THESIS

LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST OF PHOTOVOLTAIC PANELS ON LAKE STREET PARKING GARAGE

Submitted by

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ABSTRACT

LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST OF PHOTOVOLTAIC PANELS ON LAKE STREET PARKING GARAGE

In the U.S., the capacity of photovoltaic panels has already reached a level close to 14GW in 2014. The goal of the solar power industry is to meet 10% of U.S. peak electricity generation capacity by 2030 (Dincer, 2011). Photovoltaic panel systems have become a new trend to produce electric power.

Solar radiation is an abundant, inexhaustible, clean and cheap energy source. By using solar energy, solar panels are considered a clean and green method to produce electric power. However, photovoltaic panels have impacts on the environment in the production process and end-of-life process. This thesis uses a methodology that combines life cycle assessment (LCA) and life cycle cost (LCC) to analyze the life cycle impact and the cost of a PV system on a public garage located in Fort Collins, Colorado. The LCA method used in this thesis is a hybrid LCA, which is a combination of process based LCA and economic Input/Output LCA (EIO-LCA).

The result of the analysis of LCA indicates that a solar panel power system does have some advantages in reducing greenhouse gas emissions and gaseous toxic releases. However, solar panel systems have higher toxic releases to water and land than a traditional power plant. The result of LCC points out that the solar panel system on the roof of Lake Street Parking Garage cannot recover its cost during its 25-year life span.

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CHAPTER ONE: INTRODUCTION

With the growth of global population, the issues involving consumption of natural resources have become intense, and the environmental problems have become more serious in many parts of the world. Electricity production constitutes a big portion of total greenhouse gas emission in the U.S (USEPA, 2013). So reducing the pollution from electricity generation is an effective and important topic for examination. It is urgent to start looking for an alternative way to replace traditional power generation from plants using coal, oil and natural gas as raw materials. During this decade, alternative energy has become a focus of the power generation industry. Today, some mature new energy generation methods are wind power, photovoltaic panels, biogas and fuel cells (Varun & Ravi, 2009). Among them, photovoltaic panel is the most accepted and most convenient method that can be used in residential and commercial buildings.

1.1 Introduction of the Photovoltaic Panels

Photovoltaic panels do not require vast amount of space such as wind farms nor do they require large amounts of steel for construction like wind energy. Photovoltaic panels do not need collection and fermentation plants like the biogas power generation systems. Photovoltaic panels are also unlike fuel cell power generation, which requires a special structure and cumbersome maintenance process. After purchasing and installing the solar panels, you can use the photovoltaic to produce electricity immediately. Meanwhile, the operation stage of photovoltaic panel does not need too much maintenance and does not need special conditions of use, such as the specific temperature, particular PH value and so on (Cristaldi, Faifer, Rossi &Ponci, 2012). Therefore, photovoltaic panels have been used in various residential and commercial buildings, such as commercial centers, supermarkets, public parking garages and residential apartments.

Both residential and commercial buildings are complex and unified systems. If photovoltaic technology is incorporated into building design, the design should consider the technology of photovoltaic system. At the same time, some other aspects, such as architectural aesthetics and ease of use of the building should be considered as well. Currently, building integrated photovoltaic system can be divided into two categories: roof structure photovoltaic system and wall structure photovoltaic system (Vats & Tiwari, 2012). The photovoltaic on roof structure is more convenient in the construction of the buildings that have been completed, because there is no additional land requirement or additions to other facilities. Therefore, many buildings have been built with a photovoltaic roof structure.

Solar radiation is an abundant, inexhaustible, clean and cheap energy source. With the continuous development of the photovoltaic technology, the efficiency of solar panel is constantly improving. Currently, the efficiency of polycrystalline cell is about 16% -17%, and the efficiency of monocrystalline silicon cell is about 18-20 % (Taube, Kumar, Saravanan, Agarwal, Kothari, Joshi & Kumar, 2012). The continuous and steady solar power generation and the advantages of clean energy production from photovoltaic panels make their benefits more apparent. At the same time, the cost of manufacture and use of photovoltaic panels is reduced. So the applications of the photovoltaic panels are increasing in our daily life. Therefore, no matter whether the photovoltaic cells are connected with the grid or solely used to support the electricity of a standalone building, solar power generation is now an important contributing factor to electricity production.

1.2 The Trend of Photovoltaic Panels around the World

Today, a wide range of applications of photovoltaic technology is used, and the photovoltaic panel is playing an increasingly important role in alternative power generation. The earliest application of photovoltaic technology is in space, it is used as the power for satellites (El Chaar, Lamont & El Zein, 2011). In our daily life, it also serves as the power provider of unattended traffic lights, street lights, radio communication stations, large parking lot with charging stations and small household appliances. And even some independent photovoltaic power plants, which have 50KW ~ 1000KW capacity, are gradually being built (Sueyoshi & Goto, 2014). With the broad appeal of solar panels, the integration of building and photovoltaic technology has already become a popular alternative in support of electrical needs of building. Thus, building integrated photovoltaic applications is one of the most important areas in the implementation of alternative energy systems (Vats & Tiwari, 2012).

1.3 The Trend of Photovoltaic Panels in the U.S. and Colorado

In the U.S., the capacity of photovoltaic panels has reached a level close to 14GW. The goal of the solar power industry is to meet 10% of U.S. peak electricity generation capacity by 2030. (Dincer, 2011). Figure 1 shows the USA Photovoltaic industry road map.

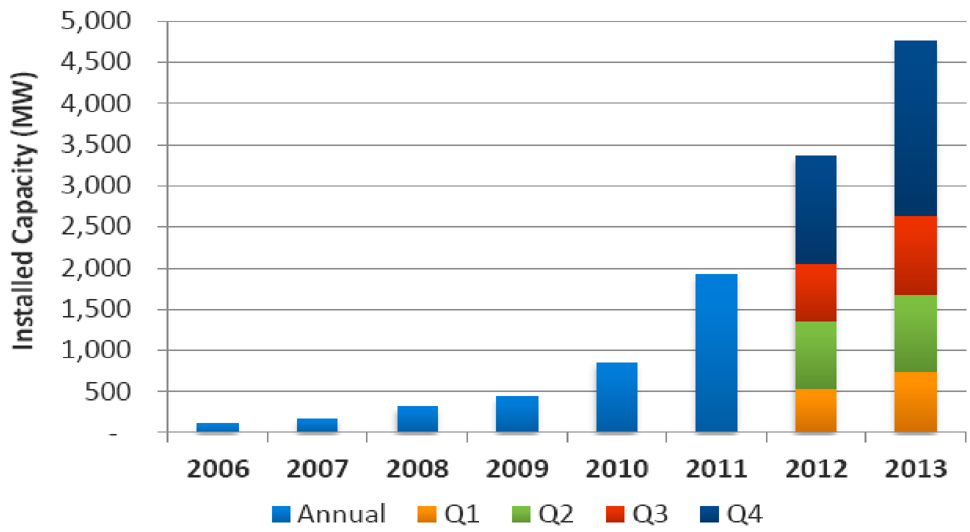

Figure 1. **The Installed Capacity of PV in the U.S.**Source: (Dincer, 2011)**.**

As a state that focuses on “green energy”, environmental protection and sustainable development, Colorado attaches great importance to the application of photovoltaic roof structures ("Colorado’s energy industry," 2013). In addition, Northern Colorado has good solar radiation conditions, because the average sun radiation that can be used to turn into power reaches 5.5 hours per day, and there are more than 300 sunny days a year (Lave & Kleissl, 2010). Therefore, the capacity of photovoltaic panels in Colorado is now more than 300MW. This capacity can provide electricity for 53,600 households (Paudel & Sarper, 2013).

1.4 The Trend of Photovoltaic Panels in Colorado State University

Colorado State University, which is located at Fort Collins, Colorado, is one of the leading universities responding to green energy and sustainable development (Rolston, 2014). Therefore, Colorado State University has also done a lot in the construction of photovoltaic panels. In the foothills campus of Colorado State University, a thirty-acre solar power plant has been built. Its capacity is 5.3MW, which is one the largest solar power plants built by a University in the country ("Building solar sustainability," 2011). In the main campus, photovoltaic panels were also built on the roof of Lake Street Parking Garage, Engineering Building, Research Innovation Center, Behavioral Science Building and Academic Village. Among them, the photovoltaic panels on Lake Street Parking Garage were built on the top floor of the parking structure. The size of it is 9000 square feet with a capacity of 133KW ("Building solar sustainability," 2011). Compared to other school buildings, the public garage structure is a special place, which does not have walls around the parking area. In addition, although the capacity of its solar panels is the largest among all the panels in the main campus, the public parking garage needs electricity 24 hours a day for 7 days a week. Thus, the solar panels obviously cannot supply enough electricity to meet the needs of the garage. Therefore, the garage also needs connection to the power grid. Meanwhile, in the city of Fort Collins, the price of electricity is relatively cheap. For example, if you buy the electricity from the city, the price for small commercial use during summer period is $ 0.093 per kWh; the winter period price is $ 0.075 per kWh. The electricity price for mid-size and large commercial use and for Industrial use is lower than this price (City of Fort Collins, 2006). Therefore, we should consider the economic benefits of installing photovoltaic panels under such electricity pricing. Meanwhile, as mentioned above, the life cycle impacts on the environment during the production process of photovoltaic panels can be analyzed to determine whether solar panel systems have lower environmental impacts and economic cost compared to direct access to the power grid from the perspective of a life cycle assessment.

1.5 The Environmental Impacts of Solar Panel System

Although there is almost no pollution and no greenhouse gas emissions during the operation stage, the photovoltaic panels have their impacts on the environment in the production process and end-of-life process. The polysilicon production process includes industrial silicon production, polysilicon production, of polysilicon ingots production, polysilicon film production, cell production and cell module production (Sherwani & Usmani, 2010). These processes will produce different solid, liquid and gaseous forms of wastes. These byproducts include carbon oxides, nitrogen oxides, dust, mist cutting fluid, distillation residues and waste silicon (Sherwani & Usmani, 2010). If these contaminants in the production process are treated inappropriately and without controls in their recovery section, and released into the environment, they pose great pollution hazards. Therefore, from the perspective of life cycle impacts, the electricity produced by solar panels is not completely green, i.e., it is not without pollution or greenhouse gas emissions.

1.6 The Methods Used in This Thesis

This study uses a combination of life cycle assessment (LCA) and life cycle cost (LCC) to do a comprehensive evaluation of environmental and economic benefits of electricity consumption for the Lake Street Garage on the campus of Colorado State University. Through the comparison of Lake Street Garage electricity consumption using solar panels versus direct access to the grid, the study explores whether it is economically and environmentally beneficial to use solar panels to provide part of the energy for Lake Street Garage from the perspective of life cycle costs. The reason for using the two methods is because LCA can only evaluate the environmental cost and will not provide insight into economic benefits (Sherwani & Usmani, 2010). Therefore, LCC is a good supplement to solve this problem. In addition to environmental effects, initial cost of purchase and installation of solar panels and electricity costs can also be analyzed. LCC is a widely accepted tool for evaluation of economic effects of alternative systems (Lakhani, Doluweera & Bergerson, 2014). It can be used to analyze the economic costs at all stages of the product life cycle. Therefore, this study uses a combination of the LCA and LCC methods.

1.6.1 The Framework of the Methods

For the material transportation and worker commute part in this thesis, process based LCA is used. Because more than one material and device needs to be transported and the labors used in construction and maintenance phases are different, EIO-LCA, which incorporates aggregate data, cannot be used directly in the calculation of these two parts. Other phases can use EIO-LCA tools directly. The method frameworks of material transportation and worker commutes are shown in Figure 2 and Figure 3.

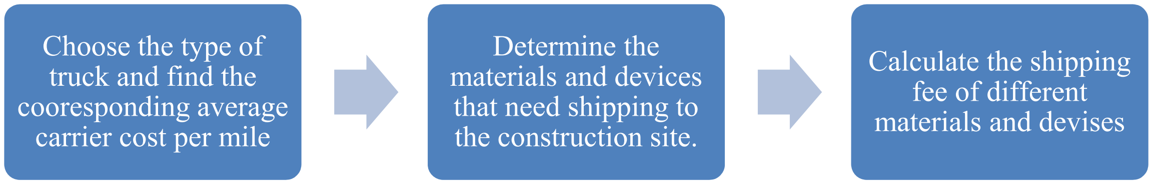

***Figure 2*. The Method Framework of Transportation**

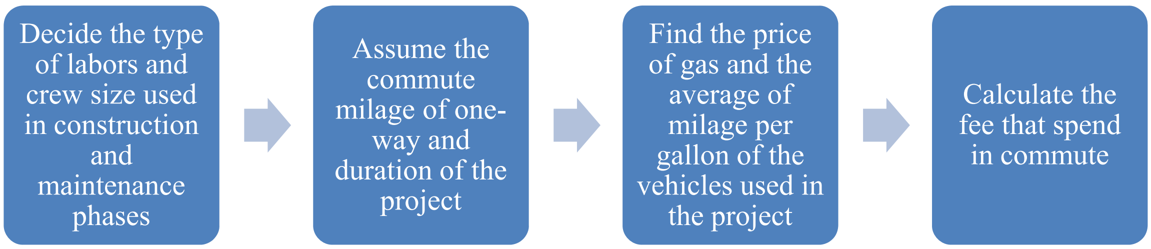

***Figure 3.* The Method Framework of Commute**

Except for these two parts, other parts of LCA are calculated by EIO-LCA online tool. EIO-LCA online tool is developed by Carnegie Mellon University. This tool contains the entire supply chain for519 commodities of the whole economy in U.S., which covers all the inputs related to the research. The method framework of EIO-LCA online tool is shown in Figure 4.

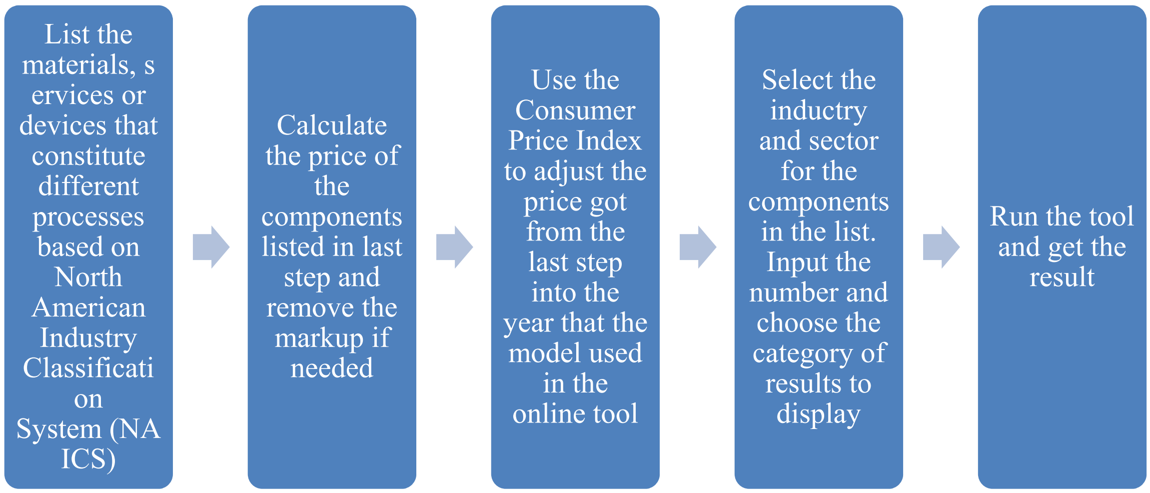

Figure 4. **The Method Framework of EIO-LCA Online Tool**

The categories of results displayed in this thesis include Greenhouse Gases and Toxic Release. The index of Greenhouse Gases contains Total Metric Tons of Carbon Dioxide Equivalent Emissions (*Total t* CO_2e), Emissions of Carbon Dioxide into the air from each sector from fossil fuel combustion sources (CO_2 *Fossil t* CO_2e), Emissions of Carbon Dioxide into the air from each sector from sources other than fossil fuel combustion (CO_2 *Process t* CO_2e), Emissions of Methane into the air from each sector (CH_4 *t* CO_2e), Emissions of Nitrous Oxide into the air from each sector (N_2O *t* CO_2e), and Emissions of all high global warming potential gases such as hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride into the air from each sector (HFC/PFCs t CO_2e). The index of Toxic Release includes toxic released to air including equipment leaks, evaporative losses from surface impoundments and spills, and releases from building ventilation systems (*Fugitive Release*), toxic released to air through confined air streams, such as stacks, vents, ducts or pipes (*Stack Release*), total toxic release to air (*Total Air*), toxic released to surface waters (*Surface Water*), toxic released to underground waters (*U'ground Water*), toxic released to land include all the chemicals (*Land*), toxic shipments offsite to other facilities for disposal, recycling, combustion for energy recovery, or treatment (*Offsite*), and toxic released to Public Owned Treatment Works (POTW metal and nonmetal). POTW is a wastewater treatment facility that is owned by a state or municipality. These definition and details can be found from Environmental Protection Agency or eiolca.net forum. It is worth noting that the unit of greenhouse gas emission is metric ton and all kinds of greenhouse gases are converted to carbon dioxide equivalent emission. The unit of toxic release is kilogram, which is the total mass of all toxic chemicals released from the projects.

