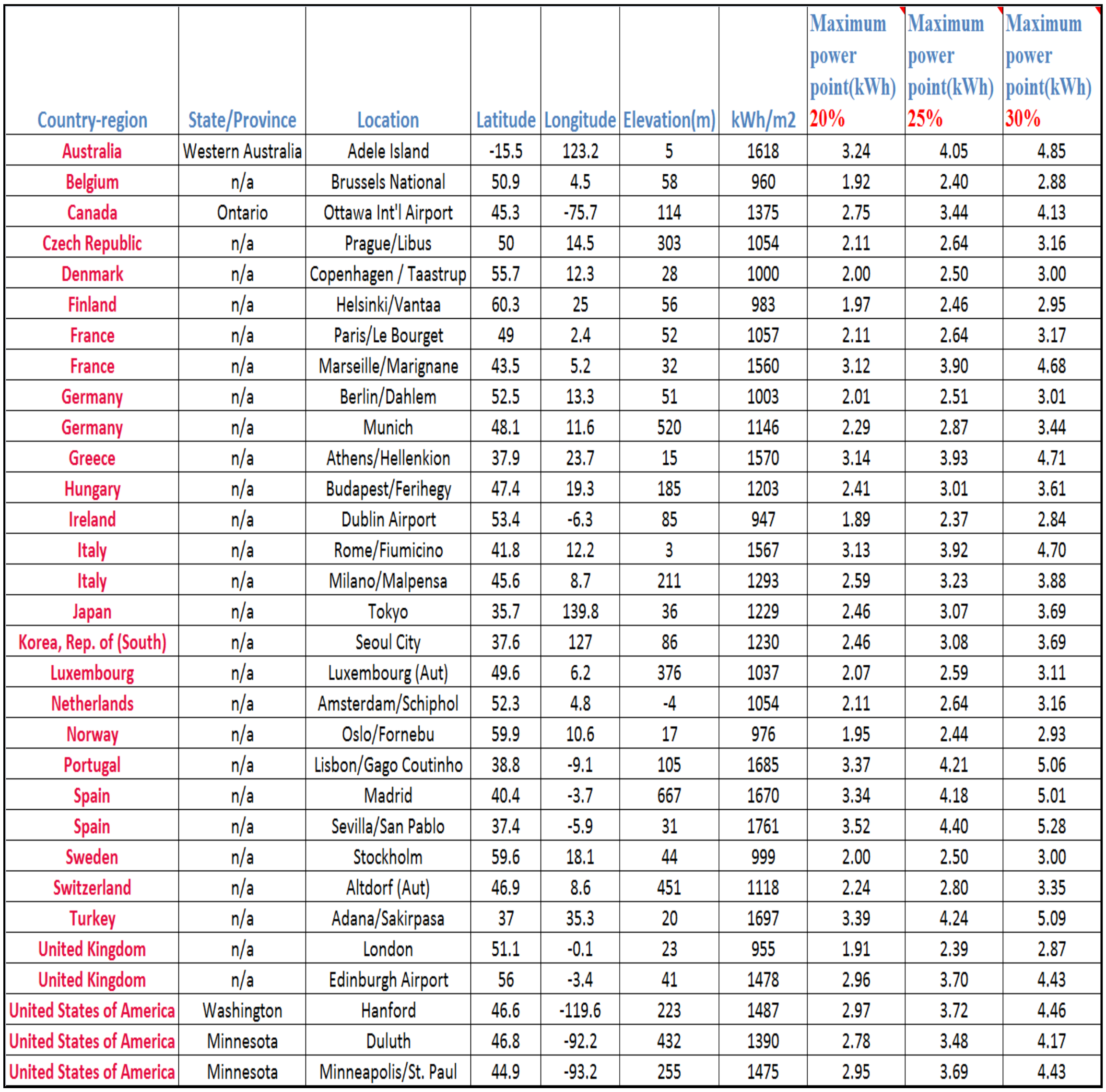
A_c = Surface area of the solar cell (Ac in m2).

It is estimated that the cell efficiency will be in the following range 20%, 25%, and 30%. If we consider the efficiency is 30% and the surface area is $0.01m^2$ then it is expected that the cell might generate approximately 3watts of power. Note: the value of E totally depends on temperature. “STC specifies a temperature of 25 °C and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5) spectrums” [S.P. Philippsa, May 2010].

$$30 = \frac{Pm}{1000 * 0.01}$$

P_m = 3 kWh (kilo Watt hour)

Table 6: Maximum Power Point at Different Location across the World



Country-region	State/Province	Location	Latitude	Longitude	Elevation(m)	kWh/m2	Maximum power point(kWh) 20%	Maximum power point(kWh) 25%	Maximum power point(kWh) 30%
Australia	Western Australia	Adele Island	-15.5	123.2	5	1618	3.24	4.05	4.85
Belgium	n/a	Brussels National	50.9	4.5	58	960	1.92	2.40	2.88
Canada	Ontario	Ottawa Int'l Airport	45.3	-75.7	114	1375	2.75	3.44	4.13
Czech Republic	n/a	Prague/Libus	50	14.5	303	1054	2.11	2.64	3.16
Denmark	n/a	Copenhagen / Taastrup	55.7	12.3	28	1000	2.00	2.50	3.00
Finland	n/a	Helsinki/Vantaa	60.3	25	56	983	1.97	2.46	2.95
France	n/a	Paris/Le Bourget	49	2.4	52	1057	2.11	2.64	3.17
France	n/a	Marseille/Marignane	43.5	5.2	32	1560	3.12	3.90	4.68
Germany	n/a	Berlin/Dahlem	52.5	13.3	51	1003	2.01	2.51	3.01
Germany	n/a	Munich	48.1	11.6	520	1146	2.29	2.87	3.44
Greece	n/a	Athens/Hellenkion	37.9	23.7	15	1570	3.14	3.93	4.71
Hungary	n/a	Budapest/Ferihegy	47.4	19.3	185	1203	2.41	3.01	3.61
Ireland	n/a	Dublin Airport	53.4	-6.3	85	947	1.89	2.37	2.84
Italy	n/a	Rome/Fiumicino	41.8	12.2	3	1567	3.13	3.92	4.70
Italy	n/a	Milano/Malpensa	45.6	8.7	211	1293	2.59	3.23	3.88
Japan	n/a	Tokyo	35.7	139.8	36	1229	2.46	3.07	3.69
Korea, Rep. of (South)	n/a	Seoul City	37.6	127	86	1230	2.46	3.08	3.69
Luxembourg	n/a	Luxembourg (Aut)	49.6	6.2	376	1037	2.07	2.59	3.11
Netherlands	n/a	Amsterdam/Schiphol	52.3	4.8	-4	1054	2.11	2.64	3.16
Norway	n/a	Oslo/Fornebu	59.9	10.6	17	976	1.95	2.44	2.93
Portugal	n/a	Lisbon/Gago Coutinho	38.8	-9.1	105	1685	3.37	4.21	5.06
Spain	n/a	Madrid	40.4	-3.7	667	1670	3.34	4.18	5.01
Spain	n/a	Sevilla/San Pablo	37.4	-5.9	31	1761	3.52	4.40	5.28
Sweden	n/a	Stockholm	59.6	18.1	44	999	2.00	2.50	3.00
Switzerland	n/a	Altdorf (Aut)	46.9	8.6	451	1118	2.24	2.80	3.35
Turkey	n/a	Adana/Sakirpasa	37	35.3	20	1697	3.39	4.24	5.09
United Kingdom	n/a	London	51.1	-0.1	23	955	1.91	2.39	2.87
United Kingdom	n/a	Edinburgh Airport	56	-3.4	41	1478	2.96	3.70	4.43
United States of America	Washington	Hanford	46.6	-119.6	223	1487	2.97	3.72	4.46
United States of America	Minnesota	Duluth	46.8	-92.2	432	1390	2.78	3.48	4.17
United States of America	Minnesota	Minneapolis/St. Paul	44.9	-93.2	255	1475	2.95	3.69	4.43

Real time data of solar insolation in kWh/m^2 at different locations across the world with exact latitude, longitude, and elevation was obtained using RETScreen Software. The RETScreen International Clean Energy Project Analysis Software is used worldwide for LCA, energy production and some other analysis. The real time solar insolation maximum power point for different locations is calculated with panel efficiencies of 20, 25, and 30 percent as illustrated in Table 6.

