

# CHAPTER 1

## INTRODUCTION

### 1.1 Solar Photovoltaic (PV) Electricity and Sustainability

The United States consumed 23% of the total global electricity generated in 2006. The U.S. consumed 3,817 TWh out of the total of 16,379 TWh electricity generated worldwide (Energy Information Administration 2008). Solar resources only contributed to 0.01% (0.6 TWh) of the total national electricity demand. In 2006, for every unit (MWh) of electricity generated nationwide, an average (kg) of 644, 2.5 and 1 of CO<sub>2</sub>, SO<sub>2</sub> and NO<sub>x</sub> emissions were released (Energy Information Administration 2007). With the U.S. electricity demand forecasted to increase steadily (annual rate 1.6%) the next two decades, utilization of the current generation mix in the future will lead to significant climate change and regional environmental impacts (Energy Information Administration 2008a). Hydropower is associated with low air emissions, but significant amounts of methane emissions are released due to decomposition of aquatic plants. In addition hydropower adversely affects downstream water quality, and fish and wildlife populations (United States Environmental Protection Agency 2009). Hence it is indeed necessary to restructure the national resource profile by using a more sustainable fuel mix such as generating increased amount of electricity from non-hydro renewable resources.

The goal of this dissertation is to develop and apply an integrated assessment framework, for one of the sustainable electricity options, solar photovoltaic (PV) technology. The geographic focus of this work is the United States. In this dissertation different types of photovoltaic modules are considered that are widely manufactured in the market at present, and the future implications of using PV technology in the electricity sector is evaluated. The word '*Sustainable*' in this context implies energy, environmental and economic sustainability. Higher output energy generated by the PV panels during their lifetime when compared to the input energy for manufacturing and end of life management constitutes energy sustainability. Generating cleaner (lower criteria pollutants and greenhouse gas emissions released) electricity when compared to the grid electricity sources constitutes environmental sustainability. PV electricity mitigates CO<sub>2</sub> emissions from the grid. Inclusion of such monetary benefits from CO<sub>2</sub>

mitigation into the evaluation of the economic performance of PV technology should encourage economic sustainability.

## **1.2 Motivation**

The total amount of photovoltaic capacity to be installed is expected to increase in the future. The United States Photovoltaic Road Map Committee forecasts the growth of total (off-grid and on-grid) PV deployment in the U.S through 2020. From 0.83 GWp (in 2007), a total installed PV capacity of 3.2 GWp (gigawatt peak) is expected to be installed by the end of 2020 (U.S. PV Roadmap 2001). With such increasing fraction of PV electricity in the grid resource profile in the future, the primary motivation of this research arises from the need for evaluating the sustainability implications of such a scenario in the United States. This dissertation examines certain implications of generating increased PV electricity in the U.S. in the future. The front end implications include primary energy, cost, labor consumption, and environmental impacts associated with manufacturing different types of PV technologies. PV panels generate different amounts of electricity based on the solar radiation available at various locations inside the U.S. This governs the energy and environmental performance, and the pollution abatement implications of installation. Photovoltaic electricity displaces resources at the margin, and not the entire average mix of resources in the grid (Denholm et al 2009). Hence there is a need to develop methodologies to accurately estimate the potential CO<sub>2</sub> abatement by PV electricity at peak demands. There is also an increasing need to develop indicators that will aid energy planners in site selection for PV installation to derive maximum CO<sub>2</sub> abatement. Both the aforementioned objectives are also important motivations for this dissertation research work.

Increased PV electricity generation has significant economic implications. The cost of PV electricity has decreased from \$5.4 per Wp (in 2001) to \$4.8 per Wp (2009) (Solarbuzz 2009). With increased installation in the future, one of the motivations is also to evaluate the specific technology and policy changes in the future that will facilitate the highest increase in the economic performance of PV technology. In the future, the increased deployment of PV technology cannot be evaluated in isolation but in competition with fossil based, non renewable and other renewable technologies. The PV deployment under such a competitive scenario is indeed dependent on its decreased production cost (due to learning curve and economies of scale effect) and CO<sub>2</sub> emission factor. Hence evaluating the amount of PV electricity to be generated in the future under constraints of a CO<sub>2</sub> cap is also an important motivation for this research.

## **1.3 Life Cycle Modeling and Integrated Framework**

The life cycle stages for a PV module include raw material extraction, material production, module manufacturing, module usage and end of life management

components. Life cycle modeling involves characterization and comparison of primary energy consumption and environmental air emissions associated with each of the life cycle stages included, among different types of PV technologies analyzed. The life cycle model of the PV technology identifies the energy and environmental impacts associated with manufacturing and end of life management stages. This dissertation applied an ‘Integrated Assessment’ framework. The integration emphasizes using results obtained in the modules developed, as modeling parameters for constructing the other modules in the dissertation. Figure 1.1 presents the integrated framework and the results obtained from the four modules constructed in this dissertation. The results of the life cycle model are integrated with other modules to further evaluate the performance of PV technology from different standpoints. The life cycle modeling results (module 1) are integrated with lifetime PV electricity output (module 2), to develop the energy and environmental performance module. Module 2 analyzes the PV technology based on energy and environmental sustainability metrics such as Net Energy Ratio (NER), Energy Payback Time (E-PBT), pollutant emission factor (grams/kWh) and a range of potential pollution abatement. The lifetime PV electricity generated was also used in conjunction with the emissions from manufacturing and end of life management to evaluate the pollutant emission factor for the PV modules. This second module also evaluates the CO<sub>2</sub> abatement potential of PV electricity, at different scales of fuel mix profiles for the conventional grid. Further, the CO<sub>2</sub> abatement potential was also analyzed under a time varying grid fuel mix throughout the life time of the PV technology.

The third module developed involves the integration of the life cycle model results with a micro-economic cost benefit analysis framework. Results from module 1 and 2 are used to develop this model. The economic model is constructed using results such as pollutant emissions associated with manufacturing, lifetime PV electricity generation and environmental benefits derived from PV electricity generation. This energy economic module evaluates the economic performance of PV technology due to cost reducing and output enhancing technological changes, and potential policy changes in the future. A set of sensitivity analyses are performed identifying the particular technological and policy parameters that provide the highest increase in the economic performance of PV technology in the future. Eventually, the life cycle results are also used in conjunction with a non-linear programming model to develop a technology transition model for PV technology. The cost and emissions results from the first module were integrated with the technology transition module. The objective function of the model is to maximize present value of discounted net consumer surplus; the constraint is the CO<sub>2</sub> cap in the impending future. This constrained optimization model analyzes the future deployment and the future marginal cost reduction of PV electricity generation, in competition with other non-renewable and renewable electricity generation sources. The deployment and decrease in marginal cost of PV technology is evaluated under different economic, technological and policy changes in the future.

## **1.4 Research Objectives**

The specific questions that this research work aims to answer are listed below categorized based on the chapters of the dissertation

### **Photovoltaic Manufacturing and Recycling**

1. What are the primary energy, cost incurred and labor consumption associated with manufacturing the five different types of PV modules in the U.S. market at present?
2. What are the environmental air emissions and impacts, associated with manufacturing the five different types of PV modules in the U.S. market at present?

### **CO<sub>2</sub> Abatement at Different Fuel Mix Scales by PV Electricity**

3. What is the potential CO<sub>2</sub> abatement of generating PV electricity, when different scales of fuel mix (national, regional, state and marginal) are applied?
4. What is the potential CO<sub>2</sub> abatement of PV electricity generated, when using a time varying fuel mix for the future?

### **PV Economics**

5. What are the potential technological (output enhancing and cost reducing) changes in the future that provide the highest increase in the economic performance of the PV technology?
6. Which policy framework (among the options considered) when implemented, provides the highest increase in the economic performance of the PV technology?

### **PV Technology Transition**

7. How will the deployment of PV technology evolve in the future, in competition with non-renewable and other renewable electricity generating technologies?
8. What is the cost reduction of PV electricity, under different economic, technological and environmental policy changes in the future?

## 1.5 Research Contributions

The specific contributions of this research work that would add to the existing knowledge, are listed below

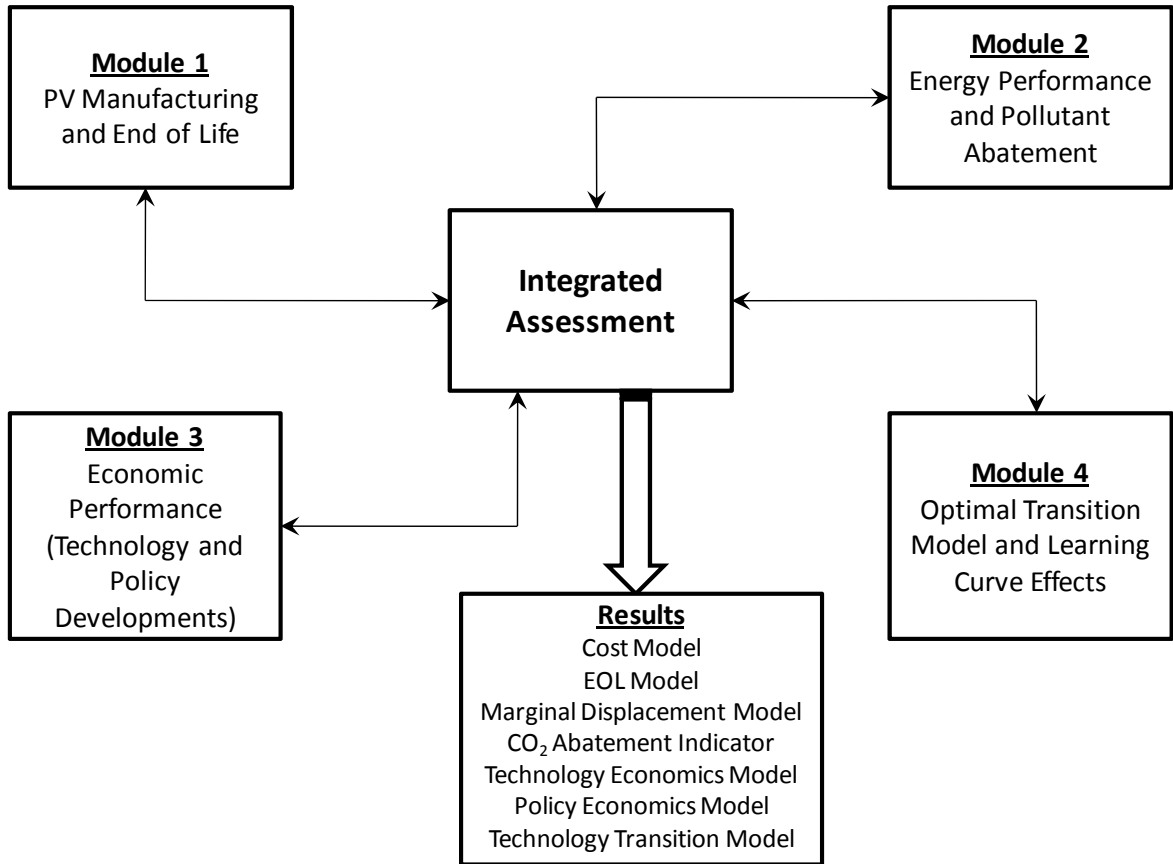
1. **Cost Model:** The model integrates information from three sources, labor intensity for PV technology manufacturing, structural differences in PV modules and wage rates from Bureau of Labor Statistics (BLS). The model analyzes the current total cost of labor for manufacturing amorphous silicon and crystalline PV modules in the U.S. This model is integrated with the technology transition model. The PV technology cost results are used to represent the marginal costs for PV electricity generation in the transition model.
2. **End of Life Management (EOL) Model:** Conventionally, LCA studies have not included the energy and emissions associated with the recycling and disposal of PV modules. The EOL recycling and disposal model was constructed for each of the five modules using data recently reported by actual recycling facilities. The model constructed investigates the net reduction in primary energy consumption and CO<sub>2</sub> emissions released, highlighting the benefits of recycling different PV technologies.
3. **Marginal Displacement Model:** This model evaluates the CO<sub>2</sub> displaced at the margin during peak demands, and compares the abatement results to the results obtained by using average fuel mix approaches at different scales. This model establishes two important results; 1. Marginal abatement can be very different from the abatement calculated using average fuel mix approaches; and 2. CO<sub>2</sub> abatement results for PV technology are a function of both the resource profile displaced at the margin and the capacity of the photovoltaics installed.
4. **CO<sub>2</sub> Abatement Indicator:** This metric captures the combined effect of variability of solar resource across the U.S. and the CO<sub>2</sub> intensity of the regional grids. It acts as a guideline for energy planners in site selection for PV installation, to derive maximum CO<sub>2</sub> abatement. The same indicator is developed for the marginal case, using the two load zones (ERCOT and CAL-ISO) considered in the study.
5. **Technology Economics Model:** The technology economics model developed evaluates the influence of output enhancing and cost reducing PV technology changes on the economic performance of PV technology. The particular

technological changes that provide the highest increase in the economic performance of PV technology are recommended.

6. **Policy Economics Model:** The policy economics model evaluates the influence of certain policy changes in increasing the economic performance of PV technology. The incorporation of pollutant allowance prices (units: cost / ton, cost / kg, cost / ounce) into the evaluation of the economic performance of PV technology is a unique feature of this module.
7. **Technology Transition Model:** In this model, the potential marginal cost of PV electricity is evaluated under different conditions of the following; 1. competing energy prices; 2. technological progress ratios; and 3. more stringent CO<sub>2</sub> emission caps. This model calculates the potential costs of PV electricity in the future, in competition with other electricity generation technologies.

## 1.6 Journal Submissions and Publications from Chapters

The four different modules are developed in this dissertation (Chapter 3, 4 5 and 6). Life cycle modeling section in Chapter 3 has been published in the 'Journal of Energy Policy' (Pacca, S.A. Sivaraman, D. Keoleian, G.A. 2007. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy (35) 3316 - 3326). Chapter 4 (marginal displacement model, CO<sub>2</sub> indicators and dynamic mix) has been submitted to 'Energy Policy' and is under review. This work is developed further by Dr. Jarod Kelly (Post Doctoral Fellow, Center for Sustainable Systems, University of Michigan). This chapter is also the basis for the paper accepted for submission in the American Society of Mechanical Engineers (ASME) conference in September 2009. This is a paper in press (Kelly, J. Sivaraman, D. Keoleian. G.A. 2009. Analysis of avoided carbon-dioxide due to photovoltaic and wind turbine technologies displacing electrical peaking facilities). The micro-economic cost benefit model developed for photovoltaics (Chapter 5) has been submitted to the 'Journal of Renewable Energy' and is under review (Sivaraman, D. Moore, M.R. 2009. Integrated Economic, Energy and Environmental Analyses of a Renewable Energy Technology: Photovoltaic Electricity in Michigan). The final module (Chapter 6) involving photovoltaic technology transition has been developed in collaboration with the Argonne National Laboratory (Argonne, Illinois). This model is expected to be integrated with the AMIGA (All Modular Industry Growth Assessment) model used by Argonne Laboratory. AMIGA contains many built in modules for different electricity generating technologies. The contribution from this dissertation is adding a specific technology characterization module for PV technology to the AMIGA model.



**Figure 1.1: Integrated framework schematic, with the four research modules in this dissertation**

## REFERENCES

Denholm, P. Margolis, R.M. Milford, J. 2009. Quantifying avoided fuel use and emissions from solar photovoltaic generation in the western United States. Environ Sci Technol (43) 226 – 232

Energy Information Administration (EIA). 2007 Annual Energy Review 2007

Energy Information Administration (EIA). 2008. International Electricity Consumption Link: <http://www.eia.doe.gov/emeu/international/electricityconsumption.html> Link accessed on March 02, 2009

Energy Information Administration (EIA). 2008a. Forecasts and Analyses Link: <http://www.eia.doe.gov/oiaf/forecasting.html> Link accessed on March 02, 2009

Solarbuzz. 2009. Solar module retail price index. Link: <http://solarbuzz.com/> Link accessed on March 03, 2009

United States Environmental Protection Agency (U.S.EPA). 2009. Clean Energy: Hydroelectricity

United States Photovoltaic Industry Road-Map. 2001



## CHAPTER 2

### PHOTOVOLTAIC (PV) TECHNOLOGY: ENERGY AND ENVIRONMENTAL PERFORMANCE, ECONOMICS AND TECHNOLOGY TRANSITION

#### 2.1 Introduction

In 2007, out of the total U.S. electricity demand of 4,160 billion kWh, 8.5% (351 billion kWh) was generated from renewable resources. The renewable portfolio of resources consisted of 30% non-hydro renewable resources that contributed 103 billion kWh to the total. A total of 606 GWh was generated from solar technologies, contributing to 0.01% of the national electricity demand. With 72% of electricity generated from fossil based resources, 3.8 million metric tons of NO<sub>x</sub>, 9.5 million metric tons of SO<sub>2</sub>, and 2,460 million metric tons of CO<sub>2</sub> was released. These emissions contributed significantly towards air pollution and climate change impacts on the environment (Energy Information Administration 2009). Even though nuclear power partially addresses the CO<sub>2</sub> problem, its radioactive waste imposes significant disposal risks on future generations. Hence the current non-renewable electricity generating sources are clearly unsustainable and change towards more sustainable technologies is necessary. In this study, the *Photovoltaic (PV) Technology*, a renewable electricity source option will be evaluated from multiple perspectives. An integrated model that consists of four modules will be built analyzing the photovoltaic technology from energy, environmental, economic, policy and technological perspectives. Figure 2.1 illustrates the integrated approach followed in this study, and also presents the research components that comprise each of the four modules in this study. The purpose of this chapter is to provide a literature review of the previous work relevant to the methods for the integrated assessment developed in Chapters 3 to 6, in this dissertation.

#### 2.2 Background and Literature Review

##### 2.2.1 Solar Radiation and Photovoltaic Electricity Output

The National Renewable Energy Lab (2008) contains data on both annual average and hourly solar radiation at different locations in the national U.S. Figure 2.2 presents

the hourly solar radiation data for San Francisco (California) and Ann Arbor (Michigan), with San Francisco receiving higher amounts of solar radiation than Ann Arbor. The hourly solar radiation (in watts/m<sup>2</sup> area of the module) for each of the 8,784 hours for the year 2004 is presented. The total annual solar radiation per unit area, under the curve for San Francisco and Ann Arbor are 1,599 and 1,337 kWh, the daily average solar radiation was calculated to be 4.37 and 3.66 kWh/m<sup>2</sup>/day. The photovoltaic electricity output is calculated (equation 2.1) using the daily average solar resource available in conjunction with technological parameters such as module area, module lifetime, module efficiency and inverter efficiency.

$$E = R \cdot A_{mod} \cdot N \cdot \eta_{conv} \cdot \eta_{inv} \quad (\text{equation 2.1})$$

This equation states that the lifetime electricity generated,  $E$  (kWh), is equal to the product of daily average solar radiation,  $R$  (kW / m<sup>2</sup> / day), area of the module,  $A_{mod}$  (m<sup>2</sup>), lifetime of the module ( $N$ , days), conversion efficiency of the module ( $\eta_{conv}$ ) and the DC-AC inverter efficiency ( $\eta_{inv}$ ). Thus, the total electricity generated from any PV system is a product of  $E$ , the total number of modules installed and their lifetime. Figure 2.3 presents the hourly output based on the technological parameters of a Kyocera multi-crystalline module, for San Francisco, California. A photovoltaic capacity of 100 MW<sub>p</sub>, generates an annual average of 149,450 MWh, throughout the lifetime of the technology. The energy and environmental performance of PV technology is evaluated by using the life cycle assessment framework. The results are normalized using lifetime PV electricity generated to calculate the primary energy consumption (MJ / kWh) and the emissions released (e.g. kg CO<sub>2</sub> / kWh).

### **2.2.2 Life Cycle Assessment (LCA) of PV Technology: Manufacturing, and Energy and Environmental Performance**

LCA is a framework designed to evaluate a product or process throughout its life cycle, including stages such as raw material acquisition, production, use, final disposal and recycling (ISO 1997). Often, LCA elucidates unseen environmental and social burdens incurred over a product's lifetime and can lead decision-makers toward forward-looking and well-informed decisions. The impacts of using the PV technology can be determined by accounting for the energy and environmental emissions associated with PV module manufacturing, end of life management and the module usage stages.

In Chapter 3, a life cycle model is constructed for five different photovoltaic modules (mono-crystalline, multi-crystalline, string ribbon, amorphous silicon and cadmium telluride) used extensively in the U.S. market at present. The crystalline technology constituted 71% of the total capacity of photovoltaics manufactured in 2004. The thin film technologies considered in this dissertation comprised 28% of the remaining capacity of photovoltaics manufactured. This section discusses previous

studies that have evaluated the energy and environmental performance of PV modules. One of the metrics used to evaluate the energy performance of PV modules is energy payback time. Energy Payback Time (E-PBT) is the ratio of the total primary energy consumed while manufacturing the system to the annual energy output of the PV system. Table 2.1 provides a summary of the E-PBT and CO<sub>2</sub> emission factor results for the studies discussed in this section. Alsema and Nieuwlaar (2000) analyzed energy payback time (E-PBT) and CO<sub>2</sub> emission factor (g / kWh) for multi-crystalline and thin film PV technologies. The total primary energy required for manufacturing a single multi-crystalline and thin-film silicon module was 4,600 MJ and 1,600 MJ respectively. For the southwestern U.S. conditions (solar radiation average 2,200 kWh / m<sup>2</sup> / year) tested, the energy payback time was reported to be 2.5 years (multi-crystalline) and 2 years (thin film), and the CO<sub>2</sub> emission factor was 60 g / kWh (multi-crystalline) and 50 g / kWh (thin-film). The study also evaluated the difference in E-PBT between ground-mounted and rooftop PV systems. The rooftop PV modules are installed at an optimum angle to receive higher amounts of solar radiation, when compared to the ground mounted configuration. When tested under medium irradiation conditions (1,700 kWh / m<sup>2</sup> / year), the rooftop systems (EPBT of 2.5 to 3 years) performed better than the ground mounted systems by 1.5 years. Figure 2.4 presents the EPBT of thin film and crystalline technologies, for both configurations; in addition the study also presents the potential increase in energy performance of PV technologies in the future. In a separate study Alsema (2000) investigated the potential improvements in energy and environmental performance of thin film and multi-crystalline PV technologies. The CO<sub>2</sub> intensity of the two PV technologies was investigated under the following three scenarios. They are 1. Potential increase in conversion efficiency 2. Not using high purity electronic grade silicon (as in the semi-conductor industry), and 3. Decrease in the thickness of thin film modules. The CO<sub>2</sub> emission factor of the thin film and crystalline technologies was (g/kWh) 50 and 60 (in 1999), and projected to go as low as 10 and 20, by 2020. Figure 2.5 presents the CO<sub>2</sub> emission factor for the PV technology options, in comparison with other grid supply options. As a side note, the cell conversion efficiency of the different types of PV modules as of 2007 is presented (Figure 2.6), with technological breakthroughs in the future the increase in conversion efficiency is expected to decrease the levelized cost (¢/kWh) of electricity. By the end of 2007 photovoltaic cell efficiencies as high as 40% were observed for multi-junction concentrators, in the research stage of development. The module efficiency is lower than the cell efficiency due to the interconnection losses.

Oliver and Jackson (2001) studied the primary energy consumption to deliver unit electricity, for a centralized PV and a building integrated PV system (BIPV) and compared the results to that of the average European grid. To deliver unit electricity, the European grid (13 MJ/kWh) consumed more than thrice the amount of primary energy consumed by the three different PV scenarios considered. The ‘net BIPV’ scenario also

took into consideration the avoided energy investment in manufacturing cladding materials for a building roof. The primary energy factor for centralized PV, BIPV and net BIPV was 4, 2.7 and 2.2 MJ/kWh respectively, indicating the energy benefits of PV electricity generation (Figure 2.7). Alsema and Wild-Scholten (2006) also analyzed the energy impacts and pay back times of mono, multi and silicon-ribbon crystalline PV technologies. The primary energy consumption (MJ / m<sup>2</sup>) for manufacturing mono, multi and silicon-ribbon modules are 5,100, 4,000 and 2,700 respectively. The energy pay back times when southern European conditions were used (solar radiation average 1,700 kWh / m<sup>2</sup> / year) are 2.8 years (mono), 2.2 years (multi) and 1.7 years (silicon-ribbon) respectively. Kannan et al (2006) studied a 2.7 kWp mono-crystalline system installed in Singapore. This study reports 6,900 MJ of primary energy to be consumed for manufacturing a single mono-crystalline module. The CO<sub>2</sub> emission factor of the mono-crystalline module is relatively high in this study, 217 g CO<sub>2</sub> / kWh. This high value is possibly due to the usage of old data sources, but it is still significantly lower than the carbon emissions released during electricity generated from coal and oil based resources. Keoleian and Lewis (2003) analyzed the energy and environmental benefits of using building integrated (thin-film silicon) photovoltaic modules. The performance of the roof shingles was calculated for different locations with different amounts of solar radiation inside the U.S. The net energy ratio (NER)<sup>1</sup> of the modules was 3.9 when installed in Detroit, Michigan and reached a maximum of 5.9 (when installed in Phoenix, Arizona). This highlights the energy advantages of the PV technology, especially when compared to conventional fossil based sources that have a net energy ratio of 0.3. The net environmental advantages of installing the BIPV system are reflected in the fact that the system avoids 1,230 g carbon, 5.3 x 10<sup>-4</sup> g lead, 4.15 g NO<sub>2</sub>, 4.81 g PM<sub>10</sub> and 7.26 g SO<sub>2</sub> for each unit (kWh) of life time PV electricity generated. The energy back time of the modules ranged from a minimum of 3.4 (in Phoenix, Arizona) to a maximum of 5.5 (in Portland, Oregon).

Keoleian and Lewis (1997) studied the energy performance of a UPM 880, a thin film laminate module. The study evaluated the NER of the module under two scenarios using conditions of a module lifetime of 20 years and installation location of Phoenix (AZ). The NER of the module was 2.77 (frame included) and 4.52 (when the frame was not included). When installed in Phoenix (Arizona) the EPBT was 1.4 years (frame included) and 1.8 years (when the frame was not included). The study identifies the energy intensity of the aluminum frame used, the frame contributed to 57% of the total primary energy consumed for module manufacturing. Pacca et al (2007) compared the energy and environmental performance of amorphous silicon and multi-crystalline modules installed in Michigan (USA). They tested the various life cycle parameters that influenced the current and future performance of PV technology. Among all the life cycle

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<sup>1</sup> Net Energy Ratio = Lifetime energy output from the system / Total primary energy consumed while manufacturing the system (applicable to this study)

parameters, using lesser amounts of input manufacturing energy improved the energy performance of both types of PV modules significantly. The energy payback time and CO<sub>2</sub> emission factor of amorphous-silicon and multi-crystalline module was reported to be 3.2 and 7.5 years, and 34.3 and 72.4 g CO<sub>2</sub> / kWh respectively. The other interesting feature of this study is the '*PV Breeder*' analysis, where the net energy ratio of PV modules was analyzed when the manufacturing energy for photovoltaics was generated from another set of PV modules. In this scenario, the NER of (thin film laminates) PVL 62 and PVL 136 modules was 23.4 and 21.1 respectively. This highlights the potential energy benefits of using renewable sources to manufacture other renewable technologies. Perpignan et al (2009) investigated the energy trade-offs in installing single and dual axis equipment to enable the PV panels to receive increased solar radiation. From a life cycle standpoint, installing tracking equipments increases the initial energy investment (for metallic structures, foundations and wiring) but also increases the productivity of the system throughout its lifetime. Figure 2.8 presents the solar resource and E-PBT for a range of latitudes (35° - 45°) in Spain, it was determined that at low latitudes the single and dual axis systems perform better than the fixed PV system. As the latitude increases, the E-PBT of the fixed system is not significantly different from that of the fixed system due to lower solar resource available. The single and dual axis E-PBT ranged from 2 – 5 years for the crystalline modules installed. At an annual solar radiation value of 1,800 kWh/m<sup>2</sup>/year, the E-PBT of dual axis and single axis systems was reported to be 0.8 and 0.87 of that of the fixed system (Figure 2.9). The results of this study indicate that energy investment in tracking equipments pays back for itself when installed in locations with higher solar radiation.

Fthenakis and Kim (2006) studied the energy and environmental impacts of manufacturing a cadmium telluride PV module. They determined that manufacturing a Cd-Te module consumes 1,200 MJ/m<sup>2</sup>, has a CO<sub>2</sub> emission factor of 18 g CO<sub>2</sub>-eq / kWh, and an energy payback time of 0.75 years. The release of cadmium into the air is one of the important human health concerns of manufacturing the Cd-Te module. Fthenakis and Kim (2006a) also quantified the cadmium emission factor (23.3 mg Cd / GWh) that was reported to be the lower than values for crystalline PV technologies. Other electricity generating sources such as coal, natural gas, oil, nuclear and the European electricity grid fuel mix also emit higher amounts of cadmium than manufacturing a Cd-Te module, on a per unit electricity basis (Figure 2.10). The manufacturing of Cd-Te module also releases less arsenic, lead, mercury and nickel emissions when compared to the crystalline PV technologies. Experimental studies have evaluated the risk of cadmium release, into air during residential fires, and into the environment after landfill disposal. In the U.S, typical residential fires reach a temperature of 800 – 900 C (in the roof) and 900 – 1,000 C (in the basement). The melting point and evaporation point of cadmium telluride is 1,041 C and 1,050 C. In addition the fact that Cd-Te is encapsulated inside a double glass wall in the PV module makes the release of cadmium during residential fires highly

unlikely. Today's Cd-Te modules also pass the toxicity characteristic leaching procedure (TCLP) for non-hazardous waste, emphasizing the fact that it is also highly unlikely that cadmium leaches out of landfills after disposal (National Renewable Energy Lab 2009).

LCA studies of PV systems do not generally include the life cycle stage of recycling and disposal of PV modules. This is predominantly due to the fact that the energy consumption during the disposal of PV modules is much lower when compared to the energy component in other life cycle stages such as raw material extraction, module manufacturing and usage of the actual modules. In fact, Battisti and Corrado (2003), report that the cumulative energy demand during disposal of the modules for a kWp multi-crystalline PV system contributes to 0.0781% of the total energy demand. It is very evident that the primary energy consumption associated with the disposal phase is definitely very low when compared to other stages. Fthenakis and Kim (2006a) analyzed the cadmium emissions into the air at various life cycle stages of a cadmium-telluride module. They report that, Brookhaven National Laboratory (BNL) and First Solar together, developed a hydro-metallurgical process for the recycling of cadmium in the Cd-Te module. The study reports that there are no cadmium atmospheric emissions during module recycling (since all the recycling processes are conducted at ambient temperature and pressure), thus refuting any human health concerns of Cd-Te module recycling. In general, disposal and recycling of most types of PV modules are associated with problems concerning the safe disposal of lead (Pb) used in the solder in PV modules (Fthenakis 2006).

Muller et al (2006) reported the energy savings from recycling a multi-crystalline wafer (module capacity 160 Wp), the study reports a 214 kWh (electricity) reduction in the total energy consumed if one used a recycled wafer instead of a newly manufactured wafer. Figure 2.11 presents the schematic of the two step recycling process, mechanical disassembly followed by chemical etching to recycle wafers recovered from modules at the end of their life. The electricity consumption was reduced from 400 kWh to 186 kWh, representing a 53.5% reduction when a recycled wafer is used. It is apparent from this study that there is a potential to reduce the total energy consumption of modules, by recycling wafers. Other than the material and energy components, the amount of solid waste generated is an important concern associated with the life cycle disposal stage of the PV modules. Fthenakis (2000) reports that a 10 MW cadmium telluride PV module facility will have to manage a total weight of 2,000 tons of solar panels at the end of their life cycle. The solid waste constitutes 0.1% semi-conductor material and the rest of it, being mainly glass. Hence, the increased amount of PV capacity installed at present requires a proper infrastructure to be developed for managing the waste streams associated with the disposal of the PV modules in the future.

First Solar, the largest manufacturer of Cd-Te modules in the world performed an industrial hygiene study in one of their pilot plants. The annual total cases of injuries

(3.8) and lost workday cases (1.2) were both lower than that of the electronic equipments manufacturing and the general manufacturing sector in the U.S. (Bohland and Smigielski 2000). There are also other toxic materials that are released into the air during photovoltaic manufacturing. Silane is an explosive gas that is used to manufacture amorphous silicon; other toxic gases such as phosphine and diborane are used to electronically dope the semiconductor material. Toxic hydrogen selenide that is sometimes used to manufacture copper indium diselenide is carefully managed by the industry by using gas detection and gas handling systems. Silane ( $\text{SiH}_4$ ) is used in both the manufacturing of crystalline cells and amorphous silicon modules. Inhalation of silane can cause severe damage to the human central nervous system, and in certain cases be fatal (National Renewable Energy Lab 2005). Silane when released into the air is also instantaneously combustible. The usage of silane in the semi-conductor industry has resulted in accidents. Based on a survey of twelve U.S. semiconductor manufacturers, the release of silane into the atmosphere caused 36 industrial accidents from 1982 to 1997. During the same time, two fatal accidents were reported in Japan due to the release of silane (Fthenakis et al 2005). On the contrary, most photovoltaic manufacturing facilities however, use sophisticated gas handling systems with safety features to minimize the risks of fire and explosion. Until now, no large scale accidents have been reported in photovoltaic manufacturing plants worldwide (Goetzberger and Hoffmann 2005). Release of toxics from landfill disposal of PV modules (as discussed above) is not of significant concern, because PV materials are predominantly encased in glass or plastic frames and also many of the materials are insoluble (National Renewable Energy Lab 2007). Proper infrastructure must be developed with sufficient capacity to handle the waste streams emanating from the photovoltaic end of life management processes.

As discussed above, a number of life cycle studies have been performed for different PV technologies. It is observed that various studies report slightly different results for similar PV technologies. This is because the energy-environmental performance of PV technologies is influenced heavily by local conditions such as solar radiation and energy sources used for manufacturing. Other factors such as small differences in the conversion efficiency of the modules analyzed and different module lifetimes used in various studies also lead to variation in results. In this dissertation a life cycle assessment is conducted to facilitate a comparison across the primary PV technologies existent in the U.S. market. The life cycle model constructed is very indicative of the latest trends in the photovoltaic industry. After constructing the life cycle model, it will be integrated with a microeconomic model that indicates the economic performance of the PV technology. The micro-economic model also internalizes the carbon externalities thus adding the monetary benefits of reduced pollution to the benefits derived from PV electricity generation. The next section discusses selected previous studies that analyzed the economic performance of PV technology.

### 2.2.3 Economic Analysis of PV Technology

Traditionally studies have evaluated the cost of PV electricity and relevant environmental benefits separately. Shaahid and Elhadidy (2008) studied the economic and environmental performance of a hybrid PV and diesel system in Saudi Arabia. For a 4 kW PV and 10 kW diesel configuration (at 22% PV penetration and 3 hours battery storage capacity), the cost of electricity was reported to be 17.9 ¢/kWh. The generation of PV electricity resulted in 19% reduction in annual diesel consumption, and in an annual abatement of 2 tons of carbon, when compared to the base case (diesel only scenario). Ren et al (2009) developed an economic optimization model to identify cost and technological parameters that influenced a PV installation decision in Japan. The study tested four parameters such as capital cost, discount rate, electricity price and conversion efficiency on their individual influence in optimizing the PV capacity installed; capital cost was reported to influence the PV installation decisions more than other parameters. The study also reported a grid electricity break-even price of 23 ¢/kWh, at which point the monetary benefits from PV electricity breaks-even with the initial investment.

Only a few other studies have analyzed the economic performance of the PV technology, by integrating the energy and environmental benefits of the technology into the economic model. Kemmoku et al (2003) investigated the influence of a carbon tax on the electricity fuel mix in Japan. A framework involving residential customers generating PV electricity in their roof tops and selling it to conventional grids was studied. The study reported that under a carbon tax world the electricity generated from coal will decrease, in combination with an increase in usage of liquefied natural gas (LNG) and nuclear resources (Figure 2.12). The study developed two economic indicators for PV electricity, a ratio of buying price of PV electricity by the electric utilities, to its generation cost. The ratio reached a value of 1.35 – 1.45 indicating the profitability of generating PV electricity. The same ratio increased to 1.50 – 1.60 when nuclear plants of high capacity were used in conjunction, proving that the economic profitability of PV electricity increases with an increase in usage of nuclear energy. In addition (by year 2025), the buying to selling price ratio (ratio of upper limit of buying price for PV electricity, to the price at which consumers are willing to sell it) of 0.68 (no carbon tax) and 0.86 (carbon tax ¥25,000 per ton carbon) indicates the influence of carbon tax in improving the economic returns when generating PV electricity (Figure 2.13). The actual buying price of PV electricity increased from 9 to 11.5 ¥/kWh (0.09 to 0.0115 \$ / kWh), when a carbon tax of ¥25,000 (\$254 per ton carbon) is implemented. Oliver and Jackson (2000) divided the total cost of electricity generation into cost of generation and external cost of CO<sub>2</sub> emissions released. The PV technology has a higher cost of electricity generation and a very low CO<sub>2</sub> externality, as opposed to the European grid which has a low generation cost but a very high CO<sub>2</sub> externality. Figure 2.14 presents the economic costs and CO<sub>2</sub> emissions associated with European grid electricity and PV technology. PV cost



of electricity (pence/kW) was 79 as opposed to the grid electricity cost of 7; on the contrary the grid electricity (0.55 kg/KW) emitted more than three times the amount of CO<sub>2</sub> emissions than the PV option (0.17 kg/kW). The paper argues that at present the PV technology is not cost competitive to compete with the other cheaper CO<sub>2</sub> abatement options, but with expected sufficient technological improvements in the future, PV technology can be a viable abatement option. Spanos and Duckers (2004) evaluated the particular time period in which it becomes economically viable for PV systems to be installed on buildings. They considered a *Net Metering* scenario in UK, in which the PV electricity generated displaces grid electricity that would have otherwise been purchased. The study also takes into account the PV technological and cost developments, avoided environmental taxes and forecasted increase in the U.K. electricity prices. With increased PV module efficiency and lower costs combined with avoided environmental taxes and increased electricity prices, the study concluded that by 2009 to 2013, PV systems will be deployed on a larger scale on top of residential buildings. According to this study, between 2009 and 2013, PV electricity is also expected to become a viable economic option when compared to the grid electricity prices.

Keoleian et al (1999) analyzed the present value avoided damage cost (at 4% discount rate) due to electricity generated from the PV system throughout its lifetime. The paper considered two separate scenarios, calculating avoided damage cost with and without carbon regulations. Without the carbon regulations (in Detroit, Michigan), the PV system reduces a present value damage cost of \$928, whereas with the carbon regulation (\$130 / ton) the present value avoided damage cost increases to \$2,195. The air pollutants and greenhouse gases included in calculating the avoided damage costs are CO, Pb, NO<sub>x</sub>, N<sub>2</sub>O, PM<sub>10</sub>, SO<sub>2</sub>, CO<sub>2</sub> and methane. The study also reports similar results for various others states inside the U.S. Bernal Agustin and Dufo-Lopez (2006) conducted an economic and environmental analysis of PV modules installed in Spain. They monetized the energy-environmental benefits derived during the entire lifetime of the PV modules to determine the total financial benefits of the PV system. Eventually they expressed the economic performance of the PV system in terms of net present value for a range of discount rates and for different amounts of subsidies provided. They reported the net present value of the amorphous silicon / multi-crystalline combination to be 1000-7000 €/kWp (at 20% subsidization and for 0 to 6% discount rates) and the damage cost avoided to be 0.37 €/kWh (Figure 2.15). They further tested the change in the economic performance of the PV modules by changing different technological parameters (e.g. reduction in O/M cost). Studies have also analyzed the decrease in production cost of PV technology as a function of increase in demand and higher deployment. Oliver and Jackson (1999) studied the potential decrease in the production cost of PV technology due to an increase in demand. The study reported the price elasticity of demand for photovoltaics to increase, once the production cost drops below a particular threshold level (Figure 2.16). As PV electricity expands its utilization to larger markets, the cost is

expected to decrease significantly in the future. Seng et al (2008) also studied the photovoltaic installation under the regulatory framework in Malaysia, and reported that residential customers are unable to breakeven with their initial investment, even with a 70% government subsidy rate. In 2007, at a subsidy rate of 70% the net present value was estimated to be (RM) – 8,000 (- \$2,293).

The economic analysis of the PV technology derives significantly from the life cycle modeling results, to monetize the energy and environmental benefits of the PV system. In this study the life cycle modeling results is integrated into the economic analysis, by modeling the electricity output of photovoltaic systems. Using the pollutant allowance prices to determine the indirect financial benefits of the PV technology is a novel feature of this study. The economic model further identifies the different technological parameters that when improved, provide the maximum increase in future economic performance of the PV technology. In the fourth module of this study, a technology transition module is constructed to investigate the growth and deployment of PV technology not in isolation, but in competition with other electricity generation technologies. This module can be integrated with macroeconomic equilibrium models such as AMIGA (explained below), information about optimal control models and previous works discussing the AMIGA model are discussed below.

#### **2.2.4 Optimal Transition Models and AMIGA**

A number of studies previously have examined the strategies that can be employed to facilitate an optimal transition to a de-carbonized economy. Nordhaus (1992) analyzed five policy options to evaluate an optimal transition path to controlling greenhouse gases. The study built a Dynamic Integrated Climate Economy (DICE) model to evaluate the five policy options (no control, optimal policy, ten year delay of optimal policy, twenty percent carbon reduction from 1990 levels and geo-engineering). Maximizing the present value of welfare (difference between benefits and damage costs), the optimal policy option has a present value benefit of (1992 \$) 271 billion, in this option the rate of greenhouse gas emissions reduction is 10% at the beginning, and then 20% in the future. From a broader standpoint, the damage cost of not controlling greenhouse gases was (1992 \$) 5.6 trillion, and the benefits of mitigation were \$271 billion higher. The study also reports the carbon tax (per ton) necessary to implement the optimal policy framework to be \$5 at the beginning, to eventually reach as high as \$20 by the end of the time period of analysis. This work proposed an economically optimal solution, for an inter-temporal challenge such as the climate change problem. Tsur and Zemel (2003) investigated the various research and development investment frameworks for backstop (e.g. renewable) technologies, to arrive at an optimal transition from a non-renewable resource. They concluded that ‘Most Rapid Approach Path’ (MRAP) investment framework facilitates the highest reduction in the marginal cost of the

backstop resource; it essentially involves investing in the backstop resource at the maximal affordable rate at the beginning when the knowledge is low, and possibly decreasing the investment with time as knowledge approaches the intended target.

Bosetti et al (2008) studied the optimal energy investment and research development strategies to stabilize CO<sub>2</sub> concentrations at 450 ppm (parts per million). Carbon capture and storage (CCS), nuclear and renewables were considered to be three potential options to achieve CO<sub>2</sub> stabilization. The study emphasizes the importance of price signals to facilitate the development of low carbon electricity generation technologies. The CO<sub>2</sub> price with and without a technological breakthrough was projected to be \$70 / ton and \$90 / ton respectively by 2030, to achieve the 450 ppm stabilization. Conceptually, CCS involves storing (disposing) CO<sub>2</sub> gas beneath the ground or sea for a long time in the future. It is akin to disposal of spent fuel rods from generating nuclear energy. The radioactivity of the spent fuel rods decreases after ten years by a factor of several thousands. The disintegration of the nuclei (e.g. cesium 137 and strontium 90) causes a gradual decay in radioactivity. (Nuclear Power: Both Sides 1983). However both forms of disposal are conceptually similar in the fact that both involve storing the waste (gas and radioactive waste) from electricity generation for a long time into the future. They both also exert risks to human lives in the future, in the event of an unexpected release of the stored waste into the environment.

Richels and Blanford (2008) studied the role of technology in a de-carbonized future electricity sector in the US; they presented a contrasting view to the above study, in terms of the effectiveness of a price signal. The study argues that any carbon price low enough to be credible, will not facilitate research development investment in renewables, hence the carbon price can most probably not be expected to bring in new renewable technologies as well. The study concludes with an interesting viewpoint that even given the fact that the CO<sub>2</sub> mitigation measures incur significant expenses; the issue of cost must be thought of as separate from the issue of transitioning to a low carbon economy for the welfare of future generations.

The All Modular Industry Growth Assessment (AMIGA) is a general macroeconomic equilibrium model of the U.S. economy that covers time periods from 1992 to 2050. AMIGA integrates features from the following components: multi-sector (examines the impact of changes in more than 300 sectors in the national U.S, determines changes in both monetary and physical units), technology representation (draws from various built in modules for electricity generation technologies, integrates energy technologies with the economic model), computable general equilibrium (employment solutions for demands, outputs, costs, and outputs of inter-related products are computed), macroeconomic (the model calculates national income, GDP, employment, consumption of goods and services, trade balance and net foreign assets) and economic growth (projects economic growth paths and long term dynamic effects of alternative

investments) (PEW Global Climate Change 2003). This model was originally developed by Dr. Donald Hanson of the Argonne National Laboratory and Dr. John ‘Skip’ Laitner of EPA Office Atmospheric Programs. Hanson and Laitner (2004) tested the cost effectiveness of technology driven reduction of carbon emissions in the U.S. They came to a conclusion that substantial amount of carbon emissions reduction can be achieved in the U.S. with a small net positive impact on the economy. However this reduction would still not be sufficient enough to achieve the Kyoto targets by 2012.

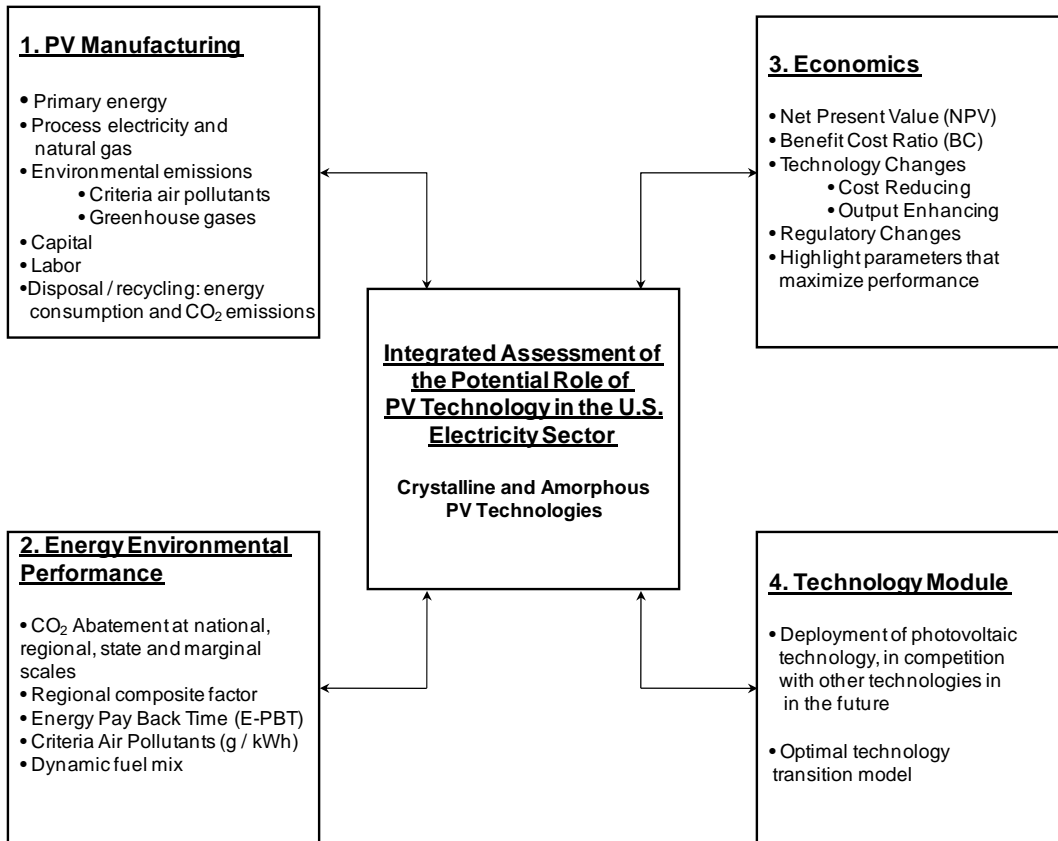
Earlier versions of this model could only handle carbon emissions when determining the interplay between the energy technologies and economic growth. The more developed recent versions of this model have the ability to take into consideration NO<sub>x</sub>, SO<sub>2</sub> and mercury emissions, pollutant allowances and banking while calculating the impact of energy technologies on the economy (Hanson and Laitner 2002). Among the many modules in the AMIGA model, this dissertation focuses on the *Technology Characterization* module. The AMIGA model has built in modules for electricity generation technologies such as coal, nuclear, gas, municipal solid waste and fuel cells (Hanson and Laitner 2002a). The technology characterization module contains information about the benefits and costs of using a particular technology to generate electricity. Some of the technological and policy drivers that increase the use of renewable sources are experience curves, research and development subsidies, production subsidies, renewable portfolio standards and allowance trading (Hanson 2004). Ultimately the model tests the influence of these technological-policy drivers on the usage of renewable sources and the consequent net economic impact (benefits and costs) of such an action. This dissertation develops a technology characterization module for photovoltaics within the U.S, which can potentially be integrated with the AMIGA model. The module will investigate the growth and deployment of PV technology, in competition with other electricity generating technologies to meet potential regulations in a carbon constrained future in the U.S.

### **2.2.5 Limitations of the Study**

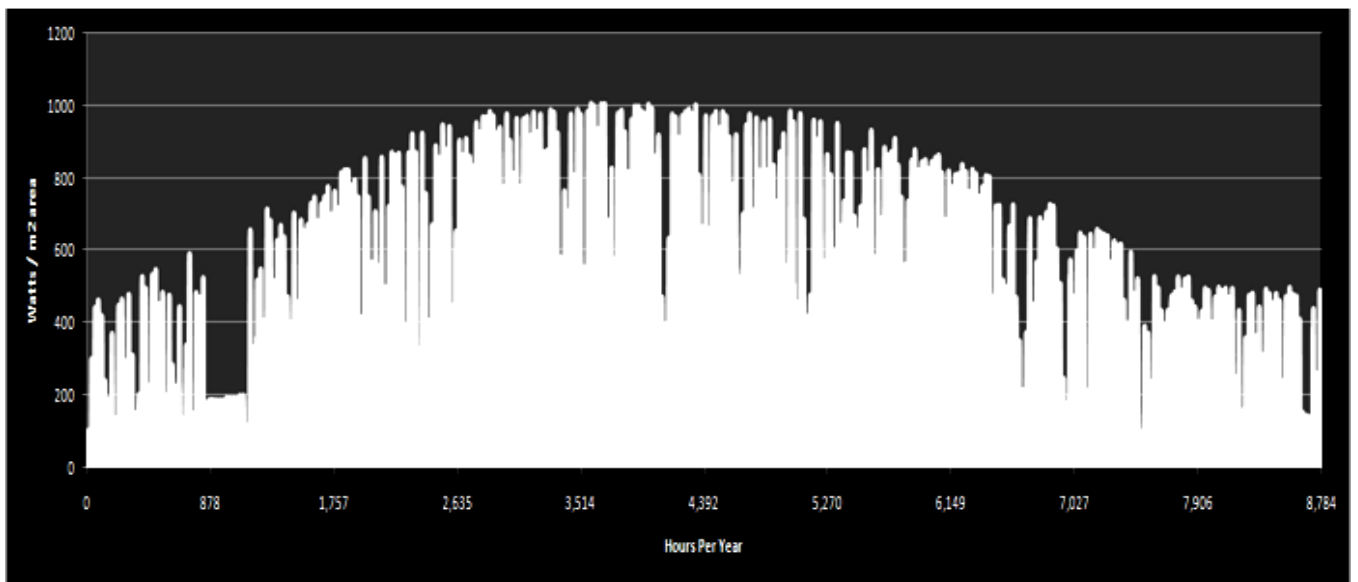
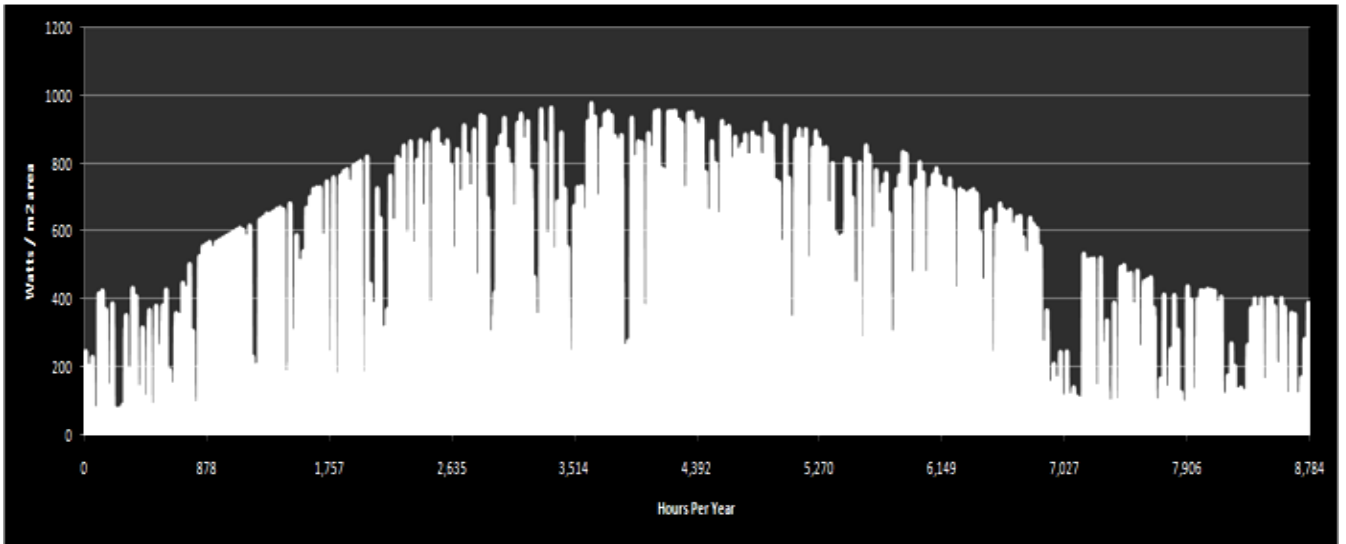
The several important limitations of this dissertation are described here. The life cycle assessment certainly includes the emissions to various compartments, but the results presented only include the environmental air emissions. Throughout this study the various facets of PV technology is investigated in terms of its applicability in generating renewable electricity, and mitigating criteria air pollutant and CO<sub>2</sub> emissions, to the air. Hence the scope of this study is limited to air emissions. PV manufacturing also generates solid waste emissions. This study goes as far as presenting the solid waste emissions from the PV manufacturing and end of life management processes. The actual strategies to develop solutions for efficient management of solid waste are left for future continuation of this work. Certain sections of the study use fuel mix projections from

Electric Power Research Institute databases that include carbon capture and storage (CCS) mechanism as an option, to transition to a low carbon fuel mix in the future. The inherent risks and uncertainties associated with carbon capture and storage is recognized and stated clearly in the relevant sections. However, using information based on the CCS option still remains a limitation of the study.