In Life Cycle Cost, inflation rate and discount rate should be assumed first. Then the costs of different phases and the money earned by the electricity produced by the system are obtained. By calculating the yearly actual discounted costs and then adding them together, LCC of the system can be obtained.

1.6.2Problem Statement

Currently, there is very little research using a methodology that combines LCA and LCC to analyze the life cycle impact and the cost of PV system on public garages. As the capacity of PV systems used on public structures grows, it is important for the owner to know the cost and environmental impact data of the system. As a public parking garage, the lighting requirement is continuous. Therefore, the PV system might not be enough to support all the electricity requirement of the entire structure. The garage must be connected to the grid and use electricity from the grid as well.

Because the traditional LCC method does not quantify the environmental impacts generated during manufacturing, construction, use, maintenance, and the disposal of PV systems, the combination of LCA and LCC provides the decision maker an overall evaluation to help decide whether a public garage should install the PV system or solely use the electricity from the grid.

1.6.3Purpose of the Research

The purpose of this research is to create a framework for performing LCA and LCC for a PV system on a public garage built in Fort Collins, Colorado. The results of this study can help direct the owner to decide whether future public garages should install the PV system instead of buying all the electricity from the grid.

1.6.4Research Questions

The research questions are:

1. What are the life cycle environmental impacts of a PV system on a public garage?
2. What are the life cycle environmental impacts of a public garage connected directly to the grid?
3. What are the life cycle costs of a PV system on a public garage?
4. What are the life cycle costs of a public garage connected directly to the grid?

1.7 Limitations

One of the limitations of this study is that a single case study was performed on one PV system located in Fort Collins, Colorado. The electricity price in Fort Collins is low compared with most of other areas of the United States. Therefore, if this system is operating in a different locale and the price of the electricity is changed, the result might be different.

Another limitation is the accuracy of the data available to the creators of the eiolca.net website that was used for the analysis of environmental impacts of the entire life cycle. The eialca.net model only gives the averages and does not show differences in superior products or services.

CHAPTER TWO: LITERATURE REVIEW

2.1 The History of Life Cycle Assessment (LCA)

LCA appeared in the late 1960s to early 1970s. The first application of LCA can be traced back to 1969, which was carried out by Coca-Cola for the evaluation of the resource consumption and emissions associated with beverage containers. In this study, the Coca-Cola Company considered whether to replace disposable plastic containers with returnable glass bottles. By analyzing the complete life cycle, from raw material extraction to final waste disposal, they were able to track the whole process from cradle to grave, which provided quantitative analysis to compare the environment-friendly conditions of each of the two choices. This study is recognized as one of the first studies of LCA and laid the basis for life cycle inventory analysis (Environmental Protection Agency, 1993). They chose the plastic bottle as the result mainly because of the lower shipping cost and the ease of recycling. The plastic bottles were lighter than the glass bottles, so the plastic bottle packaging products have lower shipping cost. Moreover, at that time, plastic was easier to recycle than glass.

In the early 1970s, more companies in the United States and Europe began to conduct similar life cycle inventory analyses. For example, in 1975, the Japan Nomura Research Institute did a first packaging LCA study for Tetra Pak, which is a multinational food packaging and processing company (Imura, et al., 1997); and following that, Franklin Associates performed an LCA for soft-drink containers for Goodyear (Franklin Associates Inc., 1978). The studies of this period commonly used the energy analysis method, a quantification method of resource use and environmental release, which was then known as the Resource and Environmental Profile

Analysis, or “REPA.” Since this method was used by many researchers in those years, a standard methodology for this kind of study was developed.

During this early period of LCA, some European researchers (as represented by Ian Boustead, United Kingdom) also developed a similar method to LCA called “Eco-balance” which was based on the balance of energy vs. mass, coupled with an ecological test. This method calculated the environmental input and output of the product during its life cycle (Ian Boustead, 1992). Even today, this method is still used as a material and product environmental assessment tool.

Despite this pioneering work done in the 1970s, it was not Life Cycle Assessment in the full sense, as it was mainly based on inventory analysis. With the emergence of the global problem of solid waste during late 1970s to the mid-1980s, the REPA research method became a more utilized analysis tool. According to REPA, some consultant companies in Europe and the United States further developed this method for a range of waste management purposes. This method studied the environmental emissions and the potential impact of resource consumption in-depth. For example, the Boustead Consulting Company in the UK did inventory analysis for much of their research, and gradually formed a set of standardized methods of analysis, which laid a solid theoretical foundation for the future development of LCA.

After the late 1980’s, with the regional and global environmental problems becoming more and more serious, and enhancement of the awareness of global environmental protection and sustainable development, a growing interest developed for LCA studies. From then on, LCA gradually turned from a simple inventory analysis to more comprehensive evaluation. Meanwhile, with the increasing amount of organizations and institutions focusing on LCA studies, the methods and terminology related to LCA began to become confused with one another, which led to conflicting results in the evaluation of the same products by different people. Therefore, it was urgent to develop a unified specification.

In 1989, the Dutch National Living, Planning and the Environment Ministry first proposed the development of a product-oriented environmental policy instead of the traditional terminal environmental control policy. This product-oriented environmental policy focuses on the production period from consumption of raw materials to the final waste disposal of the finished product, i.e., it considers all aspects of the product life cycle. This study also proposed to describe the environmental impact from the entire product life cycle and also illuminated the need for the LCA "basic methods" as well as data standardization. A unified regulation was finally determined in 1993 at the Portugal Sesimbra Seminar, and the final name was officially designated as the Life Cycle Assessment (LCA) (SETAC, 1993).

The Society of Environmental Toxicology and Chemistry (SETAC) became the international leader of the field of LCA when they hosted the International LCA Seminar in 1990 for the first time, and at this meeting, put forward the concept and officially recognized specifications of LCA. In the years since, SETAC has continued to host seminars in which the theory and methods of LCA have evolved, and promotion and sharing of extensive LCA research has been conducted (SETAC, 1993).

Even today, LCA methodology is still being researched and developed. SETAC and the International Organization for Standardization (ISO) are actively promoting the international standards for the LCA methodology. ISO has made LCA one of the most important steps of the ISO14000 environmental management system. In June 1993, ISO formally founded the

Environmental Management Standards Technical Committee (TC-207), which was responsible for the standardization of the environmental management system. The TC-207 Technical Committee reserved 10 standards numbers (ISO14040-ISO14049) for LCA in the ISO14000 series of environmental management standards (Saunders, 1996).

2.2 What is Life Cycle Assessment?

Originally, LCA was the abbreviation of Life Cycle Analysis. However, SETAC, the U.S. Environmental Protection Agency (EPA), and ISO now use LCA to represent "Life Cycle Assessment" because the word Assessment has more quantitative meaning. In Europe and Japan, researchers often use "Eco-balance" instead of LCA, but it has substantially the same meaning as LCA. Due to the complexity of the LCA method and the different purposes for LCA implementations, the concepts and methods for LCA have often had slightly different understandings: In SETAC and ISO files, the definition of LCA is constantly modified, but with further research and development, especially the standardization work on LCA by ISO, the LCA methodology has been gradually clarified.

In 1990, SETAC defined LCA as: "Life-Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, to assess the impacts of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity, encompassing extraction and processing of raw materials, manufacturing and distribution, use/reuse/maintenance, recycling, and final disposal" (Fava, Dennison, Jones, Curran, Vigon, Selke, &Barnum, 1991, Executive Summary).

In addition, in 1993 they specified the methodological framework of LCA, which includes Goal and Scope Definition, Life-Cycle Inventory, Life-Cycle Impact Analysis, and Life-Cycle Improvement Analysis. This framework is the core method of LCA, and it is still used in the process based LCA method.

In 1996, ISO developed LCA standards for ISO14040. This standard also gives the definition of LCA: “LCA is the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” (Guinee, 2002). The word “product system” here refers to an operational process of unit collections related to materials and energy and with specific function. In the LCA standard, “product” can mean both the general manufacturing production system and, for service industries, service systems. “Life cycle” refers to the continuous and interconnected stage of the production system, from the first stage of raw materials, to the final abandonment of the product.

Some other agencies also have their own descriptions for LCA, such as the definition by the U.S. EPA, which is: “LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to help you make a more informed decision” (National Risk Management Laboratory, 2006, p2). The 3M Corporation also uses the LCA concept in their management, defined as: “LCM is a process for identifying and managing the environmental, health, safety, and regulatory impacts and efficient use of resources in 3M products throughout their life cycle to guide responsible design, development, manufacturing, use, and disposal.” (3M, 2012, p56). Procter & Gamble is also a pioneer of the development of LCA and has been using LCA to direct their decision making since the late 1980s. P&G considers LCA as a responsible approach to the environmental impact of their products from design, to production, consumption and use to final deposition. (G. Rebitzer et al, 2004).

Among these definitions, the definition of ISO and EPA point out that LCA needs the inputs and outputs of the process. After the identification of these elements, quantification of the emissions, which is pointed out by SETAC, should be done to guarantee the calculation of LCA is as objective as possible.

2.3 The limitations of Life Cycle Assessment

As an environmental management tool, LCA is not always appropriate for all situations, and in each decision-making process we cannot rely on LCA methodology to solve all problems. LCA only considers the ecological environment, human health, resource consumption and other aspects of environmental problems, and does not involve technology, economic or social effects such as quality, performance, costs, profit, public image, and other factors. Therefore, each decision-making process must be combined with other types of analysis and information.

The scope of LCA also does not include all environment-related issues. For example, LCA only considers the environmental impact that has already happened or will happen with certainty, but does not regard all possible environmental risks and necessary preventive and emergency measures. LCA methodology also does not require considering the restrictions of the environmental laws and regulations, but these aspects are very important when a corporation must deal with environmental policy and decision-making processes (Remmen, 2007).

The LCA assessment method includes both objective and subjective components, and so is not exactly a scientific methodology. In LCA, subjectivity, choice, assumptions, and value judgments are involved in many aspects, such as the determination of system boundaries, the selection of data sources, the choosing of environmental damage types, the selection of calculation methods, evaluation process in the environmental impact assessment, etc. The common problem in the boundary definition is the circularity effects. It means that before one can complete a life cycle assessment of any material or process, one must have completed a life cycle assessment of all related materials and processes, which is almost impossible. So the researchers have to make an assumption to set the boundary to a limited spectrum, which can cause truncation error. Regardless of the assessment scope or the level of detail, all LCA contains subjective factors such as hypothesis, value judgments and trade-offs, and thus the conclusions of LCA require a full explanation to distinguish the information obtained by assumptions and subjective judgments from the knowledge by measurement using the scientific method.

Time and geographical constraints also exist in the original data and/or assessment results of LCA. Within the different times and geographic scope, the environmental data might be changed, so the corresponding evaluation results are only applicable for a certain time period and region, which is determined by the time period and geographic characteristic of the production system.

2.4 Economic Input/Output Life-Cycle Assessment

Economic Input-Output Analysis is proposed by economist Leontief in 1970. It mainly applies equilibrium theory to show the interdependence between production departments within a closed economic system, and then places a theoretical performance into the input-output relationship table of the U.S. economy. The purpose of an input-output analysis is to find the dependencies of the yield by using the linear equation which shows the distribution of the industrial production in the whole economic system (Lave et al., 1995).

EIO-LCA is an input-output assessment tool of LCA and is based on the economic value of 519 different commodities from the U.S. Department of Commerce. This method aims to gain the information about the various economic transactions, resource requirements, and the environmental impacts of a particular product or service (Lave, 1995). EIO-LCA can help ascertain relevant output of a product or service, such as the mineral extraction, manufacturing, transportation and other requirements (Lave et al., 1998). The reason to combine EIO with LCA is because although they may be similar in formulation style and calculation methods, there are also essential differences between these two methods: The EIO approach focuses on the energy metabolism from the socio-economic activities related to input-output, which can describe the direct and indirect carbon-based energy metabolism of the production, consumption and trade activities in detail; whereas the LCA approach focuses on the energy metabolism, toxicity, human health and other aspects of the whole life cycle, including production, consumption and recycling. Together, one can deeply analyze the energy and metabolic structure of the same type of products as well as the different types of products; however the accuracy of the input and output data determines the accuracy of both methods. EIO-LCA combines the advantages of both methods in an attempt to analyze energy metabolism of each aspect in the production chain. In addition, the online EIO-LCA software development greatly promotes the application of this method (Hendrickson et al., 1998).

2.5 LCA Studies of Photovoltaic Panel

Academia began researching photovoltaic panel life cycles, energy consumption and environmental impacts in the mid-1970s (e.g. Hunt, 1976). This research was primarily for the energy payback time estimation of monocrystalline PV systems. The results showed that the energy payback period of the ground silicon cells system is about 11.6 years (Hunt, 1976). Since then, assessment of the energy consumption and environmental effects of PV systems has gradually increased, and formed a number of important research results, including:

* Huber W. (1995) completed the entire life cycle assessment of the silicon photovoltaic process for the first time. He found that only high-efficiency PV makes sense for applications relevant to the energy economy and to make the solar supply shares to be as high as possible people should minimize electricity demand.

* Komiyama H. (1996) used Life-Cycle Assessment to analyze and compare the carbon dioxide emissions from the construction of two solar cell system power plants. The PV panels of these two power plants were made in Japan, but only one battery component was installed in Japan, while the other was installed in Indonesia. The results showed that the carbon dioxide emissions of the electric power made in Indonesia was less than that in Japan. That was mainly due to the abundant solar energy resources in Indonesia.

* Kazuhiko Kato (1997) used the ideas of Life Cycle Assessment to analyze the silicon photovoltaic systems made by abandoned materials from the semiconductor industry. As an example, he made a 3kW residential PV system and the results showed that the energy recovery period of the photovoltaic system made by the recycled silicon was about 15.5 years, and the carbon dioxide emission per unit of electricity was 91 g-C/kWh.

* Masakazu Ito (2003) completed research on the potential of large-scale photovoltaic systems from an economic and environmental perspective. Using the LCA method, the researcher estimated the energy recovery cycle, life cycle carbon dioxide emission rate and the system production costs. The researcher used a hypothetical 100MW large-scale photovoltaic power plant as an example, and found the energy payback period of the power plant is 1.7 years, the carbon dioxide emission rate is 12g-C/kWh, and the cost of the electricity the plant generated is 8.6cent/kWh if the system life is 30 years. The result of payback period in this research is reasonable, but the carbon dioxide emission rate is lower than the average.

Because of the different scale and model of the photovoltaic power plants considered in these studies Japanese researchers have representatively distinct results. In addition, these three researchers mainly calculated the carbon dioxide emissions of the projects during the whole life cycle, which cannot cover most of the potential environmental impacts beyond carbon dioxide.

* Krauter S. (2004) considered the locations and the production, transportation, installation, operation and recyclability of each component of a PV system. At the same time, the researcher took into account the reuse of raw materials, and therefore was able to calculate the capability of reducing greenhouse gas emissions from a full life-cycle perspective.

* Kannan R. (2006) did a case study on a 2.7kWh solar photovoltaic system in Singapore. In this case study, the researcher studied the energy recovery cycle, the greenhouse gas emission reduction potential, and the cost of the system. After considering the construction phase, operation phase, and waste phase, the researcher found that the solar photovoltaic system only generated a quarter of the greenhouse gas as compared with only one half of a gas turbine generator system. However the cost of the electricity was five to seven times more than oil or gas

fired power plants. The cost of the electricity from the photovoltaic system currently is lower than that because of the improvements of the technology.

* In the research of Sergio Pacca (2007), the effects of the energy recovery cycle, carbon dioxide emissions and energy production rate parameters of the whole life cycle of PV systems was observed. Research also showed that the solar-radiation intensity, the location of components, and the conversion efficiency of solar-radiation can influence the final result.

* Masakazu Ito (2009) did LCA for six different large-scale PV systems. The researcher considered the mining phase, production phase, transport phase, power plant construction, and operation phase. The research also calculated the energy recovery cycle of the system and the carbon dioxide emission rate. The results showed that the energy payback period of large-scale photovoltaic thin film battery system is only 1.8 years, and its carbon dioxide emission rate is 43-54g C02/kWh.