5.2.8 Electricity Generated

One of the important factors that need to be considered during performing LCA and evaluating economic aspects of a solar cell is the electricity generated by that particular system. In this case, as the design is in its mid phase it is speculated that the efficiency will be in the range of 20%-30%. Taking this into consideration, the estimation of electricity generation was conducted using three different efficiencies, 20%, 25%, and 30% respectively.

Life time electricity generation of a PV system, includes the following

G = Total electricity generated per m^2 (kWh/m2)

E = Conversion efficiency (%)

I = Solar Insolation (kWh/m^2)

PR = Performance ratio (%)

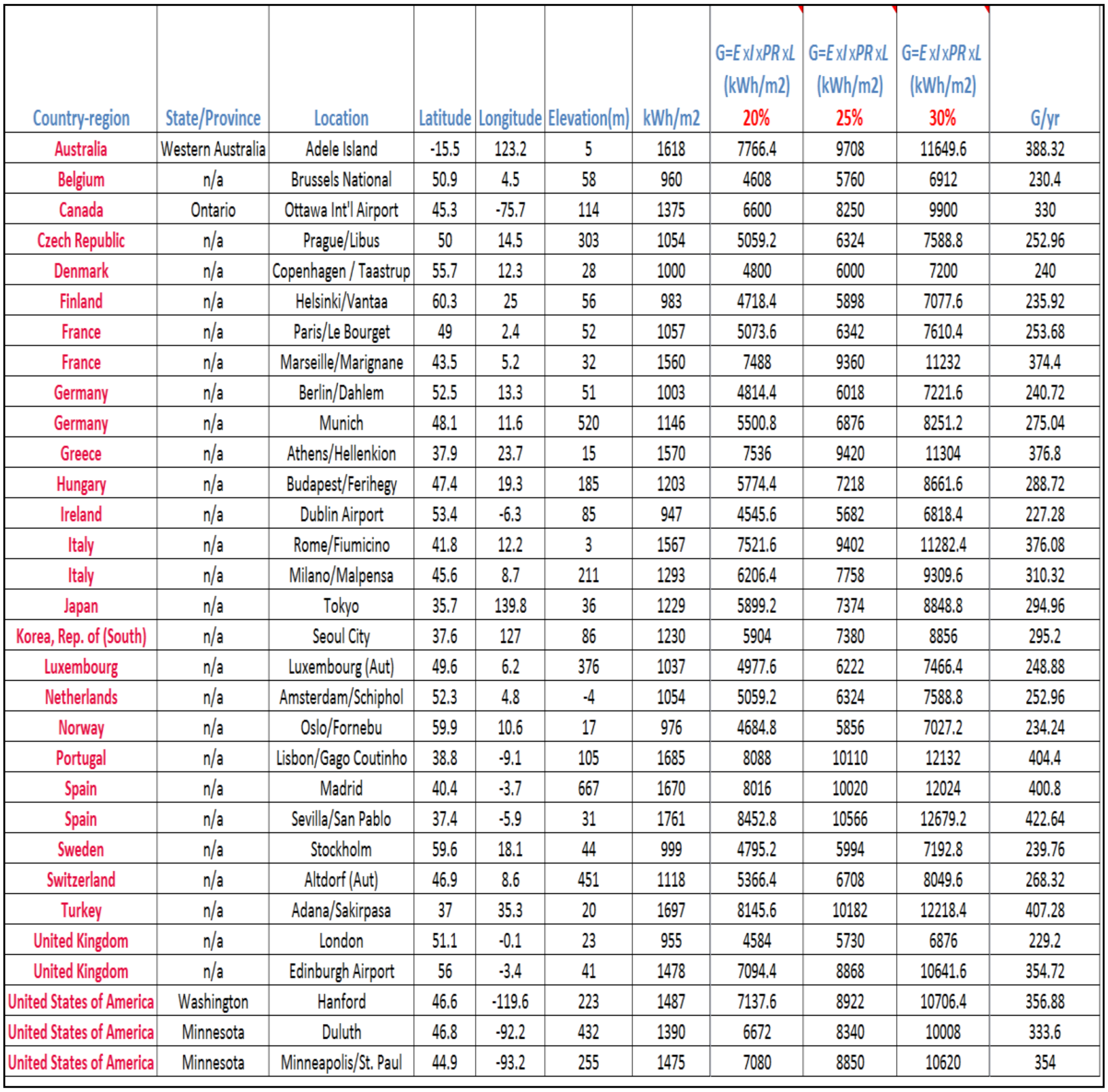
L = Life time (years)

The total life time electricity generated per m^2 of the solar module is calculated as follows:

$G = E * I * PR * L$ [Vasilis M. Fthenakis, 2008] (2)

The performance ratio is considered to be 80% [Vasilis M. Fthenakis, Jan 4, 2008] with the total life of solar cell of 30 years as illustrated in Table 7.