Another important aspect of PV manufacturing is the Occupational Safety and Health Administration (OSHA) challenges involved due to the involvement of toxic materials (discussed in section 2.2.2). The background section above discusses studies reporting about the occupational safety of PV manufacturing, and other health risks involved due to toxic materials used in the production process, accidental fires and after disposal. The PV manufacturing part of the paper presents the environmental and human health impacts of PV module production. However the specific occupational safety aspect of PV manufacturing is not discussed from this point onwards. The other assumptions relevant to each chapter are mentioned in the corresponding methods section, the above-mentioned issues are the generic limitations of this dissertation.



**Figure 2.1: Integrated framework and the research components of the four modules in this study**



**Figure 2.2: Hourly solar resource available, in Ann Arbor, Michigan (top) and San Francisco, California (bottom) for the year 2004**

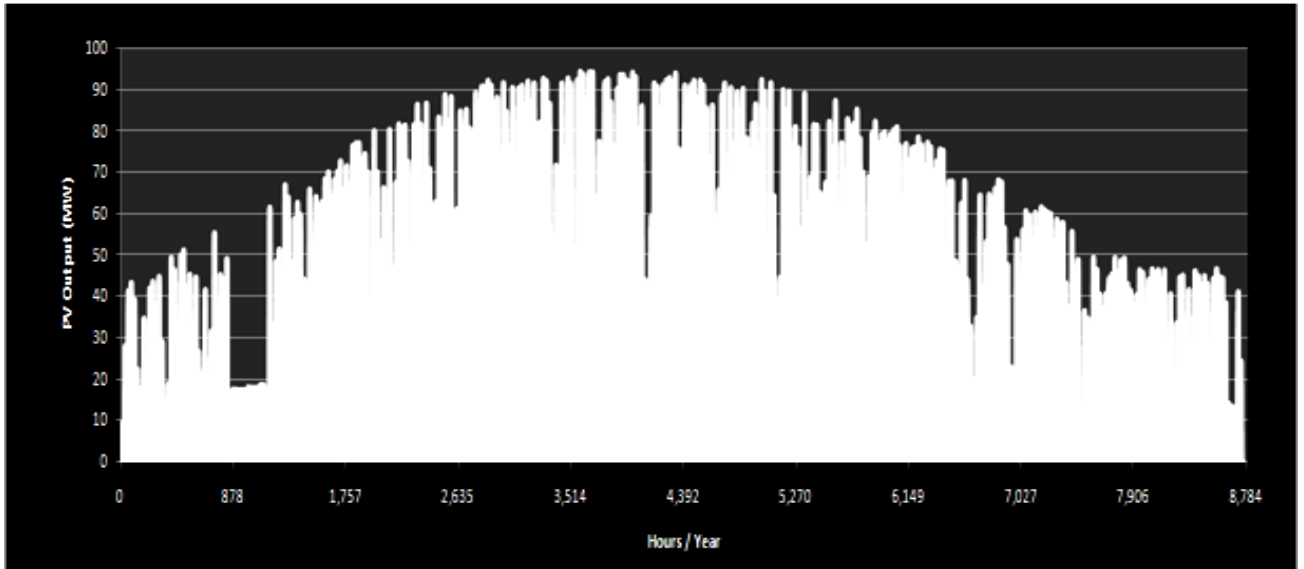


Figure 2.3: Hourly PV electricity output for a 100 MWp plant in San Francisco (CA)

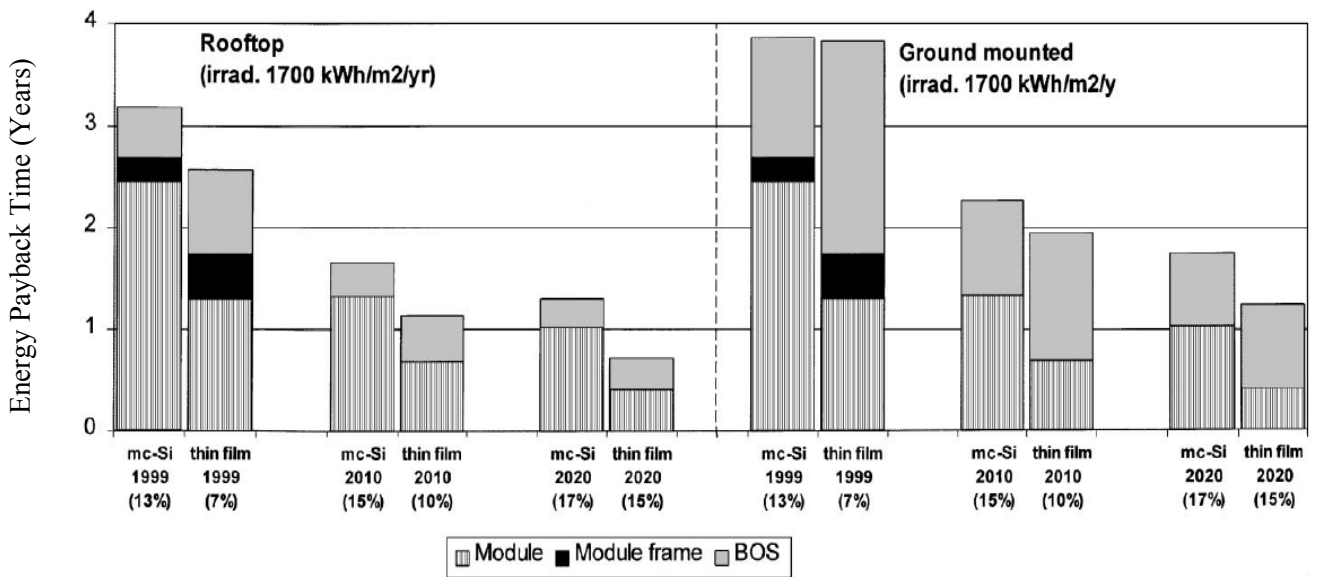


Figure 2.4: Energy payback time of multi-crystalline and thin-film options, for rooftop and ground-mounted configurations



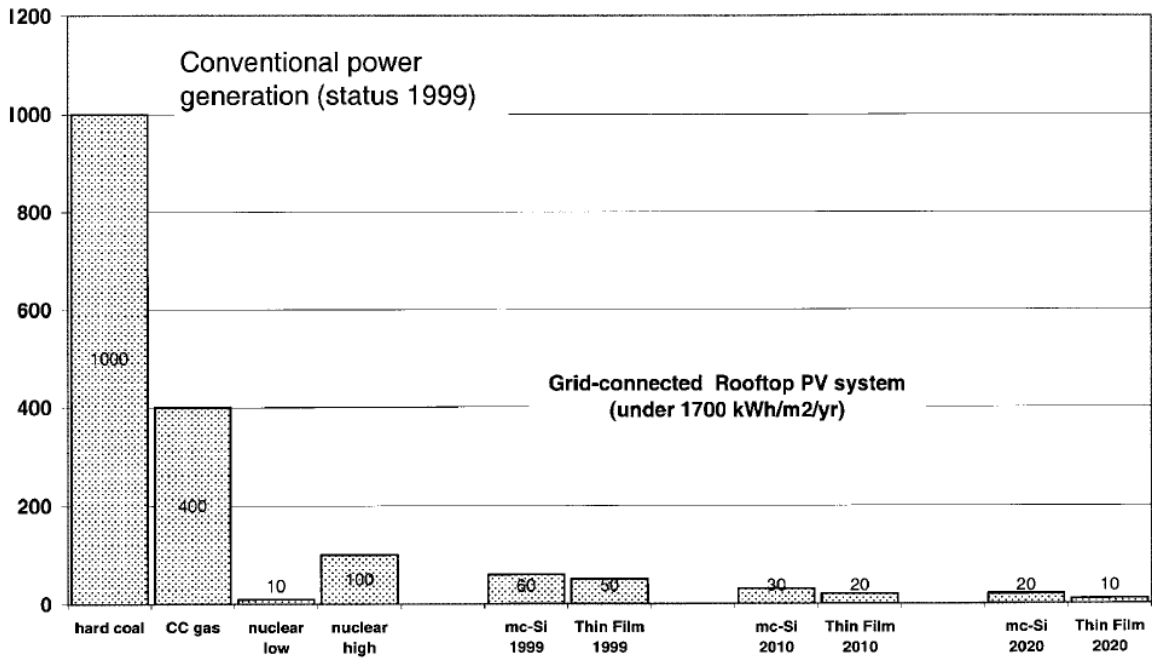


Figure 2.5: CO<sub>2</sub> emission factor for different electricity supply options (in grams/kWh of CO<sub>2</sub>). Emission factor for PV technologies is presented for 1999, and projected for 2010 and 2020

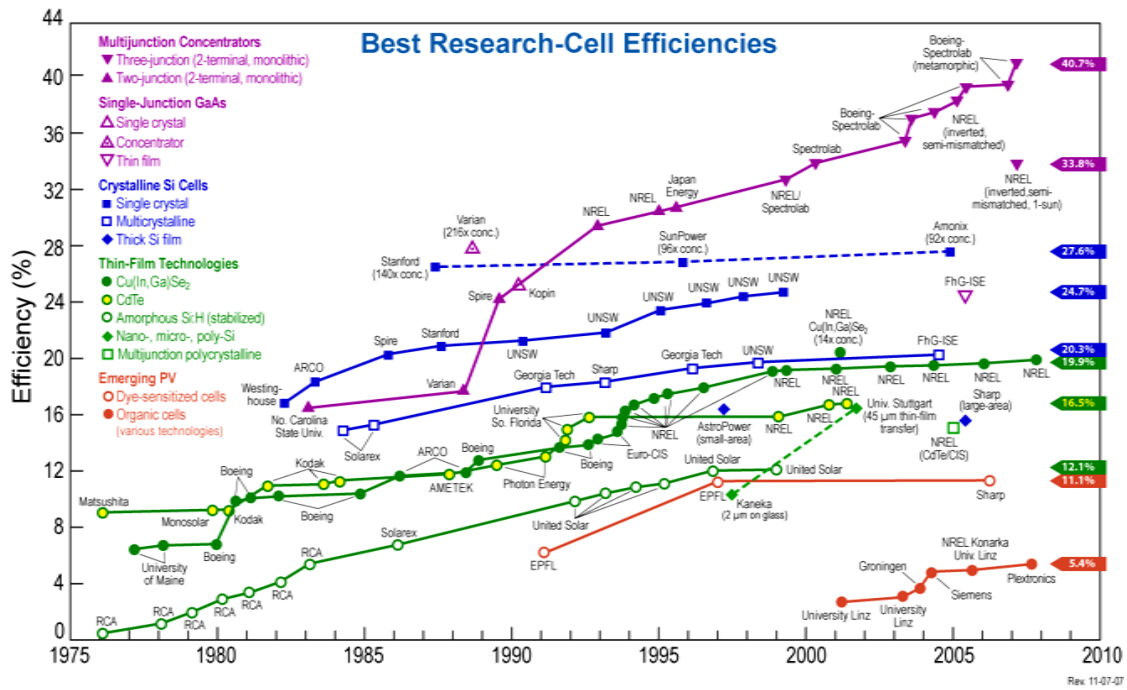
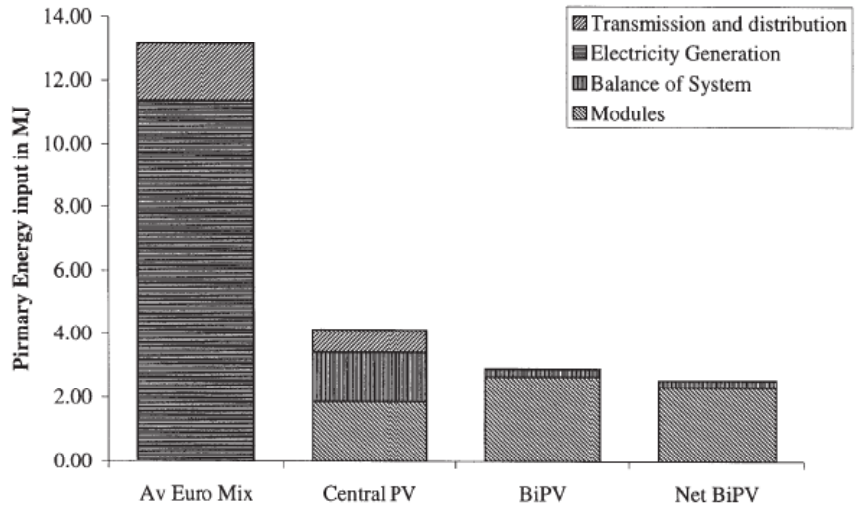
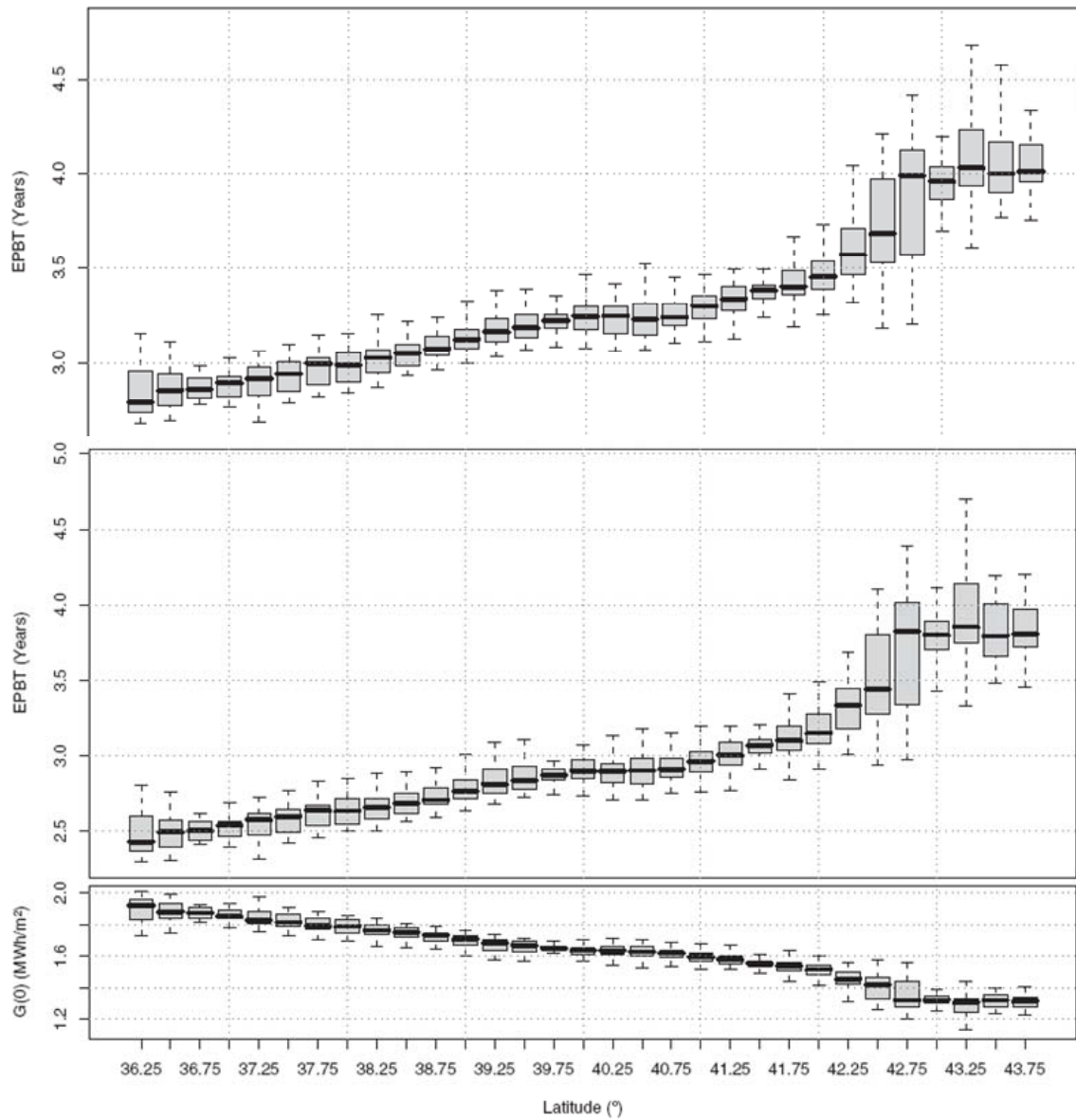


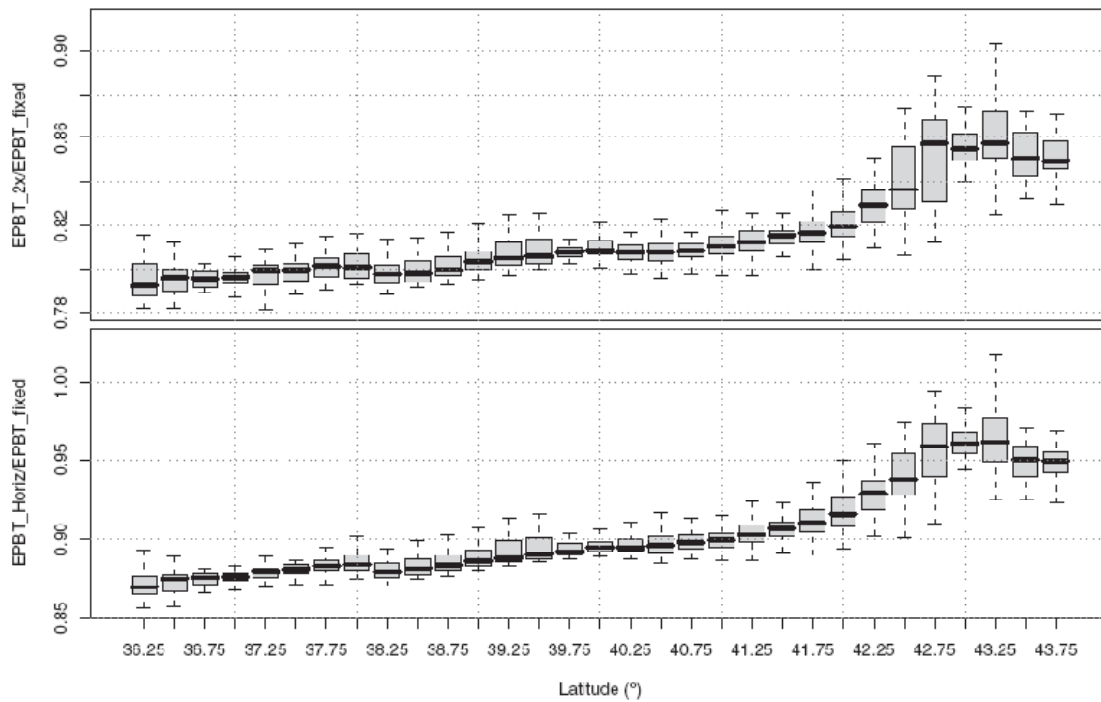
Figure 2.6: Photovoltaic cell efficiency for different types of modules, as of 2007 (from National Renewable Energy Laboratory (NREL))



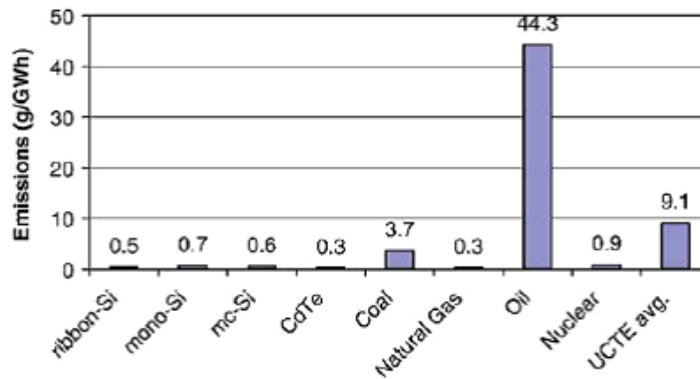
**Figure 2.7: Primary energy consumption to deliver unit electricity (MJ/kWh) for PV technology configurations and the European grid**



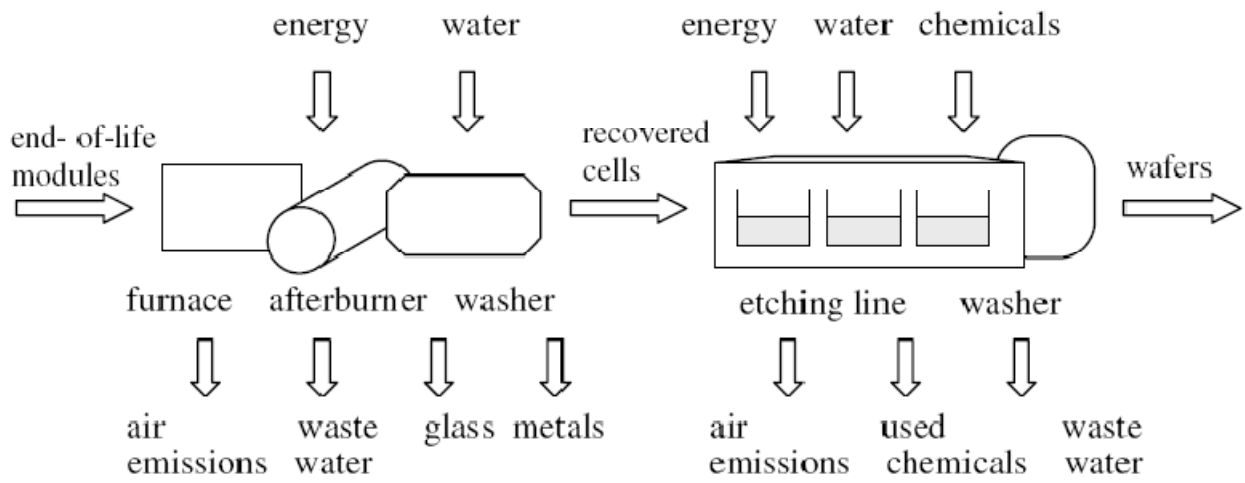
**Figure 2.8: E-PBT of a fixed system (top) and a single axis system (middle) for a range of latitudes in Spain. The corresponding solar resource available (bottom) for the latitudes is also presented**



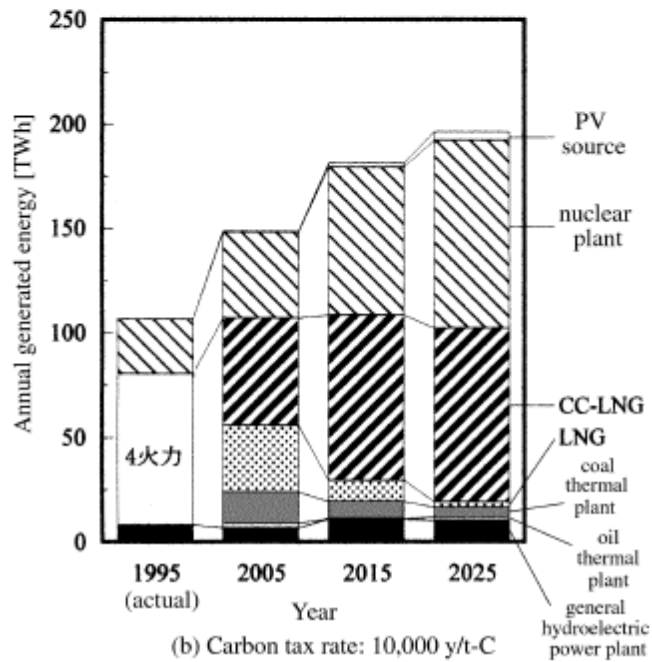
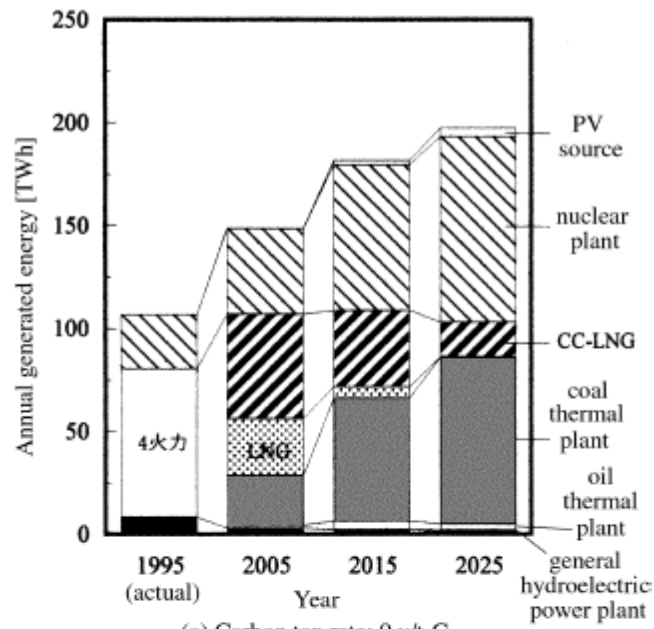
**Figure 2.9: The E-PBT ratio of dual axis/fixed (top) and single axis/fixed (bottom) for a range of latitudes in Spain**



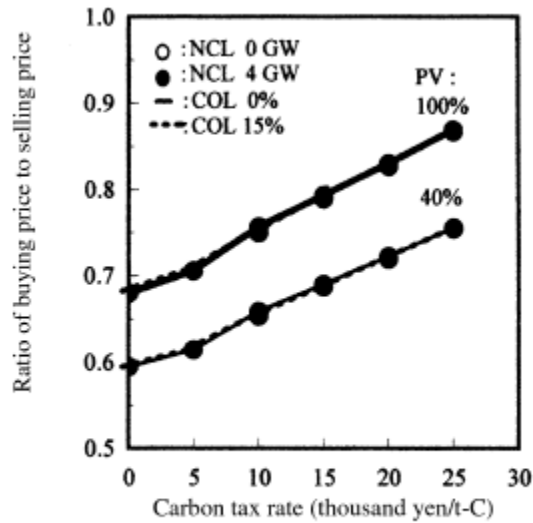
**Figure 2.10: Life cycle atmospheric cadmium emissions for different electricity generating technologies (grams/kWh)**



**Figure 2.11: The two step recycling process employed by Deutsche Solar, mechanical disassembly followed by chemical etching**

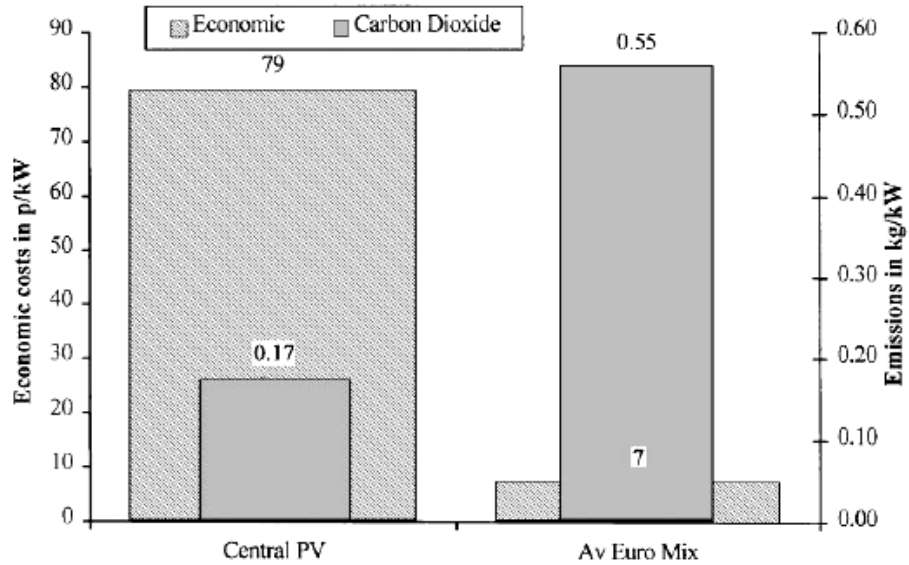


**Figure 2.12: Fuel mix in Japan's electricity grid under a no carbon tax and prevalence of carbon tax scenario**

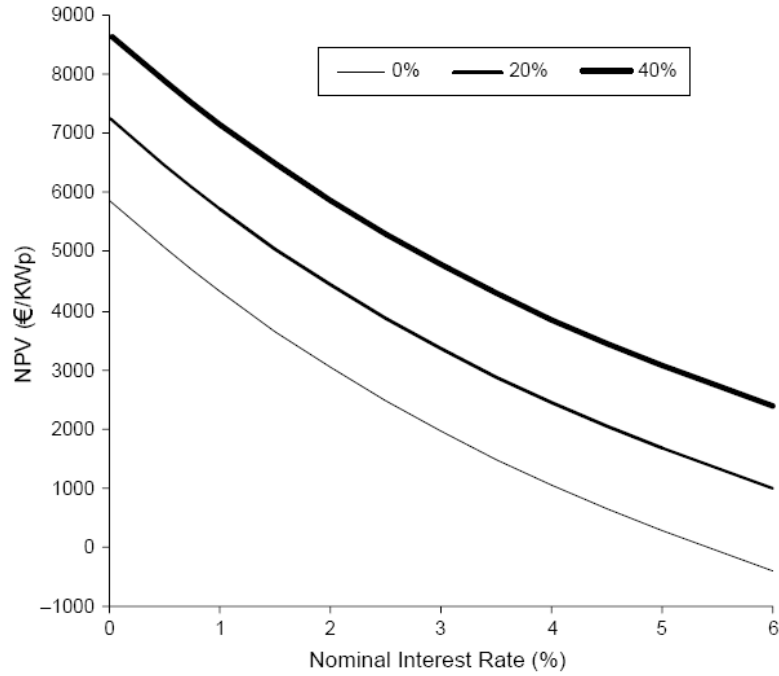


NCL: upper limit of the newly developed nuclear power plant capacity  
 COL: lower limit of the coal thermal plant annual capacity

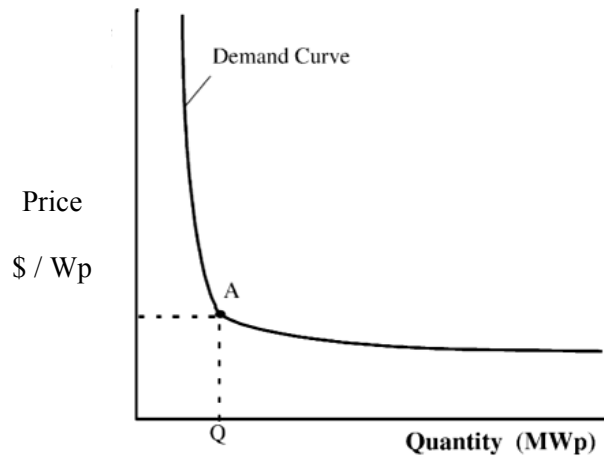
**Figure 2.13: The buying to selling price ratio for PV electricity under a range of carbon tax rates**



**Figure 2.14: Electricity generation cost and CO<sub>2</sub> emissions associated with the average European grid, and PV technology option**



**Figure 2.15: Net present value (NPV) of the photovoltaic system installed in Spain at three different subsidy rates**



**Figure 2.16: Price elasticity of demand for PV technology**



	E-PBT (Years)		CO <sub>2</sub> Emission Factor (grams / kWh)	
	Crystalline	Thin Film	Crystalline	Thin Film
Keoleian and Lewis 1997		Amorphous silicon 1.4 (frameless) and 1.8 (frame included)		
Alsema and Nieuwlaar (2000)				
Keoleian and Lewis 2003		Amorphous silicon, 3.4 (Portland, OR), 5.5 (Pheonix, AZ)		
Alsema and Wild-Scholten (2006)	Mono crystalline (2.8), Multi crystalline (2.2), String ribbon (1.7)			
Kannan et al (2006)			Mono crystalline (217)	
Fthenakis and Kim (2006)				
Pacca et al (2007)	Multi crystalline (7.5)	Amorphous silicon (3.2)	Multi crystalline (72.4)	Cadmium Telluride (18) <sup>+</sup>
Perpinan et al (2009)	Multi crystalline 2 to 5 (single to dual axis)			Amorphous Silicon (34.3)

<sup>+</sup> This particular unit is in grams CO<sub>2</sub>-eq / kWh

**Table 2.1: Summary of E-PBT and CO<sub>2</sub> emission factor results from the studies discussed**

## REFERENCES

- Agustin, J.L.B., Lopez, R.D., 2006. Economic and environmental analysis of grid connected photovoltaic systems in Spain. *Renewable Energy* (31) 1107-1128
- Alsema, E.A. 2000. Energy payback times and CO<sub>2</sub> emissions of PV systems. *Progress in Photovoltaics: Research and Applications* (8) 17 – 25
- Alsema, E.A. Nieuwlaar, E. 2000. Energy viability of photovoltaic systems. *Energy Policy* (28) 999 – 1010
- Alsema, E.A. de-Wild Scholten, M.J. 2006. Environmental impacts of crystalline silicon photovoltaic module production. Presented at the conference of life cycle engineering, Leuven, Belgium
- Battisti, R. Corrado, A. 2005. Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. *Energy* (30) 952 – 967
- Bohland, J.R. Smigielski, K. 2000. First Solar's Cd-Te module manufacturing experience: Environmental health and safety results. *IEEE* 07803-5772-8/00
- Bosetti, V. Carraro, C. Massetti, E. Sgobbi, A. Tavoni, M. 2008. Optimal energy investment and R&D strategies to stabilize atmospheric greenhouse gas concentrations. (Accepted in *Resource and Energy Economics*)
- Energy Information Administration (EIA). 2009. *Annual Energy Review 2008*
- Fthenakis, V. 2000. End of life management and recycling of PV modules. *Energy Policy* (28) 1051 – 1058
- Fthenakis, V. Carlisle, C. Chan, W. 2005. Silane safety in amorphous silicon and silicon nitride operations. Brookhaven national lab report
- Fthenakis, V. 2006. Could Cd-Te PV modules pollute the environment? National Photovoltaic Environmental Health and Safety Center. Brookhaven National Lab, New York.
- Fthenakis, V. Kim, H.C. 2006. Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics. *Mater. Res. Soc. Symp. Proc.* (895) Materials Research Society
- Fthenakis, V. Kim, H.C. 2006a. CdTe Photovoltaics: Life cycle environmental profile and comparisons. Presented in the European materials research society meeting, Nice, France
- Goetzberger, A. Hoffmann, V.U. 2005. *Photovoltaic Solar Energy Generation Chapter 9: Environmental impacts by PV systems* (Page 137)

- Hanson, D. Laitner, J. A. 2002. The AMIGA Model: Reflecting bottom up technology within a CGE framework. Presented in the US-Mexico environment, economy, energy modeling workshop
- Hanson, D. Laitner, J. A. 2002a. Modeling robust economic development strategies: Balancing energy efficiency and energy production. Presented in the Sino-U.S. – Korea economic and environmental modeling workshop
- Hanson, D. 2004. The AMIGA modeling system. Technology characterization and policy issues.
- Hanson, D. Laitner, J. A. 2004. An integrated analysis of policies that increase investments in advanced energy-efficient low carbon technologies. *Energy Economics* (26) 739 – 755
- ISO (1997). "Environmental management - Life cycle assessment - Principles and framework." ISO 14040, International Organization for Standardization
- Kannan, R. Leong, K.C. Osman, R. Ho, H.K. Tso, C.P. 2006. Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore. *Solar Energy* (80) 555 – 563
- Kemmoku, Y. Shundoh, G. Takikawa, H. Kawamoto, T. Sakakibara. T. 2003. A study of buying price of photovoltaic electricity under a carbon tax regime. *Electrical Engineering* (143) 1444 – 1452
- Keoleian, G.A. Lewis, G. McD. 1997. Application of life cycle energy analysis to photovoltaic module design. *Progress in Photovoltaics: Research and Applications* (5), 287 – 300
- Keoleian, G.A. Lewis, G. McD, Moore, M. 1999. PV-BILD: A Life Cycle Environmental and Economic Assessment Tool for Building-Integrated Photovoltaic Installations, BES-9727268
- Keoleian, G.A. Lewis, G. McD. 2003. Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the U.S. *Renewable Energy* (28) 271 – 293
- Muller, A. Wambach, K. Alsema, E. 2006. Life cycle analysis of solar module recycling process. *Mater. Res. Soc. Symp. Proc. Volume 895. 0895-G03-07.1*
- National Renewable Energy Lab. 2005. Environmental health and safety issues in photovoltaic manufacturing
- National Renewable Energy Lab (NREL). 2007. The safety of Photovoltaics.
- National Renewable Energy Lab (NREL). 2008. PV-Watts. PV performance calculator.
- National Renewable Energy Lab (NREL). 2009. Cadmium use in photovoltaics.  
Link: [http://www.nrel.gov/pv/cdte/cadmium\\_facts.html](http://www.nrel.gov/pv/cdte/cadmium_facts.html) Link accessed on February 9, 2009

- Nordhaus, W.D. 1992. An optimal transition path for controlling greenhouse gases. *Science* (258) 1315 – 1319
- Nuclear Power: Both Sides. 1983. (book by Michio Kaku and Jennifer Trainer).
- Oliver, M. Jackson, T. 1999. The market for solar photovoltaics. *Energy Policy* (27) 371 – 385
- Oliver, M. Jackson, T. 2000. The evolution of economic and environmental cost for crystalline silicon photovoltaics. *Energy Policy* (28) 1011 – 1021
- Oliver, M. Jackson, T. 2001. Energy and economic evaluation of building integrated photovoltaics. *Energy* (26) 431 – 439
- Pacca, S. Deepak Sivaraman, Keoleian, G.A. 2007. Parameters affecting the life cycle performance of PV technologies and systems. *Energy Policy* (35) 3316 – 3326
- Perpinan, O. Lorenzo, E. Castro, M.A. Eyras. R. 2009. Energy payback time of grid connected PV systems: Comparison between tracking and fixed systems. *Progress in Photovoltaics: Research and Applications* (17) 137 – 147
- PEW Global Climate Change. 2003. U.S. Energy scenarios for the 21<sup>st</sup> century
- Ren, H. Gao, W. Ruan, Y. 2009. Economic optimization and sensitivity analysis of photovoltaic system in residential buildings. *Renewable Energy* (34) 883 – 889
- Richels, R.G. Blanford. G.J. 2008. The value of technological advance in de-carbonizing the U.S. economy. *Energy Economics* (30) 2930 – 2946
- Seng, L.Y. Lalchand, G. Lin, G.M.S. 2008. Economic, environmental and technical analysis of building integrated photovoltaic systems in Malaysia. *Energy Policy* (36) 2130 – 2142
- Shaahid, S.M. Elhadidy, M.A. 2008. Economic analysis of hybrid photovoltaic diesel battery power systems for residential loads in hot regions – A step to clean future. *Renewable and Sustainable Energy Reviews* (12) 488 – 503
- Spanos, I. Duckers, L. 2004. Expected cost benefits of building integrated PV's in UK, through a quantitative economic analysis of PV's in connection with buildings focused on UK and Greece. *Renewable Energy* (29) 1289 – 1303
- Tsur, Y. Zemel, A. 2003. Optimal transition to backstop substitutes for non-renewable resources. *Journal of Economic Dynamics and Control* (27) 551 – 572

## CHAPTER 3

### ENERGY, ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF PHOTOVOLTAIC MANUFACTURING AND RECYCLING IN THE UNITED STATES

#### ABSTRACT

Increasing amounts of photovoltaic electricity are expected to be generated in a carbon constrained future. In this study a life cycle model was constructed for five PV modules used in the U.S. market at present. The three crystalline modules (area per module 1.65 m<sup>2</sup>), were smaller than the amorphous silicon module (2.16 m<sup>2</sup>) but bigger than the Cd-Te module (0.72 m<sup>2</sup>). A mono-crystalline module consumed (8,220 MJ) 1.3 and 1.6 times more primary energy than the multi-crystalline and ribbon module. The amorphous silicon module consumed (2,270 MJ) 2.6 times the primary energy of that of the Cd-Te option. The average CO<sub>2</sub> emission factor (grams /kWh) ranged from 31 to 48 for the crystalline modules, and 20 to 21 for the thin film modules. Module recycling was determined to be significantly more beneficial for crystalline modules than the thin film modules. Recycling reduced primary energy consumption by 32 to 59% for the crystalline modules, and only by 3 to 8% for the thin film modules. Recycling an energy intensive crystalline wafer and using in it the next batch of PV panels contributed to energy savings for crystalline modules. The cost of labor for technology production was also evaluated. The cost of labor for crystalline and amorphous silicon modules was \$2.12 and \$1.99 per Wp (peak watt) produced. The reduced number of steps such as glass production, cell manufacturing and frame manufacturing in the case of amorphous silicon module resulted in the decreased cost of labor. The total production cost for the crystalline modules ranged from \$2 to \$3 / Wp, and costs for amorphous silicon and Cd-Te were \$3.4 and \$2.1 per Wp respectively. The current scenario of energy and environmental impacts, cost and labor consumption associated with PV manufacturing, and the potential benefits of module recycling are presented in this study.

### 3.1 Introduction

Photovoltaic (PV) technology has been studied extensively from different standpoints, up until now. In this study the manufacturing of photovoltaics is analyzed focusing on the United States. There are two primary objectives for this study, 1. To characterize the primary energy consumption, criteria pollutants and CO<sub>2</sub> emissions associated with manufacturing and end of life management of the five photovoltaic modules considered. 2. To evaluate the total production cost and the total cost of labor associated with producing PV modules in the U.S.

A number of studies before have analyzed the primary energy consumption and CO<sub>2</sub> emissions associated with manufacturing different types of PV technologies. Alsema and Nieuwlaar (2000) reported primary energy (per unit area of the module) consumed to produce a multi-crystalline (4,600 MJ) and amorphous silicon module (1,600 MJ). Based on a solar resource availability of 1,700 kWh/m<sup>2</sup>/year, the CO<sub>2</sub> emissions factor for the multi-crystalline and amorphous silicon module was 60 grams / kWh and 50 grams / kWh respectively. Wild-Scholten and Alsema (2006) also analyzed the energy consumed to produce three types of crystalline PV modules. On a unit module area (m<sup>2</sup>) basis, 5,100, 4,000 and 2,700 MJ was consumed to produce mono, multi and ribbon module(s), respectively. Lewis and Keoleian (1997) evaluated the primary energy consumed to manufacture an amorphous thin film module (United Solar UPM 880) to be 357 MJ (with aluminum frame) and 161 MJ (without the aluminum frame). Pacca et al (2007) analyzed the life cycle energy consumed to manufacture the photovoltaic laminate (amorphous silicon) and multi-crystalline module. The amorphous silicon technology was reported to consume (13.8 MJ / Wp) 2.5 times less energy than the multi-crystalline (34.4 MJ / Wp) option. Fthenakis and Kim (2006) studied the energy consumption and greenhouse gas emissions associated with manufacturing a cadmium telluride module. Producing a module consumed 1,200 MJ/m<sup>2</sup> of primary energy and emitted greenhouse gases of 18 g CO<sub>2</sub>-eq / kWh. The release of cadmium into the air is one of the important human health concerns of Cd-Te module manufacturing. Fthenakis and Kim (2006a) also quantified the cadmium emission factor (23.3 mg Cd / GWh) that was reported to be the lower than all of the crystalline PV technologies.

The end of life management life cycle stage of PV modules has only been investigated on a limited basis until now. Only a handful of studies have discussed the recycling and disposal of PV modules, at the end of life. Fthenakis (2000) reports that a 10 MW cadmium telluride PV module facility will have to manage solar panel solid waste of 2,000 tons, at the end of their life cycle. The solid waste constitutes 0.1% semiconductor material and the rest of it, being mainly glass. Fthenakis (2004) investigated the fate of cadmium in a cadmium telluride module at its end of life. The study concludes

that because cadmium is enclosed in between two sheets of glass in the module, leaching of cadmium is impossible after module disposal in a municipal landfill. This conclusion is supported further by Sinha et al (2008), this study advises against applying the restriction of hazardous substances (RoHS) to cadmium telluride modules in Europe. The study finds the risks and impacts of cadmium release during regular operation and under catastrophic events (such as fire) to be insignificant, hence it advises against applying the precautionary principle to cadmium telluride modules. With increased amounts of PV electricity generated around the globe it becomes essential to 1. Evaluate the material and energy consumed for recycling PV modules, and 2. Determine the potential energy and environmental benefits realized due to using recycling PV modules. One of the important strengths of this study is the fact that it includes the end of life management stage for all the five modules analyzed. The recycling and disposal stage of the model was constructed by using current data, obtained from communicating with industry personnel and experts in the discipline.

Energy inputs and environmental emissions aside, labor and manufacturing cost are two of the important factors associated with photovoltaic production. Studies before, have analyzed the number of jobs that manufacturing photovoltaics creates in an economy. Tsoutsos et al (2005) reported a wide range of 2 to 3000 jobs to be created annually in Europe, as a result of photovoltaic production. To produce a mega-watt capacity of photovoltaics inside the U.S. (in California), 7.14 construction jobs and 0.12 operating jobs were reported to be created (CALPRIG 2002). This study analyzes the actual number of labor hours consumed to manufacture photovoltaics. Using information relevant to the U.S, a bottom-up model was constructed that identifies the different steps in PV production that are most labor intensive, and also the labor sectors that contribute significantly to producing photovoltaics. In addition a labor-cost model is developed that uses the labor model built, in conjunction with the wage rates for different occupational sectors. This model develops a methodology to estimate the average cost of labor to manufacture photovoltaics in the U.S.

The cost of manufacturing different PV technologies has not been analyzed extensively before, predominantly due to the proprietary nature of the data involved. Zweibel (1999) reported the direct manufacturing cost of manufacturing cadmium telluride modules to be \$90 per m<sup>2</sup> module area, with more than 50% of it contributed by material costs. The study also forecasts a 50% reduction in the total direct cost, in the future. Zweibel (2000) forecasted that with improvements in manufacturing processes, the direct material costs of thin film modules can be expected to decrease from \$44 / m<sup>2</sup> to \$23 / m<sup>2</sup>, in the future. A distinct feature of our study is the evaluation of the cost inputs required to manufacture photovoltaics. The leading manufacturers for five types of PV modules considered in the U.S. market are identified. Based on this information, the

research results for the latest direct and indirect costs of manufacturing photovoltaic modules are presented. Such cost data are further compared with the current market price of PV modules to estimate the profit margin, on a unit peak watt basis.

## **3.2 Methods**

**3.2.1 Technology Characteristics:** Three crystalline modules (mono, multi and string ribbon), and two thin film modules (amorphous silicon and cadmium-telluride) were considered for analysis in this study. The PV modules were selected based on the total capacity of different modules produced in the U.S in 2004 (Prometheus Institute 2005, PV News 2005). In the U.S. a total annual capacity of 154 MWp PV modules were manufactured in 2004. The modules considered in this analysis include 99% of the market share (Table 3.1). Table 3.1 also presents the technological characteristics of the PV modules, all of the crystalline modules have higher conversion efficiency (mono > multi > string ribbon) and peak watt capacity, when compared to the two thin film modules. The amorphous silicon and cadmium telluride modules have a power to area ratio of 63 Wp / m<sup>2</sup> and 94 Wp / m<sup>2</sup> respectively. Even with a higher peak watt capacity, the lower power to area ratio of the amorphous silicon module highlights the comparative higher area requirements for its installation.

**3.2.2 Life Cycle Model:** A life cycle model was constructed for each of the five PV modules included in the study. The model was constructed in the life cycle software Simapro (Product Energy Consultants 2008). As mentioned above, this study differs from previous LCA PV studies in the fact that it includes the end of life management (EOL) stage in the life cycle model. The stages considered in the LCA include raw material extraction, material production, PV module manufacturing and end of life management of the modules. The material and energy inputs data for the model were gathered from a combination of published databases and previous literature. However, the life cycle model constructed for the PV modules in this study used data from the same set of life cycle databases in the software Simapro. The life cycle model also used material and energy databases that reflect the conditions for material production and grid characteristics specifically in the United States. Hence there is a higher consistency among the five life cycle models constructed, enabling a better comparison among PV technology options. The material and energy input data for the three crystalline modules were obtained from Wild – Scholten and Alsema (2006). The data were categorized based on the four stages involved in crystalline module production: poly-silicon, wafer, cell and module production. The same databases used by Pacca et al. (2007) and Fthenakis and Kim (2006), were used to model the amorphous silicon and cadmium telluride modules respectively. The former study used data from Uni-Solar Ovonic, while the latter used data from First Solar Corporation. For the cadmium telluride module, a combination of process based (Simapro) and the input-output based LCA approach,



known as hybrid-LCA was used. The total material and process energy for manufacturing a Cd-Te module was modeled. Data on the total monetary expenses incurred for purchasing office supplies in First Solar Corporation was obtained. The office supplies included products made out of plastic, paper, metal and rubber, and steel and wood furniture. From the information available, the total dollar value of office supplies per module was estimated. Using sector 339940 (office supplies except paper manufacturing) in the EIO-LCA database the total primary energy consumption and environmental emissions associated with manufacturing the office supplies was calculated. By modeling the data using the various built in databases in Simapro, the life cycle stages of raw material extraction, material production, PV module manufacturing for the five PV modules were analyzed. The built in databases provide material and energy consumed and environmental emissions associated with the life cycle stages modeled.

The end of life (EOL) management stage for the modules was constructed by communicating with industry personnel and experts in the discipline. *Deutsche Solar* (Freiberg, Germany) has developed an extensive pilot program for recycling wafers, glass and metals in the crystalline modules. It is essentially a two step process: laminate burning and etching. Laminate burning facilitates module dis-assembly after which solar cells, glass and metals in the module are separated manually; the recovered glass and metals are sent to recycling partners for open loop recycling. The separated solar cells undergo etching, where metallization, anti-reflection coating and p-n junction are removed subsequently. A clean crystalline wafer can be obtained at the end of this two step process, which can be used in the next batch of module production (Bombach et al. 2007, Deutsche Solar AG 2008, Personal Communication Dr. Karsten Wambach and Anja Mueller, 2008). The energy consumed for wafer recycling was obtained from Mueller et al. (2006). Built in databases for recycling in Simapro were used to model the recycling of glass and metals.

An amorphous silicon module does have a light substrate made out of stainless steel. However, at present there is a lack of comprehensive recycling programs for amorphous silicon modules, predominantly due to the low salvage value of the embedded materials. Hence no immediate plans exist to build such an infrastructure in the near future (Personal Communication Erik Alsema 2008, Philip Davison, United Solar Ovonic 2008). Hence to indicate the current trend, the EOL component of the amorphous module involved land-fill disposal of glass, metals and plastics in the module. A more progressive outlook entailed a second EOL model to be developed, which tested the influence of recycling the glass metals and plastics in the module. An assumption of 75% recovery based on communication with plant personnel had to be made for this analysis (Personal Communication with Philip Davison 2008). Contrastingly, First Solar Corporation has developed an extensive recycling program for the cadmium telluride

modules. An important reason for the existence of such an extensive recycling program is the presence of a toxic metal such as cadmium in the Cd-Te module. The customer is contractually bound to return the modules to First Solar at the end of life, subsequent processing of the modules separates the materials into glass and cadmium containing solids. The two types of solids are sent to recycling partners for open loop recycling (First Solar 2008). To address the data gap, a recycling rate of 75% was assumed in the EOL model, based on communication with experts in the discipline (Personal Communication with Dr. Vasilis Fthenakis 2008). The material and energy consumption associated with the recycling of modules was obtained from the built in databases in Simapro. The life cycle primary energy (E) consumption and environmental emissions (discussed in detail below) is a summation of energy and emissions, associated with the four individual life cycle stages evaluated in the study (equation 1)

$$E_{\text{Life Cycle}} (\text{MJ}) = E_{\text{Raw Matl. Extraction}} + E_{\text{Matl. Production}} + E_{\text{Module Manufacturing}} + E_{\text{End of Life}} \quad (\text{eq. 1})$$

**3.2.3 Energy and Resource Consumption:** In this study, the life cycle model was used to evaluate the total primary energy, electricity and natural gas consumption associated with the four stages considered. The total primary energy is the summation of material, feedstock and process energy, for each of the five modules. The national average fuel mix was used to model electricity, reflecting the characteristics of the U.S. grid (grid efficiency: 29%).<sup>1</sup> The energy derived from combustion of natural gas was also modeled based on U.S conditions. The total primary energy consumed for module production has been reported before by other studies, this study further breaks down the total primary energy into electricity and natural gas consumed for manufacturing + EOL of the modules. The modules have different peak watt capacities and surface areas; hence the primary energy consumed in the life cycle was also evaluated on a unit peak watt capacity (MJ / Wp) and unit module area basis (MJ / m<sup>2</sup>). MJ / Wp and MJ / m<sup>2</sup> both express the total amount of primary energy consumed in the life cycle of the PV module, but normalize it based on different technological parameters. MJ / Wp normalizes the primary energy based on the module peak watt capacity, where as the MJ / m<sup>2</sup> normalizes the primary energy based on the module area.