Most of the researchers used traditional LCA methodology to assess the environmental effects of the photovoltaic industry. However, there are also some researchers who have used hybrids of LCA. For example, Zhai (2010) combined traditional LCA and EIO-LCA as a hybrid LCA, and used this method to analyze energy consumption; he found that the result from his hybrid LCA was 60% higher than the traditional LCA result. This meant that the energy consumption of processes other than the production process, such as transportation and logistics, was significant. The other reason for higher impacts is that EIO-LCA reduces the truncation error. The truncation error is explained in chapter three. In addition, transparency in reporting assumptions and defining the basis of analysis is critical in the publication of LCA results. At first glance, the results of different researchers can appear contradictory. However it is possible to understand the reason why results might not the same if the assumptions underlying the analysis are clearly articulated. Therefore, the clarity of the assumptions in this thesis are critical to understanding the results.

2.6 Life Cycle Assessment and Life Cycle Cost Integrated Methodology

LCA and LCC Integrated Methodology incorporate the economic evaluation tool, LCC, with the LCA evaluation system, and then establish the relationship between environmental impact and economic costs of the product throughout the life cycle. This combined method builds a comprehensive evaluation system of both the estimated environmental impacts and estimated economic costs.

Norris (2001) analyzed LCA and LCC and documented the obvious differences between the two methods. Moreover, he also pointed out that as an environmental evaluation tool, LCA has its own limitations when it is used as a product environmental and economic integrated assessment tool. However, the integration of LCA and LCC can simultaneously evaluate the estimated environmental impacts and estimated economic attributes and can also provide the trade-off relationships between the two methods. Therefore, this combination can affirm that the integration of LCA and LCC method is a good choice for estimating the environmental and economic impacts of a product or system.

Bengt Steen (2005) used the integration method in the analysis of the environmental cost of the life cycle of various products. This study mainly tried to import the LCA methods into LCC. In the study, the researcher found that LCA is a good supplement in the risk analysis for LCC. Kumaran Senthil (2003) imported various functions of LCC into the LCA system and proposed a new model that he called Life Cycle Environmental Cost Analysis (LCECA), which has both environmental assessment and environmental cost analysis functions. Bovea (2004) used LCA and LCC method in the product design period and found that the integration method can improve the comprehensive analysis of environmental impact and economic value.

Kannan (2007) divided the life cycle of the product into three phases when using LCA and LCC. These three phases include energy consumption, environmental emissions and economic costs. This method has been successfully applied to a case study of a power plant in Singapore. This study reveals that GHG emission of the solar PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant. However, the cost of electricity is about five to seven times higher than that from the oil or gas fired power plant. Tapia, Siebel, Baars & Gijzen (2008) also applied LCA and LCC together to assess six water treatment processes in Amsterdam, Netherlands, and were able to select a water treatment method that has a good financial condition and creates the least financial risk and environmental impacts.

Today, the integration method of LCA and LCC has already become a part of evaluation and project management software, some of which have even become commercial products, such as PTLaser and TcAce, which are developed respectively by Svlvatica (2000) and The American Association of Chemical Engineering (Reich, 2005). PTLaster primarily helps companies analyze and determine the solution that has the least environmental load and the most economic benefit. In this process, the software not only has all the attributes of LCA, but also a number of LCC features. For example, the software defines non-linear relationships, includes unintended factors, introduces multi-group schemes for multivariate sensitivity analysis, and defines uncertain system parameters to do Monte Carlo uncertainty analysis. The TcAce software utilizes a method called Total Cost Assessment, which imports the evaluation method of LCA into a complete LCC system and can also help to choose which part of the LCA evaluation result to use, according to the actual situation of subjects. Both the PTLaser and TcAce software systems integrate LCA and LCC, but use different integration forms: PTLaser puts various functions of LCC into the LCA system, whereas TcAce uses parts of the evaluation data from LCA as a supplement to LCC in order to calculate the environmental costs.

2.7 Importance of LCA Study

Although PV (Photovoltaic) systems are viewed as being clean during their operation, the energy consumption and pollutant emissions cannot be ignored when we consider the entire life cycle of PV panels, from the extraction of silicon, system installation, to recycling of the systems. Therefore, only the quantitative assessment of life cycle energy consumption and the estimated environmental effects can accurately determine whether solar panels are suitable for roof-top application. So this study focuses on the PV system on the Lake Street Garage, Fort Collins, Colorado, and analyzes the respective estimated life cycle environmental impacts and the estimated life cycle cost of the garage gaining electricity from the PV system and the public grid.

This study will provide information about photovoltaic panels on the top of a garage structure using both LCA and LCC methodologies. A key difference between this study and existing studies is that this will be one of the few that combines LCA and LCC studies of PV panels for a garage. Although the LCA data and information of this study will focus on a specific project, the methodology and the objectives of the study can provide other researchers thoughts and insights for further research on this topic.

CHAPTER THREE: METHODOLOGY

This study focuses on the costs throughout the life cycle of the rooftop photovoltaic panels of the Lake Street parking garage on the campus of Colorado State University. The methodology used in this study could be adopted by businesses and households to calculate the estimated costs and benefits of solar panels from purchase and use, to removal and recycle/disposal. The method used in this study provides one source of information needed to support a final decision on whether or not to install solar panels and determining how long it takes to recover the cost of the initial investment. People have gradually become aware that the energy from solar panels is not entirely green. The estimated environmental damage imposed during the production and recycling processes of photovoltaic panels cannot be overlooked. Therefore, when using lifecycle cost analysis (LCC) to analyze the estimated economic costs, one should also perform a life cycle analysis (LCA) on the estimated environmental impacts of solar panels. A complete assessment should include the costs in mining of raw materials, manufacturing, installation, and disposal/recycling.

In LCA, the social cost is primarily imposed by the estimated environmental emissions (Camagni, Gibelli & Rigamonti, 2002). The estimated environmental emissions include direct emissions and indirect emissions. Direct emissions directly relate to the product or device during its life cycle. Indirect emissions are the emissions from the life cycle of inputs (raw materials and energy); during the production and disposal process (Schulz, 2010). For example, the estimated emissions resulting from mining silicon, zinc, copper and other raw materials used in the production of solar panels, and the estimated emissions resulting from mining processes constitute indirect emissions. In LCA, the method usually sums these two emissions to obtain the full estimated emissions.

3.1 Economic cost

For the calculation of the estimated economic cost, LCC is the most common and most sophisticated method. As a cost-oriented approach, LCC focuses on all resources consumed by the project during its lifetime. Through LCC, these resources are quantified as costs and are accumulated to find the total cost of the device over its economic life (Bagg, 2013). Different from the cost of a project, which only calculates the cost of construction and installation, LCC includes the initial investment, operating and maintenance costs, replacement costs and disposal costs (Hin & Zmeureanu, 2014).Therefore, the calculation of LCC includes both current costs and the predicted/anticipated future costs. When calculating future costs, the net present value and internal rate of return are very important parameters. Meanwhile, these two parameters are also important parameters for comparison of various alternative investments (Spertino, Leo & Cocina, 2013).

3.1.1 The composition of economic cost

For the Lake Street garage rooftop solar panels, the LCC includes initial cost, operating cost and equipment recycling cost.

The initial cost of solar panels mainly includes the costs of acquisition of solar panel equipment, construction, installation and maintenance/transport of solar panel equipment that occurred before the solar panels were placed into operation. This data was collected or calculated from the Colorado State University Department of Facilities Management and the project breakdown from Bella Energy, the general contractor of the project.

The operation costs of solar panels are incurred mainly from the maintenance of the solar panels and the replacement of batteries. Batteries are an option for some, but not all, PV systems depending on whether the system is interconnected to the grid or if it is stand-alone. Due to the exposure to the outdoor environment, the array of solar panels may accumulate dust or dirt. In addition there are many other materials that can reduce their efficiency. Some birds may also make their nest in the structure of the solar panels, and sometimes it will affect the normal operation of solar panels. In addition, some switches within the solar panels need regular maintenance to ensure they are working properly (Liu, O'Rear, Tyner & Pekny, 2014). Therefore, the solar panels need regular maintenance, which contributes to the operation cost. This part of the cost can be obtained from historical data and maintenance records, and certain maintenance requirements requested by the equipment manufacturers.

The life of the solar panel system is about 20 to 25 years, but the life of the typical battery in the system is approximately seven years (Sherwani & Usmani, 2010). Thus, during the estimated operational life of the solar panel, the batteries will need to be replaced at least twice. This is another part of the operating costs. All the operating cost data were obtained from Colorado State University Department of Facilities Management, and the price of the battery can be estimated from the price of the same type of batteries on the open market.

The removal process of the solar panel includes the equipment for crushing, sorting and recycling of solar crystals, glasses, and metals. The cost of these processes can be offset by the source of scrap cost. The scrap cost data can be obtained from similar items from the market. Moreover, it is also possible to sell the old solar panels to third world countries that do not need the full output of the panels. The output of solar panels typically degrades at about 0.5 percent per year (Jordan & Kurtz, 2012). So after 10 years, the estimated output of the panels is still 60% of its original output. In this way, the end-of-life cost might lower. However, this thesis will not consider a resale option.

3.1.2 The adjustment of LCC

The adjustment of LCC includes the adjustment based on the discount rate and the life span of operation. When two projects are compared, the discount rate and the life span should be the same. If the life spans of two projects are not the same, the operation times of different projects should be changed into the least common multiple of the different life span (Hin & Zmeureanu, 2014). The analysis involves the comparison of the differences of the estimated environmental and estimated economic costs between the use of solar panels and purchasing electricity from the grid. Therefore, there is no need to have an adjustment based on the number of operation years, because there is only one project. Based on this assumption only the correction based on the discount rate is shown.

The analysis should also consider the potential for increases in electrical costs. For example, the average unit cost of the electricity used by the CSU garage, which can be found in the EnergyCAP system from the Colorado State University website, increased from 0.052$/kWh to 0.061$/kWh in the last three years. This increase of the annual energy costs typically shortens the payback time. Because the historical data shows that the unit cost of electricity increased 0.002$/kWh over the past three years, the trend of the increase was assumed as a linear trend for this study.

Money has different values over times. This is the time value of money (Spertino, Leo & Cocina, 2013).So compared with the simple payback calculation, the LCC calculation should also be adjusted based on a discount rate, and the cash flows of the process/system should be calculated as a present value. The net present value, which is the difference of present value of inflows and present value of outflows, is exactly based on this adjustment method. Therefore, in the LCC calculation process of this thesis, the net present value is used. The core assumption of the net present value calculation is to decide the appropriate discount rate to use. Once the discount rate is determined, the life of the Photovoltaic system should be determined. The model of the solar panels used is Sharp ND-235QCJ 235-watt solar panel, which has a 25-year limited power warranty. So the economic life of the system used in this study is 25 years. The US Department of the Treasury shows that the average Treasury Yield Curve Rates for 20 years at the time of this study is 3.30%, and the 10-year rate is 2.7%. As a state (e.g. non-profit) university, the discount rate of this solar panel project should be lower than a similar project in the private sector, because of the lower risks and elimination of profit. In addition, because CSU is a tax-exempt institution, there is no marginal federal or state income tax for this project. Therefore, the discount rate adopted in this thesis was assumed to be the average of the two previously mentioned rates; 3% [(3.30%+2.70%)/2].The annual inflation rate used in this thesis is 1.5%, which can be found from the Consumer Price Index (CPI) Inflation Calculator on the website of Bureau of Labor Statistics This calculator uses the average CPI as the database (CPI News Releases, 2014). The inflation rate used for this study is the average of yearly data of inflation rate from 2009 to 2014.

3.2 Environmental Cost

The economic first cost of a project is sufficient for the owners or users of a project to use when comparing and evaluating the investment options. However, almost all projects have non-economic or “social” costs. Therefore, in order to capture the broader costs of a project, the use of the economic cost as the sole criterion for project investment is not enough. When analyzing the estimated economic costs of a project, the estimated social costs should be analyzed at the same time. One of the most important aspects of social costs is the estimated environmental cost, which can have huge and long lasting impacts (Camagni, Gibelli & Rigamonti, 2002). For example, when evaluating solar panels, people used to consider that the electricity it produced is purely green. However, society has slowly shifted the focus on the environmental pollution and waste generated during the production and disposal stages of solar panels' overall life cycle. This shows a need to focus on a larger scale when analyzing the cost of photovoltaic panels, that is, from raw material extraction, production, operation, to recycling and disposal. This is the whole life cycle of the solar panels, which is not limited to direct economic costs.

As a commonly used tool for the analysis of the estimated environmental costs, LCA is a systematic and holistic approach. According to ISO14040 and ISO14044 standards, LCA consists of four main steps: goal and scope definition, inventory analysis, life cycle impact assessment, and life cycle result interpretation (ISO, 2006). These four steps also provide the methodological framework for the LCA process. This conventional method can be very comprehensive, but it is difficult to accurately collect all the data. There are some improved LCA methods, such as economic input and output LCA (EIO-LCA) and hybrid LCA method (Hendrickson et al., 1998). The following is a detailed description of these three types of LCA.

3.2.1 Process Based LCA

The four steps in process based LCA are explained as follows.

The goal and scope definition is the first step, and also the most important step of LCA. In this process, the boundaries of the LCA system and the functional units of LCA are defined. The main purpose of the functional unit is to provide a normalized reference for the input and output data in the calculation (ISO, 2006). This allows researchers to compare two or more products or equipment systems using a consistent measurement method. So the functional units should be clearly defined and easily measured. System boundaries decide which process directly or indirectly related to the product or device will be included in the LCA (ISO, 2006). But there will be some problems because of the system boundary definition. For example, when analyzing the environmental pollution of solar panels, it will certainly have to consider the needs of the production process of silicon ore mining. However, the pollution of ore mining is not limited to its extraction. In the mining process, equipment will use a certain amount of energy to operate machinery and the electricity generated by the power plant will cause environmental pollution. At the same time, it is also possible that it will consume electricity when getting the raw materials and generating this electricity. Hence, it is difficult to define system boundaries to cover all the processes. This means that the limited boundary of a typical process based LCA cannot easily calculate all the estimated environmental costs. This is one of the biggest drawbacks of the process based LCA. This method will produce truncation error (Crawford, 2008).Thus the estimated environmental cost of some degree of evaluation results will be underestimated.

Next the LCA life cycle inventory analysis is used to collect data for the materials and energy used in the entire project according to the boundaries set in the previous step. Inventory analysis is used in all of the LCA approaches because this step quantifies the estimated environmental costs for the calculation of the next several steps. In the course of process based LCA, these data are listed individually for each item. In EIO-LCA, the inventory list is in the form of a matrix structure. The specific structure of the matrix will be introduced in section 3.2.2.

According to the estimated environmental impact factors, LCA impact assessment classifies the data collected in the last step into one or more kinds of estimated environmental impacts. For example, nitrous oxide should be imputed as greenhouse gas, and nitrogen dioxide should be counted as an air pollutant. Then the classified pollutant should be harmonized and standardized within the estimated environmental impact factor. For example the estimated impact of several greenhouse gasses that contribute to the greenhouse effect can be translated into the effect caused by certain amount of carbon dioxide. The standard unit of measurement is metric tons of carbon dioxide equivalent ($MTCO_2e$) (IPCC, 2007).

The final step is to explain the results of the estimated impact assessment. If there is only one single program in the assessment process, this step should interpret the meaning of the results obtained from the impact assessment. If there is more than one program to be compared, the comparison of different programs should be added into the explanation.

3.2.2 EIO-LCA

As mentioned earlier, process based LCA has truncation error when it is used to define the system boundaries. To partially solve this problem, we introduce the economic input-output method into LCA, which is called EIO-LCA. So the study boundary of EIO-LCA is broader than the process based LCA. However, the main distinction between EIO-LCA and process-based LCA is the life cycle inventory analysis. EIO-LCA is mainly based on input-output tables. This table is mainly used to measure the estimated impact and the dependence of the various industries in the economic system at the national level in the US. This relationship shows the sources of inputs and outputs in each sector of the national economy, as well as the intricate technical economic relationship between industries (Chang, Ries & Wang, 2011).Since the entire input-output table is a matrix, which shows the monetary value of inputs to each sector by its columns and the value of each sector's outputs by its rows, linear algebra based methods can be used. Through this, the material and energy consumption of the upstream processes can be included. Thus, EIO-LCA can avoid at least some of the truncation error. The result of EIO-LCA is an f-times-n matrix, where f is the number of units of the environmental impacts of output factors produced by the consumption of products and services, and n is the number of industry sectors. The attempt of EIO-LCA modeling is to expand the boundaries of the LCA to the entire US economy. Inputs and outputs from outside the national boundary (e.g. imported raw material) are still difficult to accurately measure, so some error remains (Hendrickson, 2006).Table 1 shows an example structure of an Economic Input-output table.