Table 7: Life time electricity generated in kWh/m2



Country-region	State/Province	Location	Latitude	Longitude	Elevation(m)	kWh/m2	$G=E \times I \times PR \times L$ (kWh/m2) 20%	$G=E \times I \times PR \times L$ (kWh/m2) 25%	$G=E \times I \times PR \times L$ (kWh/m2) 30%	G/yr
Australia	Western Australia	Adele Island	-15.5	123.2	5	1618	7766.4	9708	11649.6	388.32
Belgium	n/a	Brussels National	50.9	4.5	58	960	4608	5760	6912	230.4
Canada	Ontario	Ottawa Int'l Airport	45.3	-75.7	114	1375	6600	8250	9900	330
Czech Republic	n/a	Prague/Libus	50	14.5	303	1054	5059.2	6324	7588.8	252.96
Denmark	n/a	Copenhagen / Taastrup	55.7	12.3	28	1000	4800	6000	7200	240
Finland	n/a	Helsinki/Vantaa	60.3	25	56	983	4718.4	5898	7077.6	235.92
France	n/a	Paris/Le Bourget	49	2.4	52	1057	5073.6	6342	7610.4	253.68
France	n/a	Marseille/Marignane	43.5	5.2	32	1560	7488	9360	11232	374.4
Germany	n/a	Berlin/Dahlem	52.5	13.3	51	1003	4814.4	6018	7221.6	240.72
Germany	n/a	Munich	48.1	11.6	520	1146	5500.8	6876	8251.2	275.04
Greece	n/a	Athens/Hellenkion	37.9	23.7	15	1570	7536	9420	11304	376.8
Hungary	n/a	Budapest/Ferihegy	47.4	19.3	185	1203	5774.4	7218	8661.6	288.72
Ireland	n/a	Dublin Airport	53.4	-6.3	85	947	4545.6	5682	6818.4	227.28
Italy	n/a	Rome/Fiumicino	41.8	12.2	3	1567	7521.6	9402	11282.4	376.08
Italy	n/a	Milano/Malpensa	45.6	8.7	211	1293	6206.4	7758	9309.6	310.32
Japan	n/a	Tokyo	35.7	139.8	36	1229	5899.2	7374	8848.8	294.96
Korea, Rep. of (South)	n/a	Seoul City	37.6	127	86	1230	5904	7380	8856	295.2
Luxembourg	n/a	Luxembourg (Aut)	49.6	6.2	376	1037	4977.6	6222	7466.4	248.88
Netherlands	n/a	Amsterdam/Schiphol	52.3	4.8	-4	1054	5059.2	6324	7588.8	252.96
Norway	n/a	Oslo/Fornebu	59.9	10.6	17	976	4684.8	5856	7027.2	234.24
Portugal	n/a	Lisbon/Gago Coutinho	38.8	-9.1	105	1685	8088	10110	12132	404.4
Spain	n/a	Madrid	40.4	-3.7	667	1670	8016	10020	12024	400.8
Spain	n/a	Sevilla/San Pablo	37.4	-5.9	31	1761	8452.8	10566	12679.2	422.64
Sweden	n/a	Stockholm	59.6	18.1	44	999	4795.2	5994	7192.8	239.76
Switzerland	n/a	Altdorf (Aut)	46.9	8.6	451	1118	5366.4	6708	8049.6	268.32
Turkey	n/a	Adana/Sakirpasa	37	35.3	20	1697	8145.6	10182	12218.4	407.28
United Kingdom	n/a	London	51.1	-0.1	23	955	4584	5730	6876	229.2
United Kingdom	n/a	Edinburgh Airport	56	-3.4	41	1478	7094.4	8868	10641.6	354.72
United States of America	Washington	Hanford	46.6	-119.6	223	1487	7137.6	8922	10706.4	356.88
United States of America	Minnesota	Duluth	46.8	-92.2	432	1390	6672	8340	10008	333.6
United States of America	Minnesota	Minneapolis/St. Paul	44.9	-93.2	255	1475	7080	8850	10620	354

Power generated at different locations gave a rough idea about the performance of the solar cell.

Table 7 also illustrates the electricity generated per year in case the solar panel does not complete its total life of 30 years.

5.2.9 Energy Payback Time

Energy payback time was calculated using the following equation:

$$EPBT = \frac{E_{input}}{E_{\frac{produced}{year}} - E_{tracking}} * \eta_{elec} \quad [Artin\ Der\ Minassians, Dec\ 7, 2006] \qquad (3)$$

As the design has no tracking system we can eliminate energy used for tracking from this equation.

$$EPBT = \frac{E_{input}}{E_{\frac{produced}{year}}} * \eta_{elec}$$

Where

Energy payback time (EPBT) is the time required for a PV system to generate the amount of energy that was initially used in the making of the system.

E_{input} is the sum of total energy that goes in the making of PV module at different phases like extraction (acquisition), purification, manufacturing etc.

$E_{produced/yr}$ is the amount of electricity a PV module will generate in one particular year.

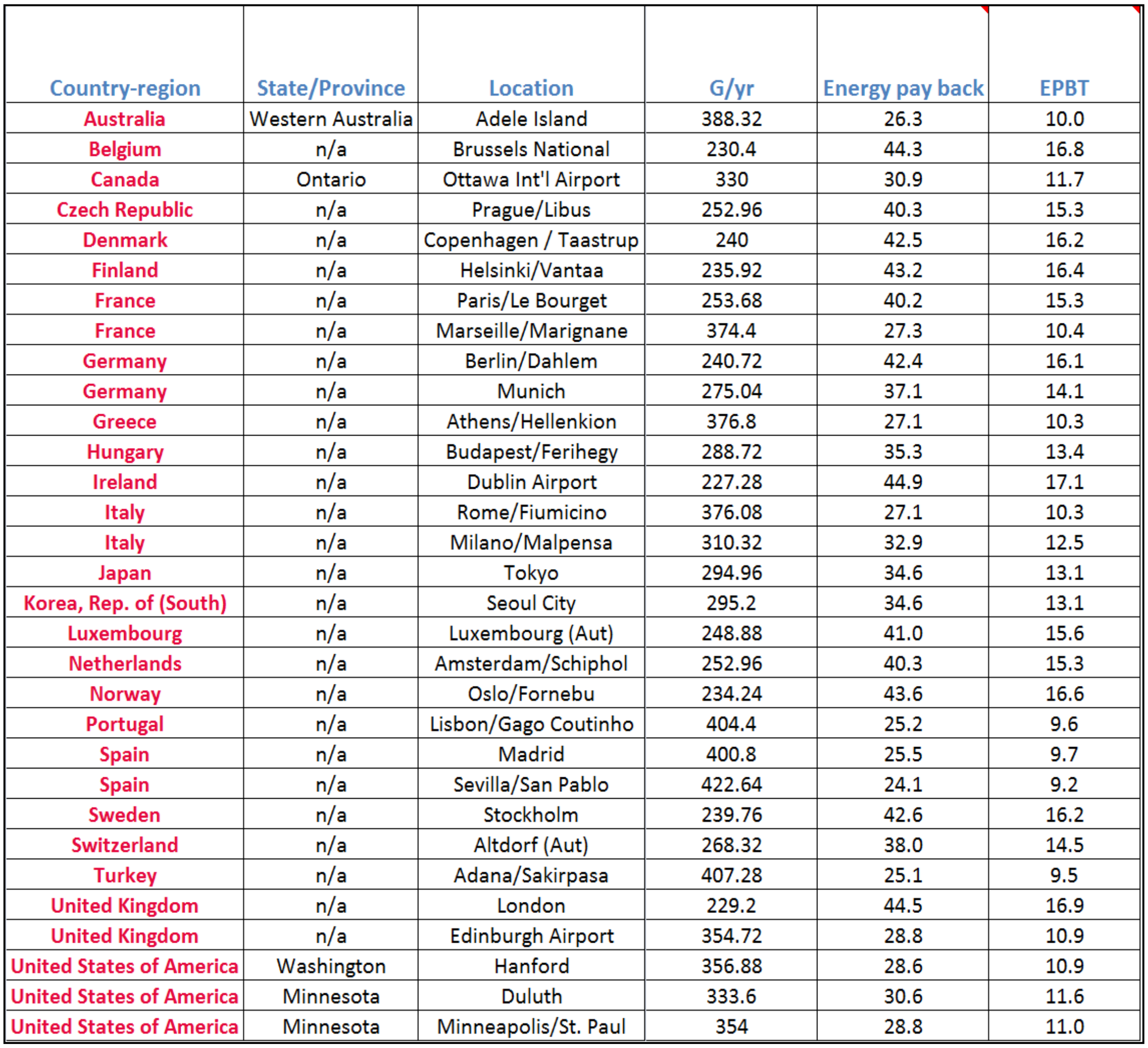
η_{elect} is the average electricity conversion efficiency of the electrical industry. In United States it is considered to be approximately 38% [Blakers, A, K. Weber, 2010].