**3.2.4 Environmental Emissions and Impacts:** Two types of environmental emissions were considered in this study: criteria air pollutants (CO, SO<sub>2</sub>, NO<sub>x</sub>, PM<sub>10</sub> and lead) and CO<sub>2</sub>. Both types of pollutants released for the life cycle of the PV modules, are reported. The Eco-Indicator method was then used to perform the environmental impact assessment (Product Energy Consultants 2008a). The impact categories considered include, global warming, smog formation, acidification and carcinogenicity potential (s).

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<sup>1</sup> Grid efficiency indicates the conversion efficiency of primary energy to electricity, for a specific electricity grid

In addition the total amount of solid waste generated from PV production and end of life was also analyzed.

**3.2.5 Labor Inputs:** A bottom up cost model is constructed for analyzing the labor inputs for the PV modules considered. The data for the analysis were gathered from a *Renewable Energy Policy Project (REPP)* report (Singh 2001). The data in the report were garnered from different photovoltaic firms in the domestic sector (U.S.) that produced a combined 60.8 MWp. The firms included in the analysis serve the domestic markets extensively. The characteristics of the data included are very indicative of the labor costs in the U.S. photovoltaic production market. The dataset was released in 2001 and hence limitations exist regarding the age of the data. But it is the most recent labor data available on such an extensive scale for PV production. Hence the data can be considered to represent the higher bound of labor consumption for PV production.

The model consists of costing the various steps involved from manufacturing to the actual installation and servicing of PV modules. The different steps include: production of glass, plastics and silicon, cell manufacturing, module assembly, wires, inverters, mounting frames, systems integration, distribution, installation and servicing. The servicing step includes the labor inputs from the professional, technical and management sector for the first ten years of the module lifetime. Servicing predominantly addresses the technical issues during module operation. For each of the above-mentioned steps, the labor inputs from the various sectors were determined. The various sectors that contribute to the PV product include professional, technical and managerial work, clerical and sales, service, processing, machining trades, bench work and structural work. For example, one of the key steps in the PV module production is the *Module Assembly*. The labor inputs from the different sectors such as professional, technical and managerial work (3.5 hours), processing (1.6 hours), bench work (8.25 hours) structural work (0.75 hours) and miscellaneous (6.85 hours) for module assembly are identified for assembling a kilo-watt (kWp) peak capacity of modules. In total, 20.95 hours of labor are required for assembling a kWp capacity of a PV module. Similarly the model uses inputs from different labor sectors for each of the steps involved in the photovoltaic production and service processes.

Two different input models were developed, one for the crystalline and one for the amorphous silicon module. Based on the differences in production steps between the two technologies, the corresponding labor inputs were allocated. The three production steps of glass production, cell manufacturing and frame manufacturing were not included for the amorphous silicon modules, based on the structural difference between the two technologies. The output of the model is in terms of labor hours and person – years. The

person-years metric was calculated assuming 49 weeks of labor per year and 40 hours of labor per week (equation 2).

$$\text{Labor (Person-Years)} = \text{Labor (Hours)} / (1,960 \text{ Hours} / \text{Person-Year}) \quad (\text{equation 2})$$

**3.2.6 Labor Cost Inputs:** The labor inputs model presents information on the different labor sectors that contribute to the production and servicing of the PV module. This information was used in conjunction with the wage rate (\$ / hour) for different labor sectors, to construct a bottom up labor cost model. The results of this model yield the cost spent on labor (in the U.S.) to manufacture the crystalline and amorphous silicon modules. The Bureau of Labor Statistics (BLS) database was used extensively for this purpose. Based on the labor sectors involved in producing the PV modules, similar labor sectors from the BLS database were selected (United States Department of Labor 2008). The sectors were selected by matching the types of occupations in the labor inputs model to that of the BLS database. The median wage rate of the corresponding labor sectors was determined (Table 3.2). This wage rate was then used in conjunction with the labor hours to determine the total cost of labor to produce the PV modules. The sector ‘Miscellaneous’ in the labor inputs model, is an aggregation of a number of occupations and is not further categorized in the original database. Hence to address such data limitations, the different steps in the PV production were analyzed to determine the sectors that contribute labor, and BLS occupations were selected based on the same. Based on the labor hours contributed to each step in the production process, a weighted median wage rate was calculated, and used for the ‘Miscellaneous’ sector.

**3.2.7 Cost Inputs:** The direct and total manufacturing costs for the five PV modules are analyzed in this section. Publicly traded companies report cost information in their corporate annual reports. A number of corporations manufacture the same PV technology. Hence considering cost information from a company on the fringes of the market is not very representative of the general cost trends in the market. The U.S. PV national survey reports the market leader for each type of PV technology based on their market share in terms of capacity of modules produced (International Energy Agency 2006). The survey reports the market leader for each technology: mono (Solar World), multi (Q-Cells and Kyocera Corporation), ribbon (Evergreen Solar), amorphous silicon (Uni-Solar Ovonic) and cadmium telluride (First Solar). Subsequently, from the latest annual reports of these corporations, the cost information was obtained.

Solar World (also known as Shell Solar) being a very large corporation presents aggregated cost data for the entire renewables manufacturing division. So, obtaining exclusive PV manufacturing cost data was not possible. Hence for the mono-crystalline technology, data from Sun Power Corp (San Jose, California), another leading manufacturer of the mono-crystalline technology in the U.S. was used (Sunpower 2007).

For all the five cases, three different cost categories were obtained: cost of product revenues, cost of research and development (R&D) and cost of selling, management and administration. The cost of product revenues represents the direct costs associated with manufacturing PV modules in each case, with the other two cost categories considered as indirect costs for PV production. Using the annual capacity of modules produced by each corporation, the cost results were expressed in cost per unit peak watt power basis (\$ / Wp) (equation 3)

$$\text{Total Manufacturing Cost (\$/Wp)} = \frac{\text{Costs of (Product Revenues + Research Development + Selling, Management and Administration)}}{\text{Annual capacity of modules produced}} \quad (\text{equation 3})$$

Each of the above-mentioned corporations manufactures different capacities of solar panels. The price per unit capacity (\$ / Wp) of panels tends to be very high for panels with a low capacity (e.g. Kyocera 1.2 W, Kyocera 20 W), when compared to the average values of panels of comparatively higher capacities. The low capacity panels being outliers were not included in the analysis. For the purposes of this study, only panels with a capacity of higher than 50 W capacity were included, and the average price (\$/Wp) of all panels available in the market for sale was analyzed and compared to the corresponding costs of manufacturing the panel. Comparing such cost and price for each corporation estimates the profit margin for each of the photovoltaic manufacturing corporation.

### 3.3 Results

**3.3.1 Energy and Resource Consumption:** In the baseline scenario, the EOL stage included only landfill disposal of the modules at the end of life. The life cycle primary energy consumption of the three crystalline modules was 8,220 MJ (mono-crystalline), 6,530 MJ (multi-crystalline) and 5,000 MJ (ribbon), the amorphous silicon and Cd-Te module consumed 2,270 MJ and 882 MJ respectively. The 3.8 kg aluminum (50% recycled) frame used in each module was 4%, 5% and 7% of the total energy consumption for mono-crystalline, multi-crystalline and ribbon modules. Module(s) landfill disposal at the end of life was not an energy intensive process and did not contribute to the life cycle primary energy consumption significantly. The primary energy consumption per unit peak watt power was 50 MJ/Wp (mono-crystalline), 40 MJ/Wp (multi-crystalline), 30 MJ/Wp (ribbon), 17 MJ/Wp (amorphous Si) and 13 MJ/Wp (Cd-Te). The primary energy consumption per unit module area was 6,600 MJ/m<sup>2</sup> (mono-crystalline), 5,200 MJ/m<sup>2</sup> (multi-crystalline), 4,000 MJ/m<sup>2</sup> (ribbon), 1,050 MJ/m<sup>2</sup> (amorphous Si) and 1,225 MJ/m<sup>2</sup> (Cd-Te). It is evident that the crystalline modules are more energy intensive than the thin film modules, both on a per unit peak watt and per unit area basis. These results emphasize the trade off in using crystalline modules, their higher conversion efficiency enables them to generate higher lifetime electricity when

compared to the thin film modules, at the same time they also entail higher energy investment during manufacturing. However, higher amounts of energy can be recovered from recycling crystalline modules, when compared to the thin film options.

The increased energy investment in the crystalline modules is an important factor that drives the recycling of crystalline modules. When the crystalline modules use recycled wafers, the life cycle primary energy consumption was 4,840 MJ (mono-crystalline), 3,150 MJ (multi-crystalline) and 1,620 (ribbon). The energy consumption in the recycled case reduced by 59%, 48% and 32% for the mono-crystalline, multi-crystalline and ribbon modules, when compared to using virgin wafers in each of the modules. The data sources indicated that there is no difference in the processes used to recycle wafers from the three types of crystalline modules. Hence the recycled crystalline modules have identical primary energy consumption, but the reduction in energy consumed is highest for mono, followed by multi and ribbon modules. The recycling of (glass, metals and plastics) in amorphous silicon module, and (glass and cadmium) in the Cd-Te module did not reduce the primary energy consumption significantly, when compared to the base case. The primary energy consumption was 2,080 MJ and 852 MJ for the amorphous silicon and Cd-Te modules. The primary energy consumption reduced by 8% and 3% for the amorphous silicon and Cd-Te modules in the recycled case, when compared to the base case with no recycling. From an energy standpoint there is more potential to derive benefits, by recycling crystalline than thin film modules. Recycling also leads to pollution reduction, discussed later in the sections below.

The higher primary energy consumption of the crystalline modules is partially contributed by their higher electricity and natural gas consumption, when compared to the two thin film modules. Manufacturing of crystalline modules consumed 449 kWh (mono-crystalline), 319 kWh (multi-crystalline) and 233 kWh (ribbon) of electricity. Electricity is predominantly consumed by the poly-silicon, wafer and cell production stages. The thin film modules were much less energy intensive, amorphous silicon and Cd-Te modules consumed 116 kWh and 42 kWh of process electricity respectively. Following similar trends, the three crystalline modules consumed significantly higher amounts of natural gas than the thin film modules during manufacturing: 428 ft<sup>3</sup> (mono-crystalline), 364 ft<sup>3</sup> (multi-crystalline), 197 ft<sup>3</sup> (ribbon), 14 ft<sup>3</sup> (amorphous silicon) and 1.3 ft<sup>3</sup> (Cd-Te). Table 3.3 summarizes the electricity and natural gas consumption results for the PV modules. Energy and resource consumption leads to release of air pollutant and greenhouse gas emissions, the emissions and impacts associated with the life cycle of the five PV modules is discussed below.

**3.3.2 Environmental Emissions and Impacts:** The life cycle CO<sub>2</sub> emissions followed similar trends to that of energy, with the crystalline modules emitting much higher CO<sub>2</sub>

emissions than the two thin film modules. In the baseline scenario, the life cycle CO<sub>2</sub> emissions (kg) on a per module basis were mono (355), multi (256), ribbon (179), amorphous silicon (114) and Cd-Te (55). Table 3.4 presents the life cycle CO<sub>2</sub> emissions on a normalized peak kilo-watt (kWp) capacity basis, for each of the five modules. When recycled wafer was used in crystalline modules, the CO<sub>2</sub> emissions reduced by 64% (mono), 50% (multi) and 35% (ribbon), when compared to the baseline case. This reflects the potential environmental benefits that can be derived out of recycling an energy intensive component, such as wafers in crystalline modules. Recycling materials from the two thin film modules provided lesser environmental benefits, with the CO<sub>2</sub> emissions of the amorphous silicon and Cd-Te module reducing by 10% and 7% respectively.

Table 3.4 also presents the criteria pollutants emitted during the life cycle of the five modules considered. For CO, NO<sub>x</sub> and SO<sub>2</sub>, the three crystalline modules (mono > multi > ribbon) released higher emissions than amorphous silicon, followed by Cd-Te module in the same order. The emissions of regional pollutants such as sulfur oxides and nitrogen oxides also followed the same trends to that of primary energy consumption. Ribbon and amorphous silicon module(s), emitted higher particulate emissions than the multi-crystalline module, with mono-crystalline and Cd-Te emitting the highest and lowest for the same category. The life cycle of the Cd-Te module released the lowest emissions in all categories except lead. The Cd-Te module follows the mono and multi-crystalline module(s) when lead emissions are considered, most of it being released from the manufacturing of the double walled glass, used in the Cd-Te module.

Table 3.5 presents the environmental impact results, for the five PV modules considered. The three crystalline modules in the order mono>multi>ribbon, followed by the amorphous silicon module exerted higher global warming (GWP), smog formation (SFP) and acidification (ARP) potential(s) than the Cd-Te module. The lead emissions during glass manufacturing led to the Cd-Te modules exerting a higher a carcinogenicity impact than the amorphous silicon module. Figure 3.1 presents the impact results, with the data presented in Table 3.5, normalized to that of the Cd-Te module. Since all of the results are normalized to the Cd-Te module, the impact exerted by the Cd-Te module for all categories tested is 1.0. The GWP, SFP, ARP and carcinogenicity potential(s) exerted by the mono-crystalline module is 6.5, 16.5, 7.3 and 8.5 times as much as the Cd-Te module, respectively. Similarly, the figure presents the impact results for all the five PV modules. On a per kWp basis, a total solid waste of (kg) 241 (mono), 137 (multi), 94 (ribbon), 104 (amorphous silicon) and 81 (Cd-Te), is released in the case of the five modules.

**3.3.3 Labor Inputs:** The labor intensity of the PV modules can be discussed from two different perspectives: the steps involved in manufacturing and servicing the PV module

and the labor sectors that contribute to the former. The total labor hours and person-years for producing a kWp of crystalline (69.7 hours, 0.036 person-years) and amorphous (64.8 hours and 0.033 person-years) modules are presented (Figure 3.2 and 3.3). Figure 3.2 presents the labor consumption of the different steps involved in producing the crystalline and amorphous silicon module. In both cases module assembly was the most labor intensive, consuming one-third of the total labor hours from different labor sectors. The other steps such as systems integration (17%), installation (15%), silicon manufacturing (8%), servicing and inverter manufacturing (both 7% each), distribution, contracting (6%), cell manufacturing (5%), wire manufacturing (3%) and mounting frame (2%) also contributed to the total of 69.7 hours. Plastic and glass manufacturing were not labor intensive; both combined only consumed 0.5% of the total labor. This section of the analysis helps identify the steps in PV production that are highly labor intensive. The steps involved in the actual production of the crystalline module consume 63% of total labor, with the remaining 37% consumed by the steps not directly involved (systems integration, distribution, installation and servicing) with module production. In the case of the amorphous silicon module, the absence of cell manufacturing, glass and frame manufacturing reduces the labor hours input by 7%, when compared to the crystalline module.

Figure 3.3 presents the different labor sectors that contribute to a total of 69.7 hours for producing the two types of PV modules. The professional, technical and management sector contributes 25 hours of labor to the different steps involved in PV production, contributing to more than one-third of the total labor consumption. Bench work, structural work, miscellaneous, processing, clerical and sales, and machining trades contribute to 15, 14, 12, 11, 7 and 5 percent of the total respectively. The service sector contributed the least to the various steps in module production. This section of the analysis helps identify the labor sectors that are heavily involved in photovoltaic production and servicing. The reduced number of production steps for the amorphous module reduces the labor inputs from the different sectors. Consequently the labor consumption reduced by 7%, when compared to the crystalline technology. Increased labor consumption can potentially lead to higher number of jobs and better living conditions. However, increased labor consumption does not necessarily imply increased sustainability from a social standpoint. It needs to be considered on an individual case basis. In some cases, increased labor can mean increased under-paid labor or child labor, especially in the case of developing countries. Since this study focuses on photovoltaic manufacturing specifically in the U.S, increased labor consumption can potentially lead to increased sustainability.

**3.3.4 Labor Cost Inputs:** Figure 3.4 presents the cost of labor for each sector, for producing and servicing a kWp of crystalline and amorphous silicon modules. The total



cost of labor is a function of both the total labor hours contributed to the production and the median wage rate. One third of the total labor is obtained from the professional, technical and management sector, the sector also has the highest wage rate (\$52.2 / hour) among all sectors analyzed. Both aforementioned reasons explain the professional, technical and management sector contributing to 62% (\$1,320 / kWp) of the total cost of labor. Other sectors such as structural work, clerical and sales, bench work, miscellaneous and processing contribute 9, 8, 7, 6 and 5 percent of the total respectively. The cost of labor for machining trades and servicing is low, and did not contribute significantly to the total. Based on this analysis, the total cost of labor in 2007 is \$2.12 per kWp capacity of crystalline modules produced. The lower number of production steps in the case of amorphous modules reduce the total cost of labor by 6.2% (\$1.99 / kWp). Essentially, this indicates the total cost spent on labor, for every step associated with producing and servicing the two PV technologies.

**3.3.5 Cost Inputs:** Sun Power Corporation (mono-crystalline) produced a total capacity of 108 MW modules in 2006. The costs associated with manufacturing silicon ingots and wafers to produce solar cells, materials, chemicals, gases and panel manufacturing are included in the direct manufacturing cost (\$1.72 / Wp). On a per peak-watt capacity basis, the corporation invested \$0.09 in research and development and incurred expenditures of \$0.2 for selling, management and administration (both indirect costs) purposes. The total manufacturing cost was \$2.01 / Wp, for the mono-crystalline technology, with the direct manufacturing cost contributing to 86% of the total. Q-Cells (multi-crystalline) produced a total capacity of 223 MW, the direct manufacturing cost (costs of raw materials, consumables, goods and services) was \$2.11 / Wp. The research and development costs were not reported; the selling, management and administration expenses amounted to \$0.57 / Wp. The total manufacturing cost was \$2.68 / Wp, the direct costs contributed to 79% of the total. Based on the environmental data reported, the water, electricity, and energy from natural gas consumed to produce a MWp capacity of modules was 869 m<sup>3</sup>, 148 MWh and 80 million Btu respectively. Q-Cells is the biggest manufacturer of photovoltaic cells in the world, however they do not manufacture the actual PV modules. The corporation manufactures cells and sells it to solar module manufacturers. Hence the cost relevant to Q-Cells discussed above indicates the cost of manufacturing multi-crystalline cells, and not modules. Prometheus Institute conducted a survey of the cost for crystalline module production from leading manufacturers in the U.S. The study reported the lowest value of cost for manufacturing multi-crystalline PV modules to be \$2.4 / Wp (Prometheus Institute 2008). The reported value of cost was only the direct cost of manufacturing modules.

Evergreen Corporation (ribbon) has two separate facilities, producing a combined total capacity of 45 MW. Direct and indirect (R&D + selling, admin) costs were \$2.03 and \$0.93 per Wp respectively, with the direct costs contributing to 69% of the total costs

incurred. United Solar (amorphous silicon) corporation produced a total capacity of 28 MW. Direct manufacturing cost (\$2.12 / Wp) contributed to 62% of the total manufacturing costs (\$3.44 / Wp). United Solar also invests significantly in their product research and development. The R&D costs were reported to be \$0.8 / Wp). First Solar (Cd-Te) corporation produced 25 MW capacity of modules in 2006. The direct manufacturing cost (\$1.26 / Wp) was 60% of the total manufacturing costs (\$2.11 / Wp). The total indirect costs were \$0.72 / Wp. The corporation also reports the cost of starting new production facilities in a year to be \$0.13 / Wp.

Figure 3.5 presents the cost results for the five PV modules, the total cost of the three crystalline modules range from (per Wp) \$2.01 to \$2.96. Among the three modules, the multi-crystalline technology has the highest direct manufacturing cost of \$2.11 / Wp. Mono and multi crystalline technologies are more developed when compared to the ribbon and amorphous silicon technologies. This is directly reflected in the research development spending by the corporations in an attempt to further develop the new technologies. The ribbon and amorphous silicon technologies spend \$0.42 and \$0.8 (per Wp) on R&D as opposed to \$0.09 per Wp observed for the mono-crystalline technology. The amorphous silicon technology has the highest total manufacturing cost among the five modules. The total manufacturing cost of the Cd-Te module was more comparable to that of the crystalline technologies.

Subsequently, the direct and total product cost of the crystalline and amorphous silicon options were compared to their corresponding market prices (Figure 3.6). First Solar (cadmium telluride technology) does not sell modules for small scale installations and they do not sell through re-sellers, distributors or installers. The corporation only sells their product through selected system integrators, independent power project developers and utility companies for exclusively large scale photovoltaic installations. Due to such limitations the market price of the Cd-Te module was unavailable, and consequently it was not included in the cost to price comparative analysis (First Solar 2008). For the multi-crystalline technology, the price of Solar Cynergy modules was used due to the fact that Q-Cells corporations sell their multi-crystalline cells to the particular module manufacturer (Solar Cynergy 2008). On a per unit watt basis, the profit margin (difference between price and cost) was highest for mono-crystalline module (\$4), the two other crystalline options and the amorphous silicon option had similar profit margins ranging from \$1.5 to \$1.7.

### **3.4 Summary and Conclusions**

This study focuses on the current United States photovoltaic (PV) market. The types of PV modules included in the analysis were based on recent production trends. The five PV modules considered, encompass 98% of the annual capacity of modules

produced recently in the U.S. In 2004, 70% of the total capacity (154 MW) of modules produced annually in the U.S were crystalline technologies, the remaining being amorphous technologies.

Four important factors associated with photovoltaic production were evaluated, energy inputs, environmental emissions, labor and cost inputs. The base case included only landfill disposal of modules at the end of life. In such a case the three crystalline modules consumed higher amounts of energy, than the two thin film modules. The life cycle primary energy consumed was 8,220 MJ for the mono-crystalline module, which is 1.3 and 1.6 times higher than the energy consumed for the multi-crystalline and ribbon modules. The amorphous silicon module consumed (2,270 MJ) 2.6 times the energy required for the cadmium telluride module. Following the same trend, the three crystalline modules consumed significantly higher natural gas and electricity, when compared to the thin film modules. From an environmental standpoint, the mono-crystalline module (355 kg) emitted 1.4 and 2 times higher CO<sub>2</sub> emissions than the multi-crystalline and ribbon modules. The amorphous silicon modules emitted twice as much CO<sub>2</sub> (114 kg) emissions, as the Cd-Te module. The three crystalline modules (mono>multi>ribbon), exerted higher global warming, smog formation and acidification impact potential(s) than the amorphous silicon modules, followed by the Cd-Te module. The manufacturing of the double-walled glass however caused the Cd-Te module to exert a higher carcinogenicity impact than the amorphous silicon module. With the current photovoltaic production in the U.S dominated by the crystalline technologies, it certainly is important to highlight the energy and environmental impacts exerted by the crystalline options.

Recycling of the module components was evaluated for its influence on energy consumed and environmental emissions. The recycling model was constructed based on the recent pilot plant established by Deutsche Solar, for recycling wafers from crystalline modules. Recycling the wafers (from the three crystalline modules) provided significant net energy benefits, the energy consumption of the crystalline modules reduced in the range of 32 to 59%, the CO<sub>2</sub> emissions reduced from 35 to 64%, for the three crystalline modules. Recycling of both the thin film module components however, did not provide any significant energy and environmental benefits. Realization of such low benefits highlights the reason for under-developed infrastructure for recycling these modules. From this analysis one can conclude that there are more potential energy and environmental benefits in recycling crystalline than thin film modules. One of the potential barriers for recycling wafers is the sheer volume of the crystalline modules that need to be recycled at the end of life. With *cumulative* crystalline photovoltaic production contributing to 92% of the total PV production in the U.S, recycling infrastructure

capable of handling large volumes of modules needs to be developed in the impending future (Trancik and Zweibal 2006).

Each of the three crystalline modules consumed, 2 and 6.8 more hours of labor for their production and servicing, than the amorphous silicon and Cd-Te modules respectively. Module assembly, systems integration and installation were the three most labor intensive steps, among the various stages analyzed; overall the steps directly involved with photovoltaic production consumed 63% of total labor inputs. The professional, technical and management, bench-work and structural work labor sectors in the same order, contributed significantly to the production and servicing of the PV modules. The labor cost model reported an average total labor cost of \$2.12 and \$1.99 to be spent, for producing and servicing a unit peak watt of crystalline and amorphous silicon photovoltaics. Identification of both the labor intensive process steps and the sectors that contribute most to PV production, will act a guideline to address challenges from a labor perspective. It will aid in streamlining the production processes to reduce labor hours and the total expenditures for labor.

Direct and indirect production costs were obtained from the market leaders for each of the five modules, inside the U.S. The cost trends of PV modules were different to the other results discussed above. On a per unit peak watt capacity produced basis, the amorphous silicon module had the highest total costs (\$3.44), among the five modules. The manufacturer of amorphous silicon also spent the highest in research-development (\$0.8 / Wp), among the five modules. The total production costs of the three crystalline modules ranged from (per Wp) \$2.01 to 2.96, the total cost of the Cd-Te module was \$2.11 / Wp. The amorphous silicon technology is relatively nascent when compared to the crystalline modules; hence the manufacturer incurs much higher research-development expenditures in an attempt to develop the technology.

In conclusion, crystalline modules consume higher amounts of primary energy, electricity and natural gas, and release higher CO<sub>2</sub> and criteria pollutants (except lead) than the two thin film options. However, recycling wafers from crystalline modules provides significant net energy and environmental benefits, benefits that are not possible with amorphous modules at this stage. Cadmium telluride modules have a strong recycling program at present because of the need to effectively manage cadmium at the end of life. Based on market data at present, the amorphous silicon technology had the highest total costs of production, including the highest investment in research-development programs among the five options. Developing a relatively new technology leads to increased research and development expenditures. This study strongly recommends extensive development of a recycling infrastructure for amorphous silicon modules. Development of such infrastructure will require a significant financial

investment but is necessary to manage the PV modules at the end of their life effectively. A portion of the R&D funding can be invested towards developing recycling programs for the technology. This study presents the current situation of photovoltaic manufacturing in the U.S, identifies challenges and offers solutions for addressing those challenges in the future.

## Figures and Tables

		Mono	Multi	String Ribbon	A-Si	Cd-Te
<b>Market Data</b>	U.S. Production (MW)	58	23	27	23	20
	U.S. Market Share (%)	38	15	18	15	13
<b>Technology Parameters</b>	Module Conversion Efficiency (%)	14	13.2	11.2	6.3	9
	Module Power (Wp)	165	165	165	136	67.5
	Module Area (m <sup>2</sup> ) (w/o frame)	1.25	1.25	1.25	2.16	0.72
	Power – Area Ratio (W / m <sup>2</sup> )	132	132	132	63	94

**Table 3.1: Market Share and Technology Characteristics of the PV Modules**

	<b>Occupational Categories: Labor Inputs Model</b>	<b>Selected Occupational Categories: BLS</b>	<b>Median Wage Rate (2007 \$ / hour)</b>
1	Prof, Tech and Mgt	Engineering Management	52.2
2	Clerical and Sales	Sales rep, wholesale and mfg, tech and scientific products	31.9
3	Service	Customer Service Reps	14.0
4	Agri, Fishery and Forestry	Farming, fishing and forestry occupations	8.9
5	Processing	Production Occupations	13.6
6	Mach. Trades	Welding, soldering and brazing machine setters, operators and tenders	15.3
7	Bench-work	Milling and planning machine setters, operators and tenders, metal and plastic	15.6
8	Structural work	Structural iron and steel workers	20.0
9	Miscellaneous		15.6
	Glass Manufacturing	Extruding, forming, machine setters, operators and tenders, synthetic and glass fibers	
	Cell Manufacturing	Semiconductor Processors	
	Module Assembly	Electrical and electronic equipment assemblers	
	Mounting Frame	Team assemblers	
	Distributing / Contracting	Transportation, storage and distribution managers	

**Table 3.2: Median wage rate(s) for the occupational categories used in the labor – cost model**

	Electricity (kWh) / Module	Natural Gas (ft <sup>3</sup> ) / Module
Mono-crystalline	449	428
Multi-crystalline	319	364
String Ribbon	233	197
Amorphous Silicon	116	14
Cadmium Telluride	42	1.3

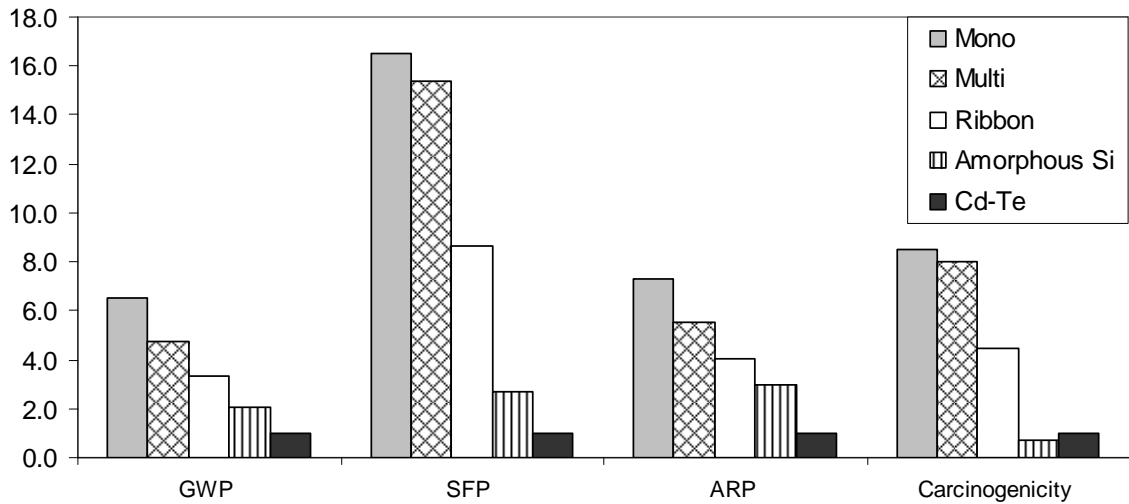
**Table 3.3: Electricity and natural gas consumption for the five PV modules considered**

Pollutant	Unit	Mono Crystalline	Multi Crystalline	String Ribbon	Amorphous Silicon	Cd-Te
Carbon Di-oxide (CO <sub>2</sub> )	kg	2,152	1,552	1,082	840	818
Carbon Monoxide (CO)	kg	2.7	2.4	1.9	1.6	0.9
Nitrogen Oxides (NO <sub>x</sub> )	kg	6.4	4.3	3.6	2.8	1.7
Particulates (PM <sub>10</sub> )	kg	0.21	0.09	0.10	0.12	0.09
Lead (Pb)	kg	5.72E-03	5.69E-03	1.93E-04	4.18E-04	1.07E-02
Sulfur Oxides (SO <sub>2</sub> )	kg	15.3	10.6	7.8	5.5	3.7

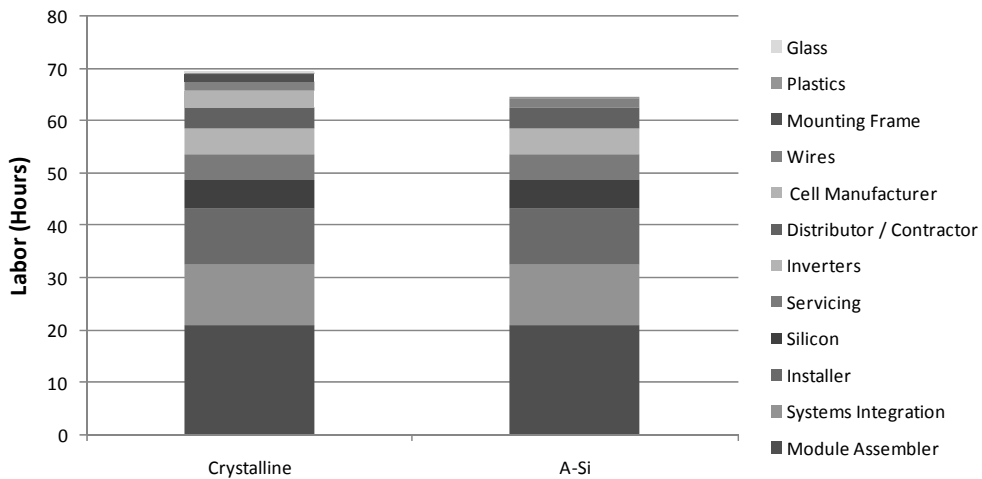
**Table 3.4: Life cycle environmental emissions released from the five PV modules, on a per kilo-watt peak power (kWp) basis**

Impact Category	Mono	Multi	Ribbon	Amorphous Si	Cd-Te
GWP (kg CO <sub>2</sub> eq.)	2,248	1,636	1,152	860	847
SFP (kg C <sub>2</sub> H <sub>4</sub> eq.)	2.8	2.6	1.5	0.5	0.4
ARP (kg SO <sub>2</sub> eq)	25	19	14	12	8
Carcinogenicity (DALY)*	1.58E-04	1.48E-04	8.24E-05	1.55E-05	4.53E-05

**Table 3.5: Environmental impacts from the life cycle of five PV modules, on a per kilo-watt peak power (kWp) basis (Eco-Indicator Method) \* Disability Adjusted Life Years**

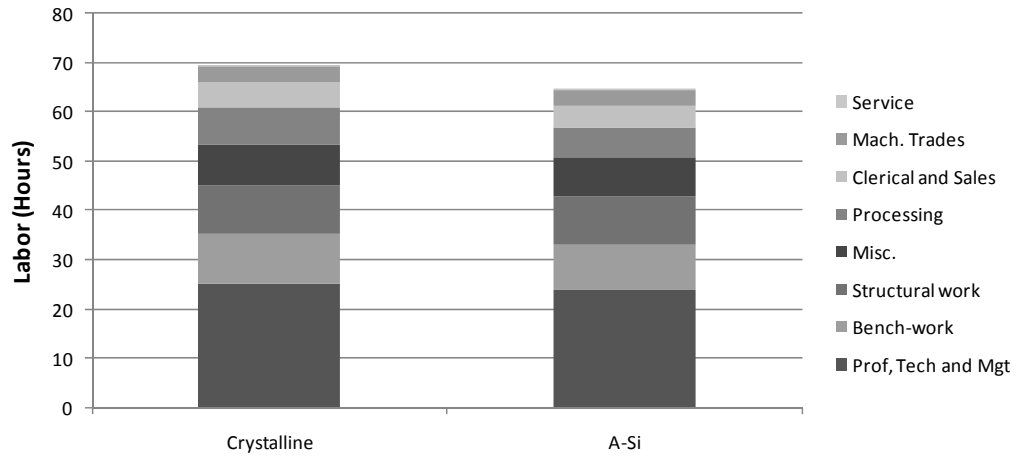


**Figure 3.1: Normalized impact potential(s) of the five PV modules (normalized to that of the Cd-Te module)**

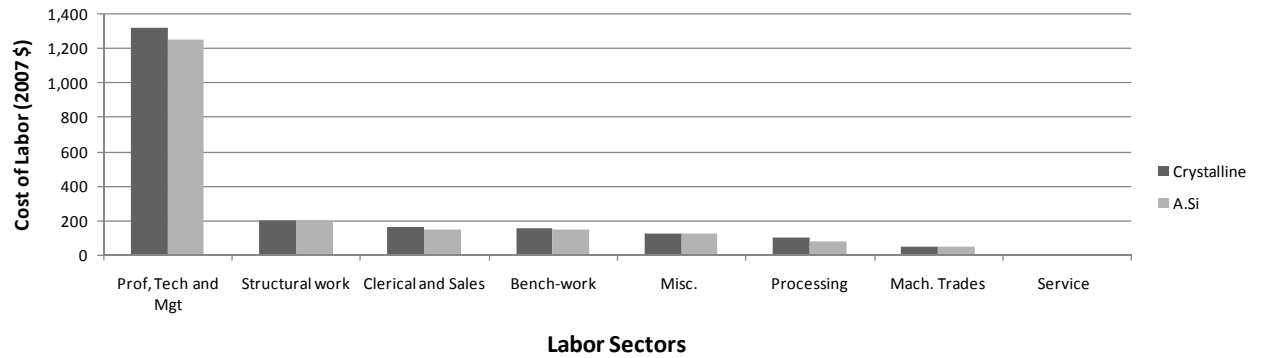


**Figure 3.2: Labor consumption of the various steps in crystalline and amorphous silicon module production – servicing (for one kWp of photovoltaics)**

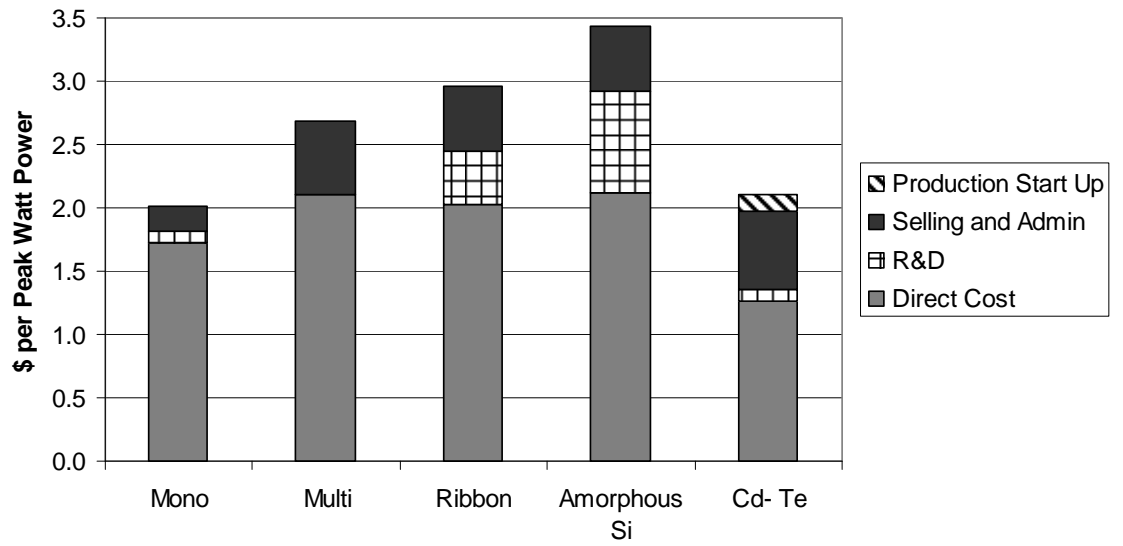




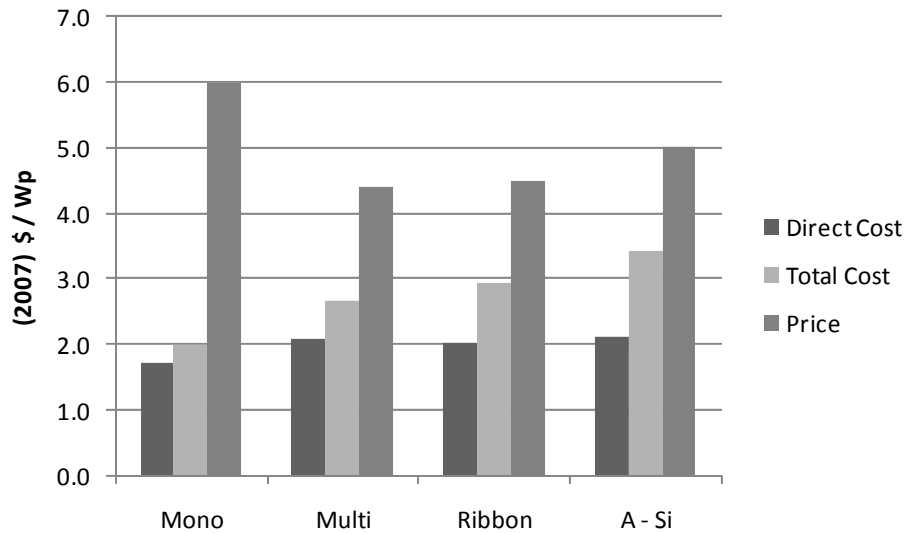
**Figure 3.3: Labor output from the different sectors for producing crystalline and amorphous silicon modules (for one kWp of photovoltaics)**



**Figure 3.4: Cost of labor for each sector, for producing crystalline and amorphous silicon modules (per kWp of photovoltaics)**



**Figure 3.5: Direct and indirect costs of manufacturing PV modules**



**Figure 3.6: Direct, total costs and market price of crystalline and amorphous silicon modules**

## REFERENCES

- Alsema, E.A. Nieuwlaar, E. 2000. Energy viability of photovoltaic systems. Energy Policy (28) 999 – 1010
- Bombach, E. Mueller, A. Wambach, K. Rover, I. 2007. Recycling of solar cells and modules – Recent Improvements. Deutsche Solar Report
- CALPRIG. 2002. Renewables Work: Job growth from renewable energy development in California (Report prepared by Brad Heavner and Susannah Churchill)
- EIOLCA (Economic Input Output Life Cycle Assessment). 2008. Link: <http://www.eiolca.net/> Link accessed on September 11, 2008
- Deutsche Solar AG. 2008. Link: <http://www.deutschesolar.de/> Link accessed on September 11, 2008
- First Solar. 2008. Environment and Recycling.
- Fthenakis, V. 2000. End of life management and recycling of PV modules. Energy Policy (28) 1051 - 1058
- Fthenakis, V. 2004. Life cycle impact analysis of cadmium in CdTe PV production. Renewable and Sustainable Energy Reviews, 8 (4) 303 - 334
- Fthenakis, V.M. Kim, H.C. 2006. Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics. Mater. Res. Soc. Symp. Proc. Vol. 895.
- Fthenakis, V. Kim, H.C. 2006a. CdTe Photovoltaics: Life cycle environmental profile and comparisons. Presented in the European materials research society meeting, Nice, France
- First Solar. 2008. Developers and Integrators.  
Link: [http://www.firstsolar.com/developers\\_integrators.php](http://www.firstsolar.com/developers_integrators.php) Link accessed on September 17, 2008
- International Energy Agency (IEA). 2006. National Survey Report of PV Power Applications in the United States. (Report prepared by Susannah Pedigo, Paul Maycock and Ward Bower)
- Lewis, G.M. Keoleian, G.A. 1997. Life cycle design of amorphous silicon photovoltaic modules. Report for United States Environmental Protection Agency (U.S.EPA), National Risk Management Research Laboratory, Ohio
- Mueller, A. Wambach, K. Alsema, E. 2006. Life cycle analysis of solar module recycling process. Mater. Res. Soc. Symp. Proc. Vol. 895 (0895 – G03 – 07.1)

Pacca, S. Deepak Sivaraman, Keoleian, G.A. 2007. Parameters affecting life cycle performance of PV technologies and systems. *Energy Policy*, 35 (6) 3316 – 3326

Prometheus Institute. 2005. Annual PV market assessment and supply chain reports

Personal Communication. 2008. Dr. Erik Alsema. Research Scientist, Copernicus Institute, Utrecht University, Netherlands

Personal Communication. 2008. Dr. Karsten Wambach and Anja Mueller, Head and Research Scientist of Solar Materials Division respectively, Deutsche Solar AG, Freiberg, Germany.

Personal Communication. 2008. Philip Davison (Manufacturing plant manager at United Solar Ovonic, Auburn Hills, Michigan, USA)

Personal Communication. 2008. Dr. Vasilis Fthenakis. Research Scientist, Brookhaven National Laboratory

Product Energy Consultants (Pre). 2008

Link: <http://pre.nl/software.htm> Link accessed on September 11, 2008

Product Energy Consultants (Pre). 2008a. Eco-Indicator 95 Impact Assessment Method

Link: <http://pre.nl/eco-indicator95/ei95-reports.htm> Link accessed on September 11, 2008

Prometheus Institute. 2008. PV Technology, Performance and Cost: 2007 Update (Report compiled by Paul Maycock and Travis Bradford).

PV News Magazine. 2005. Global PV Cell Production Capacity.

Trancik, J.E. Zweibal, K. 2006. Technology cost and cost reduction potential of photovoltaics. IEEE. Report number 1-4244-0016-3/06

Singh, V. 2001. The work that goes into renewable energy. Renewable Energy Policy Project (REPP) Report. 2001.

Sinha, P. Kriegner, C.J. Schew, W.A. Kaczmar, S.W. Traister, M. Wilson, D.J. 2008. Regulatory policy governing cadmium telluride photovoltaics: A case study contrasting life cycle management with precautionary principle. *Energy Policy* (36) 381-387

Solar Cynergy. 2008. PV Modules.

Link: <http://www.solarcynergy.com/Solar-PV-Panels.html> Link accessed on September 17, 2008

Sunpower Corp. 2007. Largest U.S. solar PV systems begins construction at Nellis air force base.

Link: <http://investors.sunpowercorp.com/releasedetail.cfm?ReleaseID=239017>

Link accessed on September 11, 2008

Trancik, J.E. Zweibal, K. 2006. Technology cost and cost reduction potential of photovoltaics. IEEE. Report number 1-4244-0016-3/06

Tsoutsos, T. Frantzeskaki, N. Gekas, V. 2005. Environmental impacts from solar energy technologies. Energy Policy (33) 289 – 296

United States Department of Labor. 2008. Bureau of Labor Statistics: Wages by area and occupation. Link: [http://www.bls.gov/oes/current/oes\\_nat.htm](http://www.bls.gov/oes/current/oes_nat.htm) Link accessed on September 11, 2008

Wild-Scholten, M.J. Alsema, E.A. 2006. Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production. Mater. Res. Soc. Symp. Proc. Vol. 895.

Zweibel, K. 1999. Issues in thin film PV manufacturing cost reduction. Solar Energy Materials and Solar Cells, 59 (1-2) 1-18

Zweibel, K. 2000. Thin film PV manufacturing: Materials costs and their optimization. Solar Energy Materials and Solar Cells, 63 (4) 375-386

## **CHAPTER 4**

### **PHOTOVOLTAIC (PV) ELECTRICITY: COMPARATIVE ANALYSES OF CO<sub>2</sub> ABATEMENT AT DIFFERENT SCALES IN THE U.S**

#### **ABSTRACT**

Solar photovoltaic (PV) electricity has the potential to mitigate CO<sub>2</sub> emissions from the grid. A comparative assessment of the CO<sub>2</sub> abatement potential of photovoltaics is conducted by analyzing different fuel mix scales in the U.S. A visual basic dispatching model was developed to evaluate abatement at the margin for the load zones Electric Reliability Council of Texas (ERCOT) and California Independent System Operator (CAL-ISO), and compared to the results obtained using national, regional and state resource profiles. Due to the predominant displacement of the less carbon intensive natural gas at the margin in ERCOT, the marginal case reduced CO<sub>2</sub> by 145 to 181,850 tons below the three average scales. In CAL-ISO, marginal displacement of natural gas abated 714 – 3,500 tons CO<sub>2</sub> more than the three average cases. This study demonstrates that the actual CO<sub>2</sub> abatement of PV electricity is dependent on the peak load resources and the capacity of installations. Subsequently a CO<sub>2</sub> indicator is developed that can be used as a guideline for selecting sites for PV installation to derive maximum abatement. Installing photovoltaics in the regional grids of Midwest Reliability Organization, Southwest Power Pool and Reliability First Corporation was determined to be most beneficial. In addition the influence of a time varying fuel mix and variability in solar resource across the U.S. on the benefits of PV technology is tested. The results of this study can guide energy planning and CO<sub>2</sub> mitigation policymaking using PV technologies in the future

## 4.1 Introduction

Electricity generation from non-hydro renewable resources is projected to increase twofold in the next two decades; Energy Information Administration (2008) projects these renewable resources to contribute 5.5% of total U.S. electricity demand by 2030. In 2007, 606 GWh of solar energy was generated contributing to 0.01% of the total demand (Energy Information Administration 2008a). A cumulative photovoltaic capacity of 500 MW was installed through 2005 in the U.S contributing to less than 0.1% of the total national capacity of electricity sources installed (PV News 2006). At present the cost of photovoltaic electricity ranges from 21 – 37 ¢/kWh (for residential, commercial and industrial sectors), which is much higher than the price of conventional grid electricity (7.2 ¢/kWh) (National Renewable Energy Lab 2005). However, recent studies have concluded that with the aid of compressed air energy storage (CAES) mechanisms and recent cost reductions in PV production, PV electricity can be expected to be cost competitive in the future (National Renewable Energy Laboratory 2008). The feasibility of complying with potentially more stringent CO<sub>2</sub> regulations in the future is determined by the pollution abatement derived from using renewable resources. From a photovoltaic standpoint, an accurate estimation of CO<sub>2</sub> abatement by PV electricity generation is an integral component of mitigating climate change and energy policy-making. This study focuses exclusively on the United States, evaluating the CO<sub>2</sub> abatement using an average national, regional and state scale approach, and comparing the results obtained to that of a marginal displacement approach.

Previous studies have used the average CO<sub>2</sub> emission factor of a grid to evaluate the carbon abatement of PV electricity. Keoleian and Lewis (2003) used a regional grid approach to calculate the avoided greenhouse gas emissions, the CO<sub>2</sub> avoided was in the range of 437 to 1,230 (g/kWh), in Boston (Massachusetts) and Detroit (Michigan) respectively. However depending on the capacity of photovoltaic installations, electricity generated either displaces only the peak load resources or the entire average of the grid resources. The entire resource profile of the grid can potentially be restructured when PV installations are high enough to be used as a peak load and intermediate load resource. Denholm and Margolis (2007 and 2007a) investigated the potential and limitations of using PV installations at the margin, and as base load sources. The minimum loading constraint for the ERCOT grid was 35%. It is impossible to utilize PV energy generated below 35% of the peak load, because the inflexibility of the base load plants will exert a significant economic penalty in such a case. Due to the inflexibility of the base load plants there is a significant amount of unusable PV energy even when PV electricity contributes to only one fifth of the total load. In a subsequent paper the authors analyzed that with 11 hours of storage capacity and a minimum loading constraint of 20%, about half the ERCOT grid's load can be supplied by PV electricity. Denholm et al 2009 evaluated the energy conserved and CO<sub>2</sub> displaced from the Western Electric

Coordinating Council regional grid using PV electricity at the margin in California and Colorado. The displacement of natural gas at the margin reduced 6000 – 9000 KJ for every kWh of PV electricity generated at the margin and the corresponding CO<sub>2</sub> emission reduction was also evaluated. An independent system operator (ISO) is an entity working under the Federal Energy Regulatory Commission, and is responsible for monitoring, controlling and satisfying the electricity demand every hour of the day throughout the year. Hence it is indeed the ISO that contains the entire list of power plants used to satisfy the demand at all time periods in a grid. The current study focuses on the marginal abatement at the independent system operator scale. A novel methodology was developed, to evaluate the CO<sub>2</sub> abated by PV electricity at the margin in two load zones, and a comparative analysis is performed using three different conventional approaches. A CO<sub>2</sub> abatement indicator for the regional grids and load zones analyzed is presented. It will aid policy-makers in identifying sites for PV installation to derive maximum CO<sub>2</sub> abatement. Such an indicator is presented for each state in the ten regional electricity grids in the U.S, and for the two load zones of ERCOT and CAL-ISO. Finally, the CO<sub>2</sub> abatement of PV electricity generation is analyzed, by using a dynamic grid fuel mix that varies annually. Projections of grid resource profile in the future were used for this analysis, and the results were compared to the abatement evaluated using a static fuel mix approach.

From an energy standpoint a metric based on both the energy payback time (E-PBT) and technology lifetime is developed. Energy payback time is the number of years it takes for the energy output from the system, to break even with the initial primary energy investment to manufacture the system. Previous life cycle studies have evaluated the energy performance of PV modules based exclusively on energy payback time. Pacca et al. (2007) performed a comparative analysis of multi-crystalline modules and thin film PV laminates. Due to increased energy investment during manufacturing, the actual energy performance of the multi-crystalline (E-PBT 7.5 years) module was lower than that of the amorphous silicon module (E-PBT 3.2). Fthenakis and Kim (2006) LCA study of the Cd-Te module reported an energy payback time of 0.75 year. Raugeri et al (2007) evaluated the energy performance of thin film technologies. The study reported the energy payback time for the copper indium di-selenide (CIS) and cadmium telluride (Cd-Te) modules to be 1.9 and 0.5 years, based on southern European solar radiation conditions. In this study the metric developed for various locations in the U.S, to evaluate the energy performance of PV technology is presented.



## 4.2 Methods

### 4.2.1 Lifetime Photovoltaic (PV) Electricity Output and Inverter Efficiency

Five photovoltaic modules (three crystalline, two thin film) were considered in this study. The total amount of electricity generated by the five PV modules, is calculated using the following formulation (equation 1)

$$E = (R) \times (A) \times (N) \times (\eta) \times (\eta_i) \quad (\text{equation 1})$$

Where

E is the lifetime electricity output, R is the average solar resource (kWh / m<sup>2</sup> / day) which includes the direct and diffused solar radiation incident on a horizontal PV panel. A is the module area (m<sup>2</sup>), N is the module lifetime (days),  $\eta$  is the module conversion efficiency and  $\eta_i$  Inverter efficiency.

The average solar radiation for all of the locations selected was obtained from PV-WATTS software developed by NREL (National Renewable Energy Lab 2008a). A specific location was selected in each of the fifty states based on the quality of solar radiation data available. Previously, several LCA studies have used a module lifetime of 20 to 30 years in their analysis (Wild-Scholten and Alsema (2006), Pacca et al. (2007). Recent quality testing of PV modules concludes that the panels do have the robustness to function up to 25 years (Mau et al. 2004). BP Solar now provides a twenty-five year warranty period for their product (BP Solar USA 2008). Dunlop and Halton (2006) evaluated the performance of crystalline modules that had been in the field for 22 years, and a majority of modules were reported to exceed 92% of the rated power output. Hence in this study a reasonable assumption of a twenty-five year lifetime period for the modules was used. The inverters specifically designed to be used in conjunction with photovoltaic systems (e.g. Ballard and Xantrex) report their product efficiency to be consistently above 95%, except at very low PV output levels. To account for a decrease in inverter efficiency under such conditions the weighted inverter efficiency values of California Energy Commission (CEC) were used. The final weighted value takes into account the inverter efficiencies at different load levels (Go Solar California 2008).