***Table 1*.The Example Structure of an Economic Input-Output Table**. Source: Hendrickson, 2006

	Input to sectors (j)				Intermediate output O	Final demand Y	Total output X
Output from sectors (i)	1	2	3	n			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	Y_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	Y_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	Y_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	Y_n	X_n
Intermediate input ***I***	I_1	I_2	I_3	I_n	GDP		
Value added ***V***	V_1	V_2	V_3	V_n			
Total input ***X***	X_1	X_2	X_3	X_n			

EIO-LCA model has its own limitations. Because EIO-LCA is based on input-output tables, it can only analyze the material and energy production process. Meanwhile, all the products are described by limited amounts of industrial composition in the input-output tables. So the data is sometimes too aggregated, and is not as detailed as process based LCA (Hendrickson, 2006). Thus for some special products, using the data of the input-output table which represents the average product will produce large errors. This potential error is somewhat addressed by using a hybrid approach to LCA.

3.2.3 Hybrid LCA

As mentioned above, the existence of truncation errors in process based LCA makes it difficult to calculate indirect emissions. Although truncation error is reduced in EIO-LCA, it cannot be used in the operation period. In addition, the data in EIO-LCA is not detailed enough for some products, and may produce relatively big errors (Hendrickson, 2006).So this LCA is not a complete assessment and also not an accurate one for some applications. Therefore, hybrid LCA, which is the blending of process based LCA and EIO-LCA, can solve many of the problems to a certain extent. This thesis respectively uses both EIO-LCA and traditional process based LCA as a hybrid LCA method in the different life periods of solar panel. The materials extraction and manufacturing, operation and maintenance periods will be analyzed by EIO-LCA. The construction and end of life of the system will be analyzed using a hybrid method.

3.3 Data Collection

This thesis analyzes the estimated economic cost and estimated environmental impacts of the rooftop photovoltaic panels on the Lake Street garage. The estimated impacts are assessed by LCC, EIO-LCA and hybrid LCA approaches. Since the EIO-LCA only covers estimated impacts associated with the production process of the equipment, it can only be used in the environmental impact assessment of the production process and some estimated environmental impacts of the resources directly used in the operation and maintenance process. This is because the estimated environmental impacts of these resources can also be represented by the estimated environmental impacts of their production process. The construction, installation and recycling processes cannot be analyzed by EIO-LCA. Therefore, in these two phases, the hybrid LCA method is employed, which uses process based LCA for the data collection and uses EIO-LCA method to calculate the data in order to limit truncation errors. Following is the description of the data sources of these three methods.

3.3.1 The Data Collection of LCC

The composition of the LCC and the methods of data collection are explained in section 3.1.1. It should be noted that the electricity generated by the solar panels on the Lake Street Garage cannot meet all the electricity needs of the building. Therefore during operation, the building still needs to buy electricity from the grid. So the cost of electricity that the building purchases should also be added into the economic cost analysis on the basis of 3.1.1.

3.3.2 The Data Collection of EIO-LCA

In this study, EIO-LCA calculation is done via a web-based online tool developed by Carnegie Mellon University. Eiolca.net, the website, provides an introduction of EIO-LCA theory, principles, online tools and tutorials throughout the online tools. This study uses the latest data provided by the website namely the US 2002 Benchmark data set. The details of the database can be found under the models section from the left side of eiolca.net. However, the economic cost data of the equipment and materials used in the Lake Street garage are from 2010 and need to be adjusted to the 2002 benchmark data used in the model. This was done by using the consumer price index (CPI) date from the project construction and the benchmark year.

3.3.3 The Data Collection of Hybrid LCA

The data collection of hybrid LCA analysis utilizes the process based LCA method and the calculation process is the EIO-LCA method. Hence, when using process based LCA to collect data, the producers' price rather than the consumers' purchasing price must be used (Mattila, Pakarinen & Sokka, 2010), because the consumers' price contains the middlemen profits and other fares. Meanwhile, before importing the data in the EIO-LCA tool, the data also needs to be converted using the CPI data using the same adjustment process as previously mentioned.

CHAPTER FOUR: DATA ANALYSIS

4.1 Components of the Analysis

4.1.1 Functional Unit of Comparison and Performance Characteristics

The functional unit of this study is the electric power supply for the Lake Street Parking Garage of Colorado State University, as captured in kWh of electric power demand. The analysis compares two electric supply systems of the parking garage. One is a 9000 square foot solar panel array located on the top floor, and the other one is the power grid of the City of Fort Collins.

Following are the assumptions of the characteristics of the functional unit:

- This project is a commercial project.
- All the materials required by the project come from North America.
- All materials are transported by diesel trucks.
- All construction machinery is driven by diesel.
- The markup on ex-factory gate price is 5 %(Goodrich, James & Woodhouse, 2012).
- The markup on retail price is 20 %(Goodrich, James & Woodhouse, 2012).

4.1.2 Boundary

This paper studies two power supply systems, so, accordingly, the boundaries of these two systems should be considered separately. The boundary of a solar panel power supply system includes material mining, solar panel components manufacturing, system running and disposal. The boundary of a coal-fired power supply system includes the construction of the power plant, as well as the process of coal mining, transportation, electricity production and transmission over the life of the plant; the city of Fort Collins power comes from a coal fired power plant.

Assumptions about the two systems are shown in Tables 2 and 3.

***Table 2*. Solar panel power supply system assumptions.**

Assumption	Data Source
The average commute distance by privately owned vehicles is 12.6 miles one-way	Federal Highway Administration ("2010 status of," 2010)
About 19.64 pounds of carbon dioxide (CO_2) are produced from burning a gallon of gasoline that does not contain ethanol	U.S. Energy Information Administration("Documentation for emissions," 2007)
About 22.38 pounds of CO_2 are produced by burning a gallon of diesel fuel	U.S. Energy Information Administration("Documentation for emissions," 2007)
The Photovoltaic components are produced in California	
The time for construction is 15 days	
The crew size of construction is two	

***Table 3*. Power plant power supply system assumptions**

Assumption	Data Source
Boundary of the power supply by grid does not contain the construction of the power plant	
Electric power is generated by coal-fired power plant	
0.00054 short tons or 1.09 pounds can generate one kilowatt-hour electricity	U.S. Energy Information Administration Frequently Asked Questions
The price of coal in Colorado in 2012 is $37.54 dollars per short ton ($31.28 dollars per short ton after removing markup).	U.S. Energy Information Administration Form EIA-7A, 'Coal Production and Preparation Report.'
The average price of electricity is $ 0.0585	
The power plant operates 8000 hours a year	Ruether, Ramezan & Balash, 2004

4.2 Life Cycle Assessment

4.2.1 Manufacturing Phase

4.2.1.1 Photovoltaic System

The equipment of the photovoltaic project contains photovoltaic modules, inverters, data communication equipment and racks. As stated in 4.1.1, the price used in the project breakdown should remove the markup, and then adjust the 2010 cost data to 2002 in accordance with the CPI before input into EIO-LCA tools. CPI data is obtained from the US Bureau of Labor Statistics Consumer Price Index Detailed Report (CPI News Releases, 2014). The Lake Street garage project was completed in January 2011. Therefore, the CPI data used in this article is 179.9 for 2010 CPI and 218.056 for 2002 CPI. Table 8 shows the calculation for each part of the project.

As shown in Appendix B, the components of photovoltaic system include solar cells, aluminum alloy racking, inverters and other electrical equipment, such as batteries and wires. The transportation fee of the raw materials destined for freight is described in the Transportation Supporting Documentation section. According to the assumptions of the markup and adjusted for CPI in 4.1.1, the relationship between column 2002 Base Year and column Retail Price 2010 is as follows:

Base Year 2002 $=Retail Price 2010 $/ (1+20%)/(1+5%)/218.056*179.9。

It is worth emphasizing that the cost used for transportation has already removed the markup, so that its value can be directly adjusted based on the CPI.

The first step in EIO-LCA calculations for solar panel systems is to find the most appropriate North American Industry Classification Sector (NAICS) Sector. In US Census Bureau 2002 NAICS Definition, Sector334413 Semiconductor and Related Device Manufacturing is described as: This US industry comprises establishments primarily engaged in manufacturing semiconductors and related solid state devices. Examples of products made by these establishments are integrated circuits, memory chips, microprocessors, diodes, transistors, solar cells and other optoelectronic devices. Accordingly sector 334413 is the most appropriate because solar cell manufacturing is included in this sector. The next step is calculation. From the project breakdown, price of solar cell can be found and the data can be filled in Table 8 Retail Price 2010 column. Then the Base Year 2002 price can be calculated. The computation of all other components used the same method. Except for transportation, all other data of Retail Price 2010are obtained from the project breakdown. Because the structure of NAICS is highly aggregated, the calculation uses Sector 335999 to represent inverter, battery and energy wire and cable. This sector is also a good description of these devices. The description of Sector 335999 in NAICS Definition is: This U.S. industry comprises establishments primarily engaged in manufacturing industrial and commercial electric apparatus and other equipment (except lighting equipment, household appliances, transformers, motors, generators, switchgear, relays, industrial controls, batteries, communication and energy wire and cable, wiring devices, and carbon and graphite products). This industry includes power converters (i.e., AC to DC and DC to AC), power supplies, surge suppressors, and similar equipment for industrial-type and consumer-type equipment. The forms and results from the manufacturing phase are taken from the eiolca.net online tool, which can be found in Appendix B.

Figures 5and Figure 6display the greenhouse gas emissions and toxic releases in the manufacturing phase of the solar panel power supply system.

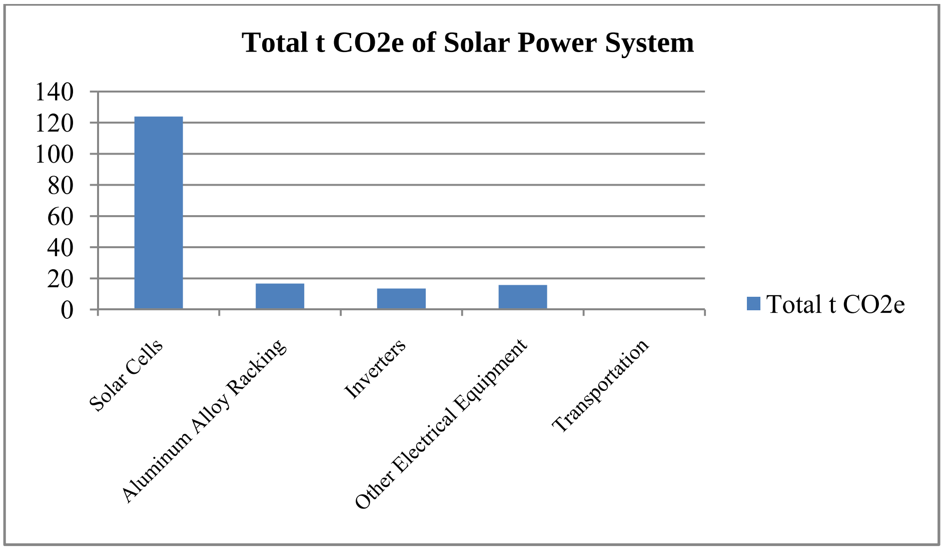

***Figure 5*. Greenhouse Gases Emission estimate in the Manufacturing Phase of Solar Panel Power Supply System** Source: eiolca.net

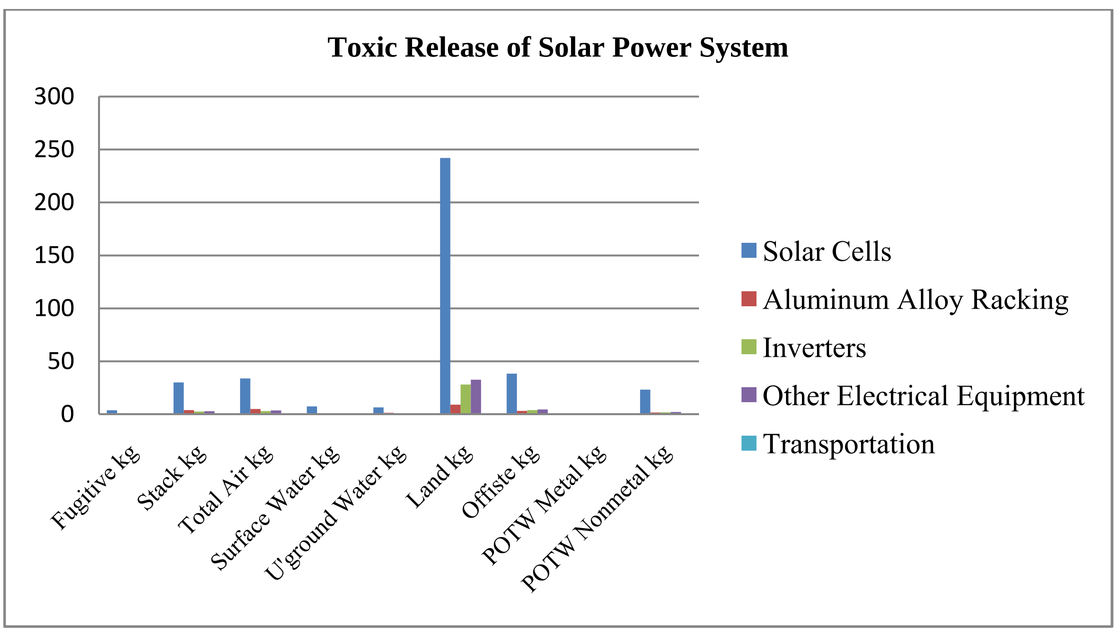

***Figure 6*. Toxic Release Emission estimate in the Manufacturing Phase of Solar Panel Power Supply System** Source: eiolca.net

From the figures, it can be seen that the aggregate pollution generated by solar cell manufacturing is higher than for other system components categories. The total greenhouse gas emission of solar cell manufacturing is 170 metric tons, and the toxic release to land is 312 kilograms. The project may be able to reduce the estimated environmental impacts by using other kinds of photovoltaic panels, such as thin film panels. However, as a garage structure, roof top photovoltaic panels might be the most convenient method to capture solar energy.

4.2.1.2 Power Grid System

In the calculations for the solar panel system, the internal grid arranged in the garage is not included. Except for the internal power system, it only needs a section for connecting the utility equipment to the building. This part is similar to the solar panel system. As noted in the assumptions, electric power is generated by coal-fired power plant. Considering it is hard to get the detailed number from the power plants, the number used for calculating in manufacturing phase and construction phase is borrowed from the article "Greenhouse gas emissions from coal gasification power generation systems" (Ruether, Ramezan & Balash, 2004). The power plant used in this article has a capacity of 543 MW and a heat rate of 8,522 Btu/kWh, which is similar to the power plants operating in Colorado.

The components for building a power plant include coal and sorbent handling system, coal and sorbent preparation and feed system, feed water and miscellaneous balance of plant systems, combustion turbine and accessories, HRSG, ducting, and stack system, steam turbine generator, cooling water system, Ash/spent sorbent handling system, accessory electric plant and instrumentation and control system. The NAICS sectors and sub-sectors are shown in Table 11.

Figure7 and Figure 8 display the greenhouse gas emissions and toxic releases in the manufacturing phase of a coal fired power grid supply system.