Unit of E_{input} and $E_{produced/yr}$ is in kWh/m^2 and that of EPBT is in years. The EPBT for our system if located at different locations across the globe is illustrated in Table 8. Some of the literature shows use of average electricity conversion efficiency of the electrical industry [Blakers, A, K. Weber, 2010] and some use a simple EPB formula i.e. E_{input} /

$E_{produced/yr}$. Table 8 contains EPB and EPBT. By using both of these calculation methods, it can be seen that there is a huge difference between their results.

EPBT at different location was a key in understanding the importance of solar insolation on the output of the design.

Table 8: Energy Pay Back Time (EPBT)



Country-region	State/Province	Location	G/yr	Energy pay back	EPBT
Australia	Western Australia	Adele Island	388.32	26.3	10.0
Belgium	n/a	Brussels National	230.4	44.3	16.8
Canada	Ontario	Ottawa Int'l Airport	330	30.9	11.7
Czech Republic	n/a	Prague/Libus	252.96	40.3	15.3
Denmark	n/a	Copenhagen / Taastrup	240	42.5	16.2
Finland	n/a	Helsinki/Vantaa	235.92	43.2	16.4
France	n/a	Paris/Le Bourget	253.68	40.2	15.3
France	n/a	Marseille/Marignane	374.4	27.3	10.4
Germany	n/a	Berlin/Dahlem	240.72	42.4	16.1
Germany	n/a	Munich	275.04	37.1	14.1
Greece	n/a	Athens/Hellenkion	376.8	27.1	10.3
Hungary	n/a	Budapest/Ferihegy	288.72	35.3	13.4
Ireland	n/a	Dublin Airport	227.28	44.9	17.1
Italy	n/a	Rome/Fiumicino	376.08	27.1	10.3
Italy	n/a	Milano/Malpensa	310.32	32.9	12.5
Japan	n/a	Tokyo	294.96	34.6	13.1
Korea, Rep. of (South)	n/a	Seoul City	295.2	34.6	13.1
Luxembourg	n/a	Luxembourg (Aut)	248.88	41.0	15.6
Netherlands	n/a	Amsterdam/Schiphol	252.96	40.3	15.3
Norway	n/a	Oslo/Fornebu	234.24	43.6	16.6
Portugal	n/a	Lisbon/Gago Coutinho	404.4	25.2	9.6
Spain	n/a	Madrid	400.8	25.5	9.7
Spain	n/a	Sevilla/San Pablo	422.64	24.1	9.2
Sweden	n/a	Stockholm	239.76	42.6	16.2
Switzerland	n/a	Altdorf (Aut)	268.32	38.0	14.5
Turkey	n/a	Adana/Sakirpasa	407.28	25.1	9.5
United Kingdom	n/a	London	229.2	44.5	16.9
United Kingdom	n/a	Edinburgh Airport	354.72	28.8	10.9
United States of America	Washington	Hanford	356.88	28.6	10.9
United States of America	Minnesota	Duluth	333.6	30.6	11.6
United States of America	Minnesota	Minneapolis/St. Paul	354	28.8	11.0

5.2.10 Comparison with Conventional PV System

To study the economics behind the design and reach a rough conclusion about the economic aspects of the design, it was desirable to compare the proposed models with a 5.8 kWp Sharp ND-208U1F model panel array which is in operation since Fall 2008 at University of Minnesota Duluth. Sharp ND-208U1F is a polycrystalline silicon PV panel with an efficiency of 14%. In approximately 18 months of operation it generated 10297 kWh of electricity. Typically, a PV solar panel of 1 square meter generates 150 Watts [solarLED, 2009]. The system at UMD has 28 panel arrays and a capacity of 5,824 Watts. According to this we can calculate the approximate size of the solar panel located at UMD will be around 38.83 m^2

If this same panel is substituted with laterally integrated solar panel, it will generate 19438.53kWh of electricity in 18 months. At the same time it will save 12370.68 kg of CO_2, 48.60 kg of NO_2, and 69.98 kg of SO_2. Our proposed PV cell design will be more efficient than the one in operation at UMD and will have zero maintenance.

Note: Producing 1000 kWh of electricity with solar power reduces emissions by nearly 8 pounds of sulfur dioxide, 5 pounds of nitrogen oxides, and more than 1,400 pounds of carbon dioxide [T.N.R.E, Jan 2004].

It can be estimated that this panel will generate about 388610.6 kWh in its total life of 30 years with the panel size of 38.83 m^2. Worth of this electricity in dollars is around $40415.5(388610.6 *10.4 [U. S. E. I. Administration (Dec, 2010)] = 4041551cents).

5.2.11 Levelized Cost of Energy (LCOE)

LCOE compares the cost of electricity produced with its real competitor's i.e. conventional sources of energy.

LCOE is also known as LEC. "The calculation of the levelized cost of electricity (LCOE) provides a common way to compare the cost of energy across technologies because it takes into account the installed system price and associated costs such as financing, land, insurance, transmission, operation and maintenance, and depreciation, among other expenses" [Campbell, Aug 2008].

$$\mathrm{LEC} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad \text{[N.E Agency, 2010]} \qquad (4)$$

LEC = Average lifetime levelized electricity generation cost

I_t = Investment expenditures in the year t, $96,000. Data was taken from already existing solar panel in Malosky stadium at UMD and sharp electronics corporation (See appendix A).

M_t = Operations and maintenance expenditures in the year t (From the proposed design it can be assumed that the cost associated in operations and maintenance is either very little or something that can assume to be negligible)

E_t = Electricity generation in the year t (As estimated the solar panel will generate 12953.70kWh per year and around 388610.6 kWh (388.6106MWh) in 30years)

r = Discount rate (As the project was totally funded and no loan was taken from any kind of credit giving organization like banks so discount rate was neglected) Note: No matter how the project is funded it is needed to account for the discount rate because it gives a rough idea of the present/future value of the investment.

r = 0.0075[U.S.F.R.D, 2010].

n = Life of the system (Ideally it is assumed that a total life of a PV system is around 30 years. n=30 years.)