### 4.2.2 Life Cycle Model and Energy Performance of PV Modules

A life cycle model was constructed for the five PV modules in the software Simapro (Product Ecology Consultants 2009). The model evaluated the total non-renewable primary energy and environmental emissions associated with manufacturing and end of life management of PV modules (equation 2). Energy Pay Back Time (EPBT) was the metric used to evaluate the energy performance of the PV modules. Two cases indicating the best and worst case scenarios for EPBT were evaluated, and

presented for the different locations considered. The E-PBT was further combined with technology life time to evaluate the fraction of lifetime required for a PV module to breakeven with its input energy (equation 3).

$$E_{Non\ Renewable\ Primary} = E_{Raw\ Matl\ Extrac} + E_{Matl\ Prod} + E_{Module\ Mfg} + E_{End\ of\ Life}$$

(equation 2)

$$\text{Lifetime Indicator} = \frac{E_{Non\ Renewable\ Primary}}{E_{PV\ Annual}} / N \quad (\text{equation 3})$$

Where  $E_{PV\ Annual} = f(R.A. (365 \frac{days}{year}). \eta. \eta_i)$ , the N is the module lifetime (in years)

### 4.2.3 CO<sub>2</sub> Abatement by PV Electricity Generation

In this study, the CO<sub>2</sub> abatement by PV electricity generation was analyzed at four different scales, national, regional, local state and marginal scales. For the first three cases, the corresponding fuel mix was obtained and modeled in Simapro. The national fuel mix was represented by Franklin database. The eight regional fuel mix and fifty local state fuel mix profiles were obtained from NERC (2006) and E-Grid (2007) respectively, and modeled. The resultant CO<sub>2</sub> emission factor of grid electricity generation was used to determine the CO<sub>2</sub> abated through PV electricity generation, for each corresponding location.

### 4.2.4 Marginal CO<sub>2</sub> Displacement

**Grid Characteristics and Assumptions:** The CO<sub>2</sub> displaced due to PV electricity generation was evaluated by displacing resources at the margin. For the purposes of this analysis, ERCOT (Electric Reliability Council of Texas) independent system operator and California independent system operator (CAL-ISO) were chosen to evaluate potential benefits. Both electric regions have different characteristics; the ERCOT serves 20 million end use retail customers contributing to 85% of the state load. The peak and the total annual demand in 2005 were 60 GW and 300 TWh<sup>1</sup>. The ERCOT grid is also electrically isolated from the rest of the U.S, with an import/export capacity of less than 1 GW. Hence electricity generated in the regional grid, is used within the grid. CAL-ISO contributes to 80% of the state load serving 30 million end use customers. The all time highest peak load was 50,270 MW in July 2006, and the total 2006 generating capacity was 56.3 GW. Both ERCOT and CAL-ISO use gas and hydro plants at the margin (Denholm and Margolis 2007, California ISO 2008). CAL-ISO differs from ERCOT in the fact that the load serving entities in CAL-ISO rely on imports, for almost one fourth of their annual electricity consumption.

<sup>1</sup> One Tera Watt Hour (TWh) = Billion Kilo-Watt Hours ( 10<sup>9</sup> kWh)

The average transmission and distribution losses of 6.5% (for ERCOT) and 2.6% (for CAL-ISO) were used in the analysis (Denholm and Margolis 2007, California ISO 2008). In this study it was assumed that 50% of the PV electricity was to be generated onsite, in which case the PV electricity will displace an equivalent amount of grid electricity and the electricity lost due to transmission and distribution in the grid. The other half of PV electricity was considered to be generated offsite. This essentially implies that the transmission and distribution losses occur for PV electricity as it would in the case of grid electricity. Hence PV electricity only displaces an equivalent amount of grid electricity, without displacing additional amounts of electricity lost due to transmission and distribution.

**Load Characteristics and Assumptions:** The hourly load for the year 2004 was obtained from FERC (Federal Energy Regulatory Commission 2008). The minimum, average and maximum loads for the annual year were 20.3 GW, 32.9 GW and 58.5 GW (for ERCOT) and 18.6 GW, 28 GW and 45.6 GW (for CAL-ISO) respectively. The load ratio (hourly load / peak annual load) for a week, for winter, spring, summer and fall for ERCOT, are plotted in (Figure 4.1). This indicates the variation in ERCOT load, at different seasons of the year. The complete list of power plants generating electricity in the grid(s) was obtained from U.S. EPA E-Grid. The data consisted of plant primary fuel, plant capacity and capacity factor, and emission factors for electricity generation. Based on the information obtained from the E-Grid database, a load duration curve (LDC) was constructed for both the grids. Based on E-Grid classification, a capacity factor of 0.0 to 0.2, 0.2 to 0.8 and 0.8 to 1.0 each represent the peak load, intermediate load and base load plants respectively (E-Grid 2008). In the case of ERCOT, the base load plants include coal and nuclear sources which can operate at low cost, but have very limited flexibility in terms of adjusting to varying demands. At the margin, the demand is met by natural gas and hydropower plants; these have a higher marginal cost but have an increased flexibility to meet varying demand each hour. CAL-ISO on the other hand uses a number of gas plants both at base loads and at the margin; other base load sources include hydropower, landfill gas, geothermal and petroleum coke resources. After using the base load plants, traditionally the intermediate and peak load plants are dispatched in the increasing order of their marginal costs. A very important parameter that determines the marginal cost of a plant is its capacity factor. Due to data limitations on the power plant marginal costs, in this study it was assumed that dispatching order is determined based exclusively on the plant's capacity factor. Further, it was also assumed that the plants were available for dispatching at all times, without being in repair or down for maintenance. In the model for California, the PV electricity generated displaced the resources at the margin exclusively in the CAL-ISO control area, and not the imports. The state of California imported 91 TWh annually in 2004 overall (Farrell et al 2006). Based on the E-Grid data, CAL-ISO imports from three plants located in Nevada. The imports are derived from a large 1.64 GW capacity bituminous Mohave coal plant and

two other smaller geo-thermal plants. Electricity from coal plants is used at base loads, and in this model other renewable sources (geothermal) were not displaced using PV electricity. Both aforementioned reasons explain the reasoning behind displacing marginal resources within the CAL-ISO load zone, and not the imports.

**Solar Radiation and Installation:** A particular location inside Texas was selected for installation of PV modules. San Antonio was selected in this case and the hourly solar radiation data were obtained for the year 2004. Selecting the site for installation was contingent on the quality of the data available. Among the three classes (class 1, 2 and 3) that indicate data quality, class 1 data (highest quality) were available for San Antonio in Texas. Class 1 indicates that the solar resource data were available at all hours from 1991 to 2005. For California, the class 1 solar resource data in the CAL-ISO control area location of San Diego (Southern California) were obtained for 2004 (National Renewable Energy Lab 2008b). A variation of equation 1 was used to calculate the photovoltaic electricity generated (equation 4), for each hour in a year. Since 2004 was a leap year, electricity generated during each of the 8,784 hours summed up to the total annual electricity generated. A CEC weighted inverter efficiency of 94% was used throughout the analysis, the entire capacity of PV modules was assumed to be installed in a single location in each state. This is a reasonable assumption because this study tested the influence of a number of PV capacity installations, with a maximum of only 1 GW. Previous studies have reported that in certain cases PV energy becomes un-usable when it displaces base load sources (Denholm and Margolis 2007, Denholm Margolis 2007a). The un-usability issue is irrelevant to this study because of the low capacity PV installations that are not large enough to displace base load sources. The primary objective in this section was to evaluate the CO<sub>2</sub> benefits realized using a marginal scale, and compare it to the results from other scales discussed above.

Annual PV Electricity Output (kWh) =  
(equation 4)

$$\sum_{t=1}^{8784} \text{Hourly Solar Resource Availability} \left( \frac{\text{kilo-Watt}}{\text{m}^2\text{-hr}} \right) \times \text{Module Area (m}^2\text{)} \times 1(\text{hr}) \\ \times \text{Module Efficiency } (\eta) \times \text{Inverter Efficiency } (\eta_i)$$

**Methodology:** A combination of visual basic for applications (VBA) software and Excel were used for the analysis. Appendix A presents the entire code for the two load zones. For each hour of the year 2004, the load and PV electricity generated were determined. Using the dispatching sequence determined for both grids, the peak load plants used at the margin to meet demand were determined. Subsequently, using the particular amount of PV electricity generated, the primary fuel and CO<sub>2</sub> emissions factor of the plants displaced at the margin for every hour of the year was analyzed. Using the plant characteristics, the total amount of CO<sub>2</sub> emissions displaced at the margin by the installed photovoltaics, was evaluated for every hour in the year. Subsequently, based on the fuel

type of the power plant displaced at the margin, the CO<sub>2</sub> emissions from pre-combustion (fuel extraction, refining and delivery) was obtained from the Franklin database and added. Hence the CO<sub>2</sub> emissions displaced in the marginal case represents the emissions reduced both in the combustion and pre-combustion processes. Additionally the CO<sub>2</sub> emissions displaced at the margin was evaluated at different capacity of PV installations. With increasing installation capacity, the emissions reduced is expected to be linear in the national, regional and state scales modeled above, owing to a constant emissions factor. However in the case of the marginal scale, the resources displaced at the margin vary with the installed PV capacity leading to a variable emissions factor. The possible difference in the actual amount of CO<sub>2</sub> emissions displaced at the margin, in comparison to the other three cases is investigated.

#### **4.2.5 CO<sub>2</sub> Abatement Indicator for Regional Grids and Load Zones**

The total CO<sub>2</sub> displaced from the grid is a function of both the grid fuel mix profile and the solar resource available in a location. Using the CO<sub>2</sub> emission factor obtained for the eight regional grids, a CO<sub>2</sub> abatement indicator was developed. This indicator (kg / m<sup>2</sup>-day) reflects the combined effect of solar resource available (kWh / m<sup>2</sup> / day) and CO<sub>2</sub> intensity (kg / kWh) of the regional grid, on the potential CO<sub>2</sub> abatement by PV electricity. This factor can be used as a guideline for energy planning, in selecting sites for PV installation to derive maximum CO<sub>2</sub> abatement. This study developed such an indicator for the regional grids, and for the two load zones analyzed.

#### **4.2.6 Dynamic Grid Fuel Mix**

In the national, regional and state scales, the CO<sub>2</sub> abatement by PV electricity generated was evaluated by using a static fuel mix for the conventional grid, throughout the lifetime of the PV technology. With an increase in electricity demand every year, new capacity additions, potential increase in renewable installations, fuel price volatility and risks of radioactive waste disposal, the fuel mix profile of the grid is expected to change with time. Two such forecasts developed by Energy Information Administration (2008) and Electric Power Research Institute (2007) were used in this section. The EIA and EPRI both forecasted an annual increase of 1.08% and 1.22% in electricity demand up until 2030. The EIA predicts an increase in coal and renewable sources, and a decrease in the utilization of nuclear, gas and oil resources. The EPRI projects a less carbon intensive fuel mix in the future, an increase in coal, nuclear and renewable sources concomitant with a decrease in gas and oil sources. Two major differences can be highlighted between the two scenarios modeled, the EPRI scenario includes a gradual increase of carbon capture and storage (CCS) that contributes to 14.6% of electricity demand by 2030, CCS is absent in the case of EIA. The usage of renewables increases at a higher rate in EIA, when compared to EPRI. The fuel mix predicted in both cases was modeled for each year in Simapro, and the CO<sub>2</sub> abated by PV electricity generation was evaluated using such a

dynamic resource profile. The results were compared to that obtained using the static fuel mix scenarios.

### 4.3 Results and Discussion

**4.3.1 Energy Pay Back Time of PV Modules:** The total non-renewable primary energy ( $E_{\text{Non-Renewable Primary}}$ ) consumed in the life cycle of the five PV modules was analyzed, a single mono, multi and ribbon module consumed (MJ) 8,220, 6,530 and 5,000 respectively. One amorphous silicon and Cd-Te module consumed (MJ) 2,270 and 882 during the life cycle. The energy payback time of the five modules was compared by installing 1 kW<sub>p</sub> capacity of each type, in all of the locations tested in the study. Table 4.1 presents the locations with the lowest five E-PBT values, followed by the 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup> and 100<sup>th</sup> percentile of E-PBT values in the U.S. The Cd-Te module had the lowest energy payback time among all the options, ranging from 1.7 to 3.9 years from Arizona to Alaska. The mono-crystalline module took the longest time to break even, with its corresponding input energy (5.9 to 13.5 years, Arizona to Alaska). It had to generate energy for more than half of its total lifetime (25 years) to break even in Alaska. The two thin film modules had an energy performance of at least 50% better than the crystalline options. The E-PBT of the amorphous silicon, string ribbon and multi module(s) ranged from, 2.1 to 4.8, 4.5 to 10.2 and 5.0 to 11.3 years respectively. Another simple metric developed in this study to evaluate the energy performance of the PV technology, is the percentage of total lifetime a PV module takes to break even with the input energy. This performance is driven by the amount of local solar resource available, in the worst case (Alaska), the crystalline modules take 41 to 54% of their total lifetime to break even with the input energy; the two thin film modules take 16 to 19% achieve the same. In the best case scenario (Arizona), the energy payback time decreases by 56% for all the five options. It is important to mention here, that even though the energy performance of the thin film options is better than the crystalline modules, a fixed capacity of mono crystalline module generates higher lifetime electricity than the two thin film options.

### 4.3.2 Comparative Marginal Abatement of CO<sub>2</sub> Emissions

In this section the CO<sub>2</sub> abatement at the margin evaluated for the load zones ERCOT and CAL-ISO are presented and compared to the abatement results obtained from the three average fuel mix scales. This section highlights the difference in results between the two approaches.

**Electric Reliability Council of Texas (ERCOT) ISO:** The displacement of resources at the margin at six different peak power capacity of photovoltaic installations (1, 100, 250, 500, 750 and 1,000) MW<sub>p</sub>, in the same location was tested. The rule of PV electricity not displacing other renewable resources was used. Hence no wind plants at the margin are displaced. The fuel mix of the displaced resources was consistent across the range of

installations tested. The average marginal fuel mix for the six cases tested is as follows, natural gas, hydropower, gases and sub-bituminous coal were (%), 98.3, 0.7, 0.7, and 0.2 of the total fuel mix, with the remainder contributed by a combination of agricultural by-products and petroleum coke. The marginal fuel mix is very different from the national, regional and state fuel mix for Texas, and hence presents different levels of pollution abatement.

The CO<sub>2</sub> emission factor for the national, regional, and state cases were used to evaluate the abatement by PV electricity, and the results were compared to the marginal case. With 98.3% displacement of electricity generated by the number of natural gas plants at the margin, the CO<sub>2</sub> abated is much lower when compared to the benefits of PV electricity using the other three scales. Natural gas is comparatively less carbon intensive when compared to other fossil fuels, and the marginal case also displaces much lower coal (0.2%) when compared to the other three scales (national 51%, regional 23% and state 39%). The combination of the above mentioned reasons explain the abatement of much lower CO<sub>2</sub> emissions in the marginal case. Figure 4.2 presents the load and PV electricity generated (at 1,000 MW capacity) for one week in the summer, along with the CO<sub>2</sub> emissions displaced at each hour. The PV electricity and the CO<sub>2</sub> displaced have very similar profiles due to the predominant displacement of natural gas at the margin. Table 4.2 presents the annual electricity generated and CO<sub>2</sub> emissions abated for different capacity of PV installations, at the four scales discussed. On an annual basis, the PV installations displaced 1.48 to 1,475 GWh (at, 1 to 1,000 MW) of total electricity. The marginal displacement case on an average reduced 145 to 181,850 tons of CO<sub>2</sub>, lesser than the other cases (Table 4.2). The pre-combustion emissions in the marginal case contributed to 13% of the total displacement. The CO<sub>2</sub> emission factor in the marginal cases was 0.62 kg/kWh, when compared to the other three scales in which the factor ranged 0.70 to 0.75 kg/kWh.

**California Independent System Operator (CAL-ISO):** The marginal displacement in the case of CAL-ISO was tested at five different PV installations (0.5, 0.75, 1.0, 1.25 and 5.0) MW<sub>p</sub>, in the same location. The total annual PV electricity generated ranged from 878 to 8,782 MWh in San Diego. Due to the higher diversity of peak load resources used at the margin in CAL-ISO (when compared to ERCOT), the CO<sub>2</sub> emission factor decreased with increasing PV installations. For the tested range of installations, the average CO<sub>2</sub> emission factor was (kg CO<sub>2</sub>/kWh) 1.22, the factor ranged from 0.92 (at 5 MW PV) to 1.34 (at 0.5 MW PV). Similar to ERCOT, CAL-ISO also predominantly utilizes natural gas at the margin to satisfy fluctuating peak demands, but the type of gas used in this load zone is more carbon intensive than ERCOT. The average marginal fuel mix based on the five cases is as follows, natural gas, jet fuel and hydropower contributed (%) 98.9, 0.9 and 0.2 of the total annual electricity generation. At 0.5 MW<sub>p</sub> PV capacity installation, 99.8% of electricity at the margin was displaced from natural gas plants.

With higher PV installations (5 MW<sub>p</sub>), only 95.2% of electricity was displaced from natural gas plants, this scenario includes both increased diversity of plants displaced at the margin, and a consequent decrease in the marginal CO<sub>2</sub> emission factor.

The average CO<sub>2</sub> intensity of the national, regional and state grid(s) ranges from 0.39 – 0.70 kg/kWh, the lower values of 0.39 and 0.48 for the state and regional case can be explained due to the usage of increased hydropower and renewables to generate electricity. Due to predominant marginal displacement of natural gas, increased average abatement of 714 – 3,500 tons of CO<sub>2</sub> is realized in the marginal case, when compared to the other three cases. The pre-combustion emissions in the marginal case contributed to 6 – 9% of the total displacement, for the five cases tested. Table 4.2 presents the CO<sub>2</sub> abated in all the five PV capacity installations tested in the CAL-ISO load zone. Hence CAL-ISO presents a contrasting scenario to that of ERCOT, using an average resource profile under-estimates the CO<sub>2</sub> abatement of PV electricity in this case due to the less carbon intensive nature of the conventional grid. In the case of ERCOT, it over-estimated the CO<sub>2</sub> abatement due to the higher carbon intensive nature of the conventional grid. Figure 4.3 presents the load, PV electricity generated and CO<sub>2</sub> abated for both the 0.5 and 5 MW<sub>p</sub> PV capacity installations.

**4.3.3 CO<sub>2</sub> Abatement Indicator for Regional Grids and Load Zones:** Table 4.3 presents the CO<sub>2</sub> abatement indicator (sorted in the descending order for each regional grid) for the different states analyzed in each regional grid. The indicator presents the combined effect of the solar resource and CO<sub>2</sub> intensity of a particular grid. Western Electricity Coordinating Council (WECC) presents an interesting case, even with the high solar radiation in the states of California and Arizona, the indicator was (3.07 (AZ) and 3.01 (CA)) comparatively lower than other grids in this case. This can be explained by the increased use of hydropower to generate electricity in the WECC grid. The MRO presents a contrasting case to that of WECC, installing PV modules in Wyoming (WY) abates the highest CO<sub>2</sub> emissions (factor: 4.51) among all cases considered. Wyoming receives lower solar radiation than Arizona and California; however the high carbon intensive resource profile of the MRO grid leads to such a result.

PV installation in the RFC grid abates high CO<sub>2</sub> emissions and the highly carbon intensive nature of the RFC grid also compensates for the lesser solar radiation received by states in this region. PV installation in the SPP grid also abates high CO<sub>2</sub> emissions, the higher than national average CO<sub>2</sub> emission factor (0.70 kg/kWh) combined with high solar radiation in the locations in this region leads to such a result. Installing PV modules in the Northeast Reliability Coordinating Council (NPCC) grid does not lead to significant CO<sub>2</sub> abatement due to both a less carbon intensive grid and comparatively lesser solar radiation received by the states in this region. Florida Reliability Coordinating Council (FRCC) presents the opposite scenario, both the higher solar radiation and carbon intensive profile of the grid leads to significant abatement in this



region. Certain states are partitioned in such a way that they belong to more than one regional grid (e.g. Texas belongs to ERCOT and WECC). In such cases specific local solar radiation was used to report the corresponding indicator for both grids. Table 4.3 can be used by energy planners as a guideline for selecting sites for PV installation to derive maximum CO<sub>2</sub> abatement. The same indicator based on the marginal displacement approach for ERCOT and CAL-ISO was also developed. The CO<sub>2</sub> indicator was 2.7 (ERCOT) and 6.4 (CAL-ISO), indicating that more than twice the abatement can be derived by installing PV modules in CAL-ISO when compared to ERCOT. The increased solar resource in Southern California and the higher CO<sub>2</sub> intensity of the peak load resources contribute to such a result. It is very important to mention that both the regional and marginal indicator results are dependent on the specific location and the PV capacities included in this analysis.

**4.3.4 Dynamic Grid Fuel Mix:** In this section of the study, the CO<sub>2</sub> abated by PV electricity generated was evaluated by considering three scenarios. The first case included a static fuel mix for the entire lifetime of PV technology; the other two cases included a dynamic fuel mix that changed annually, based on the EIA and EPRI resource profile projections for the future. The three scenarios were evaluated using a mono-crystalline technology based on conditions in California. One kilo-watt peak power capacity of PV installation generates 2,302 kWh of annual electricity for the next 25 years, in the first case the CO<sub>2</sub> abated remains a constant of 1,600 kg each year throughout the lifetime. The fraction of coal and renewables used to generate electricity is projected to increase in the future (EIA scenario), coal increases from a 49.3 % (at present) to 54.4% and renewables increases from 9.6% (at present) to 12.6%, for the time period considered. The increase in the usage of coal increased the CO<sub>2</sub> intensity of the grid, thus marginally increasing the CO<sub>2</sub> abatement by PV electricity generated every year. When compared to the static case (total 40,000 kg CO<sub>2</sub>), the EIA scenario projects a 0.8% increase in abatement (40,315 kg), with an average of 1,613 kg CO<sub>2</sub> abated annually (Figure 4.4). The EPRI also projects an increased usage of coal in the future, but it includes an option of carbon capture and storage (14.6% of fuel mix by 2030). In addition, the increase in the utilization of nuclear power (25.5%) and renewables (11.6%) by the end of the time period of analysis decreases the CO<sub>2</sub> intensity of the grid. In this case an annual average of 1,370 kg CO<sub>2</sub> is abated, with the total being 14.3% (34,300 kg) lesser than that of the static case.

**4.3.5 Limitations of Carbon Capture and Storage (CCS):** The Electric Power Research Institute proposes geological CO<sub>2</sub> storage as the strategy to facilitate increased CCS in the future until 2030. The global storage capacity has been estimated to be in the range of 400 to 1,800 giga-tons carbon, for a combination of oil and gas reservoirs, deep coal beds and deep saline aquifers. Given the current annual global CO<sub>2</sub> emissions rate of 6.6 giga-tons carbon from fossil fuel combustion, there is still significant global capacity

for geological storage of CO<sub>2</sub> in the future (Bodansky 2004). The problem extends beyond capacity however, even though geological storage decreases CO<sub>2</sub> emissions, it also has certain risks and limitations. One of the significant risks of geological storage is the risk and impact on human beings, due to the unexpected release of stored CO<sub>2</sub>. The Intergovernmental Panel on Climate Change (IPCC 2005) reported the following about long term CO<sub>2</sub> storage projects, *'It is very likely that the fraction of stored CO<sub>2</sub> retained is more than 99% for the first 100 years. It is likely that the fraction of stored CO<sub>2</sub> retained is more than 99% for the first 1,000 years'*. It can be deduced from the IPCC report that even though the CO<sub>2</sub> stored is likely to be safe, certain uncertainties about CO<sub>2</sub> releases still do exist. Mike Bickle et al (2007) reported about the findings on the Sleipner field in the North Sea. Statoil, one of the biggest Norwegian petroleum corporations has been geologically storing CO<sub>2</sub> in Sleipner field (in a geological formation under the seabed), at an annual rate of 1 million tons, since 1996. The study reports that a definite net decrease in CO<sub>2</sub> levels was observed in the lower stratum, and a net increase in CO<sub>2</sub> levels was observed in the intermediate and the upper layers. The study concludes that the CO<sub>2</sub> from the lower stratum escapes through the thin cap rock mudstones that comprise the layer, highlighting the risk of an unexpected release of CO<sub>2</sub>. The International Energy Agency (2004) maintains a FEP database for managing long term CO<sub>2</sub> storage more effectively. It is a generic database that contains information about Features, Events and Processes (FEP) of long term CO<sub>2</sub> storage, the information in the database is obtained from actual projects implemented around the globe. Hence even though the CCS reduces emissions of CO<sub>2</sub> in the short run, it is important to take into consideration the long term risks and uncertainties of such geologic storage, when restructuring the electricity fuel mix for a carbon constrained future.

#### **4.4 Summary and Conclusions**

This study developed a metric based on module lifetime, to evaluate the energy performance of the two PV technologies considered. The metric captured differences in both the life cycle primary energy investment and technological parameters in modules, and the variation in solar radiation on a national scale in the US. The crystalline and thin film modules take 41 – 54% (10.2 to 13.5 years) and 16 – 19% (4 to 5 years) of their total lifetime to breakeven with the input energy, presenting the worst case scenario (Alaska). In the best case scenario (Arizona) the energy performance improved by more than half (56%) for all of the PV modules, due to increased solar radiation. The range of solar radiation among the fifty states in the US increased the EPBT from a minimum of 2.2 years (for Cd-Te module), to a maximum of 7.6 years (mono-crystalline module).

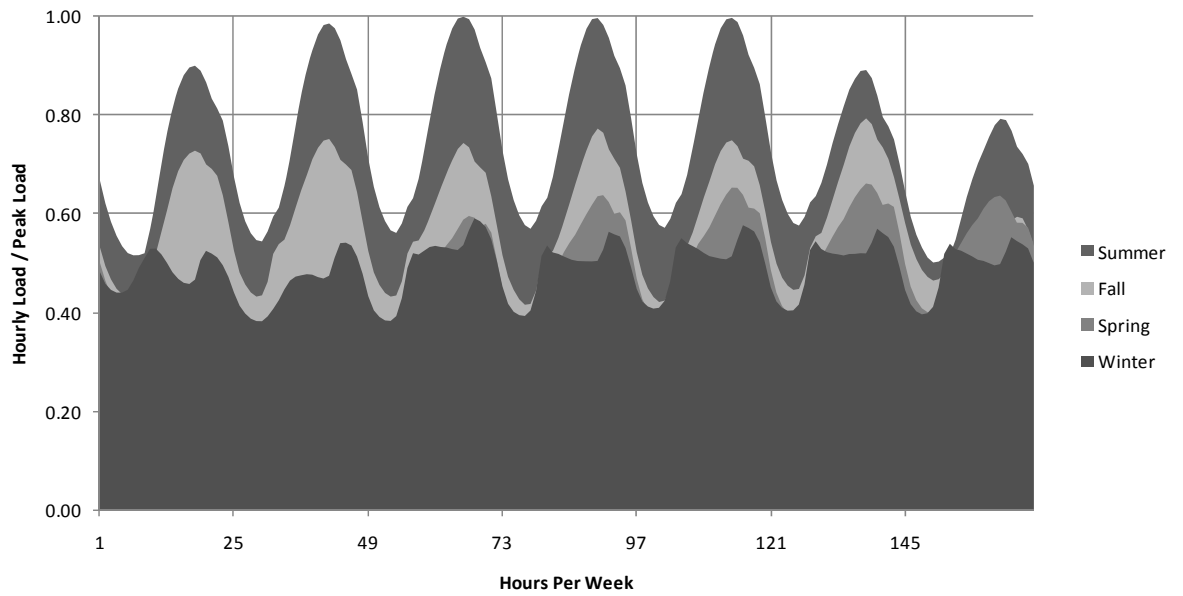
Further, a dispatching model was developed to compare the marginal CO<sub>2</sub> abatement at peak demands to the results obtained using average fuel mix approaches. In the case of ERCOT load zone, PV installations from 1 to 1,000 MWp displaced an

average of 98.3% of electricity from natural gas plants used at the margin during peak demands. The highly carbon intensive average resource profile of the national, regional and state grids for this case leads to an over-estimation of the CO<sub>2</sub> abatement of PV electricity. However, for the analyzed PV capacities, PV electricity abated 145 to 181,850 tons of less CO<sub>2</sub> (1 – 1,000 MWp PV capacity) for the marginal scale, when compared to the other three average scales. Utilization of less carbon intensive natural gas as a marginal resource explains the results obtained. The CO<sub>2</sub> emissions factor was 0.62 kg/kWh. CAL-ISO presented a contrasting scenario, owing to the less carbon intensive nature of the conventional grid, using an average scale approach under-estimated the CO<sub>2</sub> abatement of PV electricity generated. CAL-ISO consisted of a higher diversity of plants used at the margin; it also used natural gas with higher CO<sub>2</sub> emission factors to satisfy peak loads (when compared to ERCOT). With increasing PV electricity generation, different plants at the margin were utilized, consequently leading to decreasing CO<sub>2</sub> emissions factor. When analyzed on a marginal scale, the CO<sub>2</sub> emission factor (kg/kWh) ranged from 0.92 – 1.34, with the CO<sub>2</sub> abatement in the marginal scale being 714 – 3,500 tons of CO<sub>2</sub> higher, when compared to the other three cases.

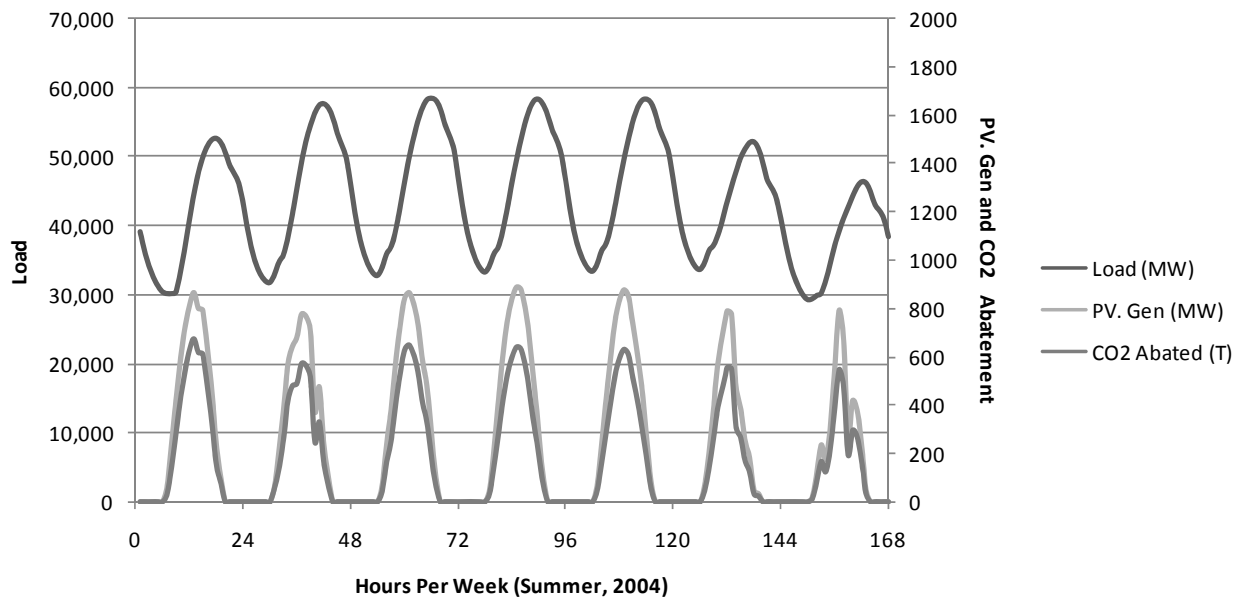
These two load zones analyzed emphasize that at low capacity installations, photovoltaic electricity generated abate significantly different amounts of CO<sub>2</sub> emissions at the margin, when compared to using an average fuel mix approach. The difference in abatement between the two approaches is very much dependent on the marginal resource profile of the load zone. An accurate estimation of the CO<sub>2</sub> abatement is very important to evaluate the feasibility of goals associated with renewable energy and climate change policy-making. This result also has important implications in evaluating the economic performance of PV technology. Trading CO<sub>2</sub> emissions as allowances in the markets provides tangible monetary benefits that increase the economic performance of the technology. An accurate estimation of potential CO<sub>2</sub> abatement also leads to a better estimation of such economic performance. A wide applicability is one of the strengths of the methodology developed in this study; the framework used here can be extended to other renewable electricity technologies as well.

PV installation in the different states in MRO, RFC and SPP regional grids facilitate maximum CO<sub>2</sub> abatement, on the contrary installation in WECC and NPCC grids does not provide high CO<sub>2</sub> abatement. The applicability of the CO<sub>2</sub> indicator is the fact that it can be used as a tool, to aid energy planners in site selection issues for PV installation, while developing a climate change road map for the future in the US. A time-varying fuel mix was modeled for the US grid based on two projections, and the lifetime CO<sub>2</sub> abatement of PV electricity was evaluated for California conditions. When compared to the static (constant fuel mix) base case, the conservative EIA estimate led to 0.8% increase in CO<sub>2</sub> abatement, due to additional amounts of coal used in the future grid mix, to meet increasing demands. The inclusion of carbon capture and storage (14.6% by

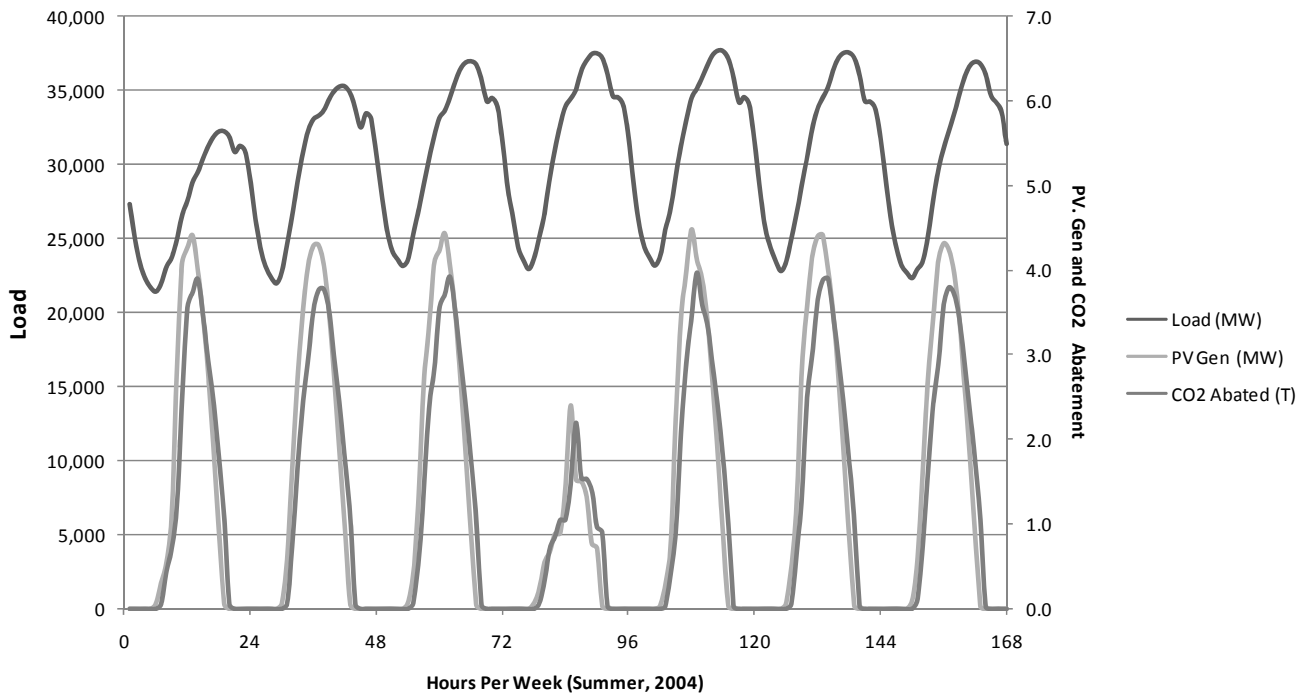
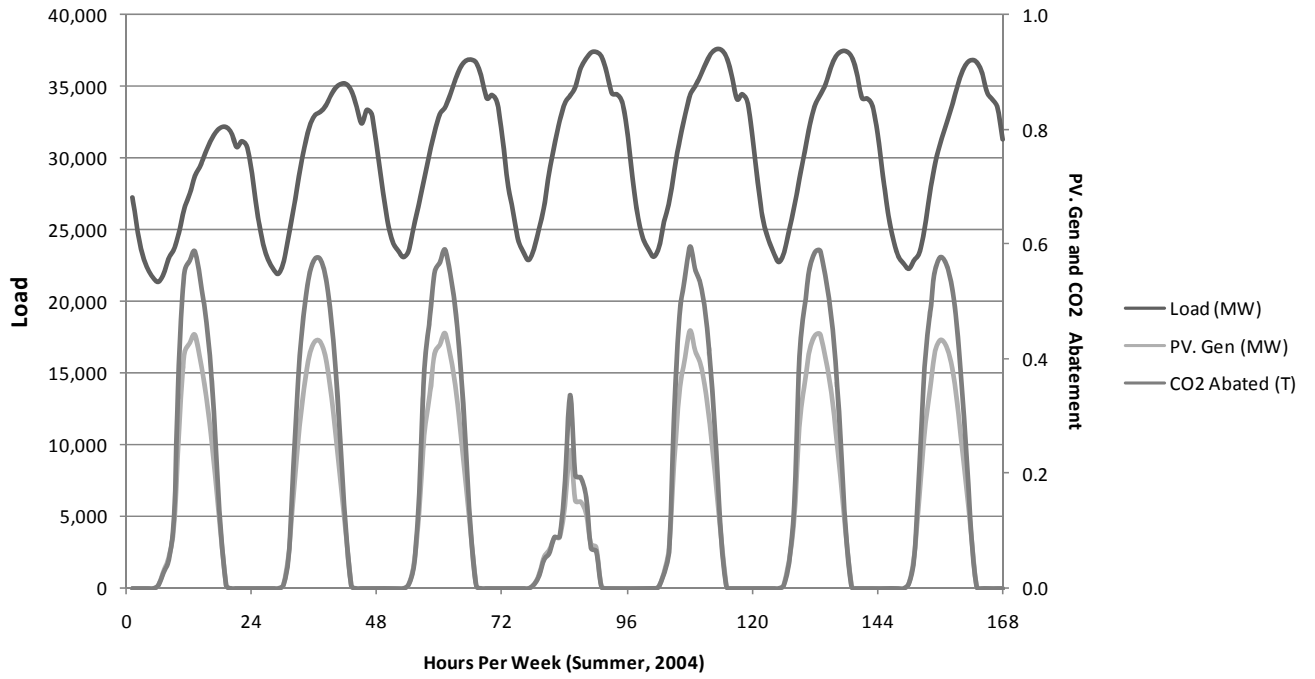
2030) decreased the overall CO<sub>2</sub> abatement of PV electricity by 14.3% (34,300 kg), in the EPRI scenario. This analysis provides a range of potential CO<sub>2</sub> abatement for the lifetime of PV technology. The analysis takes into account the variability in both demand as well as the characteristics of the conventional grid. The applicability of the study can be highlighted by the increasing amounts of PV electricity expected to be generated in the US and emphasis on climate change mitigation in the future. A novel methodology to facilitate a more refined estimation of associated environmental benefits (CO<sub>2</sub> mitigation) is developed and presented. In addition the metrics developed aid energy planners and climate change policy makers make informed decisions to derive the maximum benefit from PV technology deployment.



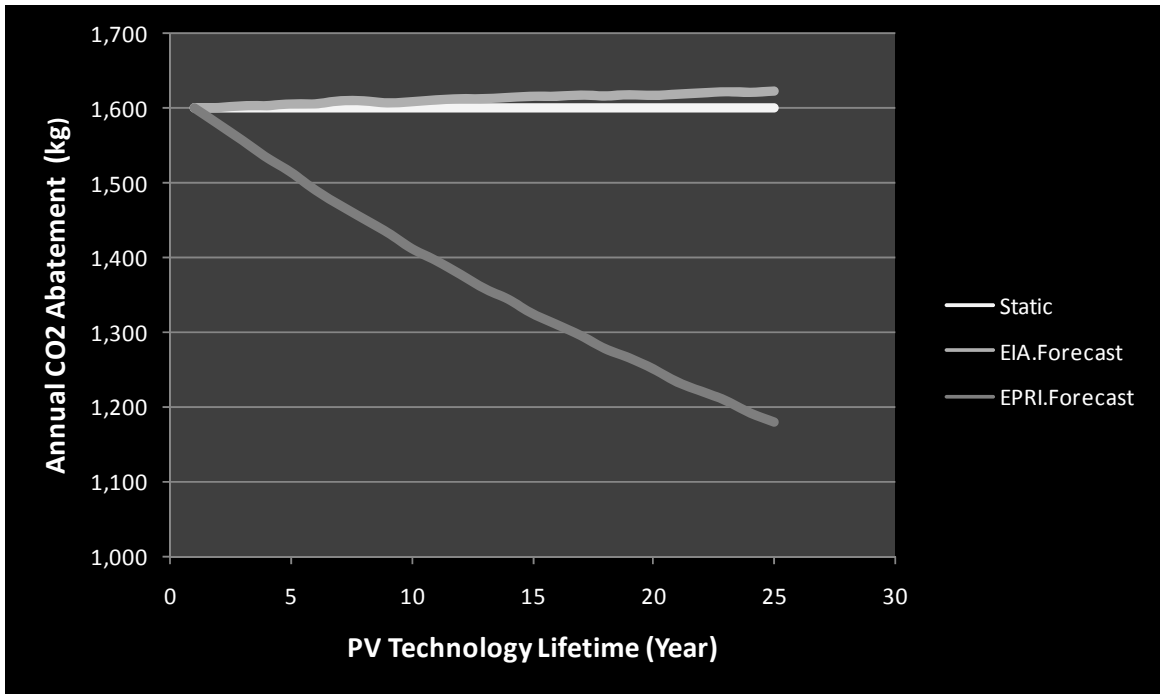
**Figure 4.1: ERCOT load ratio (hourly load / peak annual load) for one week, in the summer, fall, spring and winter 2004. Peak Load (GW): 58.5 GW**



**Figure 4.2: ERCOT load, PV electricity generation (for a 1,000 MW PV plant) and CO<sub>2</sub> displaced for a week in the summer (August 2004)**



**Figure 4.3: CAL-ISO load, PV electricity generation and CO<sub>2</sub> displaced for a week in the summer (August 2004), for 0.5 MWp (top) and 5 MWp (bottom) PV plant**



**Figure 4.4: The annual CO2 abated by PV electricity in the three scenarios considered**

State	Energy Pay Back Time (Years)				
	Cd-Te	A-Si	Ribbon	Multi	Mono
AZ (1)	1.7	2.1	4.5	5.0	5.9
CA (2)	1.7	2.1	4.6	5.1	6.0
NV (3)	1.7	2.1	4.6	5.1	6.0
UT (4)	1.8	2.2	4.8	5.3	6.3
CO (5)	1.9	2.4	5.1	5.6	6.6
HI (13)	2.1	2.6	5.6	6.2	7.3
TN (25)	2.3	2.8	6.0	6.6	7.8
NJ (38)	2.5	3.0	6.5	7.2	8.6
AK (50)	3.9	4.8	10.2	11.3	13.5
Pay Back Time / Total Lifetime (Worst Case)	16%	19%	41%	45%	54%
Pay Back Time / Total Lifetime (Best Case)	7%	8%	18%	20%	24%

**Table 4.1: Energy Pay Back Time for the five PV Modules, for the locations tested in the study**

<b>ERCOT *</b>						
PV Capacity Installed (MW)	1	100	250	500	750	1,000
Annual PV. Elec Gen (MWh)	1,475	147,462	368,655	737,310	1,105,965	1,474,620
National CO2 Abated (T)	1,037	103,666	259,164	518,329	777,493	1,036,658
Regional (TRE) CO2 Abated (T)	1,099	109,859	274,648	549,296	823,944	1,098,592
State (TX) CO2 Abated (T)	1,106	110,597	276,491	552,983	829,474	1,105,965
Marginal (ERCOT) CO2 Abated (T)	935	93,757	229,353	453,396	675,876	898,569
<b>CAL-ISO *</b>						
PV Capacity Installed (MW)	0.50	0.75	1.00	1.25	5.00	
Annual PV. Elec Gen (MWh)	878	1,317	1,756	2,195	8,782	
National CO2 Abated (T)	617	926	1,235	1,543	6,174	
Regional (WECC) CO2 Abated (T)	419	628	838	1,047	4,189	
State (CA) CO2 Abated (T)	342	514	685	856	3,425	
Marginal (CAL-ISO) CO2 Abated (T)	1,174	1,729	2,241	2,700	8,086	

**Table 4.2: PV capacity installed, annual electricity generated and CO<sub>2</sub> abated for the four scales analyzed, in ERCOT and CAL-ISO**

**\*Assumption:** All power plants used were available at all times throughout the year



SERC		WECC		RFC		MRO		NPCC		SPP	
State	CO <sub>2</sub> Indicator	State	CO <sub>2</sub> Indicator	State	CO <sub>2</sub> Indicator	State	CO <sub>2</sub> Indicator	State	CO <sub>2</sub> Indicator	State	CO <sub>2</sub> Indicator
OK	3.80	AZ	3.07	TN	4.05	WY	4.51	CT	2.83	NM	4.40
AR	3.65	CA	3.01	MD	3.78	NE	4.41	NJ	2.83	TX	4.39
FL	3.62	TX	3.01	VA	3.72	MT	4.25	RI	2.76	OK	3.99
SC	3.62	NV	3.01	DE	3.69	IA	4.06	MA	2.76	KS	3.94
TX	3.60	UT	2.88	IL	3.64	SD	4.03	NH	2.75	LA	3.83
MS	3.52	NM	2.87	KY	3.57	ND	3.96	ME	2.73	AR	3.75
GA	3.50	CO	2.73	IN	3.52	MN	3.83	PA	2.71	MO	3.68
AL	3.48	SD	2.67	NJ	3.49	IL	3.71	VT	2.66		
NC	3.47	NE	2.55	WV	3.48	WI	3.60	NY	2.60		
MO	3.46	WY	2.54	WI	3.46						
TN	3.43	ID	2.47	MI	3.38						
VA	3.35	OR	2.35	PA	3.35						
KY	3.34	MT	2.29	OH	3.34						
LA	3.31	WA	1.81								
IA	3.29										
IL	3.25										
WV	3.11										

ERCOT (TX) and FRCC (FL) have an indicator of 3.93 and 4.38

**Table 4.3: CO<sub>2</sub> Indicator for each state in the regional grids**

## REFERENCES

Bickle, M. Chadwick, A. Huppert, H.E. Hallworth, M. Lyle, S. 2007. Modeling CO<sub>2</sub> accumulation at Sleipner: Implications for underground carbon storage. *Earth and Planetary Science Letters (EPSL)* (255), 164 – 176

Bodansky, D. 2004. *Nuclear Energy: Principles, Practices and Prospects* (Page 584)

BP Solar USA. 2008. Module Warranty Period.

Link:

<http://www.bp.com/sectiongenericarticle.do?categoryId=9019650&contentId=7036652>

Link accessed on January 13, 2009

California ISO. 2008. California ISO peak load history

Denholm, P. Margolis, R.M. 2007. Evaluating the limits of solar photovoltaics (PV) in traditional electric power systems. *Energy Policy* (35) 5, 2852 – 2861

Denholm, P. Margolis, R.M. 2007a. Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies. *Energy Policy* (35) 9, 4424 – 4433

Denholm, P. Margolis, R.M. Milford, J. 2009. Quantifying avoided fuel use and emissions from solar photovoltaic generation in the western United States. *Environ Sci Technol* (43) 226 – 232

Dunlop, E.D. Halton, D. 2006. The performance of crystalline silicon photovoltaic solar modules after 22 years of continuous outdoor exposure. *Prog. Photovolt: Res. Appl.* (14) 53 – 64

E-Grid (U.S.EPA). 2007. State electricity resource mix. Database E-Grid 2006 version 2.1

E-Grid. 2008. Clean Energy. Link: <http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html>

Link accessed on January 12, 2009

Energy Information Administration (EIA). 2008. Annual Energy Outlook Projections Until 2030

Energy Information Administration (EIA). 2008a. Annual Energy Review 2008

- Electric Power Research Institute (EPRI). 2007. Electricity technology in a carbon constrained future (Steven Specker)
- Farrell, A.E. Kammen, D.M. Ling, F.H. 2006. Technologies for managing greenhouse gas emissions. The California Climate Change Center at UC Berkeley
- Federal Energy Regulatory Commission (FERC). 2008. Annual Electric Balancing Authority Area and Planning Area Report.
- Fthenkakis, V.M. Kim, H.C. 2006. Energy use and greenhouse gas emissions in the life cycle of CdTe photovoltaics. Mater. Res. Soc. Symp. Proc. Vol. 895.
- Go Solar California. 2008. Inverter Performance Test Summaries
- Intergovernmental Panel on Climate Change (IPCC). 2005. Special report on CO<sub>2</sub> capture and storage (by Bert Metz)
- International Energy Agency (IEA). 2004. CO<sub>2</sub> capture and storage: Risk scenarios database
- Keoleian. G.A. Lewis, G.M. 2003. Modeling the life cycle energy and environmental performance of amorphous silicon BIPV in the U.S. Renewable Energy (28), 271 - 293
- Mau, S. Krametz, T. Jahna, W. Fechner, H. 2004. Quality testing for PV modules according to standards and performance control for supporting manufacturing. Presented in the European Photovoltaics Solar Energy Conference and Exhibition (EUPVSEC), Paris France
- National Renewable Energy Lab (NREL). 2005. Renewable Energy Cost Trends
- National Renewable Energy Lab. 2008. The role of energy storage in modern low carbon grid (Paul Denholm)
- National Renewable Energy Lab (NREL). 2008a. PV-WATTS.  
Link: [http://rredc.nrel.gov/solar/codes\\_algs/PVWATTS/](http://rredc.nrel.gov/solar/codes_algs/PVWATTS/) Link accessed on January 13, 2009
- National Renewable Energy Lab (NREL). Renewable Resource Data Center. 2008b.  
Link: [http://rredc.nrel.gov/solar/old\\_data/nsrdb/1991-2005/](http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/) Link accessed on January 13, 2009
- North American Electric Reliability Corporation (NERC). 2006. Long term reliability assessment: The reliability of bulk power systems in North America
- Pacca, S. Deepak Sivaraman, Keoleian, G.A. 2007. Parameters affecting life cycle performance of PV technologies and systems. Energy Policy, 35 (6) 3316 – 332

Product Ecology Consultants (Pre). 2009

Link: [http://pre.nl/simapro/inventory\\_databases.htm#FRANKLIN](http://pre.nl/simapro/inventory_databases.htm#FRANKLIN)

Link accessed on January 13, 2009

PV News. 2006. U.S. market analysis. May 2006, vol. 25 (5), pp. 4-5

Raugei, M. Bargigli, S. Ulgiati, S. 2007. Life cycle assessment and energy payback time of advanced photovoltaic modules: CdTe and CIS compared to poly-Si. Energy (32) 1,310 – 1,318

Solarbuzz. 2009. Solar electricity price index.

Link: <http://solarbuzz.com/SolarPrices.htm> Link accessed on January 27, 2009

Wild-Scholten, M.J. Alsema, E.A. 2006. Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production. Mater. Res. Soc. Symp. Proc. Vol. 895.

## **CHAPTER 5**

### **INTEGRATED ECONOMIC, ENERGY, AND ENVIRONMENTAL ANALYSES OF A RENEWABLE ENERGY TECHNOLOGY: PHOTOVOLTAIC ELECTRICITY IN MICHIGAN**

#### **ABSTRACT**

Renewable energy technologies must meet conventional economic performance metrics for penetration of the energy market. This research makes both methodological and empirical contributions to the study of energy technology. Methodologically, a comprehensive framework was developed, based on dynamic life-cycle analysis, to assess a technology's economic performance. The framework enables the analysis of the various factors that affect economic performance: features of the technology; energy markets; avoided pollution; and public policy. Four economic metrics are used. A new fixture of environmental policy: cap-and-trade markets for air pollutants and greenhouse gases, was incorporated. Information from these markets helps to establish the economic benefits of avoided pollution. Empirically, the framework was applied to a photovoltaic (PV) system installed at the University of Michigan. The system earns a benefit-cost ratio of 0.29 in the base case. Finally, a sensitivity analysis was conducted over the various factors that affect performance. When benefits from avoided pollution are included, the base case increases to 0.38 and a sensitivity analysis with these benefits reaches 0.82. Collectively, the sensitivity values for three technological improvements raise the benefit-cost ratio to 2.73. This study shows the interplay of research and development, pollution markets, and solar subsidies in its integrated analysis.

## 5.1 Introduction

Eventually, our economy will need a transition from fossil to renewable fuels for generating energy, due to either the exploration and extraction costs of fossil fuels or the high environmental cost of generating energy from such fuels, or both. In 2004, out of the total annual electricity demand of 3,611 billion kWh in the U.S., only 8.81% was generated from renewable sources (Energy Information Administration EIA 2006a). It is well known that electricity generation from fossil-based sources produces significant emissions of air pollutants and greenhouse gases. In 2004, the generation of fossil fuel based electricity in the U.S. emitted 3.95, 10.3 and 2,445 million metric tons of nitrogen oxides (NO<sub>x</sub>), sulfur dioxide (SO<sub>2</sub>), and carbon dioxide (CO<sub>2</sub>), respectively (EIA 2006b). Even though nuclear power addresses the CO<sub>2</sub> problem to a certain extent, it imposes significant radioactive nuclear waste disposal risks on future generations.