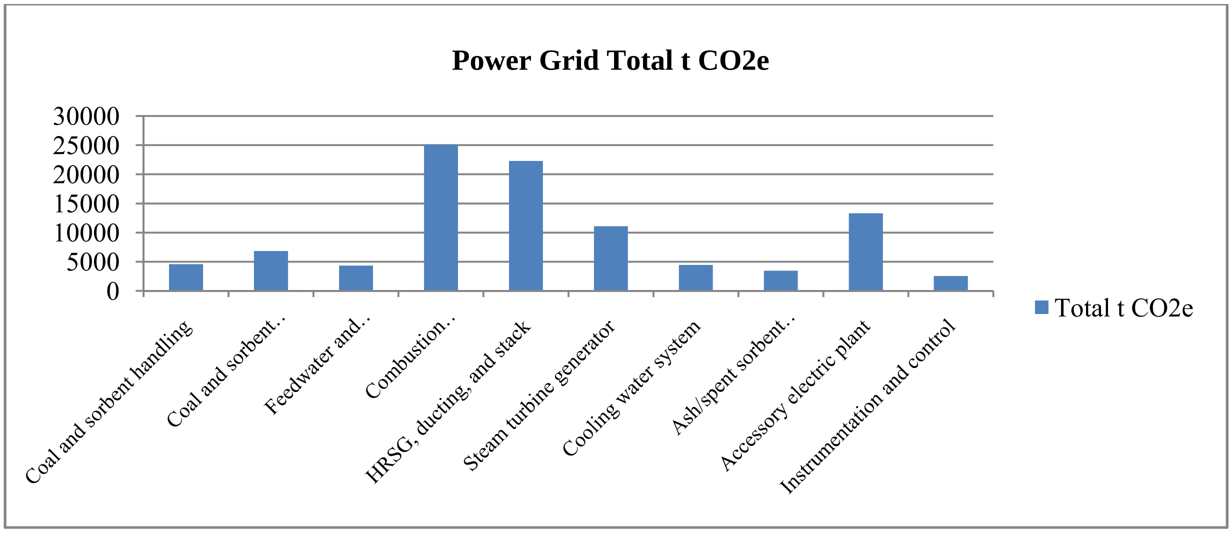

***Figure 7*. Greenhouse Gases Emission estimate in the Manufacturing Phase of Power Grid Supply System** Source: eiolca.net

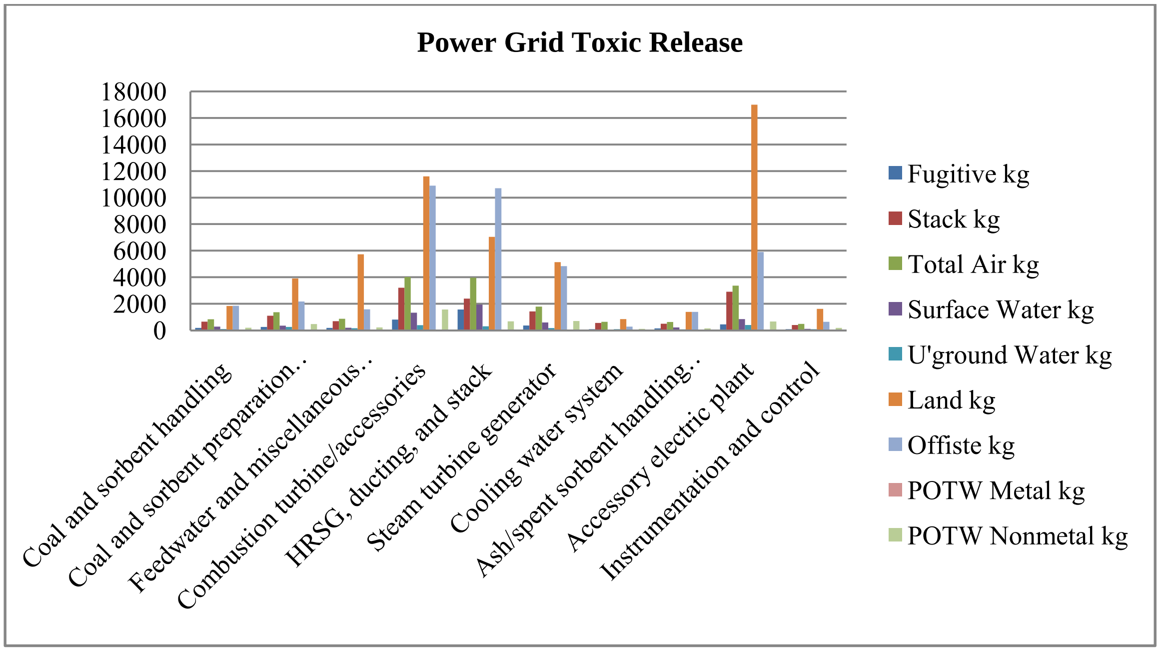

***Figure 8*. Toxic Release Emission estimate in the Manufacturing Phase of Power Grid Supply System** Source: eiolca.net

Note that the scale of these two figures is about one hundred times the scale shown in the figures of solar panel power system. It can be seen that the pollution of power plant in this phase is much higher than the solar panel system. However, the capacity of the power plant is significantly greater than that of the solar panel system. In addition, the power plant has to operate non-stop except during maintenance. So the numbers of estimated greenhouse gas emission and estimated toxic release should be adjusted according to the capacity and operation hours of different systems. The electricity that the power plant produces during the life time is 3.0408E+11 KWh, and the power that the solar system produces during the life time is 175,000 kWh. So the power plant produces 1,737,600 times as much electricity as that of the solar power system. So the estimated greenhouse gas emission and estimated toxic release of power plant in all phases should be divided by 1,737,600, and then the numbers for the power plant system can be compared with the numbers for the solar power system. After adjustment, the influence of the power plant system is very small.

4.2.2Construction Phase

4.2.2.1 Photovoltaic System

The costs related to design systems can be obtained from the engineering section of the project breakdown. Costs adjusted according to CPI are $2,024. During EIO-LCA calculation, NAICS Sector 541420 is used. This sector includes creating and developing designs, specifications and appearance of the product. The shipping cost has also been given in the project breakdown. The value the CPI adjustment is $246. The NAICS Sector used for this portion is the same as the transportation sector of the manufacturing phase.

During the construction phase, vehicles used include workers commuting vehicles, freight trucks for shipping of construction materials, tools and construction waste transportation were reviewed. The project breakdown showed this part as well. Because the workers go to work every day, the first step is to calculate the estimated environmental commuting impacts. Other activities do not happen regularly, so these transportation impacts cannot be estimated in the same way. The estimated impacts of these non-commuting transportation items were set equal to the estimated impacts of travel obtained from project breakdown minus the cost of commute.

According to similar projects, a solar panel system of similar size needs 6-8 individuals to install. It is assumed that this project needs 7 people. From the time-lapse sequence video on CSU Lake Street Parking Garage web page, the system installation takes 15 days. According to the assumptions in 4.1.2, the mileage for commuting for all workers is 2646 miles. In Weekly Retail Gasoline and Diesel Prices, US Energy Information Administration, the average price in Colorado in 2010 was $2.71 per Gallon. US Energy Information Administration shows that the average mile per gallon of Light-Duty Vehicles is 23.5. Therefore the round trip for workers costs a total of $305.47, which is $252.02 after adjusted by the CPI. The travel expenses shown in the project breakdown totaled $437.74. Then the remaining non-commuting cost is $132.27.After adjustment for CPI, the cost is $109.14. Both of these two items can use NAICS Sector 484110 for EIO-LCA calculation.

From the time-lapse sequence video, it is shown that solar panels, brackets and associated equipment was lifted by telescopic crane, and this crane is leased. NAICS sector 238990 All Other Specialty Trade Contractors can be used for this cost item. This sector includes crane rental with operator. Because the equipment rental for the project is mainly crane rental, the price of equipment rental in the project breakdown can be used here. The price is $4,344.14.After removing the markup and adjusting for the CPI, the final price is $2986.66.

These construction phase cost items are summarized in Appendix C. Figure9 and Figure 10 show the result of this phase.

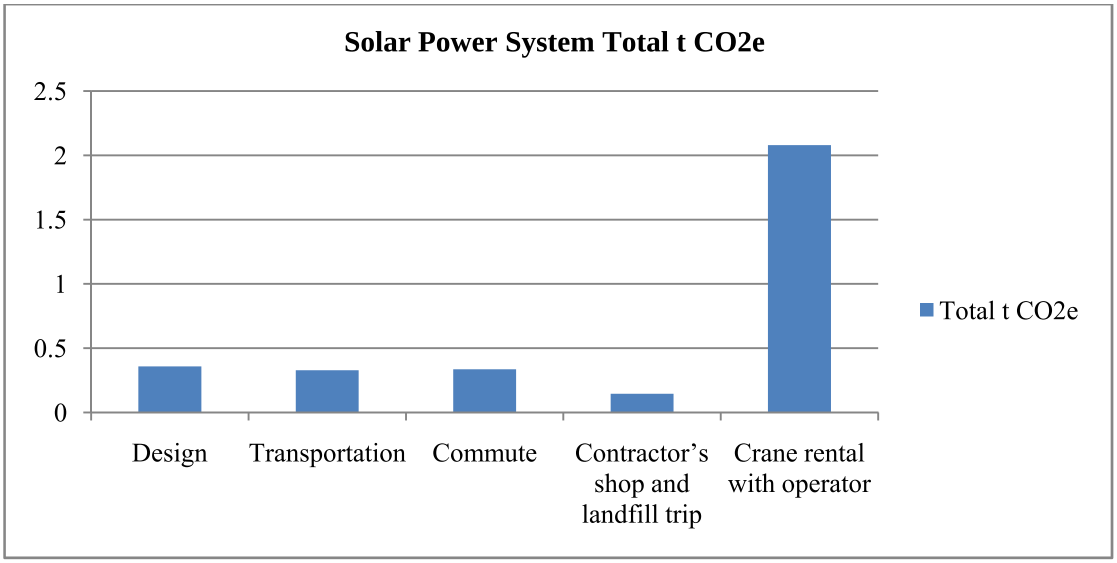

***Figure 9*. Greenhouse Gases Emission estimate in the Construction Phase of Solar Panel Power Supply System** Source: eiolca.net

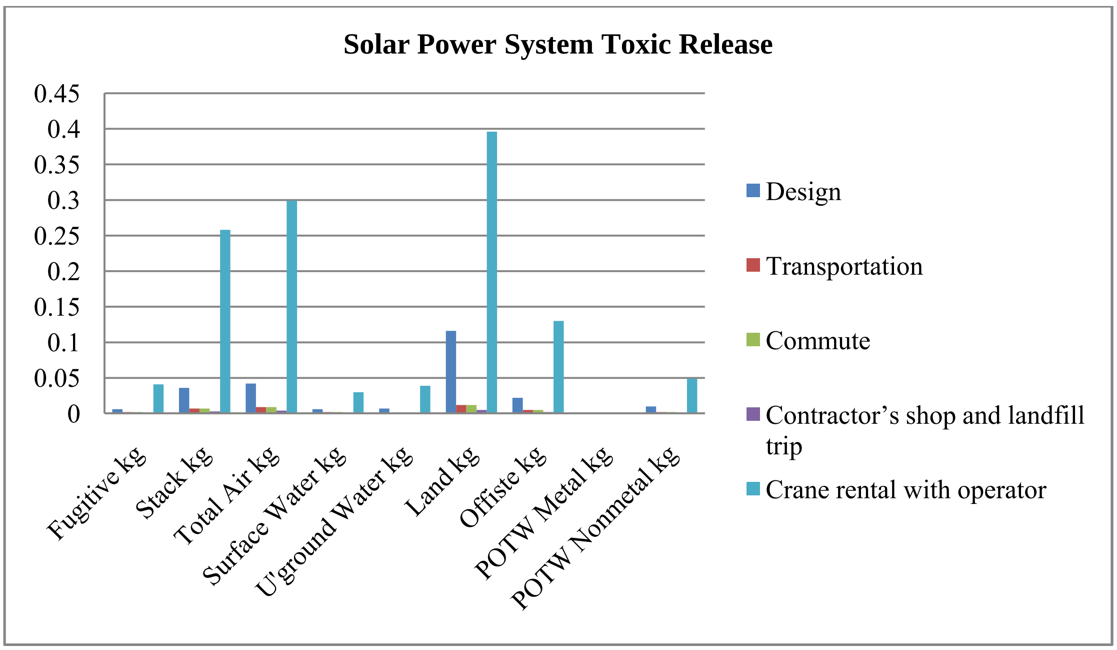

***Figure 10*. Toxic Release Emission estimate in the Construction Phase of Solar Panel Power Supply System** Source: eiolca.net

From the figures, it can be seen that the estimated greenhouse gas emission and toxic release for crane rental is much higher than other impacts. However, compared with other phases, the scale of greenhouse gas emission and toxic release in this phase is much smaller. Therefore, although the estimated environmental impacts from the crane are higher than other categories in this phase, it has much smaller estimated impacts than other categories in the other phases.

4.2.2.2 Power Grid System

The source of the numbers and the adjustment of the numbers are the same as part 4.2.1.2. Costs are summarized in Appendix C. Figure 11 and Figure 12summarize the greenhouse gas emissions and toxic releases in the construction phase.

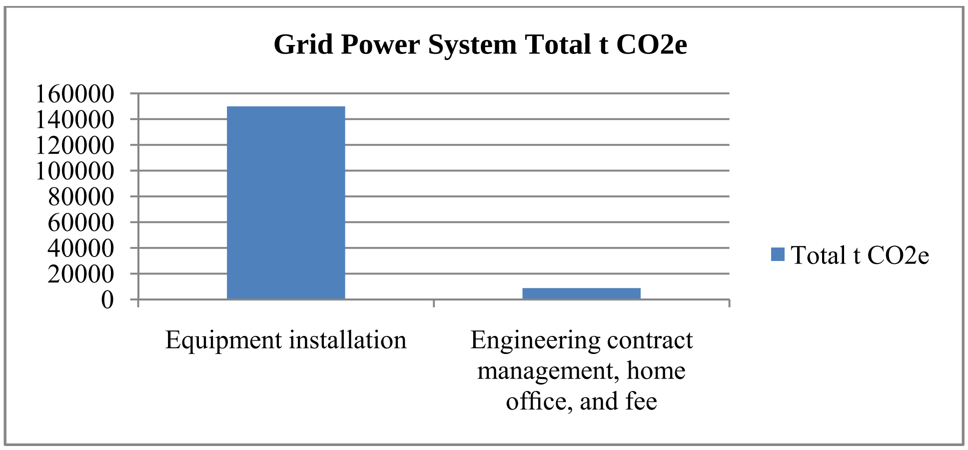

***Figure 11*. Greenhouse Gases Emission estimate in the Construction Phase of Power Grid Supply System** Source: eiolca.net

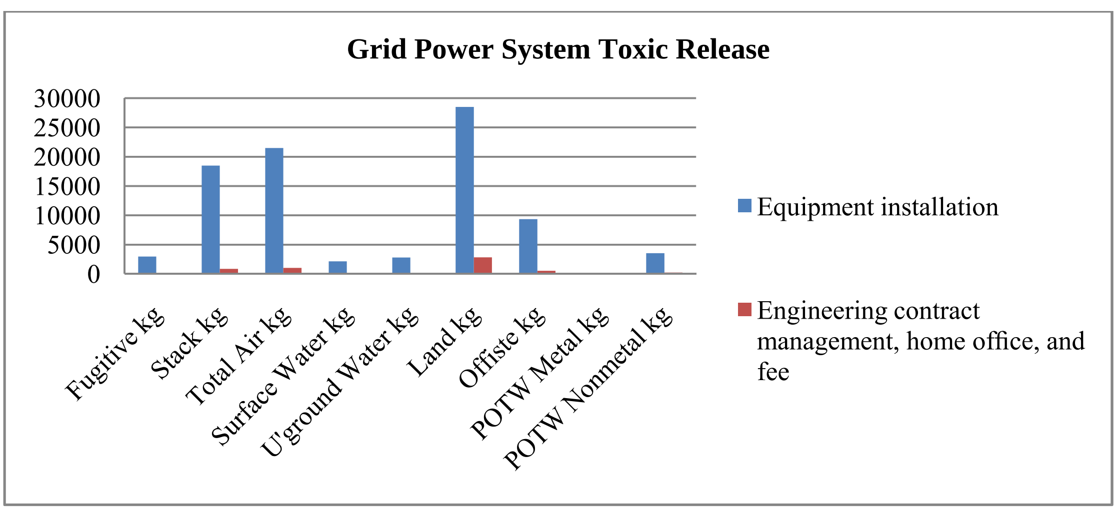

***Figure 12*. Toxic release estimate in the Construction Phase of Power Grid Supply System** Source: eiolca.net

4.2.3 Use and Maintenance Phase

4.2.3.1 Photovoltaic System

The CSU Department of Facilities Management reports that the solar panel system does not have a maintenance contract, and CSU does not have any historical maintenance data due to the newness of the system. It is assumed therefore that there is one person who will clean the solar panels once per year. The commuting cost of staff is the annual maintenance cost. The mileage for the commute is assumed to be 25.2 miles. The average price was $2.72 per Gallon. The average miles per gallon of Light-Duty Vehicles is 23.5. Therefore the cost of commute is $2.91, and the final price is $2.40 after adjusted by the CPI. The annual maintenance cost does not need to be adjusted in accordance with the inflation rate, because $2.40 is already the 2000 base year price. Normally, the life of the battery used in the solar panel system is about seven years. During the system life cycle, the battery is assumed to be replaced three times. The numbers in the project breakdown are aggregated in such a manner that the price of batteries cannot be directly determined. The assumptions and steps used to get the price of batteries used in the system is described in the following paragraphs.