F_t = Fuel expenditures in the year t (As the system does not require any external source of energy to function thus eliminating F_t from the equation)

$$\text{LCE} = \frac{\frac{96{,}000 + 0 + 0}{(1+0.0075)^{30}}}{\frac{388.6106}{(1+0.0075)^{30}}} = \$247/\text{MWh}$$

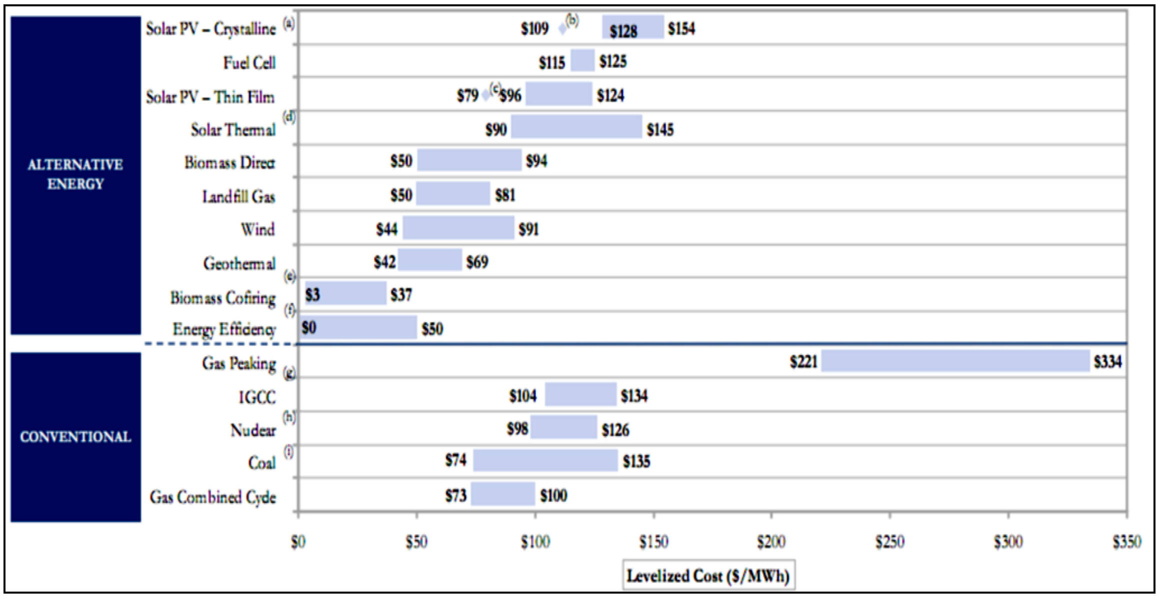


Figure 18: Levelized cost of different energies present n the market [LAZARD 2008]

Figure 18 illustrates the LCOE of different energies including thin film and crystalline solar cells. According to this it is clear that laterally integrated design has high LCOE cost ($/MWh) compared to other solar cells present in the market. But it is estimated that LCOE of laterally integrated design will reduce as the investment cost will be lower than $95,000(See appendix A).

The usual approach is to calculate future worth at the end of the first year as follows,

$$F= P+ Pi = P (1+i) \quad \text{[Richard A. Whisnant, 2003]} \qquad (5)$$

Where,

F is the future worth

I is the interest rate paid per year

P is the present worth (amount spent or received at present)

Similarly, we can see future worth at the end of second year.

$$F= [P (1+i)] (1+i) = P (1+i)^2 \quad \text{[Richard A. Whisnant, 2003]} \qquad (6)$$

And the future worth after n years is

$$F= P (1+i)^n \qquad (7)$$

Conversely, the present worth of a future sum is given by

$$P= F (1+i)^{-n} \qquad (8)$$

"i" is considered as the interest offered by a bank, but when we consider an investment in an energy system, "i" is referred as discount rate.

The discount rate is the value that the system owner puts on the capital investment in the system, and is often called the opportunity cost of the investor; that is the rate of return foregone on the next most attractive investment [Richard A. Whisnant, 2003].

$$F= a [(1+i)^n - 1] \div i \qquad (9)$$

By combining equations (2 and 3), present worth of a uniform series of amounts "a" can be stated as

$$P=a [(1+i)^n -1] / [i (1+i)^n] \qquad (10)$$

Where,

"a" is an annual amount.

OR

Uniform series present worth (USPW)

$$USPW = \frac{(1+i)^n - 1}{i(1+i)^n}$$

[Richard (2003), U.S.E.I., Dec 27 2010] (11)

For this estimation, the discount rate or interest "i" has been considered to be 0.75% (this changes according to the organization but we considered 0.75% because it is U.S. government discount rate)

Discount rate i = 0.0075

Number of periods is 29 (total life is 30 but we are not considering 30th year so 29 years)

Uniform series present worth (USPW)

$$USPW = \frac{(1+i)^n - 1}{i(1+i)^n}$$

[Richard (2003); U.S.E.I., Dec 27 2010]

= 25.98

For calculating P we just need to involve "a" in the above equation as there is a uniformity of cash flow.

P = a* 25.98

P = 4041551* 25.98

P = \$1,049,829 (Present value of electricity generated in \$)

5.3 Impact Assessment

The potential human and environmental effects of the energy or power, water, and other materials that were used during the process were assessed. Cradle to gate was considered for the assessment, i.e. from raw material acquisition to the final product manufacturing and its use. This does not include end use or disposal.

5.3.1 Environmental Emissions

One of the reasons of performing LCA is to estimate the environmental emissions of the design from cradle to gate with all the different components and processes used. Figure 19 illustrates the environmental emissions from BOS, installation, and two cells KC 120 and PVC 136. KC 120 is a type of amorphous-Si cell and PVC 136 is a type of polycrystalline-Si cell. This paper takes an in depth look at all of the possible emissions over the life cycle (Cradle to gate) of the cell and its components (Body of System)

Note *All emission data are in Kg per m^2 area of solar panel.