Electricity generation by photovoltaic systems offers one possible way to transition to a renewable fuel. Yet only 0.6 billion kWh was generated from solar resources in the U.S. in 2004 (EIA 2006a), and the future penetration of photovoltaics in the U.S. market depends heavily on its cost. The cost of a PV module per unit power has fallen significantly in the last three decades. The PV module cost of \$44 / Wp in 1976 had decreased to \$4 / Wp by 1997. The cost of production has fallen further with the recent increase in production of PV modules. However, the cost of PV electricity, at 20 ¢ / kWh, is still much higher than the cost of conventional grid electricity in 2007, 7.6 ¢ / kWh (Energy Information Administration 2008).

Although a number of studies have analyzed photovoltaic systems from distinct perspectives—either economic or environmental analysis—few studies have successfully integrated both perspectives. Since a change in the environmental performance heavily influences the economic performance, it becomes critical to develop an integrated analytical approach. Matthews et al. (2004) studied a PV system in the U.S. from an economic and environmental standpoint. They made the interesting observation that installing a PV system in locations with high costs of grid electricity may be more beneficial than installing it in places with high amounts of solar radiation. This is predominantly true in locations with high residential grid electricity prices (e.g., New York and Hawaii). Even if comparatively less PV electricity is generated in a location due to the lower solar resource available, the actual economic performance of the technology can still be better at that location by virtue of the higher grid electricity prices. Each unit of grid electricity displaced provides a higher return on investment, when compared to the location with lower grid electricity prices. The higher unit price of grid electricity compensates for the lower total amount of PV electricity generated for the case discussed above.

The economic and environmental perspectives were integrated by counting the avoided pollutant damage cost of the PV system as a benefit derived from the system. Byrne et al (2001) reported the net present value and benefit-cost ratio of amorphous (6.3 kWp capacity) and poly-crystalline (10 kWp capacity) PV modules in China. At 12% discount rates, the net present values and benefit-cost ratio for amorphous and poly-crystalline PV modules were \$- 20,500, \$- 39,500 and 0.54, 0.54, respectively. In their study, the revenues obtained from selling PV electricity to the grid were incorporated into the economic performance of the PV modules.

Agustin and Lopez (2005) analyzed a photovoltaic system in Spain. They include the subsidies provided by the government for the PV system, thereby leading to a positive NPV for the system. At a 20% subsidy rate and 3% interest rate, the NPV and the payback time of the PV system were reported to be € 3,370 / kWp and 13 years. The damage cost avoided by the PV system was € 0.37 / kWh. Their study integrated the benefits of revenues obtained from displaced grid electricity and avoided pollutant damage cost while determining the economic performance of the PV system. Pehnt (2006) applied a dynamic life cycle framework in which future improvements in technological and production parameters affect the energy and environmental performance of a renewable energy system. He tested the reduction in the environmental impacts during the production of the PV system, by changing input parameters such as using increased recycled steel and aluminum, a more sustainable fuel mix, increased PV system lifetime and module efficiency, and reduced sawing losses. Using the same framework, the analysis was extended to assess the economic performance of photovoltaics and test the change in economic performance due to expected future improvements in the various input parameters.

In this study, an economic analysis of the photovoltaic system installed at the University of Michigan was conducted. The energy and environmental results from the previous chapter was integrated with this analysis. The results from the previous chapter assessed the parameters that governed the life cycle performance of photovoltaic systems (Pacca et al. 2007). This PV system was used for the base case and analyzed based on four economic metrics: net present value (NPV), benefit-cost ratio (BC), system cost per unit power, and levelized cost of electricity (COE). Further, a number of sensitivity analyses were identified and modeled for three different areas (cost reducing technology changes, output enhancing technology changes, and policy changes) involving expected developments that will improve the economic performance of the PV system in the future. These results are compared to those of the base case. This evaluates both the current economic performance of photovoltaic systems and the expected improvement in their future economic

performance due to changes in different model parameters. Finally, the best case scenario is presented, which forecasts the highest possible economic performance of a PV system based on the combined improvements in more than one model parameter.

A distinct feature of this study is its incorporation of a new fixture of environmental policy: cap-and-trade markets for air pollutants and greenhouse gases. Adoption of a renewable technology reduces pollution emissions relative to a fossil-fuel baseline. As a novel element, this economic analysis uses data on projected market prices of several air pollutants and carbon dioxide to estimate the economic value of the emission reductions. The resulting framework can also be applied to assess the economic performance of other renewable energy technologies.

This study uses the Dana Building photovoltaic system to model the two different base cases (with and without including benefits from pollution reduction). This chapter starts out by using the conditions applicable to the Dana Building PV system (local solar radiation and pollution abatement based on the regional grid) to present the base case. After presenting the base case, different ‘Ceteris Paribas’ (evaluating the variation in results by changing one parameter while keeping the other parameters constant) scenarios were evaluated by extending the base case. The sensitivity analyses evaluate the variation in results from the base case, by testing the influence of general policy and technological parameters that influence the economic performance of PV technology. For instance subsidy framework in California and solar radiation in Phoenix (Arizona) were used to evaluate the increase in economic performance of PV technology due to a more aggressive policy structure and increased solar radiation, and compared to the base case. Other general economic factors such as reduction in manufacturing costs and operation and maintenance costs were also tested for their influence on the economic performance of PV technology. Using the PV system in University of Michigan as the starting point, the economic model extends the analysis to the test the influence of other general parameters on PV technology.

## **5.2 University of Michigan Photovoltaic System**

The United States Green Building Council (USGBC) awarded a gold level LEED (Leadership in Energy and Environmental Design) certification to the Dana Building, which houses the School of Natural Resources and Environment (SNRE) at the University of Michigan (University of Michigan 2006). The building excelled in the six evaluation criteria established by the USGBC, namely sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and innovation and operation and maintenance. Installation of a photovoltaic system on the building’s roof, contributed significantly towards achieving excellence



in the renewable energy category in the energy and atmosphere criterion. This section presents an overview of the PV system installed.

The total capacity of the PV system is 33.2 kW. The PV system consists of two types of PV modules: amorphous silicon and multi-crystalline PV modules. The amorphous and multi-crystalline modules were manufactured by United-Solar Corporation and Kyocera Solar Inc., respectively. The two kinds of amorphous modules installed are of different power capacity, 75 PVL 62 modules (4,650 W) and 132 PVL 136 modules (17,952 W). In addition, 88 KC 120 multi-crystalline modules (10,560 W) were installed. The PVL and KC modules have a solar conversion efficiency of 6.3% and 12.9%, respectively. The amorphous modules have a loss in conversion efficiency of 1.1% per year, consequently leading to lower energy generation each year. No such loss in conversion efficiency has been established for the multi-crystalline modules, and thus their energy output remained constant.

Given the solar resource available in Michigan (3.6 kWh/m<sup>2</sup>/day), the total electricity output from the modules for a lifetime of 20 and 30 years was calculated to be 0.82 million kWh and 1.20 million kWh, respectively. Consequently, the criteria air pollutant (CO, PM<sub>10</sub>, NO<sub>x</sub>, SO<sub>2</sub>, lead) and greenhouse gas emissions (CO<sub>2</sub>, Methane) reduced due to displaced grid electricity were evaluated. The study reports 0.139 g/kWh (CO), 1.28 g/kWh (PM<sub>10</sub>), 3.39 g/kWh (NO<sub>x</sub>), 5.88 g/kWh (SO<sub>2</sub>), 1.65 x 10<sup>-5</sup> g/kWh (Pb), 916 g/kWh (CO<sub>2</sub>) and 2.0 g/kWh (methane) was reduced due to PV electricity generation. The 2004 annual electricity demand of the SNRE building is 1,535 MWh; with the PV system expected to generate an average of 42,000 kWh per year, it will contribute 2.73% of the building's annual electricity demand. At present the Dana Building receives 67% of its electricity from the University of Michigan Central Power Plant, and the other 33% is purchased from the grid. With a fraction of electricity now being generated by the PV system, the purchase of electricity from the grid will decrease. This decrease in electricity purchases, and the related decrease in air emissions, creates benefits that contribute to the economic performance of the PV system.

### **5.3 Methodology for the Economic Analysis**

The section develops the methodology for the energy and economic analysis of the PV system. It describes the dynamic life cycle framework used to evaluate the environmental benefits of using PV technology. It also includes descriptions of the metrics for evaluating the economic performance of the system and the sensitivity analyses of alternative scenarios. The economic analysis uses results from the energy and environmental analyses of the PV system. The analysis is conducted in real terms, not nominal terms, for dollar values and discount rates. Dollar values are

reported in 2006\$. Three discount rates are used as a sensitivity analysis: 2%, 5%, and 8%. The low rate is a proxy for the social discount rate. The higher rates reflect market discount rates at various levels of risk.

### 5.3.1 Dynamic Life Cycle Assessment (LCA)

The environmental benefits of generating electricity from PV technology were evaluated using a life cycle framework. The resource profile for the regional grid was obtained and the fuel mix was modeled in a life cycle software Simapro. The emission factors obtained as results represent the total emissions, from both the pre-combustion and combustion stages of electricity generation. The pre-combustion stage includes mining, processing, transportation and delivery of the fuel to the power plant. The combustion stage includes the actual burning of the fuel. Such emission factors were obtained on a per unit electricity generation basis (kg / kWh) for the climate change, health hazard and criteria air pollutants considered in this study. The electricity generated from PV technology for each year in its lifetime was calculated (equation 1). PV electricity generation reduces consumption of grid electricity; using the life cycle emission factors for grid electricity obtained, in conjunction with the PV electricity generated every year, the total reduced emissions were calculated for all of the pollutants considered (eq. 2). Eventually, the reduced pollutants were classified into two categories (explained below) based on the existence of emissions trading markets, to monetize the environmental benefits.

Lifetime PV Electricity Output (kWh) =

(eq. 1)

$$\sum_{t=1}^T \text{Solar Radiation Available} \left( \frac{\text{kWh}}{\text{m}^2 \text{ - day}} \right) \times \text{Module Area (m}^2) \times \left( 365 \frac{\text{days}}{\text{year}} \right) \times \text{Module Efficiency } (\eta) \times \text{Inverter Efficiency } (\eta_i)$$

where T is the lifetime (in years) for the PV technology.

Total Pollutant Reduction (kg) =

(eq.2)

$$\sum_{t=1}^T \text{Annual Electricity Generated (kWh)} \times \text{Grid Pollutant Emission Factor} \left( \frac{\text{kg}}{\text{kWh}} \right)$$

Various sensitivity analyses in this study test the influence of technological and policy changes on the performance of PV technology. They were constructed using a dynamic LCA framework. A dynamic LCA is akin to a *ceteris paribus*

framework, where the variation in results is tested due to the influence of changing one parameter while keeping the other parameters the same (as in the base case). Consider a scenario testing the effect of an increase in the technology's conversion efficiency on its economic performance. The base case reports the economic performance of the technology based on the old conversion efficiency, using a LCA framework. The dynamic nature of the LCA is emphasized as follows. The dynamic LCA calculates the economic performance results based on the new increased conversion efficiency, while keeping the other parameters the same as before. This dynamic framework reports the variations in energy and environmental results for each scenario as compared to the base case. It is indeed these variations that change the benefits and costs in each scenario analyzed. Hence the dynamic LCA used in this study is an integral part of the benefit cost framework evaluating the economic performance of PV technology under various scenarios.

### 5.3.2 Present Value Benefits

The benefits of the PV system include the revenue generated (expenditures reduced) due to the lower amount of electricity purchased from the grid; benefits generated from valuing emissions at their market prices (for SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, and mercury (Hg)); and the damage cost reduced due to avoided air pollutant emissions (for CO, Pb, and PM<sub>10</sub>), which are not traded in markets. The total benefits for a given year are represented by equation 3.

$$B = B_{\text{displaced grid elec}} + B_{\text{emissions trading}} + B_{\text{damage cost}}$$

eq. 3

For the lifetime  $T$  of the system, Present Value Benefits (PVB) is defined using equation 4.

$$= \sum_{t=1}^T \frac{B_1}{(1+r)^1} + \frac{B_2}{(1+r)^2} + \dots + \frac{B_T}{(1+r)^T} = \sum_{t=1}^T \frac{B_t}{(1+r)^t} \quad \text{eq. 4}$$

where

- $B_t$  = monetary benefit in year  $t$ ,  $t = 1, 2, \dots, T$
- $T$  = lifetime of the PV system in years, and
- $r$  = discount rate.

Projections of the time pattern of benefits are developed as follows for the three components of equation 1. Using the PV electricity generated annually during the system's expected lifetime and the projected future price of electricity, the total amount of annual expenditures avoided is calculated for each of the next 30 years. A

forecast of the electricity price through 2030 (Energy Information Administration EIA 2006c) was applied. Then, using the principle of discounting, the present value of all future benefits is determined at 2%, 5% and 8% discount rates. This can be considered as a direct monetary benefit derived from the PV system. Throughout the paper an average flat rate price structure for electricity was used. The forecasted data obtained from the EIA 2006c is of this type. One of the limitations of using such a type of data is to not be able to quantify the benefits obtained from using a real time pricing structure for electricity.<sup>1</sup>

A 9.58% loss of power also occurs in the transmission-distribution stage in the state of Michigan (EGRID 2002). Hence every unit of electricity generated by the PV system displaces approximately (1+0.1) 1.1 unit of conventional grid electricity. The environmental analysis of the PV system evaluates the emissions avoided by displacing electricity generated from conventional fuels, with PV electricity. Emissions of both CO<sub>2</sub> and conventional air pollutants are computed. The conventional electricity for Michigan is obtained from the ECAR (East Central Area Reliability Co-ordination Agreement) grid, which has a fuel mix of 89.2% coal, 9.7% nuclear, 0.3% natural gas and fuel oil, and 0.5% hydroelectric sources (Keoleian and Lewis 2003). Using the fuel mix, the emissions associated with the ECAR electricity generation were modeled in the life cycle software Simapro to calculate the avoided emissions.<sup>2</sup>

Climate and air pollution policies are relying increasingly on cap-and-trade programs as a regulatory tool. SO<sub>2</sub> and NO<sub>x</sub> permit markets already exist in the United States; CO<sub>2</sub> and Hg permit markets are proposed; and a CO<sub>2</sub> permit market is underway in the European Union. When a market exists and is considered competitive, market price represents the marginal benefit to the economy of a reduction in emissions (Burtraw et al. 2003). A consistent set of forecasts of market prices for SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, and Hg is applied (United States Environmental Protection Agency (USEPA, 2005). The forecasts are from a USEPA analysis of a particular legislative proposal, the *Clean Air Planning Act*.<sup>3</sup> The allowance prices of pollutants are forecasted through the year 2020. The data gaps were filled by projecting the price line further for the 30 year analysis. With market prices in hand, the estimated benefits of avoided emissions are then computed by multiplying the prices by the

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<sup>1</sup> Real Time Pricing is when the customer pays a time-varying rate for electricity consumption and not a fixed average rate.

<sup>2</sup> ECAR has been integrated into the Midwest Reliability Organization (MRO) grid, by the North American Electric Reliability Organization (NERC) in 2006 (Reference: Keoleian and Lewis 2003)

<sup>3</sup> The *Clean Air Planning Act* is one of several multi-pollutant proposals under consideration in the United States (USEPA 2005). Results of the analysis of the act are used because it is one of two proposals to include a cap-and-trade program for CO<sub>2</sub>. The market prices from USEPA's analysis of the other proposals were used in the sensitivity analysis.

quantity of avoided emissions on an annual basis for 30 years; after discounting, this treatment follows the pattern of equation (4).

Other emissions, including CO, Pb, and PM<sub>10</sub>, are also avoided due to electricity generated by photovoltaics. Markets have not been constructed—and are not planned—for these pollutants. In this case, marginal damage cost represents the economic effect of a unit of emission. Conversely, an avoided emission creates a benefit as an avoided damage cost. Estimates of marginal damage cost, in \$/ton, were obtained for these pollutants from previous research (Banzhaf et al. 1996).<sup>4</sup> These figures were converted to 2006\$ by adjusting for inflation. Using the amount of air emissions reduced and the marginal damage cost of these three pollutants, the annual damage cost avoided for each of the next 30 years is determined. The present value of all the benefits is then determined at 2%, 5% and 8% discount rates. This avoided cost is another type of benefit of the PV system.

Two scenarios—labeled the ‘Baseline’ scenario and the ‘Extern’ scenario—were analyzed in this study. The Baseline scenario includes only the monetary benefits of electricity production, while the Extern scenario includes the monetary benefits from both electricity production and emissions reduction.

### **5.3.3 Present Value Costs**

The costs of setting up and operating the PV system include the PV cost (amorphous and multi-crystalline modules), inverter cost, labor cost during installation, and the PV system maintenance cost for the lifetime of the technology. Expenditures on the PV system, inverter, and installation labor are up-front costs and thus are not discounted. The market prices of the amorphous and multi-crystalline PV modules (Solarwindworks 2006, Alter Systems 2006) and Ballard 30 kW Ecostar<sup>TM</sup> inverter were used for the analysis. The installation labor cost was \$1.25 / W (Florida Solar Energy Center 2006), this cost only included the expenditures incurred in paying for the labor during PV installation; an average operation – maintenance cost factor (\$2.5 / MWh) reported for PV systems greater than 1 kilo-watt capacity was used (International Energy Agency IEA 2002). The future O/M costs of the PV system were calculated for its lifetime and discounted to the present (equation 5). The total present value cost of the system is represented by equation 6. The cost parameters are used for the ‘Base Analysis,’ which includes both the Baseline and Extern Scenarios. In addition, a number of sensitivity analyses test the influence of potential technological and policy changes on the final results. The sensitivity analyses are explained later in the section. The Present-Value Cost (PVC) in the base analysis does

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<sup>4</sup> A recent paper (Kotchen et al. 2006) also applies estimates of marginal damage costs from the Banzhaf et al. study for a similar purpose.

not include any type of subsidy provided by federal or state Governments for clean energy installations; the model was intentionally constructed this way to get an idea about the actual economic performance of the technology exclusively. The reduction in expenditures during the purchase of the system facilitated by the subsidies is tested later, in the policy analysis section of the study. For a building integrated photovoltaic arrangement, the costs incurred to prepare the building roof for PV installation were not considered in this study.

$$\begin{aligned} & \text{Present Value O/M Cost (PVC}_{O/M}) \\ &= \sum_{t=1}^T \frac{M_1}{(1+r)^1} + \frac{M_2}{(1+r)^2} + \dots + \frac{M_T}{(1+r)^T} = \sum_{t=1}^T \frac{M_t}{(1+r)^t} \end{aligned} \quad \text{eq. 5}$$

where

$M_t$  = operating and maintenance cost in year  $t$ ,  $t = 1, 2, \dots, T$   
and other variables are previously defined.

$$\begin{aligned} & \text{Present Value Total Cost (PVC)} \\ &= C_{\text{PV modules}} + C_{\text{inverter}} + C_{\text{labor}} + \text{PVC}_{O/M} \end{aligned} \quad \text{eq. 6}$$

### 5.3.4 Metrics

Two metrics are used to evaluate the economic performance of the PV system: Net Present Value (NPV) and Benefit-Cost (BC) Ratio.

**Net Present Value (NPV):** Net Present Value is the difference between the present value of benefits and present value of costs. A negative NPV value reflects a scenario in which the present value costs are higher than the present value benefits. A negative NPV would normally advise against an investment on economic grounds. However, this framework was used not to make an investment decision but to bring into the light the current economic performance of photovoltaics, and the scope and potential for improved performance with technological and policy changes.

**Benefit-Cost (BC) Ratio:** Benefit-Cost (BC) ratio is the ratio of present value benefits to present value costs. A BC ratio greater than unity represents a case in which the present value benefits exceed the present value costs; this normally would justify an investment from an economic perspective

These two metrics—NPV and BC ratio—use identical information with only a slight difference in their algebraic formulation. This is made clear in equations 7 and 8.<sup>5</sup>

$$\begin{aligned} \text{Net Present Value (NPV)} &= \text{Present Value Benefits} - \text{Present Value Costs} \\ &= \text{PVB} - \text{PVC} \end{aligned}$$

eq. 7

$$\text{Benefit – Cost (BC) Ratio} = \text{Present Value Benefits} / \text{Present Value Costs}$$

$$= \text{PVB/PVC} \quad \text{eq. 8}$$

In addition to the two metrics explained above, the cost of PV system per unit watt power (\$ /Wp) and the levelized cost of PV electricity generated (¢ / kWh) are also presented for the different scenarios analyzed. The formulae for calculating both are in equations 9 and 10.

$$\text{System Cost per Unit Power (\$ / Wp)} = \text{PVC} / \text{Total System Power Capacity}$$

eq. 9

$$\text{Levelized Cost of PV Electricity (¢ / kWh)}$$

$$= \text{PVC} / \text{Lifetime electricity generated by the PV system}$$

eq. 10

### 5.3.5 Sensitivity Analysis

The ‘Baseline’ and ‘Extern’ scenarios were developed for the *Base* system using the methods and data described above. To test the influence of various parameters on the final results, a number of sensitivity analyses were performed. Results for the ‘Baseline’ and ‘Extern’ scenarios from the Base system are then compared within the different sensitivity analyses.

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<sup>5</sup> The rationale for including both metrics is purely expository, in the sense that a BC ratio consolidates information into a simple, clear metric. This study takes advantage of this by developing several graphs (Figures 1, 5 and 6) that present results using BC ratios. At the same time, NPV is useful since it conveys an absolute magnitude, not just a ratio.

The parameters tested can be classified into three categories: cost reducing technological changes, output enhancing technological changes, and policy changes. In addition, the increase in the performance of the PV system was tested in response to three types of changes occurring together simultaneously. This scenario presents a best-case for PV technology in the future. A final note is relevant: It is recognized that new technology requires significant investment in research and development. These costs were not considered in the study.

#### 5.3.5.1 Cost Reducing Technological Changes

- **Reduction in PV System Manufacturing Cost:** The production cost of PV modules has decreased and is expected to continue to decrease. To develop a scenario for the cost reduction, the global growth rate of PV capacity was projected and applied a cost-reduction factor based on the historic learning curve for PV manufacturing costs. At the end of 2004, 1.194 GW of photovoltaic modules have been manufactured around the globe. The annual growth rate up until that point was 23.4% for 1988-2004. Assuming the same annual growth rate, the increase in PV manufacturing for the next 30 years was projected. For the 1,673 GW capacity of photovoltaics that is expected to be manufactured at the end of these 30 years, a PV module price of \$1.86 / Wp was obtained by following a 80% progress ratio on the learning curve (National Renewable Energy Lab NREL 2005). The price of other aspects of the system was assumed to be the same. The influence of this reduction in the PV module cost on the Baseline and Extern scenarios was tested.
- **Reduction in PV O/M Cost:** The annual O/M costs of the PV system depend on the location, size and type of the PV system installed. As mentioned above, this study used an average value of \$2.5 / MWh for the O/M cost. Though the O/M costs are low, they still add to the total cost of the system over its lifetime. As sensitivity, an extreme case was also evaluated: zero O/M cost for the lifetime of the PV system. Development of a completely self cleaning PV system would be relevant, when thinking about a zero O/M cost PV system.
- **Increase in Lifetime of PV Modules:** The lifetime of the PV modules also influences the economic performance of the PV system. A longer lifetime generates more electricity and also reduces the overall cost of electricity ( $\text{\$/kWh}$ ) generated from the system. A typical PV module is expected to last for a maximum of 25-30 years. In the base system the lifetime of the PV modules was assumed to be 30 years. However, the variation in the BC ratio was also



tested for the PV module lifetime of 35 years. It is also important to mention that an increase in the lifetime also increases the O/M costs of the module.

- **Recycled Multi-crystalline PV Modules:** The cost of a PV module can be decomposed into direct and indirect module costs. The direct module cost involves the cost of manufacturing the PV cells. Recycling PV modules are beneficial from an economic, energy and environmental standpoint. At present, Deutsche Solar (Freiberg, Germany) recycles multi-crystalline PV modules, which results in lower material (silicon) and process energy (57% lower) consumption (Muller et al. 2005). Recycled modules also cost less to manufacture, reducing the direct module cost significantly. Multi-crystalline PV modules have a direct module cost of \$2.1/W at present and using a recycled module reduces this cost (Sarti and Einhaus 2002). However, recycling involves additional module collection-recycling cost, and it was determined to be 13 ¢ / W (Fthenakis 2000). This cost was adjusted for inflation and added to the indirect module cost of the modules to obtain the total cost of recycled multi-crystalline PV modules (equation 11). The base PV system uses virgin material for the multi-crystalline modules. In this section, the increase in the BC ratio of the multi-crystalline modules was tested as a result of using recycled multi-crystalline modules.

$$\text{Total Cost of Recycled PV Module} = C_{\text{collection-recycling}} + C_{\text{direct module}} \quad \text{eq. 11}$$

- **Displacement of Conventional Roof Materials:** This section is not a cost reducing technological change per say, but it relates to the dual functionality of PV modules when used on top of the building's roof. Photovoltaic modules may serve a dual purpose: generating electricity and serving as the building roof. By acting as the roofing material, the PV modules essentially displace the usage of conventional roof materials. Hence, when using PV modules, one can realize monetary gains through the reduced cost of purchasing (or salvaging) conventional roof materials. Oliver and Jackson (2000) evaluated the decrease in both the unit electricity costs (pence / kWh) and CO<sub>2</sub> emissions (kg / kWh) due to the dual functionality of the PV modules. Inclusion of the dual purpose aspect of PV modules decreased the unit electricity cost and CO<sub>2</sub> emissions factor by 34 p/kWh (34 ¢/kWh) and 0.02 kg/kWh, when compared to the case where the dual functionality is not included in the analysis. Oliver and Jackson (2001) also evaluated the reduction in primary energy consumption for manufacturing the PV modules due to the inclusion of its

dual purpose. For delivering a kWh of electricity, the dual purpose aspect of the PV system reduced the primary energy consumed by 0.3 MJ (from 2.9 – 2.6 MJ), when compared to the case where the dual purpose is not included.

In this section, the average cost of traditional roof materials per unit area ( $\$/\text{m}^2$ ) was used, to evaluate the monetary benefits of installing PV modules. The costs of traditional roof materials on buildings range from 75 to 151  $\$/\text{m}^2$ , with an average of  $\$113/\text{m}^2$  (Green Roof Life Cycle Costing 2004). The total surface area of installed PV modules in this case is 444  $\text{m}^2$ . The benefits from installing PV modules were estimated to determine the increase in the economic performance, and compared to the base case.

### 5.3.5.2 Output Enhancing Technological Changes

- **Increase in Solar Conversion Efficiency:** For any given lifetime, an increase in the conversion efficiency of the PV module will increase energy output, thus eventually increasing the overall system performance. The base system had a conversion efficiency of 6.3% for the amorphous silicon modules and 12.9% for the multi-crystalline modules. The highest conversion efficiency observed as of now is 12.5% for amorphous silicon modules and 20% for multi-crystalline modules.<sup>6</sup> The highest conversion efficiency observed among all amorphous modules is 19.3% (Ullal 2004). In the sensitivity analysis, conversion efficiencies of 12.5% and 20% were used for the amorphous and multi-crystalline silicon PV modules, respectively.
- **Increase in Available Solar Radiation:** In this study the PV modules were installed in Ann Arbor, Michigan. After adjusting for the angle at which the modules are installed on the roof, the average daily total solar radiation received by the PV modules is 3.6 kWh/m<sup>2</sup>/day. Michigan falls in the middle range when comparing the amount of solar radiation received by different states in the United States. Phoenix, Arizona is one of the places at the higher end of the spectrum in terms of available solar radiation at 5.7 kWh/m<sup>2</sup>/day (or 2,100 kWh/m<sup>2</sup>/year). When the modules are tilted at an angle equal to that of the latitude in the installation location, the amount of solar resource available in Phoenix increases to 6.8 kWh/m<sup>2</sup>/day. The increase in energy

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<sup>6</sup> Studies from Lawrence Berkeley Lab report that multi-junction solar cells can reach theoretical conversion efficiencies as high as 50% (LBL 2006). However, this study uses efficiency improvements that have been observed, rather than theoretical limits.

output and the overall performance of the PV system were tested as a function of the increased available solar radiation in Phoenix.

### 5.3.5.3 Public Policy Changes

- **Emissions Trading Prices based on Four Multi-Pollutant Proposals:** The U.S. EPA has developed six multi-pollutant proposals (*Clean Power Act*, *Clean Air Planning Act*, *Clean Air Interstate Rule* and three different *Clear Skies Acts*) to reduce air emissions in the power sector. Except for the three *Clear Skies Acts*, the proposals forecast different emission trading prices. Only the *Clean Power Act* and *Clean Air Planning Act* forecast the CO<sub>2</sub> emissions trading cost for the U.S. market. In this specific multi-pollutant analyses the influence of implementing *Clean Power Act*, *Clean Air Planning Act*, *Clean Air Interstate Rule* and one of the *Clear Skies Act* (S 131) on the BC ratio of the PV system was evaluated. This sheds light on the particular proposal that, when implemented, is most advantageous to the penetration of photovoltaics and, in general, renewable electricity in the U.S.
- **Existence of a Carbon Market in the U.S. (similar to Europe):** The PV system installed reduces 1,215 tons of CO<sub>2</sub> over its lifetime of 30 years. At present, the market price of CO<sub>2</sub> (\$27.2 / ton) in the European Union is 13 times as much as on the voluntary market in the U.S. (\$2 / ton) (Chicago Climate Exchange 2008; Evolution Markets 2008). The cap set for CO<sub>2</sub> emissions reduction are much more stringent in Europe relative to the Chicago Climate Exchange, which is reflected in the difference in CO<sub>2</sub> permit prices between the two markets. Thus the higher CO<sub>2</sub> price in Europe creates a relatively higher return to a photovoltaic system there, other things equal. In this carbon market analyses, the increase in BC ratio for the PV system as if the U.S. initiated a CO<sub>2</sub> market that resulted in the price level found in the European Union was evaluated.
- **Subsidies for Solar Energy Production:** In the United States, a number of public policies exist to promote renewable energy technologies and energy efficient appliances. For solar energy, the federal government provides a tax credit of 30%, of the total cost of the system up to \$2,000. Various states in the U.S. provide different types of subsidies for solar energy, ranging from a one-time lump sum grant to incentives based on the capacity of the system installed (\$ / Watt), to performance based incentives (\$ / kWh electricity produced, over specific time periods). For example, the *California Solar*

*Initiative* (a state Government initiative in California with an objective of installing 3,000 MW of additional solar capacity by 2016) in provides an upfront cash incentive of \$3.25 for every watt of photovoltaic capacity installed. This incentive is applicable to tax-exempt organizations, such as educational institutions. In Michigan, a grant for a maximum of \$50,000 exists for large scale photovoltaic demonstration projects by organizations such as non-profits and educational institutions (Database of State Incentives for Renewables and Efficiency DSIRE 2007, Go Solar California 2008).

In this subsidy analyses, the effect of solar subsidies on economic performance of the PV system was evaluated. Among the states, California has historically been very aggressive in promoting clean technologies. This study uses both the fixed initial and performance subsidies provided by California for photovoltaic systems installed, to test the effect on performance. California provides different incentive structures for residential – commercial sectors and non-taxable sectors (such as high schools and universities) for photovoltaic installation. For every single watt capacity installed, the state government provides an initial one time incentive of \$2.50 for residential/commercial sectors and \$3.25 for non-taxable sectors. Further, performance subsidies are also provided based on the amount of electricity generated from the technology for the first five years of the technology lifetime. A performance based incentive (\$ / kWh) of 0.39 for residential – commercial sectors and 0.50 for the non-taxable sectors is provided.<sup>7</sup> In addition, the residential and commercial sectors will be able to utilize the federal tax credit of 30% available to them for installing solar power. Thus the PV system was evaluated by considering that it was installed by the residential – commercial sector and also by the non-taxable (similar to University of Michigan) sector. The state reduces the subsidy provided with time, i.e., the amount of subsidy is reduced as the over-all solar capacity installed in the state increases. Eventually, California intends to phase out the subsidies once the solar capacity has increased significantly.

Next, the one-time lump sum Michigan grant was used to set up the present value cost (deduct \$50,000 from the total). This scenario evaluated the economic performance of the system. In this case (University of Michigan), however, the federal tax credit is not applicable.

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<sup>7</sup> The State Government of California uses a discount rate of 8% for providing leveled monthly performance based incentives.

**5.3.5.4 Best-Case Technology Scenario:** Here the influence of a combined change in three technological parameters was evaluated, instead of changing parameters, one at a time. This scenario reflects a case in which both PV production (and inverter) cost and O/M cost decrease and energy conversion efficiency increases. It was a conscious decision not to include any regulatory policy changes that would increase the economic performance of the technology, so this scenario included no subsidies and used only the U.S. carbon permit price. The results from this scenario thus represent a best case for technology development.

## 5.4 Results and Discussion

The results of the analysis are presented for the four metrics, NPV, BC ratio, system cost per unit watt power, and the levelized cost of electricity generated. The results for the three discount rates are summarized in Tables 5.1, 5.2 and 5.3. In Table 5.1, a 2% discount rate is used to express the results; 2% is a good proxy for the real rate of interest (that is, the market rate minus the inflation rate). Table 5.2 and 5.3 present the same results for 5% and 8% discount rates.

**5.4.1 Base Analysis:** Over 30 years, the PV system is expected to generate 1.20 million kWh (average: 40,127 kWh / year). Using the projected U.S. grid electricity prices for the next 30 years, the total monetary value of the reduced purchase of conventional grid electricity creates present value benefits of \$75,400, \$54,300 and \$41,600 at 2%, 5% and 8%, respectively. Recall that the Baseline scenario includes only the benefit of power production, while the Extern scenario includes the benefit of power production and emissions reduction. The present value benefit from selling the avoided emissions of SO<sub>2</sub>, NO<sub>x</sub>, Hg, and CO<sub>2</sub> in the market is \$22,700, \$16,300 and \$12,500 at 2%, 5% and 8%, respectively. Un-marketed emissions of CO, Pb and PM<sub>10</sub> are also reduced due to reduced demand for conventional electricity. The present value benefit (avoided damage cost) of these reductions is \$1,070, \$770 and \$590 at 2%, 5% and 8%, respectively. The sum of the three monetary benefits at a particular discount rate represents the total present value benefit (PVB) of the PV system (Table 5.1). The monetary benefits from reduced emissions (emissions trading + reduced damage) are significant: they are about 31.5% of the gains realized from displaced electricity and 24% of the total benefits obtained.

There are four categories of cost for the PV system. The current market price of the amorphous (PVL 62 and PVL 136) and multi-crystalline PV modules (KC 120) is one component of set-up cost. The prices of a single module of PVL 62, PVL 136 and KC 120 are \$560, \$865 and \$549, respectively. The total cost of the PV modules in the system was calculated using the number of modules of each type used in the

system. The price of one Ballard inverter was \$15,000. Using the labor cost factor of \$1.25 per watt, the total labor cost for installing 33 kW PV modules was calculated to be \$41,453. Since all of these costs are one time set-up costs, they directly represent the present value costs. Using the O/M cost factor of \$2.5 per MWh, the total O/M cost for the next 30 years was determined and converted to present value at the three discount rates. The total O/M cost was \$2,500, \$1,700 and \$1,250 at 2%, 5% and 8%, respectively. The sum of the four categories of cost represents the total present value cost (PVC) of the PV system (Table 5.1).

The NPV is negative for both the Baseline and Extern scenarios of the Base analysis at a 2% discount rate. This, of course, implies a BC ratio less than unity. The NPV is -\$188,000 and the BC ratio is 0.29 for the Baseline scenario. The benefits of avoided emissions add \$23,700 to the NPV and increase the BC ratio by 0.09. Figure 5.1 also presents the BC ratio for the Baseline and Extern scenarios for the range of discount rates tested. The system cost and electricity cost are insensitive to the benefits. At 2%, the system cost is \$7.94 / Wp and the average cost of electricity is 21.9 ¢/kWh. Similar results are presented in Tables 5.2 and 5.3 for 5% and 8% discount rates. The current price of grid electricity that would render a positive NPV ( $PVB > PVC$ ) for the PV system was computed. The NPV of the Baseline and Extern scenarios is positive when the price is 28 and 25 ¢ / kWh, respectively. This is much higher than the range of electricity prices forecast over the next 30 years (7.6 – 8.2 ¢ / kWh). This comparison reflects the magnitude of cost reductions and efficiency improvements that are needed to make PV electricity cost competitive.

## 5.4.2 Sensitivity Analysis

The results of the various sensitivity analyses performed (both for Baseline and Extern scenarios) are presented in the following sections and compared with respective scenarios in the base case. The results of the sensitivity analysis are presented in three sections: cost reducing technological changes, output enhancing technological changes, and policy changes.

### 5.4.2.1 Cost Reducing Technological Changes

**Reduction in the PV Module Cost:** The change in economic performance as a result of reduction in the PV module cost to \$1.86 / Wp was tested, by keeping the other parameters similar to that of the base case. The present value cost reduced by \$143,000 when compared to the base analysis. The NPV of the modules thus increased by \$143,000 and the BC ratio (at a 2% discount rate) increased by 0.34 and 0.44 for the Baseline and Extern scenarios, respectively (Table 5.1). The BC ratio of the Baseline and Extern scenarios ranged from 0.35-0.63 and 0.46-0.82 respectively.

When compared to the base analysis (Table 5.1), there was a 54% reduction in both the total system cost per unit power (\$3.64 / Wp) and in the price of PV electricity (10 ¢ / kWh) in the Extern scenario. Note that as the cost of the PV module decreases, the cost of photovoltaic electricity becomes competitive, even comparable with the price of grid electricity as of today. To get a broader perspective, the price of a solar module as of today is about \$4.80 / Wp (Solarbuzz 2007).

**Reduction in O/M Cost:** In the base analysis, an O/M cost of 2.5 ¢ / MWh leads to a total present value O/M cost ranging from \$1,250 to \$2,500 at the tested discount rates. With the advent of self cleaning PV systems and expected improvements in the PV technology, O/M cost is expected to decrease in the future. In this section, the variability in the final results as a function of no O/M cost was tested for the Extern scenarios.

When the Extern scenarios of the base case and this case were compared (Table 5.1), the NPV of the system increased by \$2,500, since the O/M cost was comparatively small when compared to other costs, no significant increase in the economic performance was observed. Comparatively (to the base case), the cost of electricity decreased by 0.2 ¢ / kWh.

**Increase in Lifetime of PV Modules:** In this section the sensitivity of the final results based on the lifetime of the PV modules was tested. The changes in NPV and BC ratio were tested for a PV module lifetime of 35 years and compared to the base case (module lifetime 30 years). The benefits of increasing the lifetime of PV modules include revenues from additional electricity generated and reduced emissions. However, increasing the module lifetime also increases the O/M costs.

The increase in O/M costs increased the PVC only by a small magnitude; hence there was not a significant increase in the total PVC of the system. An increased lifetime of five years facilitated the generation of an additional 177,400 kWh, and an increase in electricity generation also lead to more reduced emissions. Eventually, increasing the PV module lifetime increased the BC ratio by 0.03 and 0.04 (for the Baseline and Extern scenarios), in this case. Generation of the additional amount of electricity decreased the cost of PV electricity to 19 ¢ / kWh (a 13% reduction when compared to the base case).

**Recycled Multi-Crystalline PV Modules:** The economic performance of the multi-crystalline PV modules was also tested for the case of using recycled material. Here, the labor and inverter cost were allocated based on the power capacity of the crystalline modules as a fraction of the entire PV system. When recycled modules

were used, the collection-recycling cost and indirect module cost added up to \$2.4 / Wp, reducing the module cost by \$2.18 / Wp. When recycled modules were used, the BC ratio increased by 44% indicating the potential of recycled material to reduce costs (material and energy) significantly. For the Extern scenario, the BC ratio ranged from 0.27 – 0.50 (when using virgin material) and 0.39 – 0.72 (when using recycled material). There was a 30% reduction in the total PVC for the multi-crystalline modules when recycled silicon wafer was used.

Deutsche Solar AG (Freiberg, Germany) is a company that manufactures crystalline PV modules; it has recently developed a methodology for recycling wafers from crystalline modules. The corporation has established a small scale pilot facility for recycling wafers; it has been in operation for almost two years. The recycling process takes place in two separate stages: first the outer laminate is burned to facilitate manual separation; the crystalline silicon cells, metallization, anti-reflective coating and pn-junction are removed subsequently by etching. The removed materials are then used in the next batch of crystalline PV module production (Bombach et al 2007). This pilot facility is an indication of what can be expected in the future; it emphasizes the fact that recycling potentially can play an important role in reducing the energy consumption and material costs that currently are associated with crystalline PV modules.

**Displacement of Conventional Roof Materials:** Using the cost factor of \$113 / m<sup>2</sup> for conventional roofing materials, replacing 444 m<sup>2</sup> surface area on the roof with PV modules would reduce the cost by \$50,200. The BC ratio (baseline scenario) for this scenario ranged from 0.20 – 0.35, increasing by 20% when compared to that of the base case. The results of the extern scenario ranged from 0.26 – 0.47. The system cost and cost of electricity for this scenario was \$6.4 / Wp and 17.7 ¢ / kWh, respectively.

#### **5.4.2.2 Output Enhancing Technological Changes**

**Increase in Solar Conversion Efficiency:** In the base analysis the amorphous and multi-crystalline PV modules have a conversion efficiency of 6.3% and 12.9%, respectively. In this case, the BC ratio and NPV of the PV modules were determined based on conversion efficiencies of 12.5% and 20% for the amorphous and multi-crystalline silicon PV modules, respectively. The PV system generated an additional 1.08 Million kWh over the same lifetime when compared to the base system. The average annual energy output was 76,100 kWh for this PV system when compared to 40,127 kWh for the base system.



Such an increase in the energy output increased the benefits significantly. The NPV for the baseline and extern scenarios (at  $r = 2\%$ ) increased by \$62,000 and \$81,000 respectively, when compared to the base analysis. The BC ratio of the baseline (0.29 – 0.52) and extern (0.38 – 0.68) scenarios had an increase in performance by a significant 80% when compared to the base analysis, indicating the influence of conversion efficiency on the economic performance of the technology. The system cost per unit watt remains the same as the base analysis, but the price of electricity generated reduced to a very competitive 11.54 ¢ / kWh (47% reduction). It is recognized that improvements in technology involve significant amounts of research and development costs, but those costs were outside the scope of this study. The economic performance presented here can be considered as a higher bound estimate.

**Increase in Solar Radiation:** The daily average solar radiation available in Ann Arbor, Michigan is 3.6 kWh / m<sup>2</sup>, which leads to an annual solar radiation value of 1,300 kWh / m<sup>2</sup>. However, when the modules are tilted at an angle equal to that of the latitude, an additional 0.92 million kWh of lifetime AC electricity will be generated in Phoenix, Arizona (when compared to Michigan). With this higher electricity output, the NPV increased by \$64,400 (Baseline) and \$84,700 (Extern) when compared to the base analysis. For the Extern scenarios, the BC ratio for the PV modules in Arizona and Michigan ranged from 0.39 – 0.70 and 0.21-0.38 respectively, thus higher by 86% for Arizona than Michigan for the tested range of discount rates. This provides a good idea of the potential advantages of installing the PV system in places such as Arizona where higher amounts of solar resource are available. The system cost per unit watt remains the same, but the price of electricity reduced to 12.4 ¢ / kWh.

#### 5.4.2.3 Public Policy Changes

**Emissions Trading Price Based on Four Multi-Pollutant Proposals:** To this point, market prices for emissions trading are from projections for the *Clean Air Planning Act*. These have been used to value reduced emissions. Figure 5.2 presents the allowance prices of SO<sub>2</sub>, NO<sub>x</sub>, mercury and CO<sub>2</sub> as forecasted by the *Clean Air Planning Act*, and Figure 5.3 presents the forecasted electricity prices used in this study. Here the effect on present value benefits of alternative legislative proposals was tested. The proposals include the *Clean Power Act*, *Clean Air Interstate Rule*, and *the Clear Skies Act*. These are from analysis conducted at the Office of Air and Radiation, U.S.EPA. Figure 5.4 demonstrates that the alternative proposals yield similar results: the estimated present value benefits range from \$16,600 to \$22,700. Prices from the *Clean Air Planning Act* underlie the high figure in the range. This

multi-pollutant analysis section provides the expected monetary benefits from selling emissions in the market, if any one of the air pollutant proposals is implemented in the future.

**The European Union's Carbon Price:** For the 30 year lifetime, the PV system reduces CO<sub>2</sub> emissions by 1.22 million kg. By using the European Union's CO<sub>2</sub> permit price and a 2% discount rate, the present-value benefits (and NPV) increase by \$28,300. The BC ratio is 0.48 in this case, increasing by 26% when compared to the base analysis. The system cost per unit watt and the cost of electricity remained the same. An economy-wide cap on U.S. CO<sub>2</sub> emissions of similar stringency would provide a strong incentive for electricity generation from low-carbon fuel sources.

**Subsidies for Solar Energy Production:** In this section the increase in the economic performance of the technology was tested, by analyzing the influence of subsidies provided by the states of California and Michigan. The residential – commercial sectors are provided a comparatively lower upfront and performance based incentives for installing PV systems, than the non-taxable sectors. On the other hand, the residential – commercial sectors can utilize the federal tax credit (FTC) for which the non taxable sector is ineligible. The economic results for this section are more applicable at the discount rate 8% because of the fact that the incentives provided by the state Government of California are based on  $r = 8\%$ . Considering the total capacity of the current PV system (33.2 kW), if it was installed by a non-taxable sector (similar to University of Michigan's case), then the one time upfront incentive (\$107,800) and the present value of performance based incentives (at 8%, \$94,700) add up to a total of \$202,500. Similarly, the residential-commercial sectors are expected to realize a total subsidy benefit of \$154,800 (one time upfront incentive: \$82,900; Performance based: \$73,900; FTC: \$2000). Comparing the total amount of subsidies and tax credits realized, to the total cost of the system (at 8% discount rate), the net cost of the system accounts to \$59,700 (for non-taxable) and \$103,400 (for residential-commercial) sectors. The BC ratio (extern scenario) ranged from 0.92 – 1.63 (for the non-taxable sector) and 0.53 – 0.95 (for the commercial – residential sector). In contrast, the BC ratio of the extern scenario in the base analysis ranged from 0.21 – 0.38, indicating the significant reduction in costs when purchasing the technology, facilitated by the subsidies (from a consumer perspective). These results emphasize the extent to which an economic policy tool, such as a subsidy, can reduce the consumer cost of using clean, yet expensive technologies. In a case where the BC ratio is greater than unity, a purchase decision based on economic grounds makes sense from a strictly customer perspective. Yet it is still essential to mention that subsidies do incur a significant amount of expenditures to the federal and state governments.

The one time lump sum grant (\$50,000) provided by the state Government of Michigan was also tested for its influence on the economic performance of the technology. The Michigan grant did increase the BC ratio of the technology to 0.26 – 0.46 (extern scenario), which is a 20% increase when compared to the base case. Although such a grant could play an important role in the higher deployment of solar power inside the state of Michigan, it increased the economic performance of the technology less than the California incentives. Figure 5.5 summarizes all of the ‘extern’ scenarios results, of the subsidy cases and compares them to the base case. The *California* subsidy results are primarily meaningful for the  $r = 8\%$  case (because the state Government only uses a 8% discount rate for calculation purposes). The Michigan grant, as a one-time lump sum grant, is relevant to the entire range of discount rates tested.

**5.4.2.4 Best-Case Technology Scenario:** For this case, the economic performance of the PV system was tested by using the following combination of parameters:

1. Highest module conversion efficiency observed at present (12.5% for amorphous modules and 20% multi-crystalline modules),
2. Reduced PV module cost (\$1.86/Wp), and
3. No operation/maintenance cost.

The NPV and BC ratio for the Extern scenario in this analysis were \$114,100 and 2.73 respectively (Table 5.1). When compared to the Extern scenario in the base analysis, the NPV and BC ratio in this case increased by \$278,000 and 2.35 (7.2 times), respectively. This scenario has a positive net present value and a BC ratio greater than unity. These values suggest that, if the expected future technological developments occur, investing in the more sustainable PV technology also makes sense from an economic standpoint. The BC ratio of the Extern scenario for this PV system ranges from 1.51-2.73 for the discount rates tested. The fact that the BC ratio is greater than unity even at a discount rate of 8% demonstrates that the investment is economically justifiable even when one uses a relatively high private market discount rate as opposed to a lower social discount rate. In the Baseline scenario, when only the revenues from displaced grid electricity are factored into the investment decision, the PV system still has a BC ratio ranging from 1.15 – 2.08, depending on discount rate.

## **5.5 Algebraic Relations: NPV and Technological Parameters**

The variation in the economic performance of PV technology as a function of different technological parameters is presented algebraically. With the other parameters remaining constant, the variation of the economic performance due to a change in each one of the parameters is presented. The linear relations presented are based on the framework of this study.

$$\text{NPV of PV Technology (\$)} = f (C_{Mfg}, C_{O-M}, N, \eta, R)$$

Where

NPV is the net present value of PV technology (\$)

$C_{Mfg}$  is the cost of manufacturing PV modules (\$ / Wp)

$C_{O/M}$  is the cost of operation and maintenance (\$ / MWh)

N is the module lifetime (Years)

$\eta$  is the conversion efficiency of the PV technology (%)

R is the availability of the local solar radiation (kWh / m<sup>2</sup> / day)

NPV (\$) = - 23,500 (\$ / Wp): The NPV increases by \$23,500 for every unit decrease in \$/Wp, the manufacturing cost for PV technology (the relation valid between \$6.1/Wp and \$1.9/Wp).

NPV (\$) = - 988 (\$ / MWh): The NPV increases by \$988 for every unit decrease in \$/MWh, the operation and maintenance cost of PV technology (the relation valid up until a highest O/M cost of \$2.5/MWh)

NPV (\$) = \$1493 (Year): The NPV increases by \$1,493 for a unit increase in year of the module lifetime (the relation valid up until a maximum lifetime of 35 years)

NPV (\$) = \$8,736 (%): The NPV increases by \$8,736 for a unit increase in %, the photovoltaic conversion efficiency (the relation valid up until a maximum conversion efficiency of 12.5% (amorphous modules) and 20% (crystalline modules)).

NPV (\$) = \$20,117 (kWh / m<sup>2</sup> / day): The NPV increases by \$20,117 for a unit increase in kWh / m<sup>2</sup> / day, the solar radiation available (the relation valid up until a maximum solar radiation of 6.8 kWh/m<sup>2</sup>/day)

## 5.6 Summary and Conclusions

An energy economic framework was developed that integrates energy, environmental, and economic analyses of a renewable energy technology. The economic analysis uses results from the other analyses to estimate the market and non-market value of the technology's energy and environmental outputs. The

assessment applies the methodology of dynamic life-cycle assessment over the lifetime of the technology. It incorporates predictions of inter-temporal changes in electricity output, electricity price, and pollution prices.

Cap-and-trade markets for air pollutants and greenhouse gases create the opportunity to internalize the benefits of a renewable technology's avoided emissions, that is, to increase the private financial return on an investment in renewables. When cap-and-trade markets are incorporated into the analysis, the avoided pollution emissions comprise 23% of the total market value of the photovoltaic technology, where the total value consists of the market value of electricity and avoided pollution. These new markets create the potential to put renewable technologies on an equal footing in the energy marketplace.

Use of market prices for pollutants also has a methodological advantage relative to estimates of pollution damage costs. Market prices are set by market forces and are directly observable from current and historic data, whereas damage cost estimates are derived using a series of models and associated data input. The use of market data is a revealed preference approach, and economists prefer such an approach when conducting benefit-cost analysis (Portney, 1994).

The results of this study emphasize the economic feasibility of the PV system. Here the results for the case of monetizing the avoided pollution emissions (the 'Extern' scenario) were highlighted. Figure 5.6 summarizes results from Tables 5.1 – 5.3 for a single metric, BC ratio. A key pattern is that, regardless of discount rate, the majority of scenarios generate relatively small increases in BC ratio, i.e., increases of 0.1 or less relative to the baseline. More substantial increases occurred with three scenarios: increase in conversion efficiency and solar resource availability, and PV module cost reduction. At the 2% discount rate, the BC ratio increases to 0.68, 0.70 and to 0.82 in the three scenarios, when compared to the base case. Although no single parameter raises the BC ratio over unity, a set of three technological improvements working together accomplishes this: the sensitivity values for O/M cost, PV module cost, and conversion efficiency raise the BC ratio to 2.73. On balance, these results demonstrate the importance of research and development on renewable energy technology. Many different types of solar energy subsidies exist for taxable and non-taxable sectors; the influence of two such different subsidies was tested. From a baseline BC ratio of 0.21, the different subsidies increased the ratio to 0.26, 0.53 and to a maximum of 0.92. In addition to technological innovation, public policy such as a subsidy definitely provides incentives for increased renewable electricity generation.

In conclusion, technological advances are needed before photovoltaic technologies for electricity generation become cost competitive with conventional technologies. Technology, though, is only part of the equation. As demand for electricity continues to increase and stocks of fossil fuels decrease, electricity prices are likely to increase over time. This, too, can promote demand for renewables. Concurrently, the rapid adoption of cap-and-trade programs for air pollutants and greenhouse gases helps to remove the bias toward fossil fuels, and especially coal, in energy markets. A public policy – direct subsidies of solar technologies – has a similar effect. This study shows the interplay of these forces in an assessment of a photovoltaic electricity system that was installed for research and educational purposes at the University of Michigan.