The life time of batteries in PV panel systems depends on how well they are maintained. For example, if the battery is discharged to 50% every cycle, the life time will be about twice as long as when the battery discharged to 80% (Fthenakis, 2002). If batteries used in this system are not discharged more than 80%,the storage capacity of the batteries is 1.25 times the electricity that produced by the system every day. The average annual electricity consumption for the Lake Street Garage is about 175,000kWh, so the daily usage of electricity is 480kWh.From Colorado State University's EnergyCAP system, it can be determined that about 30% of the daily consumption is used after dark. Presently, the price of batteries is about$100 per kilowatt-hour of storage (Nelson, Nehrir & Wang, 2006). Therefore, the price of batteries is 480*30%*1.25*100= 18,000 dollars. This PV panel system has around fifty 12V 212Ah deep cycle solar batteries. The typical life time of an inverter is 10-14 years. Therefore, the inverter is usually replaced in the middle of the estimated life of the solar panel system. It is assumed the inverter will be replaced in the 14th year of the system. The price of the inverter is the same as 4.2.1.1. Appendix D along with Figure 13 and Figure 14 show the calculations for the estimated maintenance impact items.

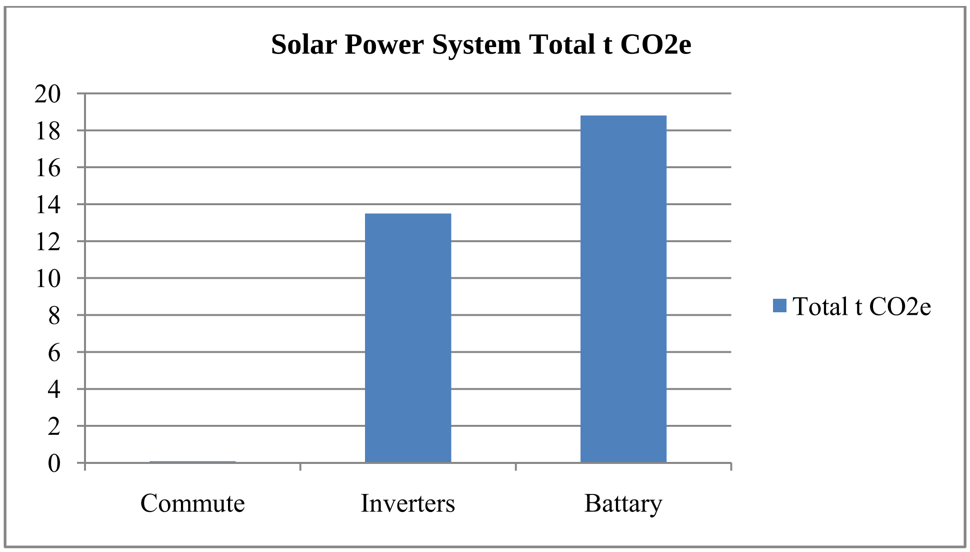

***Figure 13*. Greenhouse Gases Emission estimate in the Maintenance Phase of Solar Panel Power Supply System** Source: eiolca.net

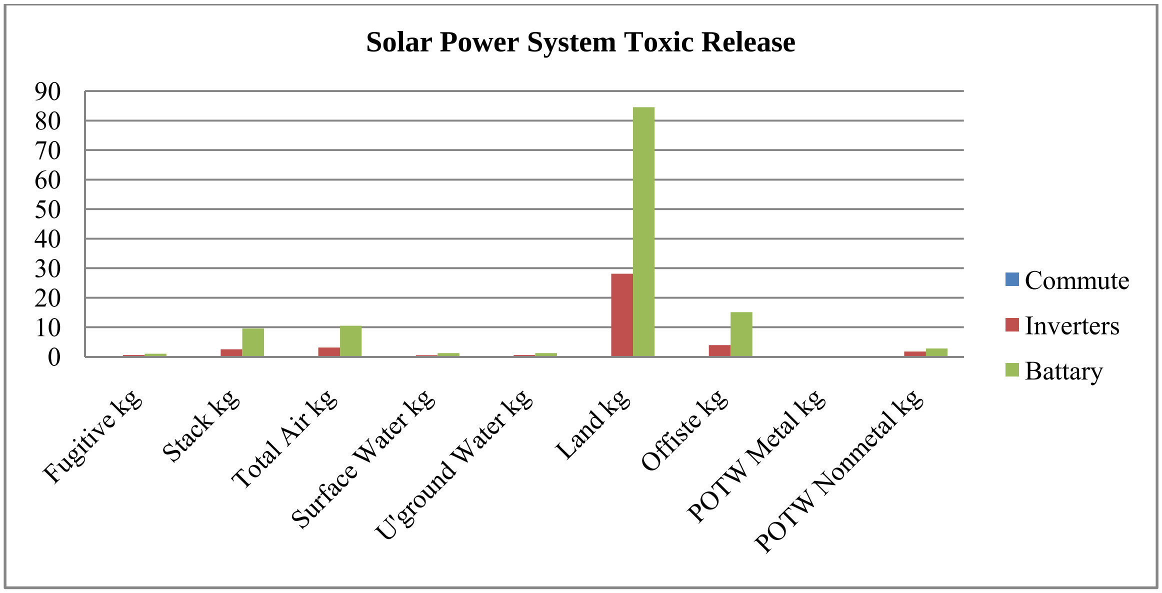

***Figure 14*. Toxic Release Emission estimate in the Maintenance Phase of Solar Panel Power Supply System** Source: eiolca.net

The figures show that both greenhouse gas emissions and toxic releases associated with battery use is high. Therefore, the system designers should consider removing the batteries and selling any unused electricity to the grid (city) and buying electricity from the city during periods of shortfall. However, this method requires the grid be a smart grid, which means an extra cost for the system. Another way to solve this problem is to connect all the solar panel systems to a single meter, so the whole campus can use the electricity from the solar panel storage system and there would be limited surplus electricity from a campus wide standpoint.

4.2.3.2 Power Grid System

The amount of electricity used in this phase is normalized to be the same unit as the amount of electricity that the solar panel system produced. So the results of this section need not bedivided by thelife span of grid systems as discussed in 4.2.1.2. According to the historical data obtained from the CSU Department of Facilities Management, the average annual electricity produced by the solar panel system of the Lake Street Garage is about 175,000kWh.In accordance with the assumption in 4.1.2, the cost of coal used in power generation that can be attributed annually to the electricity consumption is $2,955.96.The final price is $2,316.20 after CPI adjustment. All the coal mining, power generation, substation and transmission process can be set into 221100 Electric Power Generation, Transmission and Distribution sector. The base price of electricity is $10,237.5, and the final price is $8,531.25 after removing the markup. The details and calculation form is in Appendix D. Figure15 and Figure 16 show the result of this phase.

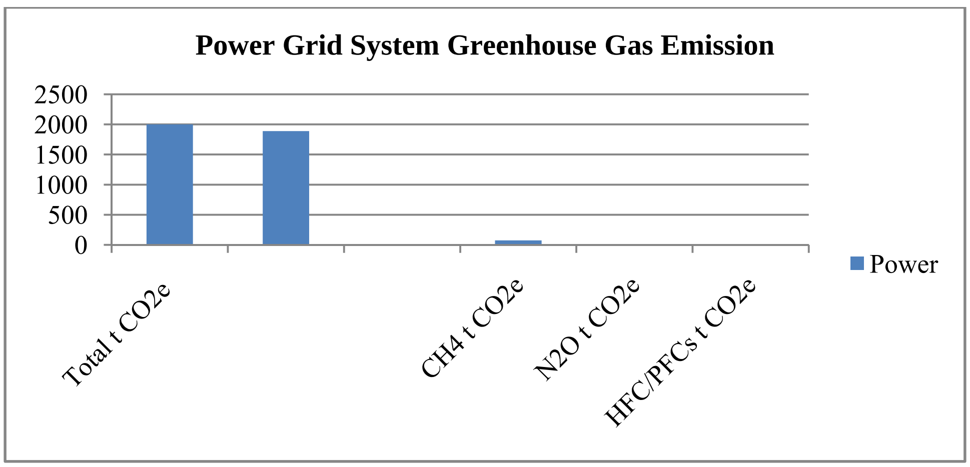

***Figure 15*. Greenhouse Gas Emission estimate in the Maintenance Phase of Power Grid Power Supply System** Source: eiolca.net

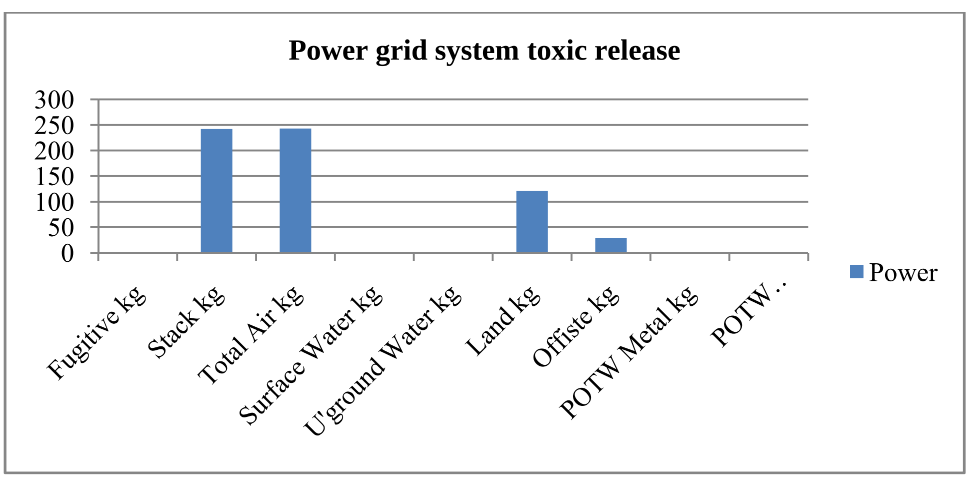

***Figure 16*. Toxic Release Emission estimate in the Maintenance Phase of Power Grid Power Supply System** Source: eiolca.net

By producing the same amount of electricity, the greenhouse emissions of a power grid system is about 100 times that of a solar panel system. This confirms the popular notion that coal fired power plants produce relatively high amounts of greenhouse gas compared to solar power.

4.2.3 End-of-Life Phase

In the 25-year time frame of this analysis, a power grid system does not enter the end-of-life phase. In addition, according to the attributed capacity consumed by the parking garage and total number of operation hours, the end-of-life influence of a power plant is very small. Therefore, in end-of-life calculation, only the photovoltaic system is considered. The materials that need to be recycled include silicon, glass, and the aluminum frame.

Section 423930 Recyclable Material Merchant Wholesalers in NAICS can be used in glass recycling assessment. Section 331314 Secondary Smelting and Alloying of Aluminum can be used for aluminum recycling. The cells used in the panels can be recovered and reused in new photovoltaic module production. Therefore, in this section, the recycling of the silicon, the primary material of cells will not be calculated. As for the solar panels, semiconductor materials only weigh 10% of the whole product weight (Fthenakis, 2002). Therefore, the weight of glass that needs to be recycled is 21,342.27lb. The price for glass recycling retrieved from the website of Larimer County is $0.01 per pound. So the cost for glass recycling is $213.42. The price for aluminum recycling is $0.35 per pound. So the price for aluminum recycling is $140. The cost of transportation and crane rental is the same as that outlined in the manufacturing section and construction section. Appendix E, Figure 17 and Figure 18 summarize the end-of-life costs and the calculation process.

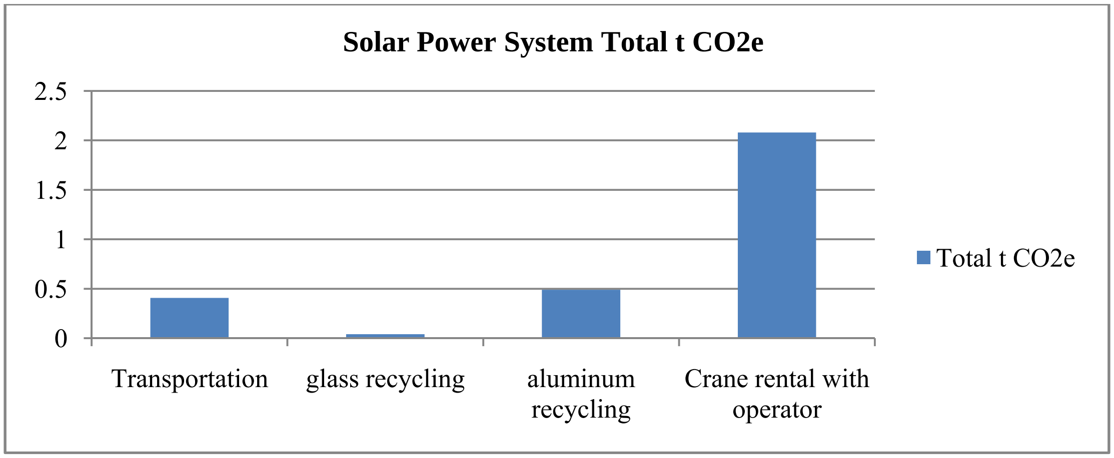

***Figure 17*. Greenhouse Gases Emission estimate in the End-of-Life Phase of Solar Panel Power Supply System** Source: eiolca.net

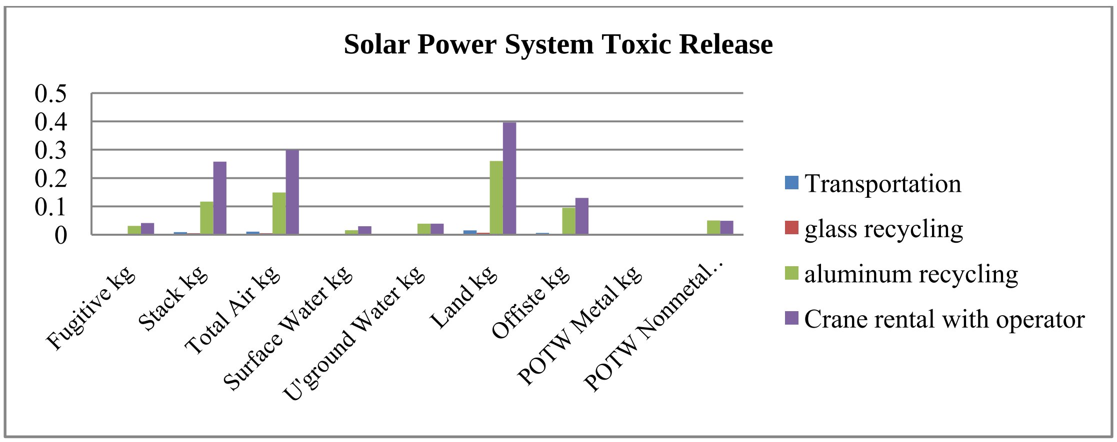

***Figure 18*. Toxic Release estimate in the End-of-Life Phase of Solar Panel Power Supply System** Source: eiolca.net

4.3 Life Cycle Cost

In life cycle cost analysis, the inflation rate is used to transform anticipated future costs to baseline current dollar value, and a discount rate is used to discount the future expenditure because of "time value of money". The effect of these two rates can cancel each other out to some degree. Suppose the discount rate is *i*, and the inflation rate of a year is *j*. If $t_0$representsthe beginning of the operation phase and t represents a time point t periods in the future, then the inflation adjusted expenditures in time period t can be represented by C in t_0-dollars. Therefore, the equivalent dollar of this expenditure is $C(1+j)^{t-t0}$, and the discounted value is

$C(1+j)^{t-t0}(1+i)^{-(t-t0)}$. Using factor V to represent $(1+j)/(1+i)$,then $LCC = \sum_{k=1}^{n} C_k V^k$.

Obtained from the project breakdown, the initial investment in the solar panel system is $533,211. In addition, the cost of the batteries and the inverter replacements during the life span also increase the cost. The cost and the assumptions can be found in 4.2.3.1.The price of the batteries is $18,000, and their life span is 7 years. The price of inverters is $54,460.08. Assume the cost of labor in maintenance is $40 per hour and the time for the work is 2 hours. Labor cost plus the commuting cost for the maintenance phase adjusted by CPI is 40*2+3=83 dollars. All the costs used in this phase are adjusted to the costs of the base year of 2011. Table 4 shows the calculation details of the LCC. The LCC column equals the discounted value of annual operating money saved from the PV system minus all the front end costs multiplied factor V. V is the factor used to show the blended rate of inflation and the discount rate derived from the formula shown earlier. From Table 4, we can see, the system cannot payback its cost in the 25-year life time of the system.