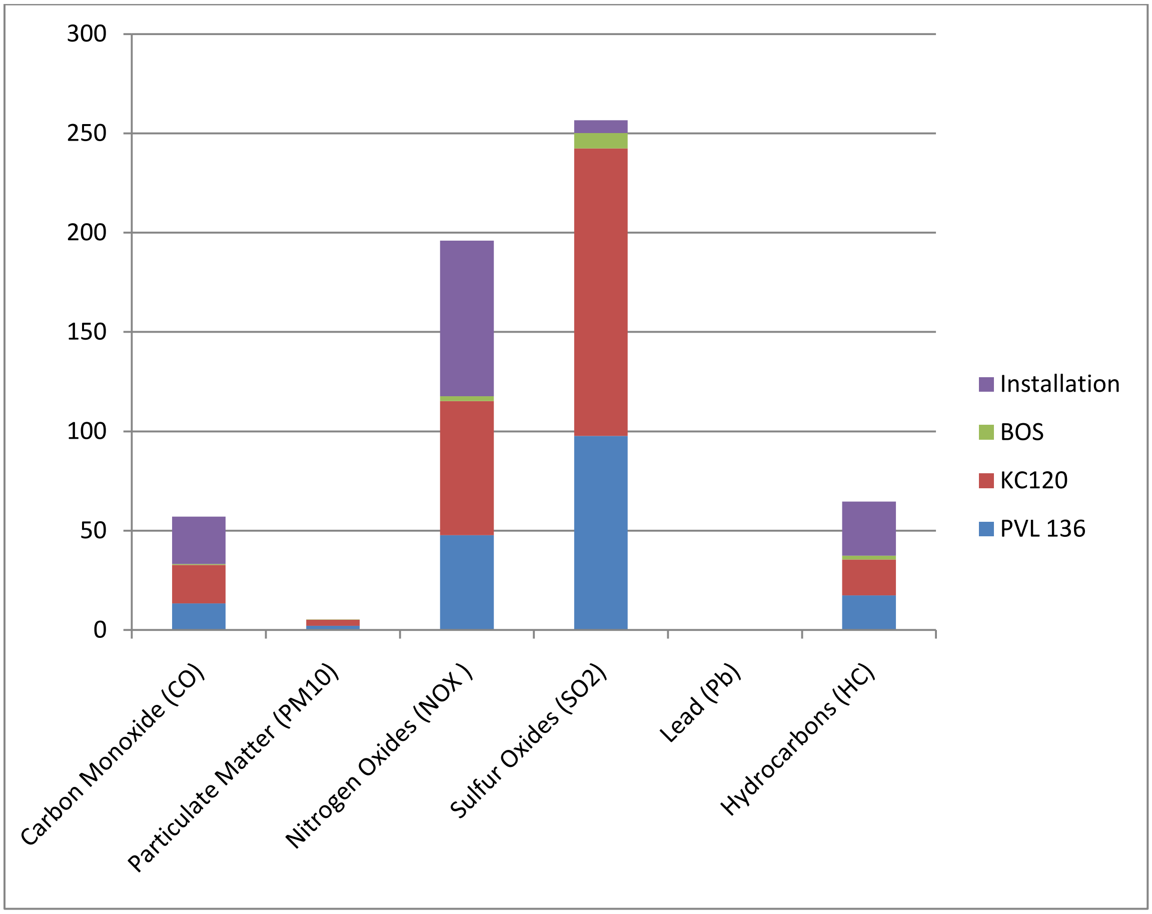


Figure 19: Environmental Emissions

5.3.2 Green House Gases

Currently, more importance is given to the green house gases mainly CO_2 because rising concentrations of CO_2 generally produce an increase in the average temperature of the earth. Increasing CO_2 concentration in the atmosphere is one of the reasons to switch to alternative energy. Figure 20 illustrates the green house gas emissions in the United States during 2001[Tyler Gregory Hicks, 2007]. Rising temperatures may, in turn, produce changes in weather, sea levels, and land use patterns. Figure 21 illustrates the emission of CO_2 and methane (CH_4) for different components.

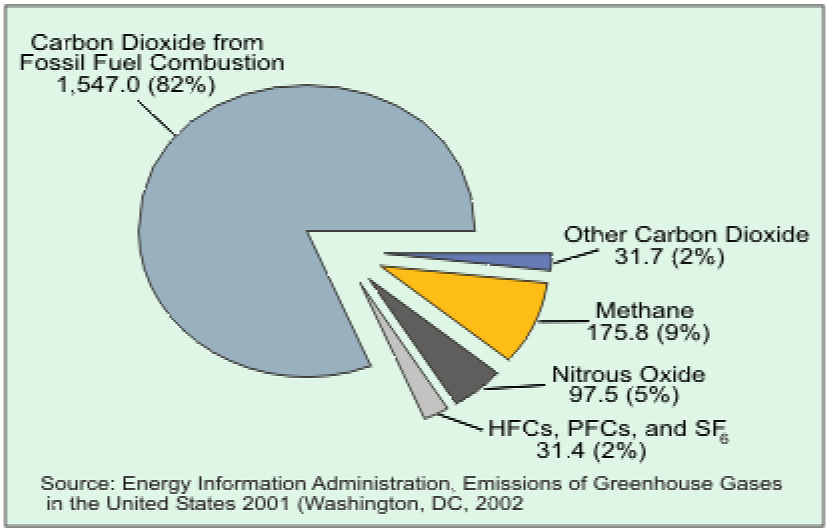


Figure 20: Green House Emission Chart [Tyler Gregory Hicks, 2007]

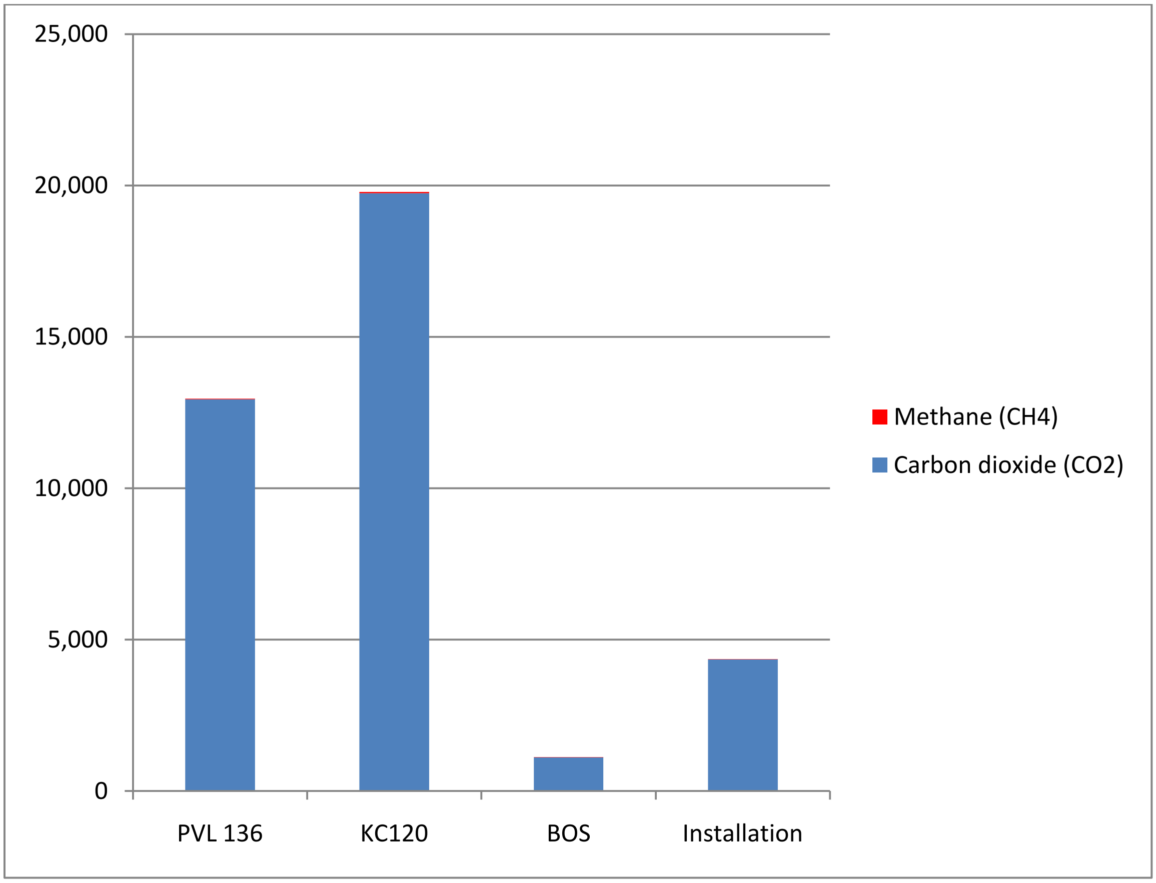


Figure 21: Green House Gases

5.3.3 Emission from CdTe

The reason behind not including CdTe with the rest of the components and cells was that CdTe emits a variety of toxic gases and particulates during its manufacturing and later stages compared to the rest of the cells. Some of these chemicals are emitted in such minute quantities that they can be easily neglected in the short term but they should be considered in a complete, long term analysis. This paper includes all the emissions even if they are in minute quantities. Figure 22 illustrates the emission from CdTe. Compared to the other semiconductors (PV cell) used in the design CdTe emits the lowest amount of CO_2 but toxic Cd at every level. “Brookhaven National Laboratory (BNL) and the U.S. Department of Energy (DOE) are nominating Cadmium Telluride (CdTe) for inclusion in the National Toxicology Program (NTP). This nomination is strongly supported by the National Renewable Energy Laboratory (NREL)”. [Fthenakis, V M, 2004]