## Figures and Tables

Analysis		Lifetime Electricity Generated	PVB	PVC	NPV	B/C	System Cost* (PVC / System Cap)	PV Electricity Cost (PVC / Lifetime Elec Generated)
		kWh	\$	\$	\$		\$ / Wp	c / kWh
Base	Baseline	1.20E+06	75,417	263,415	-187,998	0.29	7.94	21.9
	Extern	1.20E+06	99,161	263,415	-164,254	0.38	7.94	21.9
PV Module Cost Reduction	Baseline	1.20E+06	75,417	120,605	-45,188	0.63	3.64	10.0
	Extern	1.20E+06	99,161	120,605	-21,444	0.82	3.64	10.0
O/M Cost Reduction (0 O/M)	Baseline	1.20E+06	75,417	260,943	-185,526	0.29	7.87	21.7
	Extern	1.20E+06	99,161	260,943	-161,782	0.38	7.87	21.7
Increased Lifetime (35 years)	Baseline	1.38E+06	83,170	263,702	-180,531	0.32	7.95	19.1
	Extern	1.38E+06	109,942	263,702	-153,760	0.42	7.95	19.1
Displaced Roof Materials	Baseline	1.20E+06	75,417	213,219	-137,802	0.35	6.43	17.7
Increase in Conversion Efficiency	Baseline	2.28E+06	137,006	263,415	-126,409	0.52	7.94	11.5
	Extern	2.28E+06	180,139	263,415	-83,276	0.68	7.94	11.5
Increased Solar Radiation	Baseline	2.13E+06	139,793	263,415	-123,622	0.53	7.94	12.4
	Extern	2.13E+06	183,805	263,415	-79,610	0.70	7.94	12.4
European CO2 Market	Extern	1.20E+06	127,495	263,415	-135,920	0.48	7.94	21.9
Renewables Subsidy	Extern (Non Taxable, MI)	1.20E+06	99,161	213,415	-114,254	0.46	6.44	17.7
Best Case	Extern	2.28E+06	180,139	66,013	114,126	2.73	1.99	2.9

\* PV System Capacity: 33,162 W

**Table 5.1: Economic Performance Results for the Base Scenario and Other Tested Scenarios at (r = 2%)**

Analysis		Lifetime Electricity Generated	PVB	PVC	NPV	B/C	System Cost (PVC / System Capacity)	PV Electricity Cost (PVC / Lifetime Elec Generated)
		KWh	\$	\$	\$		\$ / Wp	c / kWh
Base	Baseline	1.20E+06	54,304	262,640	-208,336	0.21	7.92	21.8
	Extern	1.20E+06	71,396	262,640	-191,244	0.27	7.92	21.8
PV Module Cost Reduction	Baseline	1.20E+06	54,304	119,830	-65,526	0.45	3.61	10.0
	Extern	1.20E+06	71,396	119,830	-48,435	0.60	3.61	10.0
O/M Cost Reduction (0 O/M)	Baseline	1.20E+06	54,304	260,943	-206,639	0.21	7.87	21.7
	Extern	1.20E+06	71,396	260,943	-189,547	0.27	7.87	21.7
Increased Lifetime (35 years)	Baseline	1.38E+06	57,377	262,750	-205,373	0.22	7.92	19.0
	Extern	1.38E+06	75,668	262,750	-187,082	0.29	7.92	19.0
Displaced Roof Materials	Baseline	1.20E+06	54,304	212,444	-158,140	0.26	6.41	17.6
Increase in Conversion Efficiency	Baseline	2.28E+06	98,769	262,640	-163,870	0.38	7.92	11.5
	Extern	2.28E+06	129,857	262,640	-132,783	0.49	7.92	11.5
Increased Solar Radiation	Baseline	2.13E+06	100,673	262,640	-161,967	0.38	7.92	12.3
	Extern	2.13E+06	132,359	262,640	-130,281	0.50	7.92	12.3
European CO2 Market	Extern	1.20E+06	91,807	262,640	-170,833	0.35	7.92	21.8
Renewables Subsidy	Extern (Non Taxable, MI)	1.20E+06	71,396	212,640	-141,244	0.34	6.41	17.7
Best Case	Extern	2.28E+06	129,857	66,013	63,844	1.97	1.99	2.9

**Table 5.2: Economic Performance Results for the Base Scenario and Other Tested Scenarios at (r = 5%)**

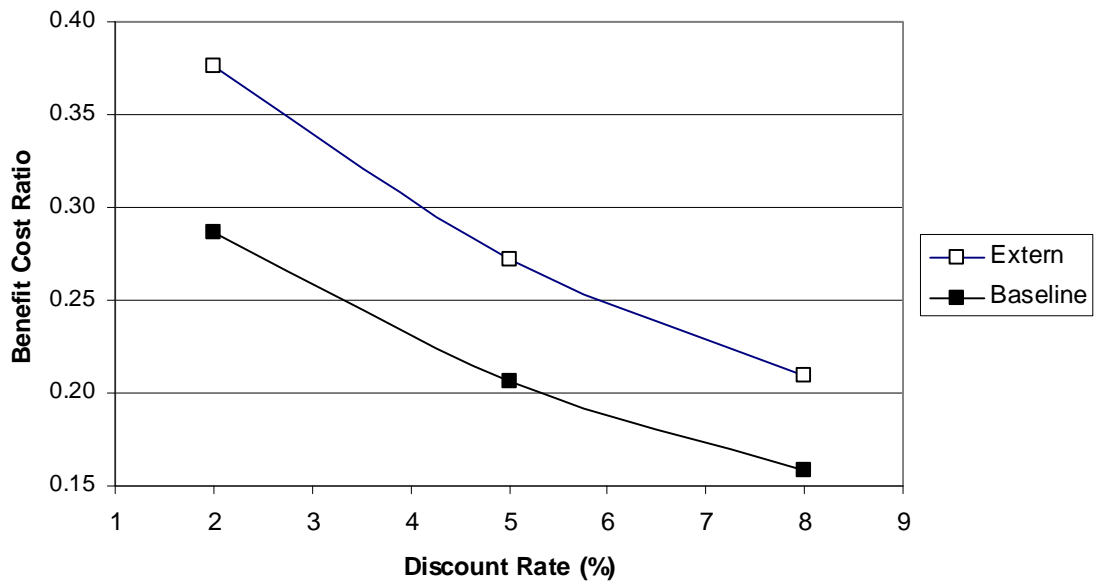


Analysis		Lifetime Electricity Generated	PVB	PVC	NPV	B/C	System Cost (PVC / System Capacity)	PV Electricity Cost (PVC / Lifetime Elec Generated)
		KWh	\$	\$	\$		\$ / Wp	c / kWh
Base	Baseline	1.20E+06	41,645	262,185	-220,540	0.16	7.91	21.8
	Extern	1.20E+06	54,770	262,185	-207,416	0.21	7.91	21.8
PV Module Cost Reduction	Baseline	1.20E+06	41,645	119,376	-77,731	0.35	3.60	9.9
	Extern	1.20E+06	54,770	119,376	-64,607	0.46	3.60	9.9
O/M Cost Reduction (0 O/M)	Baseline	1.20E+06	41,645	260,943	-219,298	0.16	7.87	21.7
	Extern	1.20E+06	54,770	260,943	-206,173	0.21	7.87	21.7
Increased Lifetime (35 years)	Baseline	1.38E+06	42,898	262,229	-219,331	0.16	7.91	19.0
	Extern	1.38E+06	56,510	262,229	-205,719	0.22	7.91	19.0
Displaced Roof Materials	Baseline	1.20E+06	41,645	211,989	-170,344	0.20	6.39	17.6
Increase in Conversion Efficiency	Baseline	2.28E+06	75,823	262,185	-186,362	0.29	7.91	11.5
	Extern	2.28E+06	99,719	262,185	-162,467	0.38	7.91	11.5
Increased Solar Radiation	Baseline	2.13E+06	77,215	262,185	-184,970	0.29	7.91	12.3
	Extern	2.13E+06	101,549	262,185	-160,636	0.39	7.91	12.3
European CO2 Market	Extern	1.20E+06	70,403	262,185	-191,783	0.27	7.91	21.8
Renewables Subsidy	Extern (Non Taxable, MI)	1.20E+06	54,770	212,185	-157,416	0.26	6.40	17.6
	Extern (Non Taxable, CA)	1.20E+06	54,770	59,688	-4,918	0.92	1.80	5.0
	Extern (Resd /	1.20E+06	54,770	103,398	-48,629	0.53	3.12	8.6

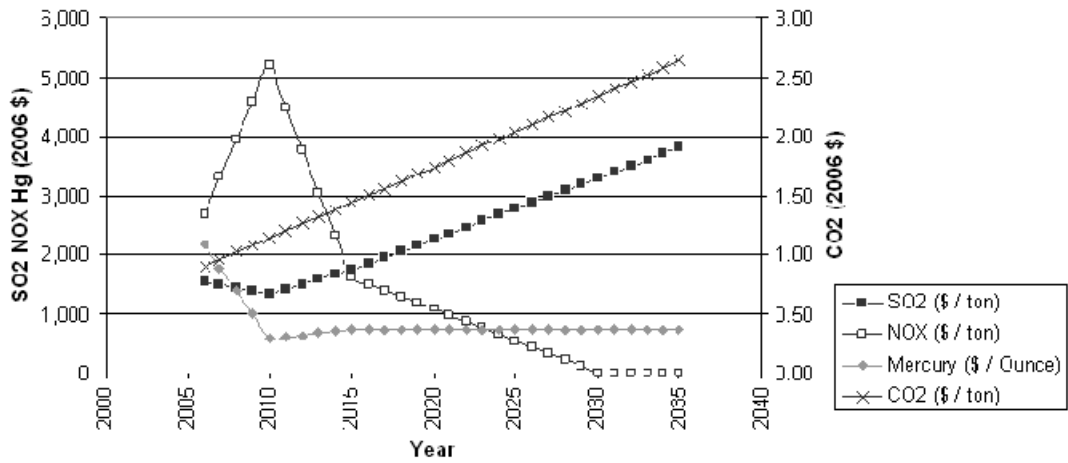
	Commercial, CA)							
Best Case	Extern	2.28E+06	99,719	66,013	33,706	1.51	1.99	2.9

+ This table summarizes the results from the ‘Renewable California Subsidies’ section analyzed only at  $r = 8$

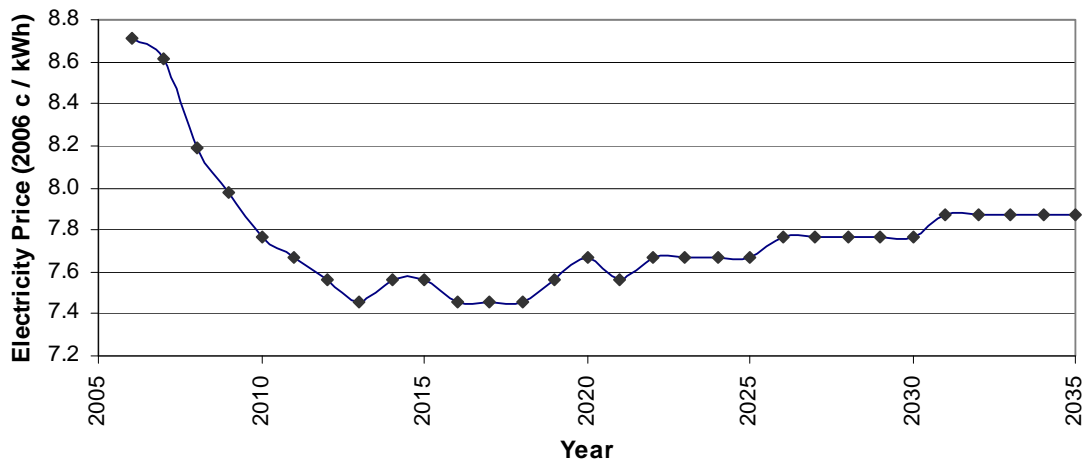
**Table 5.3: Economic Performance Results for the Base Scenario and Other Tested Scenarios at ( $r = 8\%$ )<sup>+</sup>**



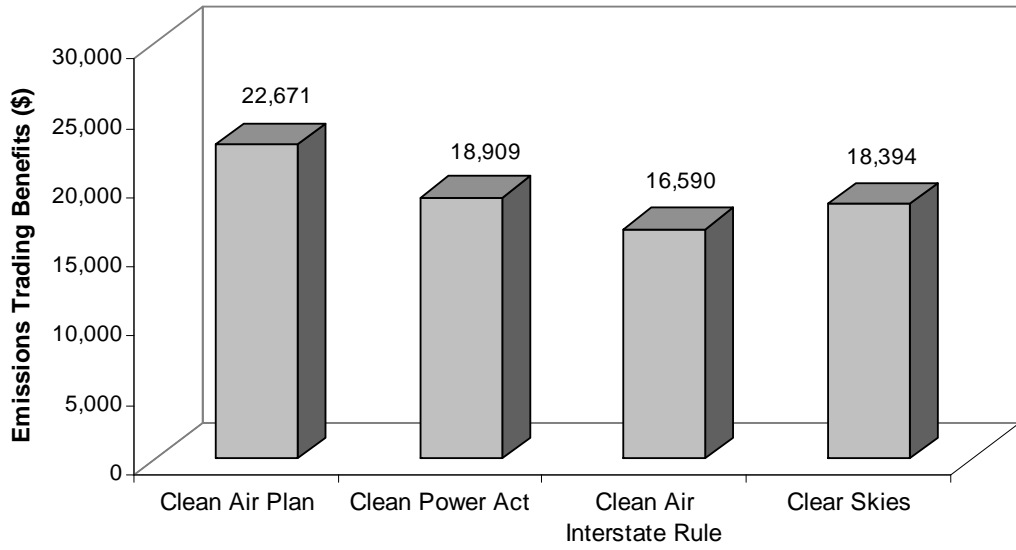
**Figure 5.1: BC ratio of the Baseline and Extern Scenarios in the ‘Base’ Analysis**



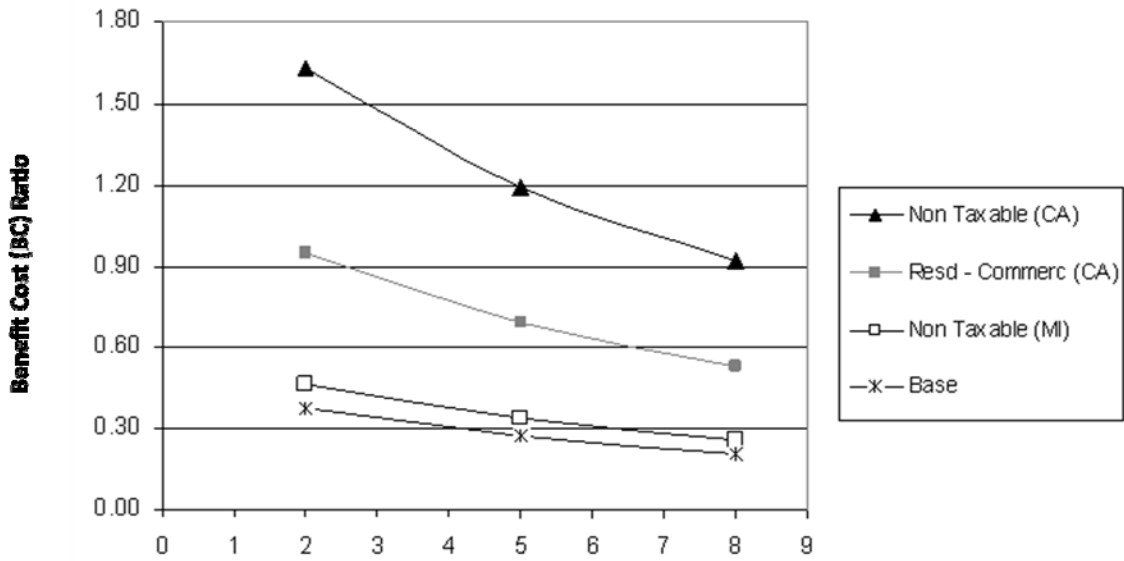
**Figure 5.2: Forecasted Allowance Prices by the Clean Air Planning Act**



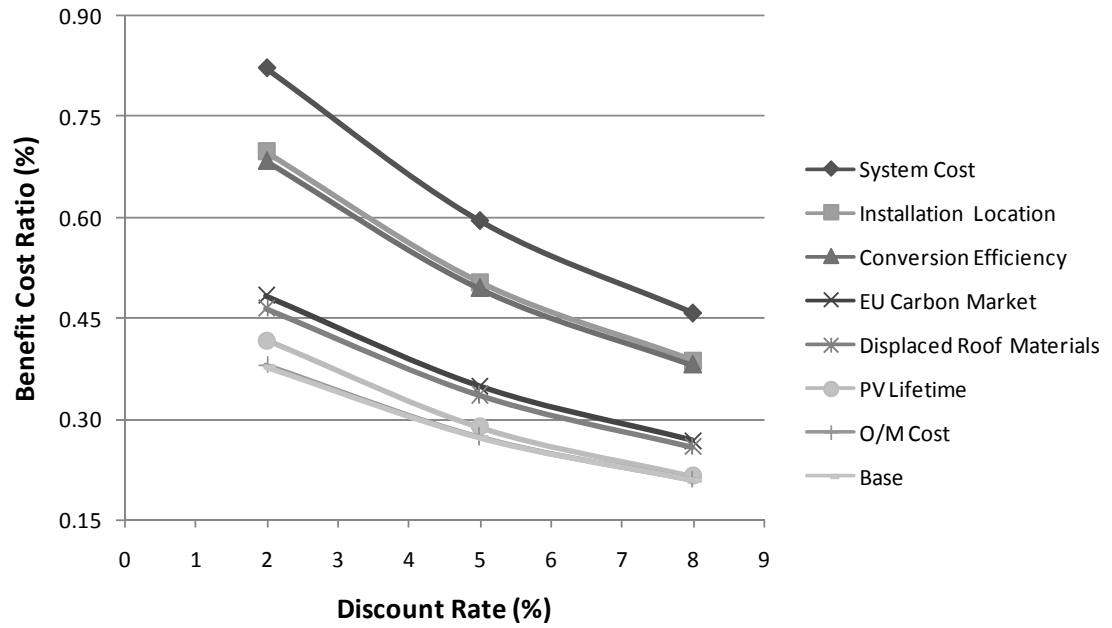
**Figure 5.3: Forecasted Electricity Prices**



**Figure 5.4: Present Value of Emission Trading Benefits ( $r = 2\%$ ) for the Four Different Pollutant Proposals**



**Figure 5.5: BC Ratio for the Extern Scenarios; Subsidy Cases Relative to the Base Case**



**Figure 5.6: Comparison of the BC Ratio of the Extern Scenarios for the Different Cases Considered ( $r = 2\%$ )**

## REFERENCES

- Agustin, J.L.B. Lopez, R.D. 2005. Economic and environmental analysis of grid connected photovoltaic systems in Spain. *Renewable Energy* (31) 1107-1128.
- Alter Systems. 2006. Link: <http://www.altersystems.com/catalog/> Link accessed on November 15, 2008
- Banzhaf, H.S. Desvousges, W.H. Johnson, F.R. 1996. Assessing the externalities of electricity generation in the Midwest. *Resource and Energy Economics* (18) 395-421.
- Bombach, E. Muller, A. Wambach, K. Rover, I. 2007. Recycling of solar cells and modules – recent improvements. Deutsche Solar AG (Freiberg, Germany)
- Burtraw, D., A. Krupnick, K. Palmer, A. Paul, M. Toman, and C. Bloyd. 2003. Ancillary benefits of reduced air pollution in the U.S. from moderate greenhouse gas mitigation policies in the electricity sector. *Journal of Environmental Economics and Management* 45, 650-673.
- Byrne, J. Alleng, G. Zhou, A. 2001. Economics of building integrated PV in China. Prepared for Green Building Workshop, Shanghai, China (July 9-10, 2001).
- Chicago Climate Exchange (CCX). 2008. Link: <http://www.chicagoclimatex.com/> Link accessed on November 15, 2008
- Database of State Incentives for Renewables and Efficiency (DSIRE). 2007. Link: <http://www.dsireusa.org/> Link accessed on November 15, 2008
- EGRID 2002 (Emissions and Generation Resource Integrated Database). United States Environmental Protection Agency. Link: [www.epa.gov/cleanenergy/egrid](http://www.epa.gov/cleanenergy/egrid). Link accessed on November 15, 2008
- Energy Information Administration (EIA) Electricity Net Generation: Electric Power Sector by Plant Type. 2006a. Link: [http://www.eia.doe.gov/emeu/aer/pdf/pages/sec8\\_10.pdf](http://www.eia.doe.gov/emeu/aer/pdf/pages/sec8_10.pdf) Link accessed on November 15, 2008
- Energy Information Administration (EIA) Emissions from energy consumption for electricity production. 2006b. Link: <http://www.eia.doe.gov/cneaf/electricity/epa/epat5p1.html> Link accessed on November 15, 2008

Energy Information Administration (EIA) Forecasts and Analyses. 2006c. Link: [http://www.eia.doe.gov/oiaf/aeo/pdf/aeotab\\_8.pdf](http://www.eia.doe.gov/oiaf/aeo/pdf/aeotab_8.pdf) . Link accessed on November 15, 2008

Energy Information Administration (EIA). 2008. Annual Energy Review. Average retail prices of electricity 1960 – 2007

Evolution Markets LLC. 2008. Weekly emissions market update. Link: [http://new.evomarkets.com/index.php?page=Carbon\\_Markets](http://new.evomarkets.com/index.php?page=Carbon_Markets) Link accessed on November 15, 2008

Florida Solar Energy Center. 2006. Link: <http://www.fsec.ucf.edu/en/research/photovoltaics/index.htm> Link accessed on November 15, 2008

Fthenakis, V.M. 2000. End of life management and recycling of PV modules. Energy Policy (28) 1051-1058.

Go Solar California. 2008. California solar initiative rebates Link: <http://www.gosolarcalifornia.org/csi/rebates.html> Link accessed on November 14, 2008

Green Roof Life Cycle Costing. 2004. Regent Park. Link: <http://www.regentpark.ca/> Link accessed on November 15, 2008

International Energy Agency (IEA). 2002. Distributed generation in liberalized electricity markets.

Keoleian, G.A. and Lewis, G. McD. 2003. Modeling the life cycle energy and environmental performance of amorphous silicon BIPV roofing in the U.S. Renewable Energy (28) 271-293.

Kotchen, M.J., M.R. Moore, F. Lupi, and E.R. Rutherford. 2006. Environmental constraints on hydropower: an ex post benefit-cost analysis of dam relicensing in Michigan. Land Economics (82) 384-403.

Lawrence Berkeley Lab (LBL). 2006. Full solar spectrum photovoltaic materials identified.

Muller, A. Wambach, K. Alsema, E. 2005. Life cycle analysis of solar module recycling process. 20<sup>th</sup> European photovoltaic solar energy conference. 6-10 June 2005, Barcelona, Spain.

Matthews, H.S. Cicas, G. Aguirre, J.L. 2004. Economic and environmental evaluation of residential fixed solar photovoltaic systems in the United States. *Journal of Infrastructure Systems (ASCE)* 105-110.

National Renewable Energy Lab. 2005. Photovoltaics Past the Tipping Point (Ken Zweibel) Link: [http://www.nrel.gov/pv/thin\\_film/pn\\_techbased\\_esh.html](http://www.nrel.gov/pv/thin_film/pn_techbased_esh.html) Link accessed on November 15, 2008

Newell, R.B. Pizer, W.A. 2003. Discounting the distant future: how much do uncertain rates increase valuations? *Journal of Environmental Economics and Management* (46) 52-71.

Oliver, M. Jackson, T. 2000. The evolution of economic and environmental cost for crystalline silicon photovoltaics. *Energy Policy* (28) 1011-1021

Oliver, M. Jackson, T. 2001. Energy and economic evaluation of building integrated photovoltaics. *Energy* (26) 431-439

Pacca, S.A. D. Sivaraman, Keoleian, G.A. 2007. Parameters affecting life cycle performance of PV technologies and systems. *Energy Policy* (35) 3316 – 3326

Pehnt, M. 2005. Dynamic life cycle assessment of renewable energy technologies. *Renewable Energy* (31) 55-71.

Portney, P. 1994. The contingent valuation debate: why economists should care. *Journal of Economic Perspectives* (8) 3-17

Sarti, D. Einhaus, R. 2002. Silicon feedstock for multi-crystalline photovoltaic industry. *Solar Energy Materials and Solar Cells* (72) 27-40.

Solarbuzz. 2007. Solar module price index. Link: <http://solarbuzz.com/> Link accessed on November 15, 2008

Solarwindworks. 2006. Link: [http://solarwindworks.com/Products/Solar\\_Modules/solar\\_modules.htm](http://solarwindworks.com/Products/Solar_Modules/solar_modules.htm) Link accessed on November 15, 2008

Ullal, H.S. 2004. Poly-crystalline thin film photovoltaic technologies: progress and technical issues. National Renewable Energy Lab Thin Film Partnership program.



United States Environmental Protection Agency (U.S. EPA). 2005. Office of Air and Radiation. Clean Air Planning Act.

University of Michigan. 2006. Greenest Academic Building in Michigan at U-M.  
Link accessed: <http://www.umich.edu/news/?Releases/2005/May05/r050405a> Link  
accessed on November 15, 2008

## CHAPTER 6

### CONSTRAINED OPTIMIZATION MODEL FOR PHOTOVOLTAIC DEPLOYMENT IN THE UNITED STATES IN THE FUTURE

#### Abstract

A constrained optimization framework was developed to evaluate photovoltaic deployment, in competition with non-renewable and other renewable technologies. A cumulative CO<sub>2</sub> constraint of 56 to 59% reduction relative to unconstrained growth was used to construct the seven models analyzing the influence of economic, technological, climate change and renewable energy policies on PV deployment in the United States. The Waxman – Markey (H.R. 2454) bill CO<sub>2</sub> reduction targets were satisfied in the models developed. Experience curve module was developed to analyze the reduction in PV electricity costs with increased utilization. When no other renewable option was available, the CO<sub>2</sub> constraint was satisfied using PV electricity thereby reducing the end cost to 20.4 ¢/kWh (23% reduction). Technological breakthroughs and subsidies reduce the PV cost to as low as 14.6 ¢/kWh and 12.7 ¢/kWh in the end respectively. Both climate change and RPS regulations do not increase PV deployment in the presence of other low cost and low carbon options such as wind. However in certain cases these regulations can indirectly increase PV deployment due to lack of other local renewable resources. When 32% cumulative PV electricity generation constraint was imposed, 0.5 billion kWh of PV electricity was used reducing the end cost to 21.7 ¢/kWh (18% reduction). PV is expected to be used only under such specific conditions. It has the potential to become cost competitive with the grid electricity costs only in the long term future.

## 6.1 Introduction

From 1995 to 2007, the total amount of installed photovoltaics in the U.S. electricity sector has increased consistently at an annual rate of 19.4 % (International Energy Agency 2009). In 2007, 606 GWh of solar energy was generated contributing to 0.01% of the total national electricity demand (Energy Information Administration 2008). With the U.S. electricity demand forecasted to increase steadily (annual rate 1.6%) the next two decades, utilization of the current generation mix in the future will lead to significant climate change and regional environmental impacts (Energy Information Administration 2008a). Also, with more than 60% of the states in the U.S. implementing renewable portfolio standards, one can expect a growth of utilization in renewable technologies in the future (Energy Efficiency and Renewable Energy 2009). However, the higher deployment of renewable technologies is not completely independent of the growth of non-renewable and other renewable technologies. The increased utilization of a renewable technology is indeed dependent on the cost, emission characteristics and experience curves of other competing technologies. In this study, the utilization, and learning and economies of scale driven cost reduction of PV electricity is analyzed under scenarios of technological changes, variation in fossil energy fuel prices and energy and CO<sub>2</sub> regulation in the future. Based on the conditions in the U.S. electricity sector, a constrained optimization model is developed to evaluate the utilization and cost reduction of PV electricity, in competition with other technology options for the next fifty years. An experience curve module is constructed for PV technology to evaluate the cost reduction with increasing usage and potential technological breakthroughs. Progress ratio based on empirical evidence is used in the experience curve formulation. Variation in cost reduction at different progress ratios was also evaluated. A simplified representation of the conventional grid is used, in all of the models developed PV electricity does not displace base load. PV electricity is not expected to penetrate base load. This is because it cannot contribute to the demand by penetrating through the minimum base load constraint due to the lack of system flexibility (Denholm and Margolis 2007). Utilization of PV electricity was evaluated under conditions of variation in natural gas electricity costs and proposed targets for renewable portfolio standards and CO<sub>2</sub> caps in the future.

## 6.2 Background

Jensen (1982) and Geroski (2000) both discussed the profile of the technology diffusion curves. Both studies reported the penetration rate to be convex at the beginning of transition. The curve then goes through an inflection point after which it becomes concave as it approaches 100% adoption. Jensen (1983) studied a firm's behavior in selecting one out of the two innovations available for utilization. The study concludes that after trial and error, the firm will opt for the technological innovation that will provide the highest increase in its net present value. Cabral (1990) evaluated the technology adoption path in the presence of network externalities. Network externalities

indicate the increased benefit an agent derives from adopting a technology if other agents in the market also adopt the technology at the same time. The study concludes that in the presence of strong network externalities the adoption path of the technology is discontinuous, and not smooth. Woerlen (2004) discusses the theoretical formulation of experience curves, and reduction in marginal production costs due to increased learning and economies of scale for renewable technologies. This study concludes that experience curves are suitable to evaluate the reduction in marginal cost of electricity generation from different technologies.

The high cost of PV electricity at present is a barrier to its increased utilization. However, because a significant proportion of solar electricity is generated during times of peak demand the value of PV electricity can be higher in the wholesale market. Borenstein (2008) evaluated the actual market value of PV electricity in the California Independent System Operator (CAL-ISO) load zone and determined its value to be 0 to 20% higher in the wholesale market. The study further evaluated the value of solar energy if consumer demand responds to variation in real time electricity prices. In this scenario, the value of solar energy was higher by 30 to 50% in the wholesale market. The current study is an extension of the work from Argonne National Laboratory by Hanson et al 2008. Hanson et al 2008 developed a strictly computational transition model using only two technology options, termed as old and new technologies. The old technology is cheaper (\$20 / m-Btu) but carbon intensive (0.02 ton carbon / m-Btu), the new technology was more expensive (\$50 / m-Btu) but less carbon intensive (0.001 ton carbon / m-Btu) than the old technology. Using this basic framework, an economically optimal technology transition model was developed for the next fifty time periods with each time period representing a year. The base case represents a scenario where the old technology satisfied the entire electricity demand. For maximizing the objective function of discounted net welfare, the economically optimal output quantities of the two technologies were evaluated under a carbon constraint. The optimal transition from old to new technology happened as early as year 1 (for 90% CO<sub>2</sub> reduction from the base case) to as late as year 35 (for 10% CO<sub>2</sub> reduction from the base case). This above-mentioned model was for energy generation in the U.S. In the current study, seven models were developed specifically focusing on the U.S. electricity sector.

### 6.3 Methods

**Theoretical Framework:** The models developed here are strictly based on a theoretical framework. The intention of developing such a framework was to enable a comparison of different electricity generating technologies with one other. The economic framework can be used to investigate the utilization and cost reduction of developing technologies, in competition with more developed technologies. The development of such a framework is one of the strengths of the study. The magnitude of the actual optimal electricity outputs

generated and CO<sub>2</sub> emissions released from the models is not representative of the U.S. electricity sector. A scaling factor should be applied to scale up the CO<sub>2</sub> emissions at the beginning to the total CO<sub>2</sub> emissions emitted by the U.S. electricity sector. Appendix B presents a step by step approach to apply the scaling factor to scale up the model emissions to the actual emissions in the U.S. electricity sector. This framework can be extended in the future to represent the actual output in the U.S. electricity sector without calibration. This is a scope issue and a limitation of the model that can be addressed by future studies.

**Model Parameters:** An optimization model was developed in this study with an objective function of maximizing discounted net welfare. The net welfare is the difference between gross welfare and the total cost of electricity generation in each time period. The model inputs are demand growth, type of electricity generating technologies (non-renewable, photovoltaics and other renewables), technology CO<sub>2</sub> emission rates, progress ratios and electricity production cost for each technology. Table 6.1 presents a complete list of abbreviations used in this paper with their corresponding explanations and units.

**Electricity Demand and Gross Welfare:** The demand function for the U.S. electricity sector was constructed based on the Department of Energy AMIGA (All Modular Industry Growth Assessment) model (Hanson and Laitner 2004) (equation 1)

$$Q(t) = (Demand\ Exponent * e^{b1(t)} * P)^{-\sigma} \quad (Eq. 1)$$

Where Q (t), and P represent demand and price at time t, b1 represents the annual rate of increase in demand and  $\sigma$  is the price elasticity of demand. The demand exponent is a calibration parameter that shifts the demand curve. It is a constant parameter used in the AMIGA model for U.S. electricity sector, the value of the parameter is  $(0.0764 * (3902e+09^{0.35})) 1950$

Equation 2 presents the ‘inverse demand’ relation between P and Q

$$P(t) = \left( \frac{Q(t)}{e^{b1(t)} * Demand\ Exponent} \right)^{-1/\sigma} \quad (Eq. 2)$$

Paul et al 2009 studied the price elasticity of demand for different sectors consuming electricity in the United States. The study concludes that in the long run the price elasticity of demand for the residential, commercial and industrial sectors ranged from 0.29 to 0.40. Hence in this study an average price elasticity of demand value of 0.35 was used.

The societal benefits of electricity consumption is measured in terms of gross welfare  $S(q,t)$ . Gross welfare is measured by the indefinite integral of inverse demand, and calculated for the next fifty time periods from the baseline year 2005 (equation 3).

$$S(q,t) = \int p(q,t) dq \quad (\text{Eq. 3})$$

**Electricity Production Technologies and Costs:** Model(s) 1 to 5 include three electricity generation technologies. PV technology competes with natural gas at the margin, and coal is used as the base load resource. This framework was extended by including seven different types of technologies in model 6. It includes non-renewable technologies (coal, oil, natural gas, nuclear), and renewable technologies (hydropower, wind and PV). The fuel costs of electricity generation for these various technologies were obtained from Energy Information Administration (2009) and American Wind Energy Association (AWEA 2009). Average cost ( $\$/kWh$ ) values of 1.8 (coal), 5.5 (oil), 10.6 (natural gas), 2 (nuclear), 0.8 (hydro), 5 (wind) were used in the analysis. The cost of all these technologies was exogenous in the models developed. However in model 2, the usage of PV technology was evaluated by varying the gas electricity costs each year. An important assumption in the model(s) is the immediate availability of the capacity of all these technologies to generate the required amounts of electricity each year. The cost model in Chapter 3 evaluated the total cost (production cost + cost of labor) for photovoltaic production. The cost model results ( $\$/Wp$ ) were used to analyze the starting price for PV electricity in time period 1. In addition the balance of system components costs were included in the analysis. The purchase cost of an inverter ( $\$/Wp$ ) used for installations was included in calculating the total levelized cost of PV electricity (National Renewable Energy Lab 2006). Trancik and Zweibal 2006 studied the cost trends in PV production in the U.S, and reported a value of  $\$/Wp$  for crystalline modules which is similar to the total initial cost of PV electricity used in this analysis ( $\$/Wp$ ).

**Solar Radiation and PV Electricity Generation:** A particular location in each state was selected to obtain the corresponding solar radiation. The location was selected based on the highest quality of data available for solar radiation (National Renewable Energy Lab 2009). Equation 4 was used to analyze the lifetime PV electricity generated.

$$\text{Lifetime PV Electricity Output} = R \times A \times N \times \eta \times \eta_i \quad (\text{Eq. 4})$$

$R$  is the average solar resource ( $kWh / m^2 / day$ ) which includes the direct and diffused solar radiation incident on a horizontal PV panel,  $A$  is the module area ( $m^2$ ),  $N$  is the module lifetime (days),  $\eta$  is the module conversion efficiency and  $\eta_i$  inverter efficiency

**CO<sub>2</sub> Emissions Factor of Technologies:** The average total fuel cycle CO<sub>2</sub> emission factor for each technology was obtained from Franklin database in the life cycle software Simapro (Product Ecology Consultants 2009). An assumption on technology

development had to be made, the CO<sub>2</sub> emissions intensity of electricity generation from different technologies was held constant throughout the fifty years. A value (kg CO<sub>2</sub>/kWh) of 1.07, 0.9, 0.59, 0.015, 0.007, 0.018 were used for coal, oil, natural gas, nuclear, hydropower and wind resources respectively. The life cycle CO<sub>2</sub> emission factor includes the emissions associated with pre-combustion (raw material extraction, refining and delivery) and combustion (actual burning of the fuel) stages of electricity generation. The crystalline module CO<sub>2</sub> emission results from the life cycle model in Chapter 3 were used in conjunction with the lifetime PV electricity generated to obtain an emission factor for PV technology (0.048 kg/kWh).

**Experience Curve Modules for Photovoltaics and Wind:** The progress ratio of the technology can potentially change in the future. With increased research and development activities the actual progress ratio of the technology decreases through technological breakthroughs, thereby decreasing the cost of technology production. With increasing input material and energy costs, the progress ratio can also increase, thereby decreasing the cost of technology production in the future at a slower rate. Hence the experience curves include the effect of both learning curves and progress ratios. Research literature reports the progress ratios for PV and wind technology based on empirical evidence and historical trends. The progress ratio ( $\beta$ ) of PV technology is observed to be 0.8 (National Renewable Energy Lab 2002). This means that for every doubling of cumulative production, the marginal cost of PV technology production decreases by  $(1 - 0.8 = 0.2)$  20% from the previous value. A progress ratio of 0.9 (based on research literature) was used to construct the experience curve module for wind technology (Energy Center of Netherlands 2002). Equation 5 presents the formulation for the experience curves and production costs.

$$C_{PV}(t) = C_{PV}^0 \left[ \left( \frac{t}{T} \right) + 1 \right]^{\log_2 \beta} \quad (\text{Eq. 5})$$

$C_{PV}^0$  represents the initial cost of PV electricity,  $T$  is the baseline PV output,  $C_{PV}(t)$  represents the cost of PV electricity in future time periods with increasing experience, and  $\beta$  represents the progress ratio. The usage of log to the base 2 (as opposed to the more common base 10) in the formula is conventionally used by International Energy Agency and other research literature to formulate experience curves.

The International Energy Agency (2000) released a comprehensive report on experience curves for renewable energy technologies. The study concludes that experience curves for emerging technologies include the effects from two entities: economies of scale and research development driven technological breakthroughs. The cost reduction in technology manufacturing due to increased production is included in the

economies of scale effect. This was termed as *Learning by Doing* effect.<sup>1</sup> The terminology used in the modeling of experience curves were based on the terms discussed in the International Energy Agency (IEA) report (International Energy Agency 2000). However other research studies do use different terms to define economies of scale and technological breakthroughs for developing energy technologies. For example Van Sark et al 2008 used the phrase learning rates to define the formula  $(1 - \text{progress ratio})$ . This study also does not differentiate between learning curves and experience curves, as opposed to the IEA report which considered learning and experience curves to be different. Hence previous studies do use different terminology to define the various aspects of learning curves, in the current study we adhere to the terms used in the IEA report mentioned above.

**Objective Function and Emission Constraints:** The mathematical formulation for the objective function and constraints is presented for each model in the individual sections. A social planner's problem is solved in this case. The objective function is to maximize the present value of discounted net welfare for the next fifty time periods with each period representing one year (baseline year 2005). Continuous discounting is used and results are presented at a discount rate of 5%. The objective function is maximized with a constraint on CO<sub>2</sub> emissions that reflects the future of the electricity sector in the U.S. (equation 6). The American Clean Energy and Security Act 2009 (Waxman Markey Bill, H.R. 2454) is a bill proposed to Congress at present in the U.S for CO<sub>2</sub> emissions regulation. From the baseline emissions in the year 2005, the bill proposes at least a 3%, 20%, 42% and 83% reduction in greenhouse gas emissions by the year 2012, 2020, 2030 and 2050 respectively (American Clean Energy and Security Act 2009). The Waxman bill proposes CO<sub>2</sub> mitigation targets for the entire U.S. economy. In this study, the emissions constraints are set by using the targets proposed in the Waxman bill. This study focuses on the U.S. electricity sector, by using the targets proposed by the Waxman bill this study assumes that the CO<sub>2</sub> reduction achieved in the electricity sector is equal to those achieved in the other sectors in the economy. This is also a theoretical model, hence the unconstrained emissions is calculated by evaluating optimal outputs without imposing CO<sub>2</sub> reduction constraints. Figure 6.1 presents both the un-calibrated and calibrated CO<sub>2</sub> emissions pathway for the unconstrained scenario, and the Waxman bill target curve. The objective function is to maximize net welfare, hence to maximize net welfare demand increases until year 7, after which it gradually decreases up until the end. In a theoretical model, the demand increasing rapidly in the beginning is consistent with the fundamental principle of discounting. The 'Discount Rate' is the rate at which the present value of increasingly distant benefits shrinks. Using a discount rate implies a preference to consume more in the early time periods, and less in the later time periods. Farber and Hemmersbaugh 1993 discuss relevance of discount rates for future decision-making. To

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<sup>1</sup> Learning by doing is also used to represent improvements made in production based on experience alone, not including economies of scale effects



quote the paper directly; ‘Discounting favors regulations that confer benefits in the present or near future over regulations whose benefits society realizes at a later date. One might even say that the purpose of discounting is to favor present benefits over future benefits. Even a modest discount rate will favor small benefits conferred today over much larger benefits conferred in the distant future’. In this *theoretical* framework, an economic objective function of maximizing net welfare is used. Hence the demand increasing rapidly in the early time periods and decreasing in the later time periods is theoretically consistent with economics. The fact that the results are based on a very theoretical framework is mentioned upfront in the methods section.

In this theoretical framework the CO<sub>2</sub> emissions from using optimal quantities of electricity can be scaled up to the actual CO<sub>2</sub> emissions in the U.S. electricity sector using a scale factor of 602. Application of the scaling factor does involve assumptions. One of the assumptions that had to be made was that the technology options available for electricity generation were the same in the U.S. electricity sector, as it was in this simplified framework. The scaling factor was also used to normalize the emissions from the model in time period 1 to the actual CO<sub>2</sub> emissions from the 2005 U.S. electricity sector. The same scaling factor was used throughout the fifty time periods to scale up the model. Implicitly this involves assuming that the difference in magnitude between the model results and the actual CO<sub>2</sub> emissions remain the same. Based on the actual emissions at the end of 2050 and the reduction proposed by the Waxman bill at 2050, a total of 56% reduction in CO<sub>2</sub> emissions was estimated to be required in the end. The actual un-calibrated cumulative cap set was  $2.68 \times 10^{11}$  kg CO<sub>2</sub> based on the model results. Hence the constraint set on CO<sub>2</sub> emissions was 56% reduction by 2050 (Figure 6.1). It needs to be mentioned that the emissions constraint is set based on the optimal amounts of electricity consumed in the unconstrained scenario. The optimal pathways of electricity generation differ for each of the models constructed evaluating technological, fossil energy costs and policy scenarios. However the CO<sub>2</sub> constraints proposed by the Waxman bill will be met by the end of 2050 in the models developed. Due to the increased number of electricity generation technologies available in Model 6 and Model 7, separate unconstrained scenarios were developed. In both those cases the CO<sub>2</sub> reduction target was determined to be 59% (model 6) and 57% (model 7) relative to unconstrained growth to meet the Waxman target by 2050, and those constraints were used for the two models.

$$Z_C \leq Z_{UC} (1 - \delta) \tag{Eq. 6}$$

Where  $Z_C$  is the constrained emissions,  $Z_{UC}$  is the unconstrained emissions and  $\delta$  is the level of emissions reduction.

**Discretization and Solution:** This is an optimal control problem described by non linear differential equations with constraints. Since solutions to these problems cannot be

obtained explicitly, discretization of the optimal problem using Euler's explicit form is used. In this study the problem is formulated using a powerful nonlinear modeling language AMPL (A Mathematical Programming Language) (AMPL 2009). One of the advantages of AMPL is the fact that the user can specify the problem in its original algebraic form. This approach enables even a large problem to be specified in a concise manner. After discretization and model formulation in AMPL, a separate mathematical solver (in this case, KNITRO) is used to solve the optimization problem. Nonlinear Interior point Trust Region Optimization ('K' is silent in KNITRO) solver is used by non-linear optimization programming languages to obtain the global minima or maxima as the optimal solution (Byrd et al 2006). Hence the optimal solutions obtained are global in nature. Out of the many possible results the key interest was in evaluating the influence of competing energy costs, experience curves and increasing carbon constraints on the usage of PV technology in the future. The specifications for the seven models constructed are presented below.

### **6.3.1 Model 1: Three Technology Model**

This model represents a simplified version of the conventional grid with three technology options available for electricity generation. The highly carbon intensive and less expensive coal technology is used as a base load resource. Energy Information Administration (2008b) and Electric Power Research Institute (2007) have developed electricity fuel mix projections for the future. Both studies report 50% of the future annual electricity generation in the U.S. to be generated from coal. Based on these projections, half the total demand each year is generated from coal in this model. The second option is the load following resource such as natural gas. The third option is the low carbon intensive but more expensive PV technology. In this model with increasing usage, the PV electricity generated only displaces natural gas and not the base load resource. Economically optimal quantities of electricity from natural gas and PV technology are evaluated for the objective of maximizing discounted net welfare. The objective function is maximized subjected to constraints on CO<sub>2</sub> emissions. Equations 7 to 10 present the formulation of the model. Eq. 7 is the objective function of maximizing discounted net welfare where optimal amount of annual electricity generated from gas and photovoltaics is calculated every year. With increasing PV electricity generation, due to learning and economies of scale effects, the cost of PV electricity generation decreases each year.  $x(t)$  represents the cumulative PV output that decreases the cost of PV electricity generation with time. Equation 8 presents total CO<sub>2</sub> emissions released from electricity generation in each time period. The CO<sub>2</sub> emissions released from generating electricity using each technology is dependent on both the total amount of electricity generated from each technology and the technology CO<sub>2</sub> emissions factor. Equation 9 presents the CO<sub>2</sub> constraint (56% reduction), with the inequality constraint on the

cumulative CO<sub>2</sub> emissions. Equation 10 presents the fuel mix constraint, with 50% of electricity in each time period being generated from coal technology.

*Objective Function: Maximise  $\{q_{NG}, q_{PV}\} (t)$*

$$\int_0^T e^{-rt} [ S \{q_C (t) + q_{NG} (t) + q_{PV} (t), t\} - \{ C_C \cdot q_C (t) + C_{NG} \cdot q_{NG} (t) + C_{PV} (x(t))q_{PV} (t) \} ] dt \quad (\text{Eq. 7})$$

$$\text{Total CO}_2 \text{ Emissions: } z (T) = \int_0^T b_C \cdot q_C (t) + b_{NG} \cdot q_{NG} (t) + b_{PV} \cdot q_{PV} (t) \quad (\text{Eq. 8})$$

$$\text{Emissions Constraint: } z (T) = Z_C \quad \text{where } Z_C \leq Z_{UC} (1 - \delta) \quad (\text{Eq. 9})$$

$$\text{Fuel Mix Constraint: } Q(t) * 0.5 = q_C (t) \quad \text{where } Q(t) = q_C (t) + q_{NG} (t) + q_{PV} (t) \quad (\text{Eq. 10})$$

### 6.3.2 Model 2: Varying Gas Energy Costs

This model follows the same formulation of model 1. However it differs from model 1 by varying the cost of gas electricity generation on an annual basis. At present one fifth of the total electricity demand in the U.S. is generated from natural gas. The Energy Information Administration forecast of natural gas costs was very conservative. The estimate did not show any significant increase in future costs and hence was not used in this analysis. The California Energy Commission (2009) has studied the influence of natural gas in the U.S. electricity market based on historical trends, and presents forecasts on energy costs from natural gas in the future. The study reports that on an average the cost of energy generation from natural gas can be expected to increase by 5.7% annually. Hence in this model the cost of gas electricity increases by 5.7% annually for the entire time period of analysis. The CO<sub>2</sub> emissions, emissions and fuel mix constraint equations from model 1 (equations 8, 9 and 10) hold for this model as well. The equations for the objective function (equation 11) and the costs of natural gas electricity (equation 12) are presented below. The  $C(t)_{NG}$  represents the variation in cost of natural gas electricity every year. Equation 12 presents the 5.7% annual increase in gas electricity costs in the future.

*Objective Function: Maximise  $\{q_{NG}, q_{PV}\} (t)$*

$$\int_0^T e^{-rt} [ S \{q_C (t) + q_{NG} (t) + q_{PV} (t), t\} - \{ C_C \cdot q_C (t) + C(t)_{NG} \cdot q_{NG} (t) + C_{PV} (x(t))q_{PV} (t) \} ] dt \quad (\text{Eq. 11})$$

$$\text{From } t = 1 \text{ to } 50, C_{NG} (t + 1) = C_{NG} (t) * (1 + 0.057) \quad (\text{Eq. 12})$$

### **6.3.3 Model 3: Variation in Progress Ratios**

This model expands model 1 by evaluating the deployment of PV technology at different progress ratios for a 32% cumulative PV generation constraint. As discussed in section 6.3 referring to the formulation of experience curves, the progress ratios of PV technology can potentially increase or decrease in the future. Increase in material and energy costs and technological breakthroughs can increase and decrease the progress ratio respectively. Based on the framework developed in this study, this section evaluates the PV technology utilization and consequent decrease in PV electricity cost at progress ratios ( $\beta$ ) of 0.6, 0.7 and 0.9. The results are compared to the results from model 1.

### **6.3.4 Solar Subsidy Structures**

In this section the influence of subsidy structures on the utilization of PV technology was evaluated for the 32% cumulative PV generation constraint. In the U.S solar subsidies provide incentives to generate increased photovoltaic energy. The state regulatory agencies provide monetary incentives by paying a constant fee for every unit of solar energy generated. At present monetary incentives ranging from 1 to 10 ¢/kWh exist in the U.S. for solar energy (Database of State Incentives for Renewables and Efficiency 2009). A sensitivity analyses for a range of subsidy structures were performed evaluating the influence of subsidies on PV utilization. The presence of subsidies decrease the initial cost of generating PV electricity.

### **6.3.5 Model 4: CO<sub>2</sub> Reduction Targets**

With an increasing necessity to address and manage the climate change problem effectively, a carbon constrained electricity sector in the future can be expected. As discussed in section 6.3 based on the Waxman-Markey bill and the unconstrained scenario, a cumulative CO<sub>2</sub> emissions constraint of 56% (by 2050) was used in all of the models developed. In this section however, PV utilization and cost reduction were evaluated for higher constraints other than 56%. More stringent CO<sub>2</sub> reduction targets of 61% and 66% were analyzed. A 32% cumulative PV electricity generation constraint was used.

### **6.3.6 Model 5: Seven Technology Model and Renewable Portfolio Standards**

Until now a CO<sub>2</sub> constraint of 56% reduction by the end of 2050 (relative to unconstrained growth) was used to meet Waxman Markey targets. However, since additional number of electricity generation technologies was available in this case, a separate unconstrained scenario was developed. The total amount of emissions in the unconstrained scenario was  $3.31 \times 10^{11}$  kg CO<sub>2</sub>. A scaling factor of 492 was used to normalize the CO<sub>2</sub> emissions from the model to the actual emissions in the U.S. electricity sector. In this case a total reduction of 59% was required to satisfy the

Waxman target by 2050. Hence a constraint of 59% was used in this model from the cap mentioned above.

In this case increased non-renewable and renewable technologies were included in the mix of resources available to meet electricity demand. Non renewable technologies of coal, oil, natural gas and nuclear, renewable technologies of hydro-power, wind power and photovoltaics were included. The emission and cost factors for each of the technologies represent the characteristics of the U.S. electricity market. Consistent with the previous four models, coal contributed to 50% of the annual electricity generation. Additional constraints on nuclear and hydropower were imposed. In 2007, 20% and 5.9% of the total electricity generation in the U.S. was derived from nuclear and hydropower resources respectively. This model assumes that a maximum of 20% and 5.9% of total electricity generation is derived from nuclear and hydropower for each time period in the analysis. These levels were set reflecting the increasing environmental challenges for generating hydro and nuclear energy. PV utilization and cost reduction were evaluated with the availability of increased low carbon technologies.

In the second part of this model PV utilization was also evaluated by imposing additional renewable portfolio constraints. A national renewable portfolio standard (H.R. 3221) is set to be proposed in the U.S. at present. The proposal contains the following targets: from 2009, 4%, 8%, 12% and 16% of the total electricity demand must be generated from renewable sources by 2011, 2013, 2016 and 2019 respectively (American Solar Energy Society 2009). In this model, similar renewable energy constraints (excluding hydropower) were imposed and the deployment of PV technology was observed. Equations 13 to 19 present the formulation of the model.

*Objective Function: Maximise*  $\{q_O, q_{NG}, q_{Wnd}, q_{PV}\} (t)$

$$\int_0^T e^{-rt} [ S(Q, t) - \{C(t) + C_{PV}(x(t))q_{PV}(t)\} ] dt \quad (\text{Eq. 13})$$

Where  $Q(t) = q_C(t) + q_O(t) + q_{NG}(t) + q_{Nuc}(t) + q_{Hyd}(t) + q_{Wnd}(t) + q_{PV}(t)$

$$C(t) = C_C \cdot q_C(t) + C_O \cdot q_O(t) + C_{NG} \cdot q_{NG}(t) + C_{Nuc} \cdot q_{Nuc}(t) \\ + C_{Hyd} \cdot q_{Hyd}(t) + C_{Wnd} \cdot q_{Wnd}(t)$$

$$\text{Total CO}_2 \text{ Emissions: } z(T) = \int_0^T b_C \cdot q_C(t) + b_O \cdot q_O(t) + b_{NG} \cdot q_{NG}(t) + \\ b_{Nuc} \cdot q_{Nuc}(t) + b_{Hyd} \cdot q_{Hyd}(t) + b_{Wnd} \cdot q_{Wnd}(t) + b_{PV} \cdot q_{PV}(t) \quad (\text{Eq.14})$$

Fuel Mix Constraint:

$$Q(t) * 0.5 = q_C(t), \quad Q(t) * 0.2 = q_{Nuc}(t), \quad Q(t) * 0.059 = q_{Hyd}(t) \quad (\text{Eq.15})$$

RPS Constraint (from baseline year 2005):

$$\text{In Year 6: } Q(t) * 0.04 = q_{Wnd}(t) + q_{PV}(t) \quad (\text{Eq. 16})$$

$$\text{In Year 8: } Q(t) * 0.08 = q_{Wnd}(t) + q_{PV}(t) \quad (\text{Eq. 17})$$

$$\text{In Year 11: } Q(t) * 0.12 = q_{Wnd}(t) + q_{PV}(t) \quad (\text{Eq. 18})$$

$$\text{In Year 14: } Q(t) * 0.16 = q_{Wnd}(t) + q_{PV}(t) \quad (\text{Eq. 19})$$

### 6.3.7 Model 6: PV and Wind Technology

In this case with four technologies available for electricity generation, a total of  $3.20 \times 10^{11}$  kg CO<sub>2</sub> emissions were released in the unconstrained scenario. A scaling factor of 487 was used to normalize the CO<sub>2</sub> emissions from the model to the actual emissions in the U.S. electricity sector. A total reduction of 57% relative to the unconstrained scenario was required to achieve the Waxman target by 2050. Hence a constraint of 57% was used in this model.