***Table 4*. Life Cycle Cost of Solar panel power supply system.**

Year	Initial Cost	Labor	Battery	Inverter	Power produced by PV panels	V	LCC
0	$533,211.00					1	($533,211.00)
1		$83.00			$10,664.06	0.985437	$10,426.97
2		$83.00			$10,664.06	0.971086	$10,275.12
3		$83.00			$10,664.06	0.956944	$10,125.48
4		$83.00			$10,664.06	0.943008	$9,978.02
5		$83.00			$10,664.06	0.929275	$9,832.71
6		$83.00			$10,664.06	0.915742	$9,689.52
7		$83.00	$18,000.00		$10,664.06	0.902405	($6,694.89)
8		$83.00			$10,664.06	0.889264	$9,409.35
9		$83.00			$10,664.06	0.876313	$9,272.32
10		$83.00			$10,664.06	0.863551	$9,137.29

11		$83.00			$10,664.06	0.850975	$9,004.22
12		$83.00			$10,664.06	0.838583	$8,873.09
13		$83.00		$54,460.08	$10,664.06	0.82637	($36,260.31)
14		$83.00	$18,000.00		$10,664.06	0.814336	($6,041.51)
15		$83.00			$10,664.06	0.802476	$8,491.05
16		$83.00			$10,664.06	0.79079	$8,367.40
17		$83.00			$10,664.06	0.779273	$8,245.54
18		$83.00			$10,664.06	0.767925	$8,125.46
19		$83.00			$10,664.06	0.756741	$8,007.13
20		$83.00			$10,664.06	0.745721	$7,890.52
21		$83.00	$18,000.00		$10,664.06	0.734861	($5,451.89)
22		$83.00			$10,664.06	0.724159	$7,662.37
23		$83.00			$10,664.06	0.713613	$7,550.78
24		$83.00			$10,664.06	0.703221	$7,440.82
25		$83.00			$10,664.06	0.69298	$7,332.46
						NPV	($402,521.94)

It is worth noting that this solar project was entrusted to the contractor Bella Energy for construction. If the Department of Facilities Management would have installed the equipment by itself, the initial investment for this project may have been lower than this price. Meanwhile, in 2010, the federal and state governments implemented some incentives on solar energy. The federal government has a Federal Tax Credits for Solar and Wind Energy Systems, and the state government has the Recharge Colorado program. So after adding these subsidies, the initial investment may be correspondingly reduced on future solar panel system installations for owners with tax burden.

CHAPTER FIVE: CONCLUSION

The life cycle assessment and life cycle cost analysis of electric consumption for the Lake Street Parking Garage is provided in Chapter 4.In this chapter, an analysis is given to compare two categories that have environmental impacts. One is estimated greenhouse gas emission, the other is estimated toxic release. As for the estimated greenhouse gas emissions, the result is consistent with our common sense. If the garage is powered by coal-fired power plant, the total estimated carbon dioxide emission during the full life cycle is greatly higher than the estimated emissions of the solar energy powered system. However, the result of the estimated toxic release is not the same as what might have been assumed. The estimated toxic release of a coal-fired power plant is not absolutely higher than the estimated toxic release of a solar energy system. The coal-fired power plant has higher estimated toxic release of air pollutants than that of the solar system, but it has lower estimated water body toxic releases than that of the solar system. Based on these estimates people cannot simply claim which power supply system is absolutely better. Table 5 shows the detailed comparative analysis.

***Table 5*.Estimated Greenhouse Gas Emission Comparison** Source: eiolca.net

Material Description	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFC t CO2e
PV Panels	238.955	162.598	23.533	11.736	2.339	39.283
Coal-fired power plant	2000	1890	6.67	73.7	12	12.3

5.1 Greenhouse Gas Emission analyses

The data calculated in chapter 4 are aggregated together and shown in Table 5. As can be seen from the table, the biggest difference in greenhouse gas emission between two power supplies are greenhouse gas fossil fuel combustion. The estimated greenhouse gas emissions from a coal-fired power plant are significantly higher than the estimated emission of the solar energy system. The EIO-LCA tool can show the top ten sectors in the economic chain that produce greenhouse gases emissions. Table 6 shows the sectors of coal-fired power plant system, and power generation, which accounts for 94% of the estimated greenhouse gases emissions, the highest greenhouse gases emission sector. A total estimated greenhouse gas emission of coal-fired power generation is 2000t CO_2e, which is 8.37 times the estimate emitted from a solar energy system. Compared with a 25-year life span, 8.37 times might not be as high as would initially be assumed. In other words, the solar energy system is not really a completely zero emission system and may not reduce estimated greenhouse gas emission as significantly as might be assumed. However, the number still shows that the solar energy system has advantages on reducing estimated greenhouse gas emission.

It can also be noted that CO_2 Process and HFC / PFC emissions of the solar energy system are higher than that from the coal-fired system. CO_2 Process emission is mainly produced from the production of the battery and solar cells. Coincidentally they are also main sources of fossil fuel CO_2. The battery is only calculated separately in the maintenance phase. If it is calculated separately in the manufacturing phase, the CO_2 Process and Fossil fuel estimated CO_2 emissions of the solar power system will be higher than what is presented in Table 5. In addition, HFC / PFC estimated emissions of the solar energy system are mainly from the manufacture of solar cells as well. Thus, it can be seen that although the solar energy system is indeed significantly better than the coal-fired power system in estimated greenhouse gases emissions, the manufacture of solar cells and batteries still generate significant estimated amounts of greenhouse gases. If the efficiency of energy storage and power generation could increase in the future, solar energy systems will have greater value in terms of reducing estimated environmental impacts. There is a way to eliminate the use of batteries for energy storage. It is to connect the solar power system to the power grid. This can enable the solar power system to sell surplus power to the grid and buy electricity from the grid when production of solar energy is inadequate. However, this kind of system requires the power grid to have the ability to handle bi-direction energy flows. That means that the old power grid would need to be upgraded to a Smart Grid. At the same time, on-grid solar energy systems create more difficulties in electric load forecasting.

Table 6 shows the top sectors for estimated greenhouse gas emissions. Table 7 shows the estimated toxic release comparison.

***Table 6*. Top ten estimated greenhouse emission sectors of coal-fired power plant system**
Source: eiolca.net

	Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
	Total for all sectors	*2000*	*1890*	*6.67*	*73.7*	*12.0*	*12.3*
221100	Power generation and supply	1880	1850	0.000	5.10	11.5	11.9
212100	Coal mining	49.0	5.53	0.000	43.4	0.000	0.000
211000	Oil and gas extraction	27.5	7.75	5.04	14.7	0.000	0.000
486000	Pipeline transportation	14.3	6.54	0.018	7.75	0.000	0.000
482000	Rail transportation	5.53	5.53	0.000	0.000	0.000	0.000
324110	Petroleum refineries	4.23	4.22	0.000	0.013	0.000	0.000
484000	Truck transportation	1.95	1.95	0.000	0.000	0.000	0.000
230301	Nonresidential maintenance	1.87	1.87	0.000	0.000	0.000	0.000

	Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
	and repair						
331110	Iron and steel mills	1.61	0.607	0.991	0.010	0.000	0.000
221200	Natural gas distribution	1.55	0.140	0.000	1.41	0.000	0.000

5.2Toxic Release analyses

The reason that this research selected to compare estimated toxic release is because the manufacturing of solar panels, as mentioned in the second chapter, will produce toxic byproducts. The environmental impacts of a coal fired power plant also include toxic wastes, such as SO_2 and NO_x. So the comparison of toxic release is warranted. As can be seen from Table 7, the estimated fugitive toxic releases of the solar power system release are 9.6 times that of a coal-fired power system. Fugitive air mainly comes from leakage and evaporation, making it hard to control. If the workers do not have proper protective measures, they may have serious health issues. The equipment used in coal fired power plants has very stringent regulatory requirements so less fugitive toxic release is produced in a coal-fired power plant.

Table 7 also shows that the coal-fired power system has higher estimated gaseous toxic releases than the solar power system, but has lower estimated toxic releases to water and land. This is consistent with common sense. A coal-fired power plant generates a great amount of SO_2 and NOx, while the solar panel manufacturing process mainly produces waste water and solid wastes. But toxic gas is harder to collect and control than liquid and solid wastes. Therefore, the equipment for toxic release control and collection is necessary for both methods, and a coal-fired power plant will need more equipment for collection and control.

Table 7. **Toxic Release Estimate Comparison** Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmetal kg
PV Panels	9.293	67.566	76.887	12.812	12.842	561.161	93.782	0.264	37.905
coal-fired power plant	0.969	242	243	1.86	0.565	121	29.5	0.017	0.888

From a municipal sewage treatment standpoint, the solar power system may have more issues than a coal-fired power plant. Crystalline silicon can cause a problem of drinking water contamination if it is not treated properly after the end-of-life. Solar energy users should be responsible for appropriately recycling the materials and equipment they used.

5.3 LCC analyses

The solar power system of the Lake Street Parking Garage cannot recover its initial cost in 25 years. However, the solar power system helps the university reduce its carbon footprint. The university has committed to reducing the net carbon footprint to zero by 2050. In addition, traditional electricity costs are expected to escalate which could shorten the simple payback, in terms of cost, substantially. At the same time, if a carbon penalty is imposed on traditional power sources, the cost of traditionally produced power would increase and shorten the simple payback further, and producing power on campus helps reduce the university's demand on the distribution system, which may delay hitting capacity limits requiring payment to the city for additional plant investment fees.

5.4 Conclusion

According to the analyses above, a solar power system does have some advantages in reducing the estimated greenhouse gas emissions. This research does not consider the personal safety of workers nor the economic costs of pollution control, so it is difficult to determine which system is better only according to the data of toxic release. Although the estimated fugitive toxic release of solar panel manufacturing, which would harm the health of workers, is higher than the estimates for a coal-fired power plant, the dangerous condition and harsh environment of coal mining is also accompanied with hazards to the health of workers. In addition, there are certain requirements when choosing the site of a coal fired power plant, including access to large amounts of water resources to produce steam. Coal fired power plants also cover a wide area, including the railroad system and fields for holding fly ash, which might pose problems for high population density area. On the contrary, solar panels can be used on the roof and other places that do not affect the community life as significantly as coal fired plants. Therefore, it is difficult to state with certainty which energy supply system is better.

In summary, this research provides decision makers some guidance related to the choice of power supply. Moreover, the research also inspires decision makers to consider more decision factors related to personal safety, living environment and so on. With the development of solar technology, the efficiency of solar panels will improve, and solar power may eventually replace fossil fuels. The manufacturing cost of solar panels is anticipated to decline in the future, making it more likely those organizations will increase their use of solar panels.

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APPENDIX A

Eiolca.net Home Page

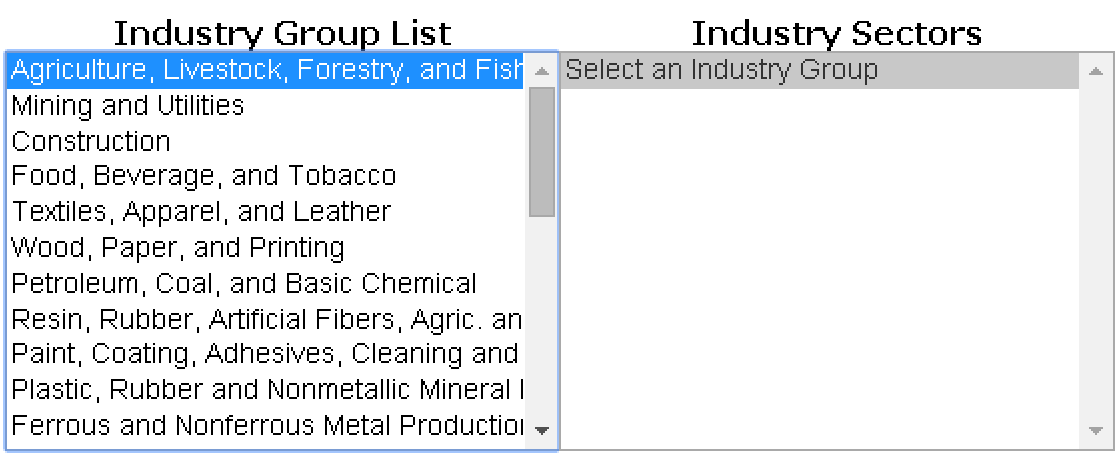
Source: EIOLCA.net, downloaded 10-27-2014

Step 1: Choose a model

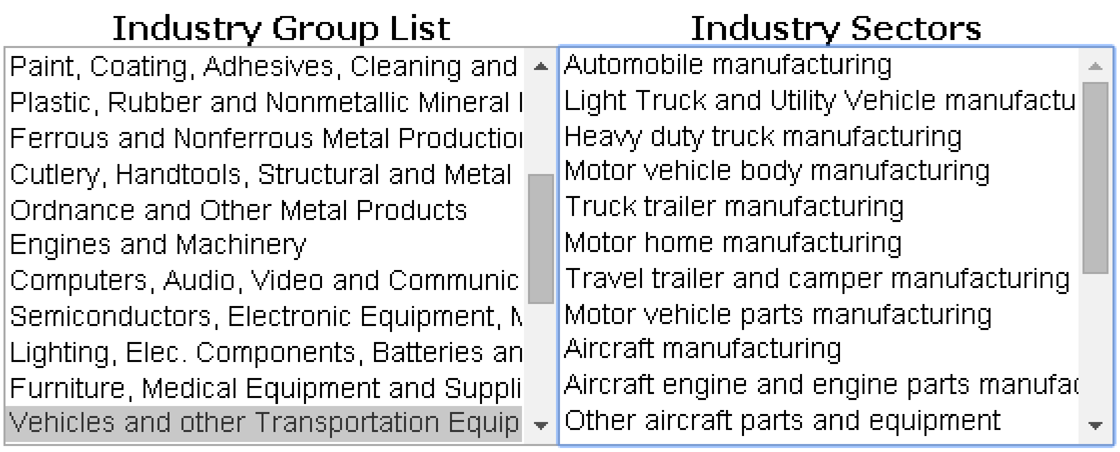
The first step in using the EIO-LCA model is to select the model year and country for industry data from the drop down list. Models exist for the years 1992, 1997, and 2002. The most recent data available is from 2002, and this tutorial will focus on the use of the United States 2002 model. Data is also available for Germany, China, Spain, and Canada and can be selected from the model year drop down list.

Step 2: Select industry and sector

The next step is to select an industry sector to analyze. For the 2002 model, industry sectors divide the economy into 428 divisions grouping businesses that produce similar goods or services, or that use similar processes. Other model years divide the economy into a different number of sectors according to changes in standards. Next, we need to find the industry sector that produces the output we want to analyze.



If you click on an industry sector name in the second column, a description of the types of facilities included in that sector appears at the bottom of the page. This allows you to determine if the sector produces the output you want. So, we can see that the sector "Automobile manufacturing" includes facilities which assemble automobiles, passenger cars, and electric automobiles among others. That sounds like the sector we are interested in. Click on the Select this Sector button to continue your analysis.



Step 3: Select a level of economic activity

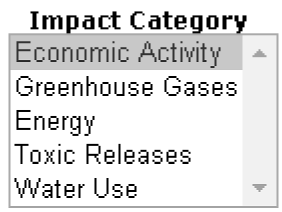
The third step is to determine the level of economic activity for the desired sector, or what is the value (in dollars) of the output demanded by the sector. This can also be considered the demand for the output produced by the sector.

Any dollar amount is allowed. You can choose to enter a dollar amount that is representative of a single output (e.g., $20,000 for an automobile, $40,000 for a year at a private college), or enter a dollar amount that is representative of an increase in output for the sector.

Step 4: Select the effects to display

The second step is to select the effects you want to view in the results. One of the 5 options can be selected from the menu: Economic Activity, Greenhouse Gases, Energy, Toxic Releases, or Water Use.

Note that for the impacts analyzed in the EIO model, upstream activities are included in the results. For instance, when analyzing toxic releases for the Automobile Manufacturing sector, all of the toxic releases that occur as a result of the upstream activities from all other sectors in the economy are included in the results. This will be further explained later when we discuss interpreting the results.



Step 5: Run the Model

Now that you have selected a sector, entered a dollar amount of economic activity, and determined the effects to display, the EIO-LCA tool has all the information it needs to run the model. Click on the Run Model button to start the analysis. Results will display, typically within about 10 seconds.