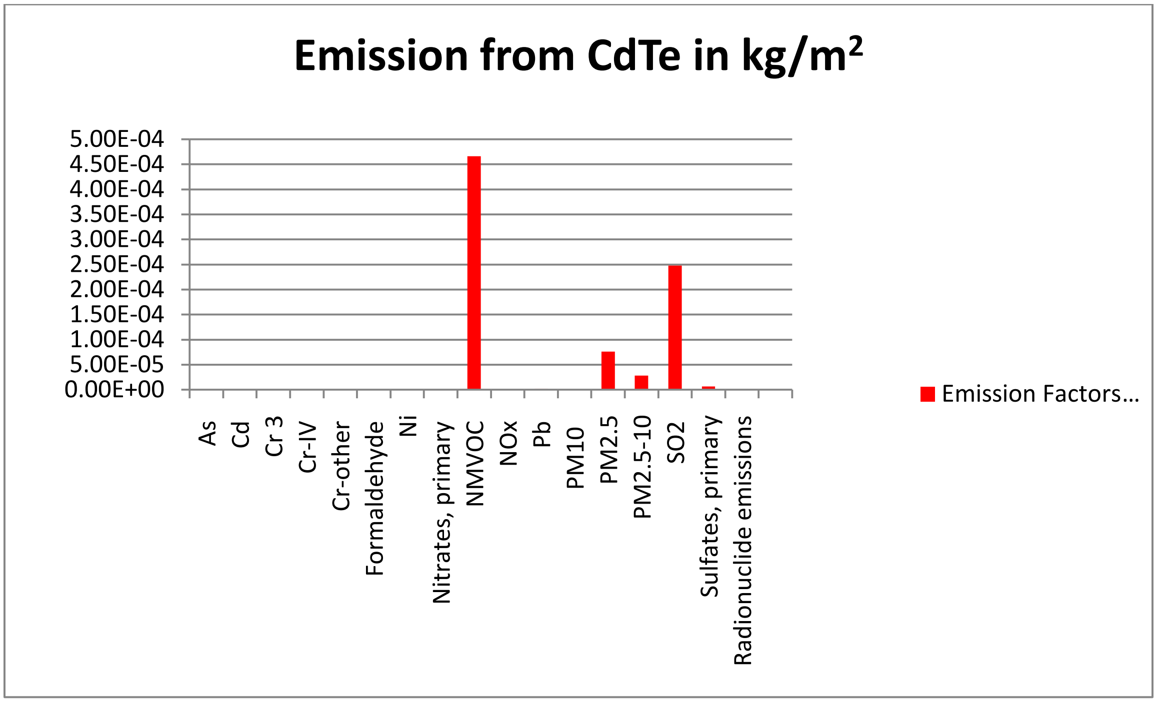


Figure 22: Emission from CdTe in kg/m^2

5.4 Interpretation

This includes evaluation of the results of the inventory analysis and impact assessment to recommend the product or sub product used. A final decision cannot be made without comparing the system with a PV panel that is already in service using the evaluation criteria of energy generated and savings (CO_2).

From the LCA conducted and economic calculation performed in this study, it seems that the design is close to being sustainable. If the following areas could be further evaluated the system has potential to be a sustainable option for the future of PV solar cells. Primary energy of the InGaN should be reduced by finding an alternative manufacturing process. Polycrystalline-Si solar cells have dominated the solar market.

They have good efficiency but their primary energy requirement should be lowered by alternative manufacturing processes and their manufacture emits comparatively large amounts of green house and other gases. Amorphous-Si has low primary energy requirement but comparatively high CO_2 emission.

According to the study, design 3, consisting of Cadmium Telluride (CdTe), Amorphous-Si, and Polycrystalline-Si semiconductors, has a lower primary energy requirement which results in a comparatively low EPBT of 10.7 years. However, the polycrystalline material used in the model emits comparatively large amounts of green house and other gases. The trade off should be made between EPBT and emissions (see figure 19, 21, and 22).

From the levelized cost of energy calculation it can be concluded that laterally integrated design has high LCOE cost ($/MWh) compared to other solar cells present in the market. But it is estimated that the LCOE of laterally integrated design will reduce as the investment cost will be lower than $85,000. The system can be considered economical due the fact that it can generate $1,049,829 present worth of electricity.

Chapter 6: Conclusions

Polycrystalline-Si has a high primary energy requirement from conversion of silica to solar grade-Si. The primary energy requirement should be lowered by the use of alternative manufacturing process similar to one developed at the University of Cambridge called the FFC Cambridge process. Amorphous-Si has low primary energy but emits comparatively large amounts of green house (see figure 19) and others gases (see figure 21). CdTe emits a small quantity of cadmium. An in-depth study needs to be done either to minimize its use or recycle cadmium completely (cradle to cradle). If the system intends to reach the mass production phase and be a viable sustainable design, it needs to focus on the emissions caused from the semiconductors used in the design.

Comparison with the Polycrystalline-Si panel at University of Minnesota-Duluth gave a rough idea of a similarly sized laterally integrated panel. If operated for a duration of 18 months, it will generate 19438.53 kWh of electricity. At the same time it will save 12370.68 kg of CO_2, 48.60 kg of NO_2, and 69.98 kg of SO_2 and have zero maintenance costs.

The current results indicate that solar insolation has a big effect on the output of the solar cell. The difference between the highest and lowest EPBT period was about 7.4years. EPBT is comparatively high as the study includes embodied energy of every component used in the system from its cradle. This work also points to the fact that EPBT of a system needs to be lowered. It will be achieved by selecting alternate processes which will eventually lower the primary energy requirement of the entire system; this constitutes a big step towards sustainable design.

From the levelized cost of energy calculation it could be concluded that laterally integrated design has high LCOE cost ($247/MWh) compared to other solar cells present in the market. But it is estimated that LCOE of laterally integrated design will reduce as the investment cost will be lower than $96,000. The system can be considered economical due the fact that it can generate $1,049,829 present worth of electricity.

6.1 Discussions

LCA is a good design tool and should be used in the design phase. ISO 14000 provides a good framework for analyzing a new design. ISO standards can be successfully combined with other approaches to get satisfactory results even with limited data. These results can be used for decision making. LCA can not only help to select materials and processes but will be a great tool to find alternatives for materials and process. LCA can be used to find a tradeoff between process and materials as it gives a rough idea about embodied energy, EPBT, emission etc.

The current study suggests that primary energy of the entire design can be reduced if the embodied energy required in the manufacturing of cells and concentrator can be reduced by using alternate manufacturing processes. This will result in low EPBT. Further study of polycrystalline-Si and its manufacturing processes should be done because it has good efficiency but requires a great amount of primary energy and emits a large amount of CO_2 compared to other PV cells.

The RETScreen software was used to evaluate the laterally integrated design at different locations around the globe. The laterally integrated design can be used efficiently around the globe and will not require any design change, even when it comes to marketing this product globally (will help in supply chain management when it comes to mass production).

A comparison with the solar panel located at UMD gave a rough idea about economic aspects of the design. Laterally integrated PV design will generate more energy and less emission with the same dimensions and without any maintenance.

Use of software will be a great help in performing an eco audit at the design stage. A rough example of using CES EduPack Eco Audit Tool (software) is illustrated in Figure 23 and Figure 24.