Up until this point the cost of wind energy was considered to be exogenous and constant for the entire time period of analysis in the models developed. From 1989, the amount of wind energy generated has increased at an average annual rate of 15% in the U.S. electricity sector (Energy Information Administration 2009a). Such rapid growth of wind energy deployment in the recent past has resulted in 0.8% (32.1 billion kWh) of the national electricity demand generated from wind resources currently. In this case coal, gas, PV and wind were the four technologies available to satisfy demand during each time period. Coal technology serves 50% of the total demand; wind and PV only displace natural gas. An experience curve model was constructed for wind technology using the baseline experience and a progress ratio of 0.9.  $\beta_1$  and  $\beta_2$  are the progress ratios for PV and wind technology,  $k(t)$  is the cumulative wind energy generation that decreases the cost of wind electricity with time. Utilization of PV electricity was evaluated with and without imposing cumulative PV electricity generation constraints. Equations 20 to 25 present the algebraic equations for the formulation of this model.

*Objective Function: Maximise*  $\{q_{NG}, q_{Wnd}, q_{PV}\}(t)$

$$\int_0^T e^{-rt} [ S \{q_C(t) + q_{NG}(t) + q_{Wnd}(t) + q_{PV}(t), t\} - \{C_C \cdot q_C(t) + C_{NG} \cdot q_{NG}(t) + C_{Wnd}(k(t))q_{Wnd}(t) + C_{PV}(x(t))q_{PV}(t)\} ] dt \quad (\text{Eq. 20})$$

Total CO<sub>2</sub> Emissions:  $z(T) =$

$$\int_0^T b_C \cdot q_C(t) + b_{NG} \cdot q_{NG}(t) + b_{Wnd} \cdot q_{Wnd}(t) + b_{PV} \cdot q_{PV}(t) \quad (\text{Eq. 21})$$

$$\text{Emissions Constraint: } z(T) = Z_C \quad \text{where } Z_C \leq Z_{UC}(1 - \delta) \quad (\text{Eq. 22})$$

Fuel Mix Constraint:  $Q(t) * 0.5 = q_C(t)$

where  $Q(t) = q_C(t) + q_{NG}(t) + q_{Wnd}(t) + q_{PV}(t)$  (Eq. 23)

Experience Curves

$$C_{PV}(t) = C_{PV}^0 \left[ (t^1/T_1) + 1 \right]^{\log_2 \beta_1} \quad (\text{Eq. 24})$$

$$C_{Wnd}(t) = C_{Wnd}^0 \left[ (t^2/T_2) + 1 \right]^{\log_2 \beta_2} \quad (\text{Eq. 25})$$

## 6.4 Results and Discussion

### 6.4.1 Model 1: Three Technology Model

National Renewable Energy Lab (NREL 2004) research studies forecast the potential installation of photovoltaics in the United States electricity sector. Until 2050, NREL projects 7% to 32% of annual electricity in the U.S. to be generated from photovoltaics under different scenarios. With no additional incentives from today, 7% of national electricity demand is forecasted to be met by PV technology in the future. With increased research development and policy incentives, up to a maximum of 32% national demand is forecasted to be satisfied by photovoltaics in the future. This model develops three scenarios: an unconstrained PV scenario, and 7% and 32% cumulative PV generation by the end of fifty years

In this model only three technologies were available for electricity generation. To meet the very stringent Waxman target of 83% reduction from the baseline year of 2005 (56% total area reduction) by 2050, a combined strategy of load reduction and significant PV utilization was employed from the very beginning. Figure 6.2 presents the annual demand, annual CO<sub>2</sub> emissions, PV cost and cumulative PV electricity generation for the PV unconstrained scenario. The annual demand steadily decreases from 8.7 billion kWh at the very beginning to 1.6 billion kWh at the end of fifty years. When no constraints were imposed on PV utilization, a cumulative total of 104 billion kWh of PV electricity was utilized to meet the CO<sub>2</sub> constraint, reducing the end cost of PV electricity by 81% to 5 ¢/kWh in the end. Figure 6.3 presents the calibrated CO<sub>2</sub> emissions pathway for the 56% reduction constraint. Since the initial optimal quantities of electricity generated from the different technologies are different for each model, different scaling factors need to be used to calibrate the actual model results to that of the U.S. electricity sector. The results from all the models are scaled up to the total CO<sub>2</sub> emissions released in 2005 by the U.S. electricity sector. That scaling factor is consistently applied across the fifty time periods to scale up the model results. Each scaling factor used is mentioned explicitly in the figures presented. When the unconstrained and the constrained calibrated CO<sub>2</sub> emissions pathways are compared with each other, from Figure 6.3 one can conclude that the model satisfies the Waxman reduction targets in the end.

When constraints were imposed on cumulative PV electricity generation the annual demand started lower at the beginning than in the above-mentioned case. Since only a finite amount of renewable technology was available, the demand decreased from 5.9 billion kWh in the beginning, to 1.7 billion in the end and still met the CO<sub>2</sub> emissions constraints. Utilization of PV electricity was necessary to meet the stringent CO<sub>2</sub> constraint. However, owing to the higher initial cost of PV technology (26.5 ¢/kWh), in a constrained optimization framework PV electricity was used towards the end of the fifty years. The net welfare is maximized for each time period at a discount rate of 5%. Due to discounting, costs incurred in later time periods decrease the net welfare to a lower extent when compared to costs incurred in the immediate future. A cumulative total of 0.11 billion kWh of PV electricity was used for the fifty years in the 7% cumulative PV scenario, reducing the initial cost by 6% to 24.9 ¢/kWh in the end. In the 32% cumulative PV scenario, a total of 0.7 billion kWh of PV electricity was used reducing the PV end cost by 23% to 20.4 ¢/kWh.

#### **6.4.2 Model 2: Varying Gas Energy Costs**

With gas electricity costs increasing by 5.7% every year, it becomes affordable to utilize the backstop photovoltaic technology earlier in time when compared to model 1. A total of 0.7 billion kWh of PV electricity was utilized in model 1. In this case, a total of 2.7 billion kWh PV electricity was used reducing the cost of PV electricity to 15.2 ¢/kWh (43% reduction) at the end of fifty years. Such increase in gas electricity costs increased the PV electricity generation by 2 billion kWh during the entire time period. Hence increasing costs of competing fossil energy generation provides an incentive for higher utilization of PV technology in the future.

#### **6.4.3 Model 3: Variation in Progress Ratios**

Model 1 evaluated PV technology utilization at a progress ratio of 0.8. Similar to model 1, PV utilization was evaluated at progress ratios of 0.6, 0.7 and 0.9 in this section. A comparatively lower progress ratio leads to a decrease in the cost of PV electricity generated, at a higher rate. The end cost of PV electricity in model 1 was 20.4 ¢/kWh (23% reduction). The end cost of PV electricity at progress ratio 0.9, 0.7 and 0.6 was 23.4 ¢/kWh (12% reduction), 17.5 ¢/kWh (34% reduction) and 14.6 ¢/kWh (45% reduction) respectively. Figure 6.4 presents the cost curves for the four scenarios evaluated. The linear equations (Eq. 26 to 29) for the four cost curves are presented below.

$$\text{PR (0.9): } Y = -0.006(x) + 26.5 \quad (\text{Eq. 26})$$

$$\text{PR (0.8): } Y = -0.014(x) + 26.5 \quad (\text{Eq. 27})$$

$$\text{PR (0.7): } Y = -0.025(x) + 26.5 \quad (\text{Eq. 28})$$



$$\text{PR (0.6): } Y = -0.04(x) + 26.5 \quad (\text{Eq. 29})$$

The Y intercept for each of these curves is the initial cost of PV electricity (26.5 ¢/kWh). However, with decreasing progress ratios the cost of PV electricity decreases at a higher rate with utilization. The different rates at which the cost decreases are reflected in the slopes of the equation. The slope of the curve at progress ratio 0.9, 0.8, 0.7 and 0.6 was -0.006, -0.014, -0.025 and -0.04. Potential technological breakthroughs in the future provide incentives for PV utilization by decreasing the cost of PV electricity at a higher rate. This section provides the range of possible end cost of PV electricity in the future.

#### **6.4.4 Solar Subsidy Structures**

Providing subsidies decreases the initial cost of PV electricity. As explained above due to the higher initial cost when compared to coal and gas, PV electricity is only used towards the end of the fifty years. When tested at a subsidy rate of 1 to 10 ¢/kWh, in the end the cost of PV electricity reduced to as low as 12.7 ¢/kWh. For the 1 ¢/kWh, 3 ¢/kWh, 5 ¢/kWh, 7 ¢/kWh and 10 ¢/kWh subsidy rate structures, the end cost of PV electricity was 19.6 ¢/kWh, 18.1 ¢/kWh, 16.5 ¢/kWh, 15 ¢/kWh and 12.7 ¢/kWh respectively. With no subsidy (model 1) the end cost of PV electricity reduced to 20.4 ¢/kWh. It is also necessary to mention that the regulatory agency still incurs significant expenditures while providing subsidies for a specific type of technology.

#### **6.4.5 Model 4: CO<sub>2</sub> Reduction Targets**

Based on the Waxman bill and unconstrained scenario, a 56% CO<sub>2</sub> reduction target was used in all the models. In this model, two other CO<sub>2</sub> reduction targets of 61% and 66% were analyzed. Figure 6.3 interprets results from model 1 for the PV unconstrained scenario, and it has been established that the 56% reduction target does satisfy the Waxman bill targets. In this model a 32% cumulative PV electricity generation constraint was used to evaluate PV deployment and cost reduction. Due to the finite availability of the renewable resource, the demand at the beginning decreased accordingly (when compared to model 1) to still meet the cumulative stock constraint in the end. The cumulative CO<sub>2</sub> emissions in the unconstrained scenario were 2.68x10<sup>11</sup> kg CO<sub>2</sub>. It was the cap set and it remains the same throughout the seven models developed. Figure 6.5 presents the CO<sub>2</sub> emissions pathway from the optimal quantities of electricity generated from different technologies for the three reduction targets analyzed. For the inequality CO<sub>2</sub> emissions constraint, the 56%, 61% and 66% reduction requires not more than a total of 1.18x10<sup>11</sup> kg, 1.05x10<sup>11</sup> kg and 9.11x10<sup>10</sup> kg to be released until 2050. The total emissions for the three cases were 1.14 x10<sup>11</sup> kg, 1.01 x10<sup>11</sup> kg and 8.8 x10<sup>10</sup> kg CO<sub>2</sub> respectively, obeying the emissions constraint. Figure 6.5 also presents the calibrated CO<sub>2</sub> emissions pathway (66% reduction constraint) for the 32% PV cumulative generation scenario used in this case, the Waxman targets are satisfied. When scaled up

by a factor of 665 the 66% emissions pathway looks similar to the 56% emissions pathway, however to highlight the difference between the pathways, Figure 6.5 also presents the un-calibrated annual emissions.

In the 56% reduction scenario, a total of 0.7 billion kWh of PV electricity was used reducing the PV end cost by 23% to 20.4 ¢/kWh. With increasingly stringent reduction targets the demand reduces to comparatively lower levels to obey the constraint. Hence in the 61% and 66% reduction scenarios, 0.65 billion kWh and 0.57 billion kWh of PV electricity was used reducing the end cost by 22% to 20.8 ¢/kWh, and by 20% to 21.3 ¢/kWh respectively. In the actual electricity sector there will be more low carbon and low cost technology options available. Hence such stringent CO<sub>2</sub> constraints will potentially be met using cleaner, but less expensive technologies before using PV technology. The influence of increased availability of technology options is evaluated in the next model.

#### **6.4.6 Model 5: Seven Technology model and Renewable Portfolio Standards**

With the availability of wind and hydropower as additional low cost and low carbon technologies, PV technology was utilized in significantly lower quantities than in model 1. When no constraints were imposed PV electricity was not utilized, wind electricity was exclusively used from the beginning to satisfy the CO<sub>2</sub> emissions constraint. Due to its low cost characteristics, wind electricity was used even in the early time periods as its utilization does not lead to a significant decrease in net welfare. PV technology was only used when cumulative generation constraints were imposed. Due to the availability of wind technology, PV technology was used to a lower extent in the end only when utilization constraints were imposed. A cumulative PV electricity generation of 0.13 billion kWh for the fifty years led to a decrease of 6% in the cost of PV electricity in the end (24.9 ¢/kWh). In model 1 the end cost of PV electricity was 19.3 ¢/kWh.

When renewable portfolio constraints were imposed in the second part of the model, wind technology was consistently used over PV technology to satisfy the RPS targets. Wind technology contributed to 99% of the total renewable energy that needed to be generated to satisfy the RPS constraints. Hence RPS constraints do not directly promote PV utilization. In this model the cost of wind electricity was exogenous, in the next model an experience curve module was built for wind technology and the PV deployment was evaluated.

#### **6.4.7 Model 6: PV and Wind Technology**

When no constraints were imposed on cumulative PV electricity generation, wind electricity was used exclusively to satisfy the CO<sub>2</sub> emissions constraint. Wind electricity was used even in the early time periods as its utilization does not decrease the discounted

net welfare significantly. A total of 125 billion kWh was used reducing the end cost by 22% to 3.91 ¢/kWh. This is an interesting trend for it is the exact opposite result obtained from model 1. In model 1 when no constraints on PV were imposed, significant amounts of PV electricity were used to eventually satisfy the emissions constraint. In this case for the same emissions constraint, no PV electricity was used due to the availability of another low cost and low carbon technology. Hence from an economic standpoint, PV cannot compete directly with wind in the immediate future. However, resource constraints (e.g. lack of wind resource) in certain locations can potentially lead to photovoltaic utilization.

PV was only used when constraints on its utilization were imposed. Based on NREL forecasts, 7%, 17% and 32% cumulative PV electricity generation constraints were imposed. In the 7%, 17% and 32% cumulative PV electricity generation constraint scenarios, a total of 0.132 billion kWh, 0.31 billion kWh and 0.59 billion kWh of PV electricity was utilized respectively. The end cost reduced to 24.8 ¢/kWh (6.4% reduction), 23.1 ¢/kWh (13% reduction) and 21.2 ¢/kWh (20% reduction) in the three cases. Figure 6.6 presents the initial and the end cost of PV electricity for the three scenarios. In addition Figure 6.6 also presents the reduction in the cost of PV and wind electricity for the scenarios analyzed. Between the two renewable resources, wind will be selected consistently over PV owing to its lower cost. PV however has the potential to be used in locations without adequate wind resources, and other renewable resources in general.

## **6.5 Strengths and Limitations**

The strengths and limitations of this study are discussed in this section. This study represents a highly simplified version of the conventional electricity grid. In a conventional grid a non-hydro renewable technology does not displace base load resources, but only peak and intermediate load resources. The current study incorporates certain fundamental dispatching features into the model. In six of the models constructed in this work, PV and wind electricity displace electricity generated from a load following resource such as natural gas. The costs of competing gas electricity and wind electricity were varied each year using forecasts and constructing experience curve modules respectively. The framework developed is the strength of the study. The framework facilitates observing the deployment and cost reduction of a developing technology, in competition with other renewable and non-renewable technologies available. The framework can be used for a policy analysis using other greenhouse gases, human health and regional pollutants. Certain features of realism are added to the models developed. However the models are still theoretical in nature. The variation in results with changing parameters explain the behavior of the models developed, and is an important step in potentially developing more increasingly realistic models for the U.S. electricity in the

future. This study significantly improved the strict theoretical framework constructed by Hanson et al 2008. It includes realistic life cycle CO<sub>2</sub> emission factors, cost parameters, price elasticity of demand, current PV and wind energy baseline outputs, CO<sub>2</sub> reduction targets, RPS targets and gas electricity costs, all of which indicate the improvements from the previous work. In essence, this work should be considered as an important intermediate step towards developing an energy economic policy paper for photovoltaic technology, and other developing technologies in the future.

The limitations of the current study are discussed in this section. Since the focus of this work was PV technology, the cost of other technologies was considered to be exogenous in the model. This limitation was partially addressed to a certain extent by varying the costs of natural gas (Model 6.3.2) and wind electricity (Model 6.3.7) in the models developed. The scope of this paper was also strictly limited to the cost and CO<sub>2</sub> emissions associated with PV technology production. Secondary impacts of increased utilization of PV electricity such as increased land use requirements were not considered. The secondary impacts of increased usage of electricity from other technologies were also not considered. Other renewable technologies such as biomass and geothermal sources were not included in the model. It is also assumed that the optimal amounts of electricity used from different technologies are available for usage each year. Other issues such as temporal and spatial aspects of using renewable technologies and the intermittency limitations were not considered. Using a demand curve that reflects the actual output in the U.S. electricity sector will also improve the realism of the model. The primary goal of this paper was to develop a theoretical framework to observe the deployment of PV technology, in competition with other electricity generation technologies under different technology, policy and economic changes. The models developed serve the objectives of this paper. Addressing the above-mentioned limitations in the future will improve the realism of the work and decrease the theoretical underpinnings of the models.

## **6.6 Summary and Conclusions**

In this study a constrained optimization framework was developed to evaluate photovoltaic deployment in competition with non-renewable and other renewable technologies. Seven different models evaluating PV utilization and consequent experience driven cost reduction were analyzed under different economic, technological, climate change and renewable energy policy scenarios. This study specifically focused on the United States, economically optimal amounts of PV electricity was evaluated for the next fifty years (starting from 2005) with a constraint on CO<sub>2</sub> emissions.

Cumulative reduction outlined in the Waxman bill was used to establish the reduction required relative to the unconstrained model. (Refer Appendix B for more detailed explanations on the approach). A 56% reduction target was used from model 1 to model

5. Model 6 and 7 include increased number of electricity generation technologies, and hence separate unconstrained scenarios were developed. Based on the unconstrained scenario emissions and Waxman CO<sub>2</sub> curve, 59% and 57% reduction target was used in model 6 and model 7 respectively.

Parameters from the actual U.S. electricity sector are used to construct the various models, however the framework is still highly theoretical and model outputs are not equal in magnitude to the actual output in the electricity sector at present. Due to the fact that the results involve different optimality pathways for each model, different scaling factors were used to scale up the results and compare the reduction achieved with that of the Waxman targets. Waxman targets are satisfied in each of the seven models developed. The particular scaling factor used was explicitly mentioned in the figures presented. Due to the very theoretical nature of the model, such a scaling factor had to be used to calibrate the model results, to enable comparison with that of the Waxman targets. It is very important to note that using such scaling factors enables only an approximate calibration of the model results to the real world CO<sub>2</sub> emissions.

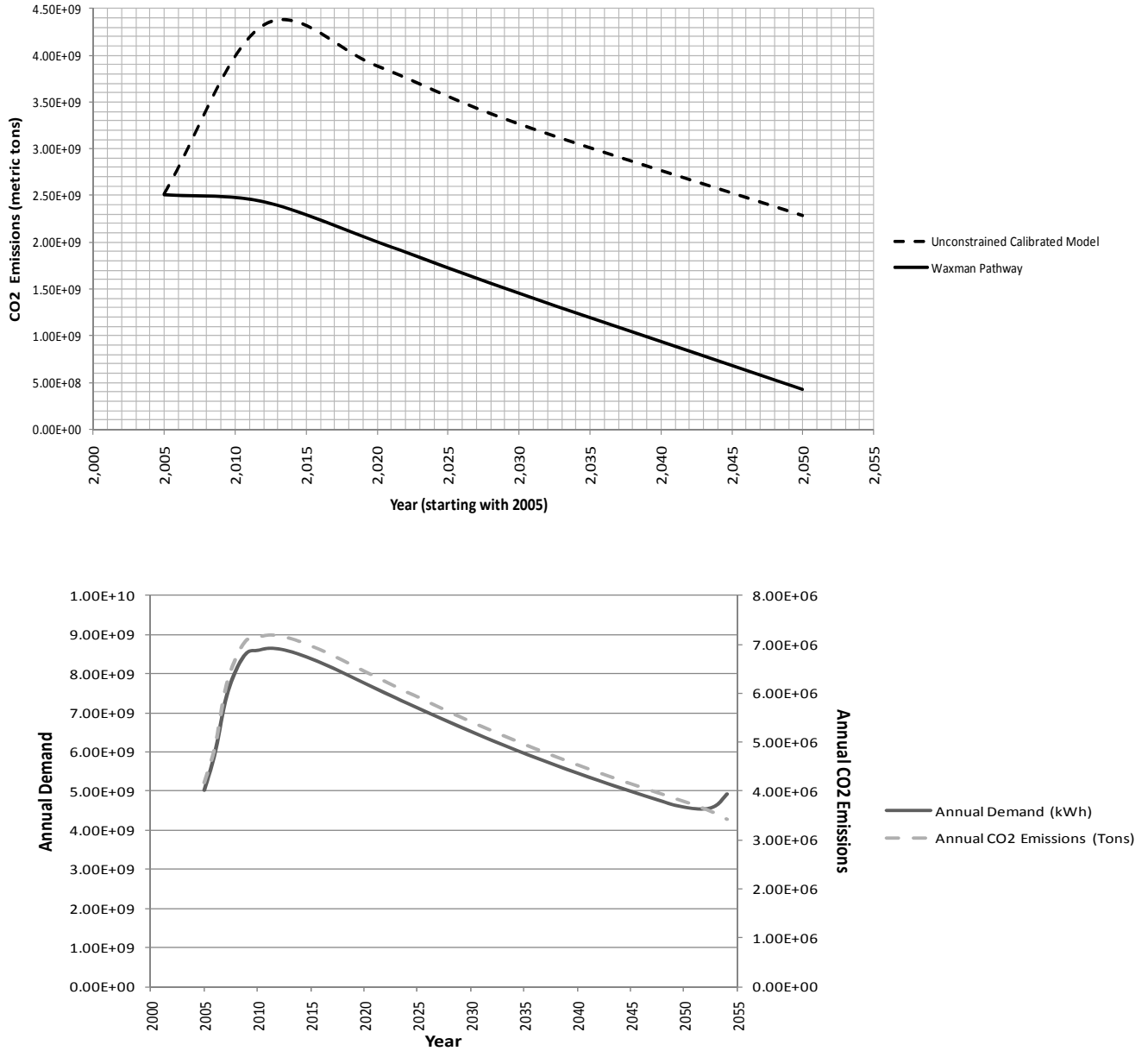
When no other renewable technology option was available, the expensive PV technology was utilized significantly to satisfy the stringent 56% CO<sub>2</sub> constraint. With no cumulative generation constraints, a total of 104 billion kWh of PV electricity was used reducing the end cost by 81% to 5 ¢/kWh in the end. When cumulative generation constraints based on NREL forecasts were imposed on PV electricity, a total of 0.7 billion kWh of PV electricity was used reducing the PV end cost by 23% to 20.4 ¢/kWh. Owing to its high cost PV electricity was utilized towards the end of the fifty years. PV utilization in the end decreases the discounted net welfare to a lower extent than the utilization in the beginning.

When competing gas electricity costs increased at an annual rate of 5.7%, PV utilization became affordable earlier in time. An additional 2 billion kWh of PV electricity was used in this case, decreasing the cost of PV electricity to 15.2 ¢/kWh (43% reduction) in the end. Photovoltaic technological breakthroughs decrease the cost of PV electricity at a higher rate with utilization. When evaluated at progress ratios of 0.7 and 0.6 the end cost of PV electricity was 17.5 ¢/kWh (34% reduction) and 14.6 ¢/kWh (45% reduction) respectively. Solar subsidies decrease the cost of PV electricity generated by decreasing the initial cost. When evaluated at a 10 ¢/kWh subsidy rate structure, the end cost of PV electricity reduced to as low as 12.7 ¢/kWh. Both potential technological developments and subsidies narrow the cost gap between PV electricity and the conventional grid. However both do incur expenditures, technological breakthroughs require significant investment in PV research and development and subsidies require investment from a regulatory agency to promote solar energy.

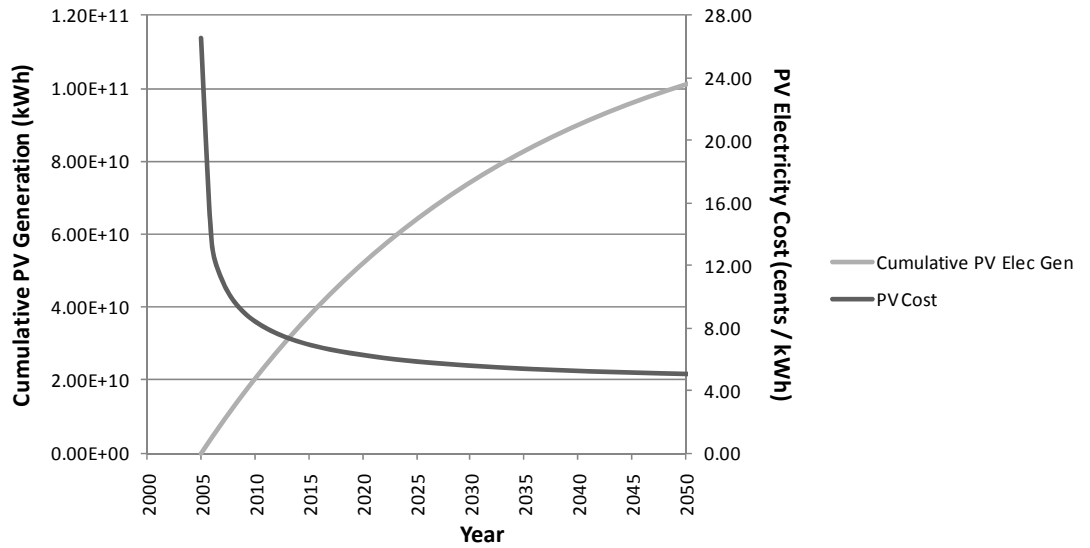
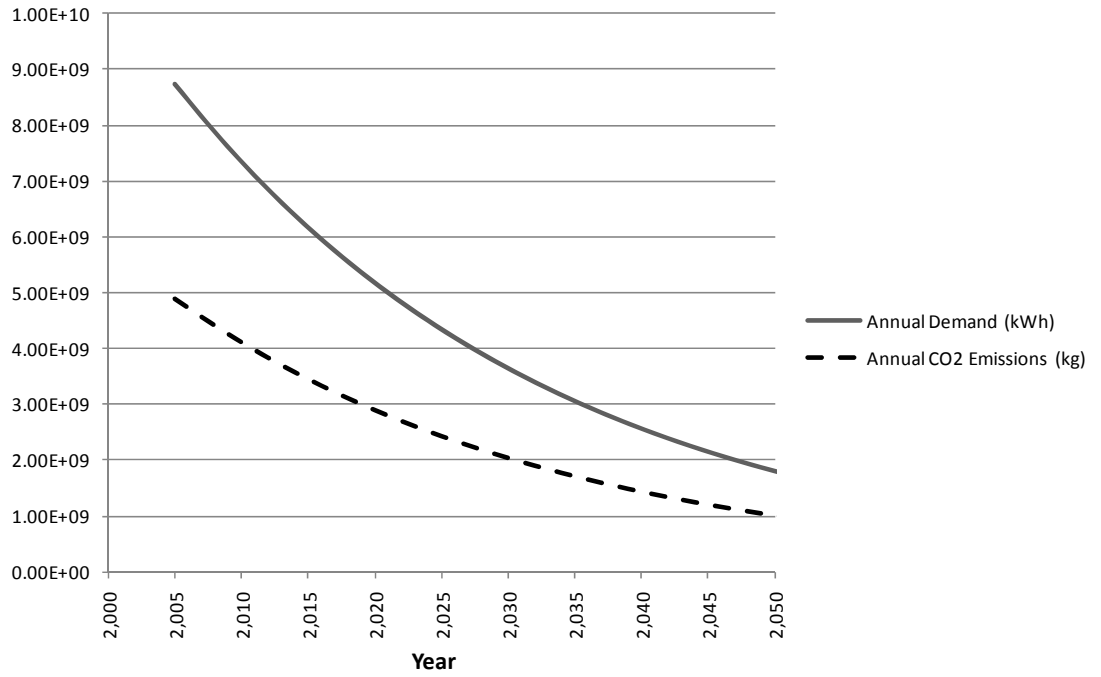
With increasingly stringent CO<sub>2</sub> emissions constraints, the demand was reduced to lower levels from the beginning to satisfy the constraint. In the 61% and 66% reduction scenarios, 0.65 billion kWh and 0.57 billion kWh of PV electricity was used reducing the end cost by 22% to 20.8 ¢/kWh, and by 20% to 21.3 ¢/kWh respectively. Based on the theoretical framework developed in this study, climate change regulations only increase PV utilization when unconstrained PV electricity was available. With constraints imposed on PV utilization, CO<sub>2</sub> reduction targets were satisfied by reducing demand to lower levels in the beginning when compared to the PV unconstrained scenario. In the real world, more technology options do exist for electricity generation. Hence PV deployment was also evaluated by increasing the number of competing technologies. When wind technology was available, wind was consistently selected over photovoltaics to satisfy the emissions constraints. PV was only used when cumulative generation constraints were imposed. When RPS constraints were imposed, almost 99% of the renewable energy required to meet RPS targets was derived from wind technology. Wind technology was also used in the early time periods due to its lower cost and consequent lower reduction in net welfare. RPS constraints however do have the potential to promote PV utilization indirectly in locations with a lack of wind resource (and other renewable resources in general). When 32% cumulative PV electricity generation constraint were imposed, 0.59 billion kWh of PV electricity was used reducing the end cost to as low as 21.2 ¢/kWh (20% reduction).

PV technology is not expected to be cost competitive with grid electricity costs in the near future. Technological breakthroughs and subsidies do not drive the PV electricity costs down to the range of grid electricity costs. In a carbon constrained world, it must be used in significant quantities to achieve drastic cost reductions. It will only be used in such quantities if no other low carbon and low cost technology options are available. The cost and emission characteristics of wind technology make using wind technology much more economically profitable when compared to PV technology. Hence climate change regulation and RPS targets can only indirectly increase PV utilization in locations where there is a lack of other more cost effective renewable resources. More targeted strategies such as increased investment in research and development for PV technology is necessary for further cost reductions. With such strategies PV technology can potentially become cost competitive with grid resources in the long term future.

## Figures and Tables

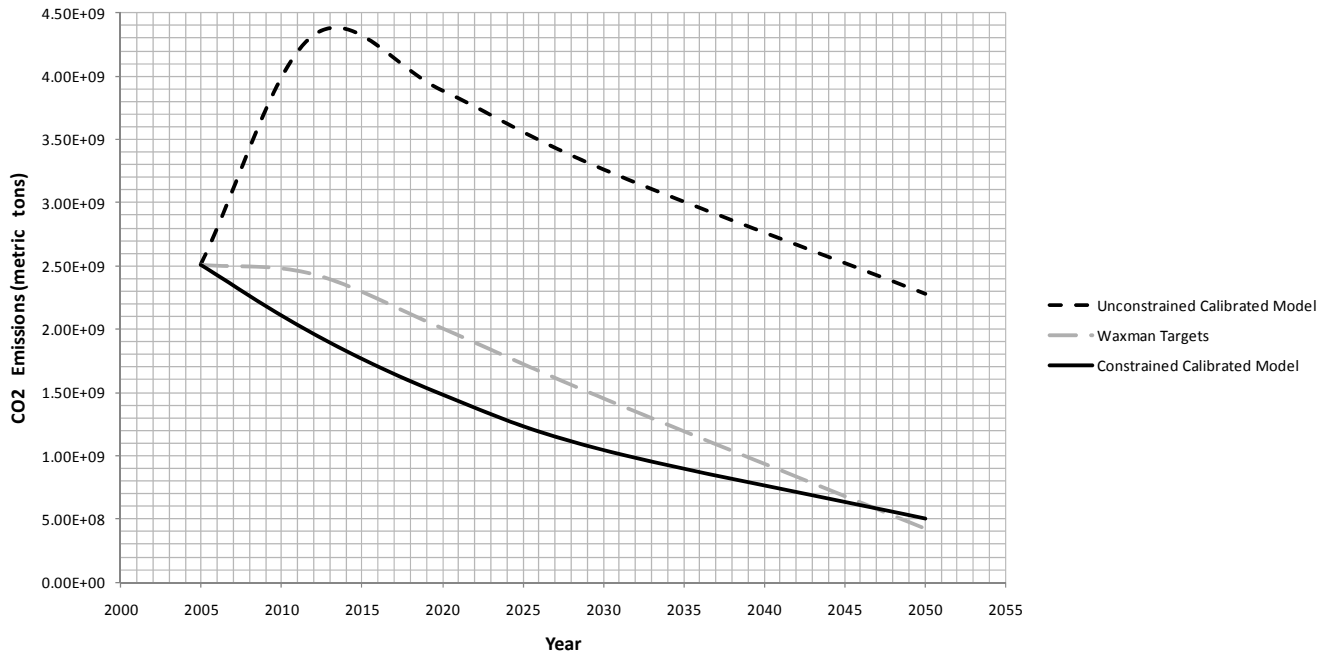


**Figure 6.1: Calibrated CO<sub>2</sub> emissions pathway (for the unconstrained scenario) and Waxman bill reduction targets (top), un-calibrated CO<sub>2</sub> emissions pathway and annual demand (for the unconstrained scenario) (bottom). Scale factor of 602 applied for calibration**

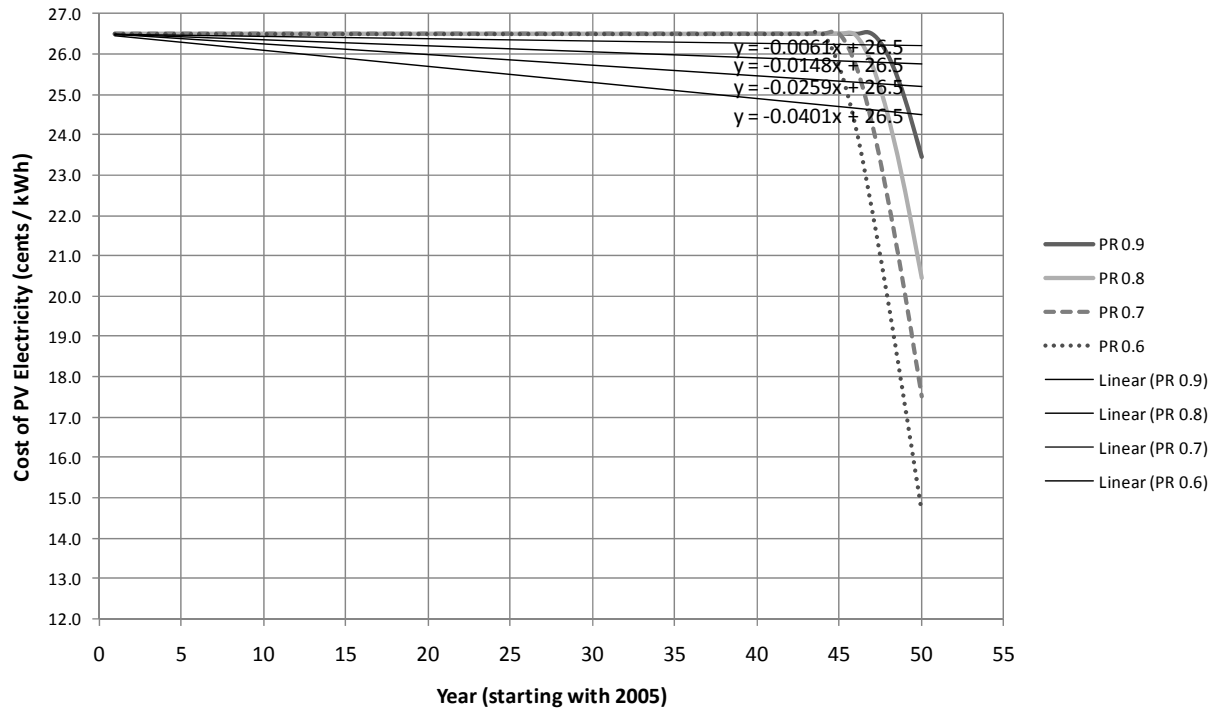


**Figure 6.2: Annual demand and annual CO<sub>2</sub> emissions (top), PV electricity utilization and cost of PV electricity (bottom) from time periods 1 to 50**

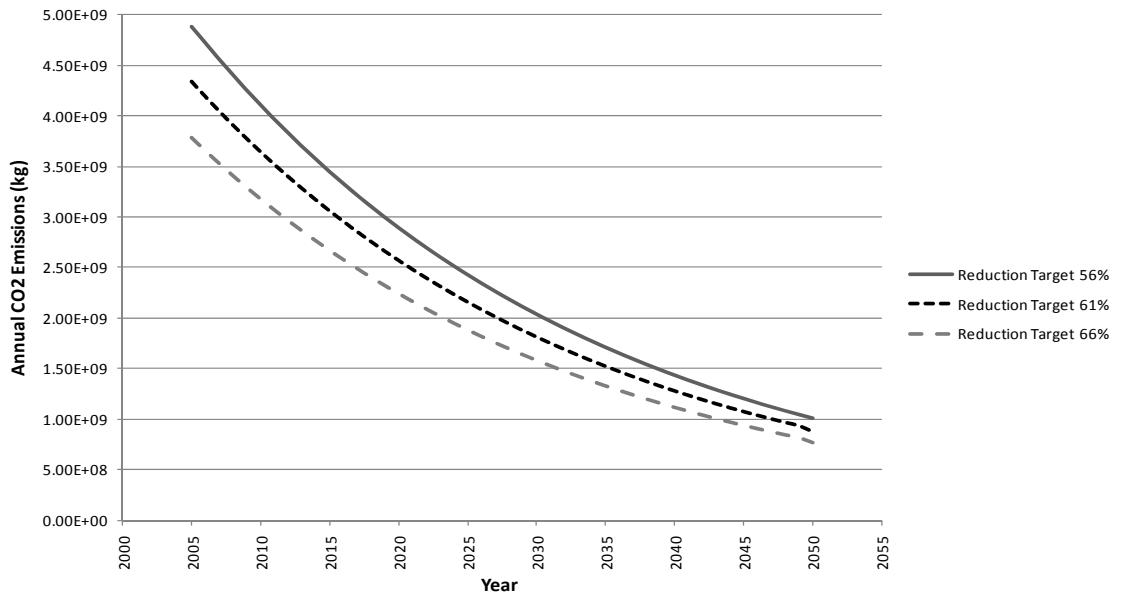
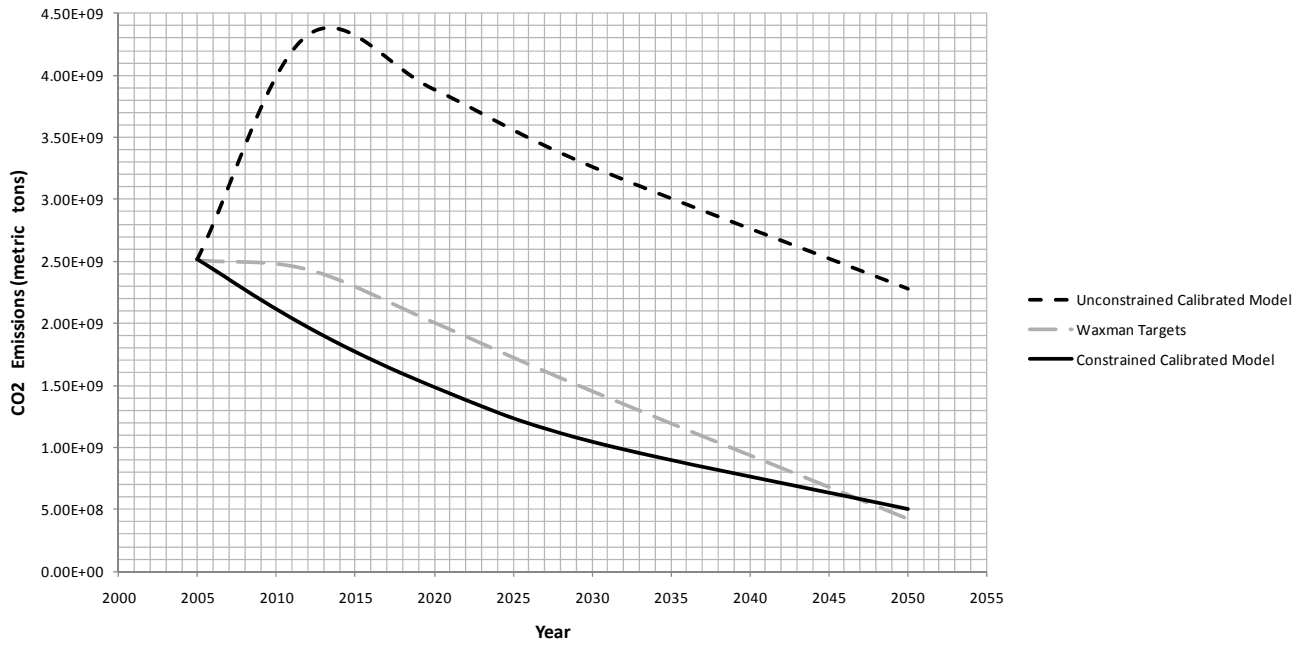




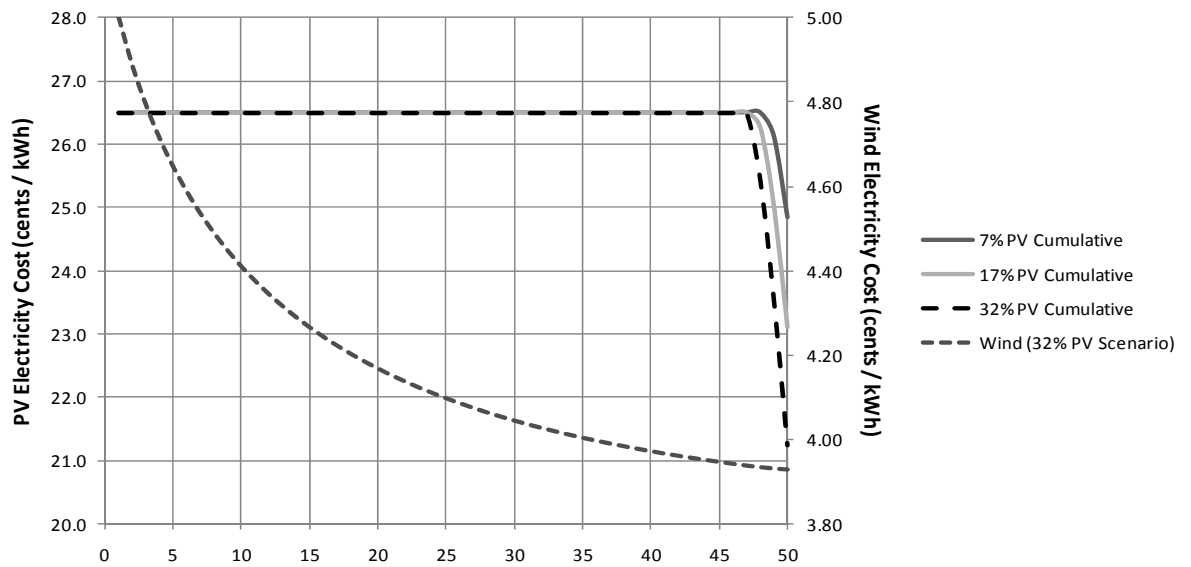
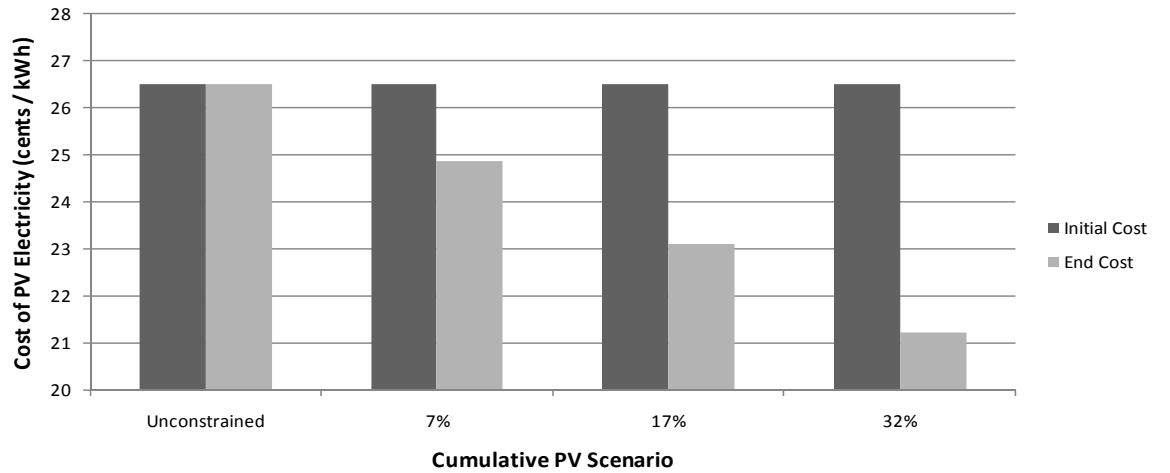
**Figure 6.3: Calibrated CO<sub>2</sub> emissions pathways (for the unconstrained and constrained scenario) and Waxman bill reduction targets. Scale factor of 602 and 514 applied for calibrating unconstrained and constrained pathways**



**Figure 6.4: The cost curves and corresponding linear equations for PV electricity at progress ratio 0.9, 0.8, 0.7 and 0.6.**



**Figure 6.5: Calibrated CO<sub>2</sub> emissions pathways (for the unconstrained and constrained 66% scenario) and Waxman bill reduction targets. Scale factor of 602 and 665 applied for calibrating unconstrained and constrained pathways (top). Un-calibrated CO<sub>2</sub> emissions pathways for the three reduction scenarios evaluated (bottom)**



**Figure 6.6: PV electricity initial and end cost (top), and cost curves of wind and PV electricity for the three cumulative PV electricity generation constraint scenarios (bottom)**

Abbreviation(s)	Explanation	Units
$q(p, t)$	Electricity demand at time period $t$	kWh
$p(q, t)$	Inverse demand function	$\$/\text{kWh}$
$S(q, t)$	Gross welfare at time period $t$	$\$$
$b_l$	Annual growth rate of electricity demand	%
$\sigma$	Price elasticity of demand	N.A.
$r$	Discount rate	%
$t$	Time period ranging from 1 to 50	N.A.
$Z_c$	Constrained emissions	kg
$Z_{uc}$	Unconstrained emissions	kg
$\beta, \beta_1, \beta_2$	Progress Ratio	N.A.
$\delta, \delta_1, \delta_2, \delta_3, \delta_4$	CO <sub>2</sub> Reduction targets	%
$Q(t)$	Total amount of electricity generated in each time period	kWh
$q_c$	Total annual electricity generated from coal	kWh
$q_o$	Total annual electricity generated from oil	kWh
$q_{ng}$	Total annual electricity generated from gas	kWh
$q_{nuc}$	Total annual electricity generated from nuclear	kWh
$q_{hyd}$	Total annual electricity generated from hydropower	kWh
$q_{wnd}$	Total annual electricity generated from wind	kWh
$q_{pv}$	Total annual electricity generated from photovoltaics	kWh
$x(t)$	Cumulative photovoltaic electricity generation	kWh
$k(t)$	Cumulative wind electricity generation	kWh
$C_c$	Average cost of generating electricity from coal	$\$/\text{kWh}$
$C_o$	Average cost of generating electricity from oil	$\$/\text{kWh}$
$C_{ng}$	Average cost of generating electricity from gas	$\$/\text{kWh}$
$C_{nuc}$	Average cost of generating electricity from nuclear	$\$/\text{kWh}$
$C_{hyd}$	Average cost of generating electricity from hydro	$\$/\text{kWh}$
$C_{wnd}$	Average cost of generating electricity from wind	$\$/\text{kWh}$
$C_{pv}$	Cost of generating electricity from photovoltaics	$\$/\text{kWh}$
$b_c$	CO <sub>2</sub> emission factor of generating electricity from coal	kg / kWh
$b_o$	CO <sub>2</sub> emission factor of generating electricity from oil	kg / kWh
$b_{ng}$	CO <sub>2</sub> emission factor of generating electricity from gas	kg / kWh
$b_{nuc}$	CO <sub>2</sub> emission factor of generating electricity from nuclear	kg / kWh
$b_{hyd}$	CO <sub>2</sub> emission factor of generating electricity from hydropower	kg / kWh
$b_{wnd}$	CO <sub>2</sub> emission factor of generating electricity from wind	kg / kWh
$b_{pv}$	CO <sub>2</sub> emission factor of generating electricity from photovoltaics	kg / kWh

**Table 6.1: Glossary of abbreviations and their corresponding explanations and units used in the study**

## REFERENCES

- A Mathematical Programming Language (AMPL). 2009.  
Link: <http://www.ampl.com/> Link accessed on June 28, 2009.
- American Clean Energy and Security Act. 2009. Waxman Markley Bill (932 pages).  
Document can be accessed from the House of Representatives webpage:  
[http://energycommerce.house.gov/Press\\_111/20090515/hr2454.pdf](http://energycommerce.house.gov/Press_111/20090515/hr2454.pdf)  
Link accessed on July 1, 2009.
- American Solar Energy Society (ASES). 2009  
Link: [http://www.ases.org/index.php?option=com\\_myblog&show=Hearing-Tuesday-for-20-national-RPS.html&Itemid=27](http://www.ases.org/index.php?option=com_myblog&show=Hearing-Tuesday-for-20-national-RPS.html&Itemid=27)  
Link accessed on June 29, 2009.
- American Wind Energy Association (AWEA). 2009. Resource Cost.  
Link: [http://www.awea.org/faq/wwt\\_costs.html](http://www.awea.org/faq/wwt_costs.html)  
Link accessed on May 11, 2009.
- Borenstein, S. 2008. The market value and cost of solar photovoltaic electricity production. University of California Energy Institute.
- Byrd, R.H. Nocedal, J. Waltz, R.A. 2006. KNITRO: An integrated package for non linear optimization.
- Cabral, L. (1990). On the adoption of innovations with network externalities. Mathematical Social Sciences (19) 299 – 308.
- California Energy Commission. 2009. Natural gas price forecast and uncertainty. (Electricity Supply Analysis Division).
- Database of State Incentives for Renewables and Efficiency (DSIRE). 2009.  
Link: <http://dsireusa.org/solar/index.cfm?ee=1&RE=1&spf=1&st=1>  
Link accessed on July 22 2009
- Denholm, P. Margolis, R. M. 2007. Evaluating the limits of solar photovoltaics in traditional electric power systems. Energy Policy (35) 2852 - 2861
- Electric Power Research Institute (EPRI). 2007. Electricity technology in a carbon constrained future (Steven Specker).
- Energy Center of Netherlands (ECN). 2002. Learning and diffusion for wind and solar power technologies.

Energy Efficiency and Renewable Energy (EERE). 2009. States with renewable portfolio standards

Link: [http://apps1.eere.energy.gov/states/maps/renewable\\_portfolio\\_states.cfm#chart](http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm#chart)

Link accessed on June 21, 2009.

Energy Efficiency and Renewable Energy (EERE). 2009a.

Link: [http://www1.eere.energy.gov/buildings/news\\_detail.html?news\\_id=12607](http://www1.eere.energy.gov/buildings/news_detail.html?news_id=12607)

Link accessed on July 22, 2009

Energy Information Administration (EIA). 2008. Annual Energy Review 2008.

Energy Information Administration (EIA). 2008a. Forecasts and Analyses

Link: <http://www.eia.doe.gov/oiaf/forecasting.html> Link accessed on June 21, 2009.

Energy Information Administration (EIA). 2008b. Annual Energy Outlook Projections Until 2030.

Energy Information Administration (EIA). 2009. Electricity Costs

Link: <http://www.eia.doe.gov/fuelelectric.html> Link accessed on May 11, 2009.

Energy Information Administration (EIA). 2009a. Annual Energy Review 2008

Link: <http://www.eia.doe.gov/emeu/aer/renew.html> Link accessed on July 30, 2009

Farber, D. A., and P. A. Hemmersbaugh. 1993. The shadow of the future: Discount rates, later generations, and the environment. *Vanderbilt Law Review* 46: 267-304. The article can be accessed at <http://www.ciesin.org/docs/010-291/010-291.html#a>

Geroski, P. 2000. Models of technology diffusion. *Research Policy* (29) 603 – 625.

Hanson, D. Kryukov, S. Leyffer, S. Munson, T.S. 2008. An optimal control model for technology transition. Mathematics and Computer Science Division, Argonne National Laboratory.

Hanson, D. Laitner, J. A. 2004. An integrated analysis of policies that increase investments in advanced energy efficient low carbon technologies. *Energy Economics* (26) 739 – 755.

International Energy Agency (IEA). 2000. Experience curves for energy technology policy.