APPENDIX B

The Calculation Forms of Manufacturing Phase

***Table 8*. Photovoltaic System Component Costs and Base Year Values.**

Material Description	NAICS Sector	NAICS Sub-Sector	Retail Price 2010 $	Adjustment factor	CPI	Base year 2002 $
Solar Cells	Semiconductors, Electric Equipment, and Media Reproduction	334413: Semiconductor and Related Device Manufacturing	$315,094	0.794	0.825	$206,316.17
Aluminum Alloy Racking	Ferrous and nonferrous metal production	331312: Primary aluminum production and manufacturing aluminum alloys	$7,630	0.794	0.825	$4,995.88
Inverters	Lighting, Electrical Components, Batteries	335999: All Other Miscellaneous Electrical Equipment and Component Manufacturing	$54,460	0.794	0.825	$35,659.14
Other Electrical Equipment	Lighting, Electrical Components, Batteries	335999: All Other Miscellaneous Electrical Equipment and Component Manufacturing	$63,354	0.794	0.825	$41,482.73
Transportation	Trade, Transportation, and Communications Media	484121: General Freight Trucking, Long-Distance, Truckload	$353	1.000	0.825	$291.64

***Table 9*. Greenhouse Gases Emission in the Manufacturing Phase of Solar Panel Power Supply System** Source: eiolca.net

Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Solar Cells	124	80.7	9.74	5.86	1.38	26.7
Aluminum Alloy Racking	16.7	9.55	3.06	0.547	0.053	3.49
Inverters	13.5	10.5	1.52	0.862	0.132	0.54
Other Electrical Equipment	15.7	12.2	1.77	1	0.153	0.628
Transportation	0.408	0.38	0.007	0.019	0	0
	170.308	113.33	16.097	8.288	1.718	31.358

***Table 10*. Toxic Release Emission in the Manufacturing Phase of Solar Panel Power Supply System** Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmetal kg
Solar Cells	3.73	30.1	33.8	7.41	6.48	242	38.4	0.139	23.2
Aluminum Alloy Racking	1.06	4	5.05	0.553	1.33	9.07	3.21	0.017	1.72
Inverters	0.579	2.51	3.09	0.527	0.531	28.1	3.94	0.015	1.77
Other Electrical Equipment	0.674	2.92	3.6	0.613	0.618	32.7	4.59	0.018	2.06
Transportation	0.002	0.009	0.011	0.002	0.002	0.015	0.006	0	0.003
	6.045	39.539	45.551	9.105	8.961	311.885	50.146	0.189	28.753

Table 11. Power Grid System Component Costs and Base Year Values.

Material Description	NAICS Sector	NAICS Sub-Sector	Producer Price 1998 k$	CPI	Base Year 2002 k$
Coal and sorbent handling	Machinery and EnginesMaterial handling equipment manufacturing	333922 Conveyor and Conveying Equipment Manufacturing	5550	1.104	6125.116
Coal and sorbent preparation and feed	Machinery and EnginesFluid power process machinery	333999 All Other Miscellaneous General Purpose Machinery Manufacturing	10300	1.104	11367.333
Feedwater and miscellaneousbalance of plant systems	Other Metal Hardware and Ordnance ManufacturingValve and fittings other than plumbing	332919 Other Metal Valve and Pipe Fitting Manufacturing	6800	1.104	7504.647
Combustion turbine/accessories	Machinery and Engines	333611 Turbine and Turbine Generator Set Units Manufacturing	57300	1.104	63237.687
HRSG, ducting, and stack	Cutlery, Handtools, Structural and Metal ContainersPlate work and fabricated structural product manufacturing	332312 Fabricated Structural Metal Manufacturing	21000	1.104	23176.116
Steam turbine generator	Machinery and Engines	333611 Turbine and Turbine Generator Set Units Manufacturing	25400	1.104	28032.064
Cooling water system	ConstructionNonresidential manufacturing structures	237110 Water and Sewer Line and Related Structures Construction	5766	1.104	6363.499
Ash/spent sorbent handling system	Machinery and EnginesMaterial handling equipment manufacturing	333922 Conveyor and Conveying Equipment Manufacturing	4200	1.104	4635.223
Accessory electric plant	Lighting, Electrical Components, Batteries	335311 Power, Distribution, and Specialty Transformer Manufacturing	14800	1.104	16333.643
Instrumentation and control	Semiconductors, Electric Equipment, and Media Reproduction	334513 Instruments and Related Products Manufacturing for Measuring, Displaying, and Controlling Industrial Process Variables	5220	1.104	5760.920

***Table 12*. Greenhouse Gases Emission in the Manufacturing Phase of Power Grid Supply System** Source: eiolca.net

Material Description	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Coal and sorbent handling	4570	3040	1130	262	31.6	110
Coal and sorbent preparation and feed	6840	4950	1220	415	66.1	191
Feedwater and miscellaneousbalance of plant systems	4350	3200	723	248	31	140
Combustion turbine/accessories	25100	18000	5060	1440	155	520
HRSG, ducting, and stack	22300	13500	7100	1230	113	370
Steam turbine generator	11100	7970	2240	638	68.5	231
Cooling water system	4440	3450	598	243	119	27.4
Ash/spent sorbent handlingsystem	3460	2300	856	198	23.9	83.3
Accessory electric plant	13300	8810	3350	802	76.4	246
Instrumentation and control	2540	1910	348	160	26.1	88.1
	98000	67130	22625	5636	710.6	2006.8

Table 13. **Toxic Release Emission in the Manufacturing Phase of Power Grid Supply System** Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmetal kg
Coal and sorbent handling	184	649	833	282	94.8	1830	1840	4.07	192
Coal and sorbent preparation and feed	259	1100	1360	347	249	3910	2170	6.22	474
Feedwater and miscellaneousbalance of plant systems	181	687	869	197	156	5730	1580	5.19	216
Combustion turbine/accessories	803	3210	4020	1330	391	11600	10900	30.4	1570
HRSG, ducting, and stack	1570	2390	3970	1940	297	7040	10700	13.1	673
Steam turbine generator	356	1420	1780	588	173	5140	4840	13.5	697
Cooling water system	88.1	550	638	64	82.9	844	277	1.41	105
Ash/spent sorbent handlingsystem	139	491	630	214	71.7	1390	1390	3.08	145
Accessory electric plant	443	2910	3360	847	396	17000	5900	9.89	666
Instrumentation and control	80.6	398	479	103	82.1	1610	640	2.23	186
	4103.7	13805	17939	5912	1993.5	56094	40237	89.09	4924

APPENDIX C
The Calculation Forms of Construction Phase

***Table 14*. Photovoltaic System Construction Costs and Base Year Values.**

Sectors	NAICS Sector	NAICS Sub-Sector	Retail Price 2010 $	Adjustment factor	CPI	Base Year 2002 $
Design	Professional and Technical Services	541420 Industrial Design Services	$2,454.22	0.952	0.825	$1,928.36
Transportation	Trade, Transportation, and Communications Media	484121 General Freight Trucking, Long-Distance, Truckload	$297.90	0.952	0.825	$234.07
Commute	Trade, Transportation, and Communications Media	484110 General Freight Trucking, Local	$305.47	0.952	0.825	$240.02
Contractor's shop and landfill trip	Trade, Transportation, and Communications Media	484110 General Freight Trucking, Local	$132.27	0.952	0.825	$103.93
Crane rental with operator	Construction	238990 All Other Specialty Trade Contractors	$4,344.14	0.833	0.825	$2,986.66

***Table 15*. Greenhouse Gases Emission in the Construction Phase of Solar Panel Power Supply System** Source: eiolca.net

Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Design	0.315	0.267	0.011	0.026	0.007	0.005
Transportation	0.344	0.32	0.006	0.016	0	0
Commute	0.353	0.328	0.006	0.017	0	0
Contractor's shop and landfill trip	0.153	0.142	0.003	0.007	0	0
Crane rental with operator	2.08	1.62	0.28	0.114	0.056	0.013
	3.245	2.677	0.306	0.18	0.063	0.018

***Table 16*. Toxic Release Emission in the Construction Phase of Solar Panel Power Supply System** Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmetal kg
Design	0.01	0.05	0.059	0.008	0.009	0.067	0.02	0	0.015
Transportation	0.002	0.007	0.009	0.002	0.001	0.013	0.005	0	0.002
Commute	0.002	0.008	0.009	0.002	0.001	0.013	0.005	0	0.002
Contractor's shop and landfill trip	0	0.003	0.004	0	0	0.006	0.002	0	0.001
Crane rental with operator	0.041	0.258	0.299	0.03	0.039	0.396	0.13	0	0.049
	0.055	0.326	0.38	0.042	0.05	0.495	0.162	0	0.069

***Table 17*. Power Grid System Construction Costs and Base Year Values.**

Sector	NAICS Sector	NAICS Sub-Sector	Producer Price 1998 k$	CPI	Base Year 2002 k$
Equipment installation	ConstructionNonresidential manufacturing structures	236210 Industrial Building Construction	194424	1.104	214571.101
Engineering contract management, home office, and fee	Professional and Technical Services	541300 Architectural, Engineering, and Related Services	42773	1.104	47205.333

***Table 18*. Greenhouse Gases Emission in the Construction Phase of Power Grid Supply System** Source: eiolca.net

Material Description	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Equipment installation	150000	116000	20100	8180	4000	925
Engineering contract management, home office, and fee	8770	7320	507	693	150	99.9
	158770	123320	20607	8873	4150	1024.9

***Table 19*. Toxic release in the Construction Phase of Power Grid Supply System** Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmetal kg
Equipment installation	2970	18500	21500	2160	2800	28500	9350	47.7	3550
Engineering contract management, home office, and fee	158	878	1040	140	164	2850	546	2.43	243
	3128	19378	22540	2300	2964	31350	9896	50.13	3793

APPENDIX D

The Calculation Forms of Use and Maintenance Phase

***Table 20*. Photovoltaic System Maintenance Costs and Base Year Values**

	NAICS Sector	NAICS Sub-Sector	Retail Price 2010 $	Adjust ment factor	CPI	ti me s	Base Year 2002 $
Commute	Trade, Transportation, and Communications Media	484110 General Freight Trucking, Local	$2.91	1	0.825	25	$60.00
Inverters	Lighting, Electrical Components, Batteries	335999: All Other Miscellaneous Electrical Equipment and Component Manufacturing	$54,460	0.794	0.825	1	$35,659 .14
Battery	Lighting, Electrical Components, Batteries	335911 Storage Battery Manufacturing	$18,000.00	0.794	0.825	3	$35,357 .89

***Table 21*. Greenhouse Gases Emission in the Maintenance Phase of Solar Panel Power Supply System** Source: eiolca.net

Material Description	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Commute	0.084	0.078	0.002	0.004	0	0
Inverters	13.5	10.5	1.52	0.862	0.132	0.54
Battery	18.8	13	2.02	0.867	0.142	2.79
	32.384	23.578	3.542	1.733	0.274	3.33

***Table 22*. Toxic Release Emission in the Maintenance Phase of Solar Panel Power Supply System** Source: eiolca.net

Secto r	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'groun d Water kg	Land kg	Offsit e kg	POTW Metal kg	POT W Nonm etal kg
Com mute	0	0.002	0.002	0	0	0.003	0.001	0	0
Invert ers	0.579	2.51	3.09	0.527	0.531	28.1	3.94	0.015	1.77
Batte ry	0.976	9.56	10.5	1.19	1.24	84.5	15.1	0.023	2.77
	1.555	12.072	13.592	1.717	1.771	112.603	19.041	0.038	4.54

***Table 23*. Power Grid System Maintenance Costs and Base Year Values.**

Sector	NAICS Sector	Base Year 2002 $
Power	221100 Electric Power Generation, Transmission and Distribution	213281.25

***Table 24*. Greenhouse Gases Emission in the Maintenance Phase of Power Grid Power Supply System** Source: eiolca.net

Sector	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Power	2000	1890	6.67	73.7	12	12.3

***Table 25*. Toxic Release Emission in the Maintenance Phase of Power Grid Power Supply System** Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmeta l kg
power	0.969	242	243	1.86	0.565	121	29.5	0.017	0.888

APPENDIX E
The Calculation Forms of End-of-Life Phase

***Table 26*. Photovoltaic System End-of-Life Costs and Base Year Values.**

Material Description	NAICS Sector	NAICS Sub-Sector	Retail Price 2010 $	Adjustment factor	CPI	Base year 2002 $
Transportation	Trade, Transportation, and Communications Media	484121: General Freight Trucking, Long-Distance, Truckload	$353.49	1	0.825	$291.64
glass recycling	Trade, Transportation, and Communications MediaWholesale trade	423930 Recyclable Material Merchant Wholesalers				$213.42
aluminum recycling	Ferrous and nonferrous metal production	Section 331314 Secondary Smelting and Alloying of Aluminum				$140.00
Crane rental with operator	Construction	238990 All Other Specialty Trade Contractors	$4,344.14	0.833	0.825	$2,986.66

***Table 27*. Greenhouse Gases Emission in the End-of-Life Phase of Solar Panel Power Supply System** Source: eiolca.net

Material Description	Total t CO2e	CO2 Fossil t CO2e	CO2 Process t CO2e	CH4 t CO2e	N2O t CO2e	HFC/PFCs t CO2e
Transportation	0.408	0.38	0.007	0.019	0	0
glass recycling	0.041	0.036	0.001	0.003	0	0
aluminum recycling	0.489	0.277	0.09	0.016	0.002	0.104
Crane rental with operator	2.08	1.62	0.28	0.114	0.056	0.013
	3.018	2.313	0.378	0.152	0.058	0.117

***Table 28*. Toxic Release in the End-of-Life Phase of Solar Panel Power Supply System**
Source: eiolca.net

Sector	Fugitive kg	Stack kg	Total Air kg	Surface Water kg	U'ground Water kg	Land kg	Offsite kg	POTW Metal kg	POTW Nonmetal kg
Transportation	0.002	0.009	0.011	0.002	0.002	0.015	0.006	0	0.003
glass recycling	0	0.005	0.005	0	0	0.007	0.002	0	0.001
aluminum recycling	0.031	0.117	0.149	0.016	0.039	0.26	0.095	0	0.05
Crane rental with operator	0.041	0.258	0.299	0.03	0.039	0.396	0.13	0	0.049
	0.074	0.389	0.464	0.048	0.08	0.678	0.233	0	0.103

APPENDIX F

Transportation Supporting Documentation

This part states the relevant data of transportation and calculates the price to be used in EIO-LCA shipping phase. Since the project was completed in January 2011, the data was collected during 2010 and 2011.

According to a Federal Highway Administration report, Work Zone Road User Costs (Mallela & Sadasivam, 2011), the calculation of the average payload should choose three-axis single-unit trucks and five-axis combination as samples. It is because these two kinds of models are most commonly used in the transport process and they are also the most economical and reasonable trucks. Their report also provided the average payload of these two trucks as 25,000 lb and 42,000 lb respectively. This research selects the 42,000 lb average payload combination truck, because energy consumption (BTU / ton-mile) of the combination truck is less than the consumption of single-unit truck. According to the report of American Transportation Research Institute, the average carrier cost per mile in 2011 is $1.548 (Fender & Pierce, 2012).Based on these assumptions and data, NAICS Sector 484121 should be used during EIO-LCA of transportation section. US Census Bureau Description describes this sector as: This industry comprises establishments primarily engaged in providing long-distance general freight truckload (TL) trucking. These long-distance general freight truckload carrier establishments provide full truck movement of freight from origin to destination. The shipment of freight on a truck is characterized as a full single load not combined with other shipments.

The freight needed in EIO-LCA includes two parts. One is the freight of raw material needed by manufacturers, and the other part is the fright of the product from the manufacturer to the site. Since the project breakdown already listed freight of the product, this freight can be used directly in EIO-LCA after remove the markup. Following is the calculation of the shipping of products. According to the freight showed in project breakdown, the device manufacturer is in Colorado. Assuming the manufacturer of silicon is in California, and the transport distance to the manufacturer is 1,100 miles. Assuming the manufacturer of aluminum racking is Aloca and the origin is Pittsburgh. The transport distance is 1,500 miles. Glass and other small parts such as inverter, batteries, etc. are local products. The transport distance is assumed as 300 miles. The freight of raw materials only considers crystalline silicon, aluminum racking and glass.

Sharp 235 W Panels made by polycrystalline silicon is used in the project. The data from different vendors shows that polycrystalline silicon is about 6-10g per watt. The total capacity of this project is 133 KW. So the weight of crystalline silicon is 1,064,000g (assumed 8g/watt), which is 2,346 lb. The size of Sharp 235 W Panel is 64.6 "x 39.1" x 1.8 " and each panel weights 41.9lb. So the solar panels used in this project are about 23,713.62 lb. The weight difference, 21,367.62lb, between crystalline silicon and solar panels is the weight of glass. According to the price of aluminum alloy racking showed in the project breakdown, the weight of the racking is estimated to be 400 lb.

Table 29.**The Calculation of Transportation**

Material	Est. WGT	Est. Miles	$ per lb	Est. $ ship
Polycrystalline silicon	2346	1100	0.040542857	95.113543
Aluminum Tack	400	1500	0.055285714	22.114286
Glass	21367.62	300	0.011057143	236.26483

Total: 353.4927