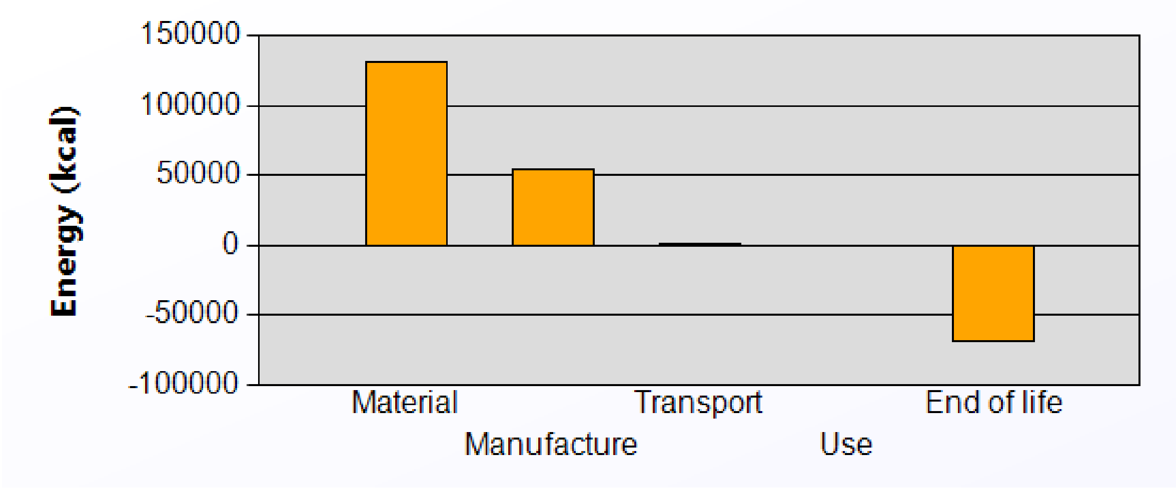


Figure 23: Energy Used at Different Phases

Figure 23 shows an Energy audit report generated from CES EduPack Eco Audit Tool of soda lime glass and borosilicate glass which forms our primary and secondary glass in the laterally integrated PV design with a life span of 30 years. Figure 24 shows CO_2 emissions over the entire life cycle. Software also helps in determining end use or disposal methods to minimize the environmental impact.

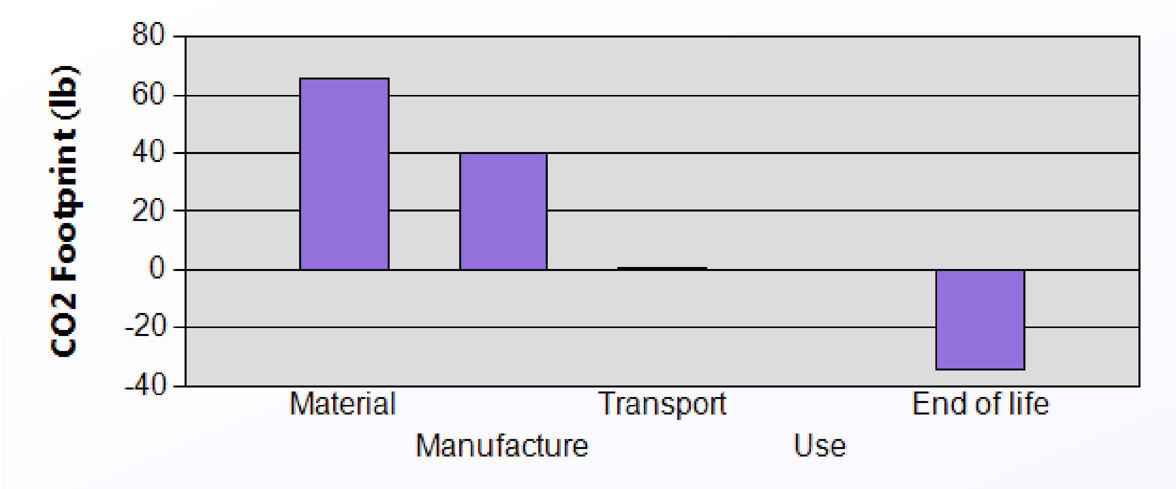


Figure 24: CO2 Foot Print at Different Phases

Chapter 7: Future Research

It is a strong belief that no single method is capable of providing a big picture of the environmental impacts; every method has its own limitations and is appropriate for a specific field of applications. ISO standards need to be further studied by incorporating sustainability multi-method multi-scale assessment (SUMMA) [Ulgiati S, Raugei M, Bargigli S.] approach in the ISO standards. SUMMA includes accounts material flow and embodied energy as well as energy synthesis and CML 2 baseline 2000(see appendix A). This will only be possible with huge databases.

Laterally integrated PV architecture is the future of the PV panels but it still needs to be further evaluated by using more advanced commercial software and databases. At present companies like GaBi, RETScreen, and CES EduPack Eco Audit Tool don’t have the required databases of the semiconductors and processes used in this design but these companies are working on expanding their materials and process databases. Having these databases will help us to choose the materials and processes in the design phases and avoid the future complexity of managing the emissions.

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Abbreviations

CO	carbon monoxide
CO_2	carbon dioxide
EPBT	energy payback time
GWh	Gigawatt-hour
InGaAs	Indium Gallium Arsenic
ISO	International Standards Organization (International organization of standardization)
kWh	kilowatt-hour
kWp	Kilowatt-Peak
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle inventory assessment
LCM	Life cycle management
MJ	Mill joules
NO_2	nitrogen dioxide
NREL	National Renewable Energy Laboratory

P_m	Maximum power point
PV	photovoltaic
SO_2	sulfur dioxide
Te	Tellurium
Zn	Zinc

Appendix A

PV panel size

The wafer size is of size 2.5mm^2. From this it can be calculate that there will be 400 wafers of every semiconductor of size 1m^2. Design has three different semiconductors that means total of 12000 wafers. But the numbers of cells in a PV panel is 400 cells. But every cell has a definite spacing between each. In laterally integrated design the spacing is assumed to be 0.666mm. This adds 0.2667 m^2 in the total design. This makes the total size of the panel will be 3.2667m^2.

Emergy synthesis

It attempts to evaluate all the free energy or other support materials that are being used in the making of the system for example, sunlight, wind etc. It also includes the energy that is required for the formations of the employed fossil fuels [Marco Raugie, May 12 2006]

CML 2 baseline 2000

It's an advance LCA software offered in many commercial LCA software packages. It has many indicators for environmental emissions like global warming potential (GWP), acidification potential (AP), freshwater aquatic ecotoxicity potential (EP) etc [Marco Raugie, May 12 2006].

Cost of System

Cost of 1 solar panel of 208watts is around $699 there are 28 panels at UMD that makes a total of $19572 considering the discount on taxes the total to be around $20,000.

Laterally integrated solar panel is concentrator type solar panel. The number of cells required to reach highest efficiency will be less compared to UMD solar panel. At the same time use of volume hologram will also help to reduce the number of cells and increase the panel efficiency. Considering this it is expected that the cost of cell will reduce by 30%.

Table 9: Cost of System source: sharp electronics corporation and Solar Power at Malosky Stadium UMD

Item Description	**Cost**
Cost of solar cell	$ 14,000
Installation of Solar panels, racking system, field wiring and system protection	$67,850.00
Installation of grid power inverter, switchgear and disconnects	$17,189.00
Total	**$96,039**