International Energy Agency (IEA). 2009. National survey report for PV applications in the United States.

Jensen, R. 1982. Adoption and diffusion of an innovation of uncertain profitability. *Journal of Economic Theory* (3) 182 – 193.

- Jensen, R. 1983. Innovation adoption and diffusion when there are competing innovations. *Journal of Economic Theory* (29) 167 – 171.
- National Renewable Energy Laboratory (NREL). 2002. Experience curves and photovoltaic technology policy (by Robert Margolis).
- National Renewable Energy Laboratory (NREL). 2004. The role of solar in the long term outlook of electric power generation in the U.S. (report by Robert Margolis and Frances Wood).
- National Renewable Energy Lab (NREL). 2006. A review of PV inverter technology cost and performance projections.
- National Renewable Energy Lab (NREL). Renewable Resource Data Center. 2009. Link: [http://rredc.nrel.gov/solar/old\\_data/nsrdb/1991-2005/](http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/) Link accessed on July 13, 2009.
- Paul, A. Myers. E. Palmer. K. 2009. A partial adjustment model for U.S. electricity demand by region, season and sector. *Resources for the Future*.
- Product Ecology Consultants (Pre). Life cycle software Simapro. 2009. Link: <http://pre.nl/> Link accessed on June 26, 2009.
- Trancik, J.E. Zweibal, K. 2006. Technology cost and cost reduction potential of photovoltaics. IEEE. Report number 1-4244-0016-3/06.
- Van Sark, W.G.J.H.M Alsema, E.A. Junginger, H.M. de Moor, H.H.C. Schaeffer, G.J. 2008. Accuracy of progress ratios determined from experience curves: The case of crystalline silicon photovoltaic module technology development. *Prog Photovolt Res Appl* (16) 441-453
- Woerlen, C. 2004. Experience curves for energy technologies. *Encyclopedia of Energy* (2) 641 – 649.



## CHAPTER 7

### CONCLUSIONS AND FUTURE WORK

#### 7.1 Summary and Conclusions

This dissertation developed an integrated framework to evaluate photovoltaic electricity generation in the United States. The *Integration* aspect is highlighted by the fact that the results from one module were used as input parameters for developing the other modules in the study. For example, the results from Chapter 3 included cost parameters and CO<sub>2</sub> emission factors for PV technology. These results were used as input parameters for comparing the deployment of PV technology with other competing technologies in Chapter 6.

The methodology developed used an energy economic framework to incorporate the energy and environmental characteristics of PV technology into the evaluation of the economics, utilization and marginal cost reduction in the future. Four main areas of research were presented. Life cycle modeling of five different types of PV panels, evaluation of CO<sub>2</sub> abatement potential of PV technology at different scales in the U.S, identification of technology and policy parameters that provide the highest increase in economic performance, and evaluating competitive PV deployment and cost reduction under various technological, energy and climate change policy scenarios in the U.S. in the future.

The first module evaluated the energy consumption and environmental emissions associated with manufacturing five PV types of panels. A mono-crystalline panel consumed (8,220 MJ) 1.3 and 1.6 times more primary energy than the multi-crystalline and string ribbon panels. The amorphous silicon panel consumed (2,270 MJ) 2.6 times the primary energy of that of the Cd-Te option. The average CO<sub>2</sub> emission factor (grams /kWh) ranged from 31 to 48 for the crystalline panels, and 20 to 21 for the thin film panels. Module recycling was determined to be significantly more beneficial for crystalline panels than the thin film panels. Recycling reduced primary energy consumption by 32 to 59% for the crystalline panels, and only by 3 to 8% for the thin

film panels. The higher energy savings obtained from recycling crystalline panels is due to the recycling of the energy intensive crystalline wafers in the module. The three crystalline modules also consumed significantly higher amounts of natural gas than the thin film modules during manufacturing: 428 ft<sup>3</sup> (mono-crystalline), 364 ft<sup>3</sup> (multi-crystalline), 197 ft<sup>3</sup> (ribbon), 14 ft<sup>3</sup> (amorphous silicon) and 1.3 ft<sup>3</sup> (Cd-Te). The cost of labor for crystalline and amorphous silicon panels was \$2.12 and \$1.99 per unit peak watt capacity produced. The reduced number of steps such as glass production, cell manufacturing and frame manufacturing in the case of amorphous silicon panel resulted in the decreased cost of labor. Chapter 3 presents the current energy and environmental impacts, cost and labor consumption associated with PV manufacturing, and the potential benefits of module recycling. The results from this module were used in each of the next three modules developed.

The second module analyzed the CO<sub>2</sub> abatement potential of PV installation in the U.S. at different fuel mix scales. The abatement results of the average national, regional and state scales were compared to that of a marginal displacement approach applied to the load zones of ERCOT (Electric Reliability Council of Texas) and CAL-ISO (California Independent System Operator). Natural gas has lower carbon intensity when compared to other fossil resources such as coal and oil. Due to the predominant natural gas displacement at the margin in ERCOT, the marginal case reduced CO<sub>2</sub> by 145 to 181,850 tons below the three average scales (for PV capacities of 1 to 1,000 kWp capacity installations). The marginal abatement was 15% lower when compared to the average fuel mix cases. In CAL-ISO, marginal displacement of natural gas abated 714 to 3,500 tons CO<sub>2</sub> more than the three average cases. This module was used to develop a regional grid CO<sub>2</sub> indicator to determine site selection for PV installation, to facilitate maximum abatement. Installing PV modules at locations in MRO, SPP and RFC grid was determined to be most beneficial, NPCC grid proved to be the least favorable option. In addition the influence of a time varying fuel mix and variability in solar resource across the U.S. on the benefits of PV technology was investigated. The time varying fuel mix used EIA and EPRI resource profile and demand growth projections. The EIA and the EPRI scenarios led to 0.8% increase and 14.3% decrease in annual abatement respectively, when compared to the baseline using a static fuel mix throughout the technology lifetime. The variation of solar resource across the national U.S, increased the energy payback time from a minimum of 2.2 years, to a maximum of 7.6 years for the Cd-Te and mono-crystalline PV panels. When installed in Phoenix, Arizona the energy payback time of cadmium telluride module decreased by 2.2 years when compared to being installed in Anchorage, Alaska (decreased from 3.9 years to 1.7 years). When installed in Phoenix, Arizona the energy payback time of the mono-crystalline module decreased by 7.6 years when compared to being installed in Anchorage, Alaska (decreased from 13.5 years to 5.9 years). This result presents a more refined approach to evaluate CO<sub>2</sub> abatement by PV electricity generation. It also develops indicators that can

be used for energy planning and CO<sub>2</sub> mitigation policy-making using PV technology in the future.

The third module integrated results from a dynamic life cycle assessment of PV technology with micro-economic cost benefit analysis. This module constructs a base case and performs a set of sensitivity analyses to test the variability of results due to technological and regulatory changes in the future. The benefit cost (BC) ratio of the base model was 0.29. The inclusion of monetization of reduced emissions (allowance trading and reduced damage costs) increased the BC ratio to 0.38. A novel feature of this economic model is the incorporation of allowance trading prices in cap and trade markets into the evaluation of the economic performance of PV technology. Inclusion of air pollutant and greenhouse gas permit prices from open markets increased the economic performance of PV technology by 23%. This emphasized the importance of such markets in increasing renewable technology deployment. Regardless of discount rate, the majority of scenarios generate relatively small increases in BC ratio, such as 0.1 or less, relative to the baseline. More substantial increases occurred with three scenarios: increase in conversion efficiency and solar resource availability, and PV module cost reduction. At the 2% discount rate, the BC ratio increases to 0.68, 0.70 and to 0.82 in the three scenarios, when compared to the base case. Two different subsidy structures for solar installation currently existent in the U.S. were analyzed. An upfront and performance based subsidy (California) increased the economic performance of photovoltaics more than a onetime lump sum grant (Michigan, \$50,000). Although no single parameter raises the BC ratio over unity, a set of three technological improvements working together accomplishes this: the sensitivity values for O/M cost, PV module cost, and conversion efficiency raise the BC ratio to 2.73. The parameters for allocation of financial resources, to increase the economic performance of PV technology are identified.

In the fourth module, a constrained optimization framework was developed to evaluate photovoltaic deployment in competition with non-renewable and other renewable technologies. Seven different models evaluating PV utilization and consequent experience driven cost reduction were analyzed under different economic, technological, climate change and renewable energy policy scenarios. This study specifically focused on the United States. Economically optimal deployment of PV electricity was evaluated for the next fifty years (starting from 2005) with a constraint on CO<sub>2</sub> emissions. The 56% cumulative CO<sub>2</sub> emissions constraint was obtained by using a combination of the unconstrained scenario emissions from the model, and Waxman bill (H.R. 2454) reduction targets until 2050. When cumulative generation constraints based on NREL forecasts were imposed on PV electricity, a total of 0.7 billion kWh of PV electricity was used reducing the PV end cost by 23% to 20.4 ¢/kWh. Owing to its high cost PV electricity was utilized towards the end of the fifty years. PV utilization in the end decreases the discounted net welfare to a lower extent than the utilization in the

beginning. Photovoltaic technological breakthroughs decrease the cost of PV electricity at a higher rate with utilization. When evaluated at progress ratios of 0.7 and 0.6 the end cost of PV electricity was 17.5 ¢/kWh (34% reduction) and 14.6 ¢/kWh (45% reduction) respectively. Solar subsidies decrease the cost of PV electricity generated by decreasing the initial cost. When evaluated at a 10 ¢/kWh subsidy rate structure, the end cost of PV electricity reduced to as low as 12.7 ¢/kWh. With increasingly stringent CO<sub>2</sub> emissions constraints, the demand was reduced to lower levels from the beginning to satisfy the constraint. In the 61% and 66% reduction scenarios, 0.65 billion kWh and 0.57 billion kWh of PV electricity was used reducing the end cost by 22% to 20.8 ¢/kWh, and by 20% to 21.3 ¢/kWh respectively. When wind technology was available, wind was consistently selected over photovoltaics to satisfy the emissions constraints. PV was only used when cumulative generation constraints were imposed. When RPS constraints were imposed, almost 99% of the renewable energy required to meet RPS targets was derived from wind technology. Wind technology was also used in the early time periods due to its lower cost and consequent lower reduction in net welfare. RPS constraints however do have the potential to promote PV utilization indirectly in locations with a lack of wind resource (and other renewable resources in general). When a 32% cumulative PV electricity generation constraint was imposed, 0.59 billion kWh of PV electricity was used reducing the end cost to as low as 21.2 ¢/kWh (20% reduction).

PV technology is not expected to be cost competitive with grid electricity costs in the near future. Technological breakthroughs and subsidies do not drive the PV electricity costs down to the range of grid electricity costs. In a carbon constrained world, it must be used in significant quantities to achieve drastic cost reductions. It will only be used in such quantities if no other low carbon and low cost technology options are available. The cost and emission characteristics of wind technology make using wind technology much more economically profitable when compared to PV technology. Hence climate change regulation and RPS targets can only indirectly increase PV utilization in locations where there is a lack of other more cost effective renewable resources. More targeted strategies such as increased investment in research and development for PV technology is necessary for further cost reductions. With such strategies PV technology can potentially become cost competitive with grid resources in the long term future.

## 7.2. Contributions

This dissertation embodies several contributions to the existing knowledge in the fields of energy systems analysis and renewable energy economics. These contributions provide a foundation for the future researchers and practitioners to improve the energy economic evaluation of photovoltaic technologies, and other renewable electricity generation technologies in general. The contributions from this dissertation are as follows.

1. In general the end of life management (EOL) stage for PV technologies has not been included in the life cycle models. This dissertation contributed by developing a comprehensive recycling and disposal model for five PV panels, and including it in the life cycle model. This particular model helps evaluate the *net* primary energy conserved and *net* emissions reduced due to recycling crystalline modules. The labor cost model developed for crystalline and amorphous silicon panels determined the total cost of labor the economy will spend in manufacturing PV panels. The National Renewable Energy Laboratory forecasts 7% to 32% of annual demand to be contributed by PV technologies at the end of 50 years from now.<sup>1</sup> Hence the evaluation of energy savings from recycling (from EOL model) and labor cost are expected to contribute towards understanding the cost and energy implications of manufacturing photovoltaics on a large scale in the future.
2. This dissertation developed a more refined approach to evaluate the CO<sub>2</sub> abatement by PV technology. The marginal displacement model takes into consideration both the PV installation and the profile of the peak load sources, to evaluate the abatement which was different from the results using average fuel mix profiles. One of the strengths of this model lies in the fact that it can be applied to other renewable electricity generation technologies as well. The regional and marginal CO<sub>2</sub> indicators developed, aid in selecting the optimal sites for PV installation to facilitate maximum CO<sub>2</sub> abatement. This metric is a powerful tool that can be used for future CO<sub>2</sub> mitigation policymaking and energy planning, through PV electricity generation. The time varying fuel mix model provided an estimate regarding the variability in future CO<sub>2</sub> abatement. This abatement is a function of changes in both demand and the resource profile of the electricity sector in the future.

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<sup>1</sup> Reference: National Renewable Energy Laboratory (NREL). 2004. The role of solar in the long term outlook of electric power generation in the U.S. (report by Robert Margolis and Frances Wood).

3. This dissertation identified the technological and policy changes that facilitate the highest increase in the economic performance of PV technology. Such identification provides a specific target for the allocation of research and development financial resources in the future. It helps derive the maximum benefit from a specific investment. The cost benefit model also incorporated cap and trade allowance trading prices into the evaluation of the economic performance of PV technology. This is a novel feature of the study. This feature can be extended for the economic evaluation of other renewable electricity generation technologies as well.
4. Growth of renewable electricity generation technologies does not happen in isolation. This dissertation establishes a constrained optimization framework in which PV competes with other electricity generation technologies. The results from this model aid in identifying the cost and usage of photovoltaic electricity under conditions of increase in gas electricity costs, technological breakthroughs, renewable portfolio standards, solar subsidies and more stringent CO<sub>2</sub> emission constraints. The contribution from this chapter is the development of an economic framework that can be used to compare the growth of developing technologies, with other renewable and conventional grid technologies.

### **7.3 Future Work**

In this study the life cycle model was integrated with grid dispatching model and the cost benefit model to evaluate the marginal CO<sub>2</sub> abatement and economic performance of the technology. Such an integrated approach can be applied to evaluate other developing renewable technologies in the U.S. electricity sector in the future. A LCA framework accounts for the material and energy inputs and outputs at each stage in the life cycle of a technology. The model's capacity to capture the complex interplay between impacts associated with technology manufacturing and end of life management, and lifetime technology output at different installations sites highlighted the importance of two key factors. Primary energy consumption during manufacturing and site variability of solar resource govern the energy and environmental performance of the PV technology. Hence any renewable electricity generation technology, with variability in the resource availability for electricity generation at different sites, is an excellent candidate for evaluation using this framework. Wind power is an example of one such candidate.

A key component of the life cycle model is also characterizing how the energy and environmental performance of PV technology is governed by the module production phase. This step is particularly applicable for some of the nascent technologies in the market at present. Five different photovoltaic modules were evaluated in this dissertation.

Three types of crystalline technologies (mono-crystalline, multi-crystalline and string ribbon) and two types of thin film technologies (amorphous silicon, cadmium telluride) were evaluated. Given the recent developments in the field of nano photovoltaic technology, applying a LCA framework to evaluate nano-PV will highlight the energy and environmental impacts associated with manufacturing this technology.

The environmental cap and trade framework incorporated into the economic evaluation of PV technology can be applied to other renewable technologies. Inclusion of pollutant permit prices from the emissions trading market provides a framework to recognize the monetary value of the 'Green' attribute of renewable electricity. Recognition of the green attribute internalizes the externalities of electricity generation. In a carbon constrained world, this framework can be applied to evaluate the economics of renewable energy and electricity generation technologies. The technology transition model provides a foundation that can be used by other energy practitioners to develop a more comprehensive model in the future. This dissertation focused on PV technology and hence the experience curve component was developed for the same. While the cost of natural gas and wind electricity was varied, other electricity costs were exogenous in the models constructed. While it served the purpose of this dissertation, the learning rates and cost projections if included for other technologies will refine the model. The magnitude of the actual optimal electricity outputs generated and CO<sub>2</sub> emissions released from the models does not accurately represent the U.S. electricity sector. The demand function used in the future development of this work should ideally reflect the actual annual output from the U.S. electricity sector.

The framework developed for PV technology in this dissertation, can also be used for reducing other regional and human health pollutants (e.g. sulfur oxides, nitrogen oxides and mercury) using renewable technologies. Developing such a transition model for the U.S. electricity sector will increase our understanding about the inter-play between cost, environmental characteristics and deployment among different electricity generation technologies. This study did not consider the spatial and temporal dimensions, and the intermittency challenge associated with using PV technology. The study also did not consider the secondary impacts of electricity generation (e.g. water use and land use) from PV technology. Inclusion of these features when constructing similar models in the future will contribute towards a better understanding regarding the trade-offs involved with PV electricity generation.

## APPENDIX A

### Visual Basic Code: ERCOT

ERCOT Code

Sub A()

Sheets("Consol.Data").Select

finalrow = Cells(Rows.Count, 2).End(xlUp).Row

For i = 4 To finalrow

Worksheets("consol.data").Cells(i, 4).NumberFormat = "0,0"

Worksheets("consol.data").Cells(i, 8).NumberFormat = "0,0"

P = Worksheets("consol.data").Cells(i, 3).Value

If P > 0 Then

D = Worksheets("consol.data").Cells(i, 2)

Worksheets("consol.data").Cells(i, 8) = D

End If

Next i

Worksheets("Consol.Data").Cells(4, 5).NumberFormat = "0,0"

a1 = Worksheets("consol.data").Cells(4, 2).Value



```
Worksheets("consol.data").Cells(4, 5) = a1
```

```
Sheets("Consol.Data").Select
```

```
finalrow = Cells(Rows.Count, 2).End(xlUp).Row
```

```
For s = 5 To finalrow
```

```
Worksheets("consol.data").Cells(s, 5).NumberFormat = "0,0"
```

```
Worksheets("consol.data").Cells(s, 5) = Worksheets("consol.data").Cells(s - 1, 5) +  
Worksheets("consol.data").Cells(s, 2)
```

```
Next s
```

```
Sheets("Consol.Data").Select
```

```
For j = 4 To finalrow
```

```
P = Worksheets("consol.data").Cells(j, 3).Value
```

```
If P > 0# Then
```

```
v = Worksheets("consol.data").Cells(j, 1)
```

```
v1 = Worksheets("consol.data").Cells(j, 5)
```

```
Worksheets("consol.data").Cells(j, 7) = v
```

```
Sheets("CC.Supply").Select
```

```
For k = 7 To 8790
```

```
If Worksheets("CC.Supply").Cells(3, k) = v Then
```

```
finalrow = Cells(Rows.Count, 2).End(xlUp).Row
```

```
For i = 5 To finalrow
```

```
If Worksheets("CC.supply").Cells(i, v + 6).Value > v1 Then
```

```
u = Worksheets("CC.supply").Cells(i, 4).Value
```

```
c = Worksheets("CC.supply").Cells(i, 5).Value
```

If  $(u \geq P)$  Then

$E1 = P * c$

Worksheets("consol.data").Cells(j, 15) = E1

Worksheets("consol.data").Cells(j, 14) = Worksheets("CC.supply").Cells(i, 6)

Worksheets("consol.data").Cells(j, 16) = P

Else:  $E1 = u * c$

Worksheets("consol.data").Cells(j, 15) = E1

Worksheets("consol.data").Cells(j, 14) = Worksheets("CC.supply").Cells(i, 6)

Worksheets("consol.data").Cells(j, 16) = u

$u1 = \text{Worksheets("CC.supply").Cells}(i - 1, 4).\text{Value}$

$c1 = \text{Worksheets("CC.supply").Cells}(i - 1, 5).\text{Value}$

If  $(P - u) \leq u1$  Then

$E2 = (P - u) * c1$

Worksheets("consol.data").Cells(j, 18) = E2

Worksheets("consol.data").Cells(j, 17) = Worksheets("CC.supply").Cells(i - 1, 6)

Worksheets("consol.data").Cells(j, 19) =  $(P - u)$

Else:  $E2 = u1 * c1$

Worksheets("consol.data").Cells(j, 18) = E2

Worksheets("consol.data").Cells(j, 17) = Worksheets("CC.supply").Cells(i - 1, 6)

Worksheets("consol.data").Cells(j, 19) = u1

$u2 = \text{Worksheets("CC.supply").Cells}(i - 2, 4).\text{Value}$

$c2 = \text{Worksheets("CC.supply").Cells}(i - 2, 5).\text{Value}$

If  $(P - u - u1) \leq u2$  Then

$E3 = (P - u - u1) * c2$

Worksheets("consol.data").Cells(j, 21) = E3

Worksheets("consol.data").Cells(j, 20) = Worksheets("CC.supply").Cells(i - 2, 6)

Worksheets("consol.data").Cells(j, 22) = (P - u - u1)

Else: E3 = u2 \* c2

Worksheets("consol.data").Cells(j, 21) = E3

Worksheets("consol.data").Cells(j, 20) = Worksheets("CC.supply").Cells(i - 2, 6)

Worksheets("consol.data").Cells(j, 22) = u2

u3 = Worksheets("CC.supply").Cells(i - 3, 4).Value

c3 = Worksheets("CC.supply").Cells(i - 3, 5).Value

If (P - u - u1 - u2) <= u3 Then

E4 = (P - u - u1 - u2) \* c3

Worksheets("consol.data").Cells(j, 24) = E4

Worksheets("consol.data").Cells(j, 23) = Worksheets("CC.supply").Cells(i - 3, 6)

Worksheets("consol.data").Cells(j, 25) = (P - u - u1 - u2)

Else: E4 = u3 \* c3

Worksheets("consol.data").Cells(j, 24) = E4

Worksheets("consol.data").Cells(j, 23) = Worksheets("CC.supply").Cells(i - 3, 6)

Worksheets("consol.data").Cells(j, 25) = u3

u4 = Worksheets("CC.supply").Cells(i - 4, 4).Value

c4 = Worksheets("CC.supply").Cells(i - 4, 5).Value

If (P - u - u1 - u2 - u3) <= u4 Then

E5 = (P - u - u1 - u2 - u3) \* c4

Worksheets("consol.data").Cells(j, 27) = E5

Worksheets("consol.data").Cells(j, 26) = Worksheets("CC.supply").Cells(i - 4, 6)

Worksheets("consol.data").Cells(j, 28) = (P - u - u1 - u2 - u3)

Else: E5 = u4 \* c4

Worksheets("consol.data").Cells(j, 27) = E5  
Worksheets("consol.data").Cells(j, 26) = Worksheets("CC.supply").Cells(i - 4, 6)  
Worksheets("consol.data").Cells(j, 28) = u4  
u5 = Worksheets("CC.supply").Cells(i - 5, 4).Value  
c5 = Worksheets("CC.supply").Cells(i - 5, 5).Value

If (P - u - u1 - u2 - u3 - u4) <= u5 Then  
E6 = (P - u - u1 - u2 - u3 - u4) \* c5  
Worksheets("consol.data").Cells(j, 30) = E6  
Worksheets("consol.data").Cells(j, 29) = Worksheets("CC.supply").Cells(i - 5, 6)  
Worksheets("consol.data").Cells(j, 31) = (P - u - u1 - u2 - u3 - u4)  
Else: E6 = u5 \* c5  
Worksheets("consol.data").Cells(j, 30) = E6  
Worksheets("consol.data").Cells(j, 29) = Worksheets("CC.supply").Cells(i - 5, 6)  
Worksheets("consol.data").Cells(j, 31) = u5  
u6 = Worksheets("CC.supply").Cells(i - 6, 4).Value  
c6 = Worksheets("CC.supply").Cells(i - 6, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5) <= u6 Then  
E7 = (P - u - u1 - u2 - u3 - u4 - u5) \* c6  
Worksheets("consol.data").Cells(j, 33) = E7  
Worksheets("consol.data").Cells(j, 32) = Worksheets("CC.supply").Cells(i - 6, 6)  
Worksheets("consol.data").Cells(j, 34) = (P - u - u1 - u2 - u3 - u4 - u5)  
Else: E7 = u6 \* c6  
Worksheets("consol.data").Cells(j, 33) = E7  
Worksheets("consol.data").Cells(j, 32) = Worksheets("CC.supply").Cells(i - 6, 6)  
Worksheets("consol.data").Cells(j, 34) = u6

u7 = Worksheets("CC.supply").Cells(i - 7, 4).Value

c7 = Worksheets("CC.supply").Cells(i - 7, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6) <= u7 Then

E8 = (P - u - u1 - u2 - u3 - u4 - u5 - u6) \* c7

Worksheets("consol.data").Cells(j, 36) = E8

Worksheets("consol.data").Cells(j, 35) = Worksheets("CC.supply").Cells(i - 7, 6)

Worksheets("consol.data").Cells(j, 37) = (P - u - u1 - u2 - u3 - u4 - u5 - u6)

Else: E8 = u7 \* c7

Worksheets("consol.data").Cells(j, 36) = E8

Worksheets("consol.data").Cells(j, 35) = Worksheets("CC.supply").Cells(i - 7, 6)

Worksheets("consol.data").Cells(j, 37) = u7

u8 = Worksheets("CC.supply").Cells(i - 8, 4).Value

c8 = Worksheets("CC.supply").Cells(i - 8, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7) <= u8 Then

E9 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7) \* c8

Worksheets("consol.data").Cells(j, 39) = E9

Worksheets("consol.data").Cells(j, 38) = Worksheets("CC.supply").Cells(i - 8, 6)

Worksheets("consol.data").Cells(j, 40) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7)

Else: E9 = u8 \* c8

Worksheets("consol.data").Cells(j, 39) = E9

Worksheets("consol.data").Cells(j, 38) = Worksheets("CC.supply").Cells(i - 8, 6)

Worksheets("consol.data").Cells(j, 40) = u8

u9 = Worksheets("CC.supply").Cells(i - 9, 4).Value

c9 = Worksheets("CC.supply").Cells(i - 9, 5).Value

```

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8) <= u9 Then
E10 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8) * c9
Worksheets("consol.data").Cells(j, 42) = E10
Worksheets("consol.data").Cells(j, 41) = Worksheets("CC.supply").Cells(i - 9, 6)
Worksheets("consol.data").Cells(j, 43) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8)
Else: E10 = u9 * c9
Worksheets("consol.data").Cells(j, 42) = E10
Worksheets("consol.data").Cells(j, 41) = Worksheets("CC.supply").Cells(i - 9, 6)
Worksheets("consol.data").Cells(j, 43) = u9
u10 = Worksheets("CC.supply").Cells(i - 10, 4).Value
c10 = Worksheets("CC.supply").Cells(i - 10, 5).Value

```

```

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9) <= u10 Then
E11 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9) * c10
Worksheets("consol.data").Cells(j, 45) = E11
Worksheets("consol.data").Cells(j, 44) = Worksheets("CC.supply").Cells(i - 10, 6)
Worksheets("consol.data").Cells(j, 46) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9)
Else: E11 = u10 * c10
Worksheets("consol.data").Cells(j, 45) = E11
Worksheets("consol.data").Cells(j, 44) = Worksheets("CC.supply").Cells(i - 10, 6)
Worksheets("consol.data").Cells(j, 46) = u10
u11 = Worksheets("CC.supply").Cells(i - 11, 4).Value
c11 = Worksheets("CC.supply").Cells(i - 11, 5).Value

```

```

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10) <= u11 Then
E12 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10) * c11
Worksheets("consol.data").Cells(j, 48) = E12

```

```

Worksheets("consol.data").Cells(j, 47) = Worksheets("CC.supply").Cells(i - 11, 6)

Worksheets("consol.data").Cells(j, 49) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 -
u10)

Else: E12 = u11 * c11

Worksheets("consol.data").Cells(j, 48) = E12

Worksheets("consol.data").Cells(j, 47) = Worksheets("CC.supply").Cells(i - 11, 6)

Worksheets("consol.data").Cells(j, 49) = u11

u12 = Worksheets("CC.supply").Cells(i - 12, 4).Value
c12 = Worksheets("CC.supply").Cells(i - 12, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11) <= u12 Then
E13 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11) * c12
Worksheets("consol.data").Cells(j, 51) = E13

Worksheets("consol.data").Cells(j, 50) = Worksheets("CC.supply").Cells(i - 12, 6)

Worksheets("consol.data").Cells(j, 52) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 -
u10 - u11)

Else: E13 = u12 * c12

Worksheets("consol.data").Cells(j, 51) = E13

Worksheets("consol.data").Cells(j, 50) = Worksheets("CC.supply").Cells(i - 12, 6)

Worksheets("consol.data").Cells(j, 52) = u12

u13 = Worksheets("CC.supply").Cells(i - 13, 4).Value
c13 = Worksheets("CC.supply").Cells(i - 13, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12) <= u13 Then
E14 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12) * c13
Worksheets("consol.data").Cells(j, 54) = E14

Worksheets("consol.data").Cells(j, 53) = Worksheets("CC.supply").Cells(i - 13, 6)

```

Worksheets("consol.data").Cells(j, 55) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12)

Else: E14 = u13 \* c13

Worksheets("consol.data").Cells(j, 54) = E14

Worksheets("consol.data").Cells(j, 53) = Worksheets("CC.supply").Cells(i - 13, 6)

Worksheets("consol.data").Cells(j, 55) = u13

u14 = Worksheets("CC.supply").Cells(i - 14, 4).Value

c14 = Worksheets("CC.supply").Cells(i - 14, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13) <= u14 Then

E15 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13) \* c14

Worksheets("consol.data").Cells(j, 57) = E15

Worksheets("consol.data").Cells(j, 56) = Worksheets("CC.supply").Cells(i - 14, 6)

Worksheets("consol.data").Cells(j, 58) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13)

Else: E15 = u14 \* c14

Worksheets("consol.data").Cells(j, 57) = E15

Worksheets("consol.data").Cells(j, 56) = Worksheets("CC.supply").Cells(i - 14, 6)

Worksheets("consol.data").Cells(j, 58) = u14

u15 = Worksheets("CC.supply").Cells(i - 15, 4).Value

c15 = Worksheets("CC.supply").Cells(i - 15, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14) <= u15  
Then

E16 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14) \* c15

Worksheets("consol.data").Cells(j, 60) = E16

Worksheets("consol.data").Cells(j, 59) = Worksheets("CC.supply").Cells(i - 15, 6)

Worksheets("consol.data").Cells(j, 61) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14)



Else:  $E16 = u15 * c15$

Worksheets("consol.data").Cells(j, 60) = E16

Worksheets("consol.data").Cells(j, 59) = Worksheets("CC.supply").Cells(i - 15, 6)

Worksheets("consol.data").Cells(j, 61) = u15

u16 = Worksheets("CC.supply").Cells(i - 16, 4).Value

c16 = Worksheets("CC.supply").Cells(i - 16, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14 - u15) <= u16 Then

E17 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14 - u15) \* c16

Worksheets("consol.data").Cells(j, 63) = E17

Worksheets("consol.data").Cells(j, 62) = Worksheets("CC.supply").Cells(i - 16, 6)

Worksheets("consol.data").Cells(j, 64) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14 - u15)

Else:  $E17 = u16 * c16$

Worksheets("consol.data").Cells(j, 63) = E17

Worksheets("consol.data").Cells(j, 62) = Worksheets("CC.supply").Cells(i - 16, 6)

Worksheets("consol.data").Cells(j, 64) = u16

u17 = Worksheets("CC.supply").Cells(i - 17, 4).Value

c17 = Worksheets("CC.supply").Cells(i - 17, 5).Value

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

End If

Exit For

End If

Next i

End If

Next k

End If

Next j

End Sub

## Visual Basic Code: CAL-ISO

```
Sub A()  
Sheets("Consol.Data").Select  
finalrow = Cells(Rows.Count, 2).End(xlUp).Row  
  
For i = 4 To finalrow  
Worksheets("consol.data").Cells(i, 4).NumberFormat = "0,0"  
Worksheets("consol.data").Cells(i, 8).NumberFormat = "0,0"  
P = Worksheets("consol.data").Cells(i, 3).Value  
If P > 0 Then  
D = Worksheets("consol.data").Cells(i, 2)  
Worksheets("consol.data").Cells(i, 8) = D  
End If  
Next i  
  
Worksheets("Consol.Data").Cells(4, 5).NumberFormat = "0,0"  
a1 = Worksheets("consol.data").Cells(4, 2).Value  
Worksheets("consol.data").Cells(4, 5) = a1  
Sheets("Consol.Data").Select  
finalrow = Cells(Rows.Count, 2).End(xlUp).Row
```

```
For s = 5 To finalrow
Worksheets("consol.data").Cells(s, 5).NumberFormat = "0,0"
Worksheets("consol.data").Cells(s, 5) = Worksheets("consol.data").Cells(s - 1, 5) +
Worksheets("consol.data").Cells(s, 2)
Next s
```

```
Sheets("Consol.Data").Select
For j = 4 To finalrow
P = Worksheets("consol.data").Cells(j, 3).Value
If P > 0# Then
v = Worksheets("consol.data").Cells(j, 1)
v1 = Worksheets("consol.data").Cells(j, 5)
Worksheets("consol.data").Cells(j, 7) = v
```

```
Sheets("CC.Supply").Select
For k = 7 To 8790
If Worksheets("CC.Supply").Cells(3, k) = v Then
i = 599
u = Worksheets("CC.supply").Cells(599, 4).Value
c = Worksheets("CC.supply").Cells(599, 5).Value
If (u >= P) Then
E1 = P * c
```

```

Worksheets("consol.data").Cells(j, 15) = E1
Worksheets("consol.data").Cells(j, 14) = Worksheets("CC.supply").Cells(i, 6)
Worksheets("consol.data").Cells(j, 16) = P
Else: E1 = u * c
Worksheets("consol.data").Cells(j, 15) = E1
Worksheets("consol.data").Cells(j, 14) = Worksheets("CC.supply").Cells(i, 6)
Worksheets("consol.data").Cells(j, 16) = u
u1 = Worksheets("CC.supply").Cells(i - 1, 4).Value
c1 = Worksheets("CC.supply").Cells(i - 1, 5).Value

If (P - u) <= u1 Then
E2 = (P - u) * c1
Worksheets("consol.data").Cells(j, 18) = E2
Worksheets("consol.data").Cells(j, 17) = Worksheets("CC.supply").Cells(i - 1, 6)
Worksheets("consol.data").Cells(j, 19) = (P - u)
Else: E2 = u1 * c1
Worksheets("consol.data").Cells(j, 18) = E2
Worksheets("consol.data").Cells(j, 17) = Worksheets("CC.supply").Cells(i - 1, 6)
Worksheets("consol.data").Cells(j, 19) = u1
u2 = Worksheets("CC.supply").Cells(i - 2, 4).Value
c2 = Worksheets("CC.supply").Cells(i - 2, 5).Value

If (P - u - u1) <= u2 Then
E3 = (P - u - u1) * c2
Worksheets("consol.data").Cells(j, 21) = E3

```

Worksheets("consol.data").Cells(j, 20) = Worksheets("CC.supply").Cells(i - 2, 6)

Worksheets("consol.data").Cells(j, 22) = (P - u - u1)

Else: E3 = u2 \* c2

Worksheets("consol.data").Cells(j, 21) = E3

Worksheets("consol.data").Cells(j, 20) = Worksheets("CC.supply").Cells(i - 2, 6)

Worksheets("consol.data").Cells(j, 22) = u2

u3 = Worksheets("CC.supply").Cells(i - 3, 4).Value

c3 = Worksheets("CC.supply").Cells(i - 3, 5).Value

If (P - u - u1 - u2) <= u3 Then

E4 = (P - u - u1 - u2) \* c3

Worksheets("consol.data").Cells(j, 24) = E4

Worksheets("consol.data").Cells(j, 23) = Worksheets("CC.supply").Cells(i - 3, 6)

Worksheets("consol.data").Cells(j, 25) = (P - u - u1 - u2)

Else: E4 = u3 \* c3

Worksheets("consol.data").Cells(j, 24) = E4

Worksheets("consol.data").Cells(j, 23) = Worksheets("CC.supply").Cells(i - 3, 6)

Worksheets("consol.data").Cells(j, 25) = u3

u4 = Worksheets("CC.supply").Cells(i - 4, 4).Value

c4 = Worksheets("CC.supply").Cells(i - 4, 5).Value

If (P - u - u1 - u2 - u3) <= u4 Then

E5 = (P - u - u1 - u2 - u3) \* c4

Worksheets("consol.data").Cells(j, 27) = E5

Worksheets("consol.data").Cells(j, 26) = Worksheets("CC.supply").Cells(i - 4, 6)

Worksheets("consol.data").Cells(j, 28) = (P - u - u1 - u2 - u3)

Else: E5 = u4 \* c4

Worksheets("consol.data").Cells(j, 27) = E5

Worksheets("consol.data").Cells(j, 26) = Worksheets("CC.supply").Cells(i - 4, 6)

Worksheets("consol.data").Cells(j, 28) = u4

u5 = Worksheets("CC.supply").Cells(i - 5, 4).Value

c5 = Worksheets("CC.supply").Cells(i - 5, 5).Value

If (P - u - u1 - u2 - u3 - u4) <= u5 Then

E6 = (P - u - u1 - u2 - u3 - u4) \* c5

Worksheets("consol.data").Cells(j, 30) = E6

Worksheets("consol.data").Cells(j, 29) = Worksheets("CC.supply").Cells(i - 5, 6)

Worksheets("consol.data").Cells(j, 31) = (P - u - u1 - u2 - u3 - u4)

Else: E6 = u5 \* c5

Worksheets("consol.data").Cells(j, 30) = E6

Worksheets("consol.data").Cells(j, 29) = Worksheets("CC.supply").Cells(i - 5, 6)

Worksheets("consol.data").Cells(j, 31) = u5

u6 = Worksheets("CC.supply").Cells(i - 6, 4).Value

c6 = Worksheets("CC.supply").Cells(i - 6, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5) <= u6 Then

E7 = (P - u - u1 - u2 - u3 - u4 - u5) \* c6

Worksheets("consol.data").Cells(j, 33) = E7

Worksheets("consol.data").Cells(j, 32) = Worksheets("CC.supply").Cells(i - 6, 6)

Worksheets("consol.data").Cells(j, 34) = (P - u - u1 - u2 - u3 - u4 - u5)

Else:  $E7 = u6 * c6$

Worksheets("consol.data").Cells(j, 33) = E7

Worksheets("consol.data").Cells(j, 32) = Worksheets("CC.supply").Cells(i - 6, 6)

Worksheets("consol.data").Cells(j, 34) = u6

u7 = Worksheets("CC.supply").Cells(i - 7, 4).Value

c7 = Worksheets("CC.supply").Cells(i - 7, 5).Value

If  $(P - u - u1 - u2 - u3 - u4 - u5 - u6) \leq u7$  Then

$E8 = (P - u - u1 - u2 - u3 - u4 - u5 - u6) * c7$

Worksheets("consol.data").Cells(j, 36) = E8

Worksheets("consol.data").Cells(j, 35) = Worksheets("CC.supply").Cells(i - 7, 6)

Worksheets("consol.data").Cells(j, 37) =  $(P - u - u1 - u2 - u3 - u4 - u5 - u6)$

Else:  $E8 = u7 * c7$

Worksheets("consol.data").Cells(j, 36) = E8

Worksheets("consol.data").Cells(j, 35) = Worksheets("CC.supply").Cells(i - 7, 6)

Worksheets("consol.data").Cells(j, 37) = u7

u8 = Worksheets("CC.supply").Cells(i - 8, 4).Value

c8 = Worksheets("CC.supply").Cells(i - 8, 5).Value

If  $(P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7) \leq u8$  Then

$E9 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7) * c8$

Worksheets("consol.data").Cells(j, 39) = E9

Worksheets("consol.data").Cells(j, 38) = Worksheets("CC.supply").Cells(i - 8, 6)

Worksheets("consol.data").Cells(j, 40) =  $(P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7)$

Else:  $E9 = u8 * c8$



```
Worksheets("consol.data").Cells(j, 39) = E9
Worksheets("consol.data").Cells(j, 38) = Worksheets("CC.supply").Cells(i - 8, 6)
Worksheets("consol.data").Cells(j, 40) = u8
u9 = Worksheets("CC.supply").Cells(i - 9, 4).Value
c9 = Worksheets("CC.supply").Cells(i - 9, 5).Value
```

```
If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8) <= u9 Then
E10 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8) * c9
Worksheets("consol.data").Cells(j, 42) = E10
Worksheets("consol.data").Cells(j, 41) = Worksheets("CC.supply").Cells(i - 9, 6)
Worksheets("consol.data").Cells(j, 43) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8)
Else: E10 = u9 * c9
Worksheets("consol.data").Cells(j, 42) = E10
Worksheets("consol.data").Cells(j, 41) = Worksheets("CC.supply").Cells(i - 9, 6)
Worksheets("consol.data").Cells(j, 43) = u9
u10 = Worksheets("CC.supply").Cells(i - 10, 4).Value
c10 = Worksheets("CC.supply").Cells(i - 10, 5).Value
```

```
If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9) <= u10 Then
E11 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9) * c10
Worksheets("consol.data").Cells(j, 45) = E11
Worksheets("consol.data").Cells(j, 44) = Worksheets("CC.supply").Cells(i - 10, 6)
Worksheets("consol.data").Cells(j, 46) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9)
Else: E11 = u10 * c10
Worksheets("consol.data").Cells(j, 45) = E11
```

```

Worksheets("consol.data").Cells(j, 44) = Worksheets("CC.supply").Cells(i - 10, 6)
Worksheets("consol.data").Cells(j, 46) = u10
u11 = Worksheets("CC.supply").Cells(i - 11, 4).Value
c11 = Worksheets("CC.supply").Cells(i - 11, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10) <= u11 Then
E12 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10) * c11
Worksheets("consol.data").Cells(j, 48) = E12
Worksheets("consol.data").Cells(j, 47) = Worksheets("CC.supply").Cells(i - 11, 6)
Worksheets("consol.data").Cells(j, 49) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 -
u10)
Else: E12 = u11 * c11
Worksheets("consol.data").Cells(j, 48) = E12
Worksheets("consol.data").Cells(j, 47) = Worksheets("CC.supply").Cells(i - 11, 6)
Worksheets("consol.data").Cells(j, 49) = u11
u12 = Worksheets("CC.supply").Cells(i - 12, 4).Value
c12 = Worksheets("CC.supply").Cells(i - 12, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11) <= u12 Then
E13 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11) * c12
Worksheets("consol.data").Cells(j, 51) = E13
Worksheets("consol.data").Cells(j, 50) = Worksheets("CC.supply").Cells(i - 12, 6)
Worksheets("consol.data").Cells(j, 52) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 -
u10 - u11)
Else: E13 = u12 * c12
Worksheets("consol.data").Cells(j, 51) = E13

```

```

Worksheets("consol.data").Cells(j, 50) = Worksheets("CC.supply").Cells(i - 12, 6)
Worksheets("consol.data").Cells(j, 52) = u12
u13 = Worksheets("CC.supply").Cells(i - 13, 4).Value
c13 = Worksheets("CC.supply").Cells(i - 13, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12) <= u13 Then
E14 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12) * c13
Worksheets("consol.data").Cells(j, 54) = E14
Worksheets("consol.data").Cells(j, 53) = Worksheets("CC.supply").Cells(i - 13, 6)
Worksheets("consol.data").Cells(j, 55) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 -
u10 - u11 - u12)
Else: E14 = u13 * c13
Worksheets("consol.data").Cells(j, 54) = E14
Worksheets("consol.data").Cells(j, 53) = Worksheets("CC.supply").Cells(i - 13, 6)
Worksheets("consol.data").Cells(j, 55) = u13
u14 = Worksheets("CC.supply").Cells(i - 14, 4).Value
c14 = Worksheets("CC.supply").Cells(i - 14, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13) <= u14 Then
E15 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13) * c14
Worksheets("consol.data").Cells(j, 57) = E15
Worksheets("consol.data").Cells(j, 56) = Worksheets("CC.supply").Cells(i - 14, 6)
Worksheets("consol.data").Cells(j, 58) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 -
u10 - u11 - u12 - u13)
Else: E15 = u14 * c14
Worksheets("consol.data").Cells(j, 57) = E15

```

Worksheets("consol.data").Cells(j, 56) = Worksheets("CC.supply").Cells(i - 14, 6)

Worksheets("consol.data").Cells(j, 58) = u14

u15 = Worksheets("CC.supply").Cells(i - 15, 4).Value

c15 = Worksheets("CC.supply").Cells(i - 15, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14) <= u15

Then

E16 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14) \* c15

Worksheets("consol.data").Cells(j, 60) = E16

Worksheets("consol.data").Cells(j, 59) = Worksheets("CC.supply").Cells(i - 15, 6)

Worksheets("consol.data").Cells(j, 61) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14)

Else: E16 = u15 \* c15

Worksheets("consol.data").Cells(j, 60) = E16

Worksheets("consol.data").Cells(j, 59) = Worksheets("CC.supply").Cells(i - 15, 6)

Worksheets("consol.data").Cells(j, 61) = u15

u16 = Worksheets("CC.supply").Cells(i - 16, 4).Value

c16 = Worksheets("CC.supply").Cells(i - 16, 5).Value

If (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14 - u15) <=

u16 Then

E17 = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14 - u15) \* c16

Worksheets("consol.data").Cells(j, 63) = E17

Worksheets("consol.data").Cells(j, 62) = Worksheets("CC.supply").Cells(i - 16, 6)

Worksheets("consol.data").Cells(j, 64) = (P - u - u1 - u2 - u3 - u4 - u5 - u6 - u7 - u8 - u9 - u10 - u11 - u12 - u13 - u14 - u15)

```
Else: E17 = u16 * c16
Worksheets("consol.data").Cells(j, 63) = E17
Worksheets("consol.data").Cells(j, 62) = Worksheets("CC.supply").Cells(i - 16, 6)
Worksheets("consol.data").Cells(j, 64) = u16
u17 = Worksheets("CC.supply").Cells(i - 17, 4).Value
c17 = Worksheets("CC.supply").Cells(i - 17, 5).Value
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
End If
Exit For
End If
```

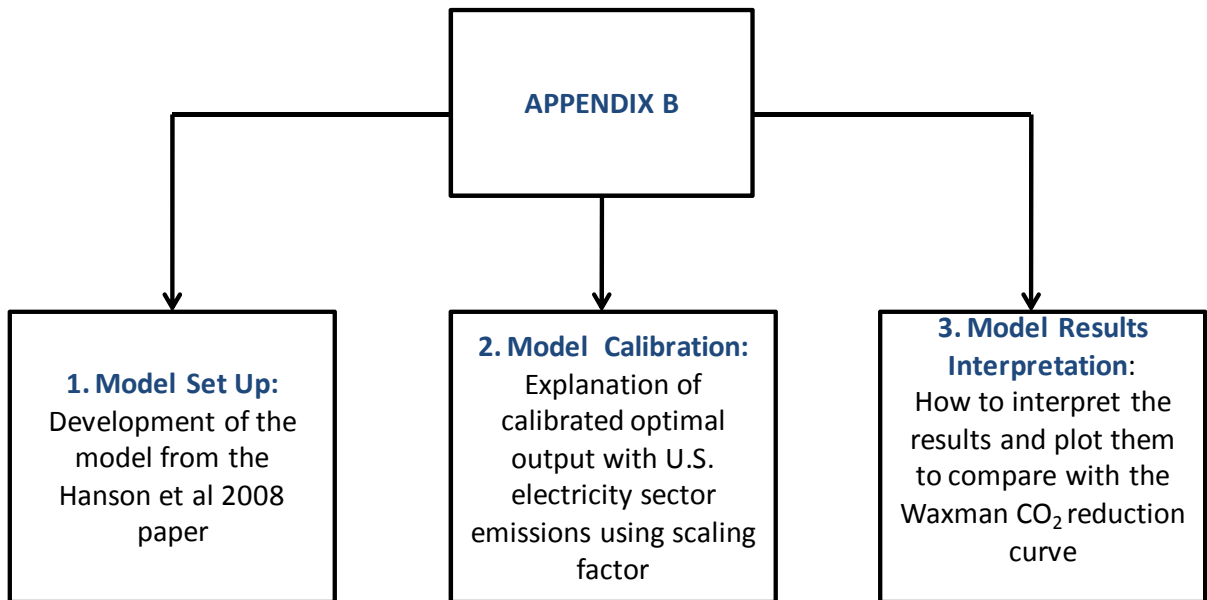
Next k

End If

Next j

End Sub

## APPENDIX B



**Figure A.1: Explanation of the methodological framework used in Chapter 6**

## **Model Set Up: Development of the Model from Hanson et al 2008 Study**

**Demand and Objective Function:** Demand specifications obtained from Dr Hanson are included in the model. This enables calculation of discounted net welfare (this is the objective function which is maximized)

**Constraint:** The constraint was CO<sub>2</sub> emissions. Cumulative reduction outlined in the Waxman Markey Bill was used to establish the required reductions relative to the unconstrained model.

**Technology Options and Fuel Mix Constraint:** Increased number of electricity generation technologies included in the model (coal, gas, oil, wind, nuclear, hydro and PV). Fuel mix constraint (50% of annual demand met by coal technology) imposed

**Electricity Cost and CO<sub>2</sub> Intensity:** Realistic cost parameters (Source: Energy Information Administration) and total fuel cycle CO<sub>2</sub> emission factors included for all technologies'

**Experience Curves:** Experience curve modules developed for PV and wind using realistic baseline outputs (Source: Energy Information Administration)

Models were run using fossil energy costs, technology, CO<sub>2</sub> policy, and renewable energy policy and subsidy scenarios in the U.S. The section above presents important features that this study has developed starting from the initial Hanson study

## **Model Calibration: Calibration of the Model Results to the Actual Conditions in the U.S. Electricity Sector**

Step 1: Run the model unconstrained (no reduction in CO<sub>2</sub> emissions)

Step 2: Take the model CO<sub>2</sub> emissions results and calibrate them to the total CO<sub>2</sub> emissions released from the U.S. electricity sector. This requires the application of a scaling factor to develop a calibrated model so that the results can be compared to Waxman targets

Step 3: In this study the calibration is based on the total CO<sub>2</sub> emissions in the baseline year of 2005 (2.51 billion metric tons CO<sub>2</sub>). Take the unconstrained model emissions in time period 1, and multiply it with a scaling factor to normalize it to the 2005 year



emissions. The scaling factor = (Year 2005 actual CO<sub>2</sub> emissions in the U.S. electricity sector / CO<sub>2</sub> emissions from the model in time period 1)

Step 4: Apply the same scaling factor to the emissions from the fifty time periods in the unconstrained model, to develop the calibrated CO<sub>2</sub> emissions curve of the unconstrained model

Step 5: The difference between the area beneath the unconstrained calibrated CO<sub>2</sub> curve and area beneath the Waxman reduction targets curve is 56%

Step 6: Now, run the model with a 56% reduction in cumulative CO<sub>2</sub> emissions, when results are calibrated now Waxman targets must be satisfied in the end.

### **Model Results: Interpretation of Results**

Step 7: In the constrained model, the optimal quantities of electricity outputs and CO<sub>2</sub> emissions from each technology for each time period is generated

Step 8: Use the same calibration approach and calibrate the CO<sub>2</sub> emissions in time period 1 from the model, and normalize it to the 2005 CO<sub>2</sub> emissions from the U.S electricity sector. You might have to use a different scaling factor in this case, because the starting points differ in each model due to optimality. However the formula (Step 3) for calculating the scaling factor remains the same.

Step 9: Plot the calibrated CO<sub>2</sub> curve for all time periods, and the total area beneath the curve must be lower than the total area of the Waxman CO<sub>2</sub> curve. Step 1 to 8, is applicable for model(s) 1 to 5.

Step 10: For model 6 and model 7, separate unconstrained scenarios were developed. Step 1 to 9 can be applied for these two models too, only difference is in the revised CO<sub>2</sub> reduction target obtained from Step 5 (it is 59% for model 6 and 57% for model 7 respectively). Using the revised target and following the other steps, the results from model 6 and model 7 can be reproduced.

Step 11: This is the basic approach to run all of the seven models developed.

## AMPL Code

```
#### Main model file (Z_optpen.mod)

# Optimal technology penetration, Model I
# Z(T) constraint, no adjustment costs
# Model by Deepak Sivaraman, Don Hanson, Todd Munson, AMPL code by Deepak
# Sivaraman, Todd Munson, Steve Kryukov
# March 24, 2008

#### 1. parameters #####
# setting parameter as constants

# for computing from other parameters (e.g. h)

## time
param tf := 50;          # Final time (T)
param nh > 0, integer, default 50;      # Number of subintervals (N)
param h := tf/nh;       # period length
# use of the default clause allows us to change nh in the run file

## rates
param r := 0.05;        # discount rate
param delta := exp(-r*h); # period discount factor

## Demand & Surplus

param sigma := 0.35;    # exponential, elas of demand for U.S. elec is around 0.4)
param S0 := 0.0764*(3902e+9^sigma); # Cf * (q0 ^ sigma), q0 demand in period 1
param b := 0.016;      # growth rate

## emissions (z)

param bf := 1.07;      # pollution rate of fossil fuels (kg / kWh)
param bpv := 0.048;   # pollution rate of PV tech (kg / kWh)
param bng := 0.59;    # pollution rate of nat. gas (kg / kWh)
param a := 0.0;       # environmental time preference rate (for discounting)
param Zmax := 2.68e+11; # maximum pollution (when unconstrained, in kg)
param Zred := 0.56;   # reduction in pollution, set negative to make it non-binding
```

```

# this is used in constraint z[nh] <= Zmax*(1-Zred)

# you can find Zmax by increasing Zmax and decreasing Zred (or making it negative)

# until constraint on z[nh] does not bind. That "unconstrained" z[nh] becomes the new
Zmax

## production costs - unit cost for each technology

#units in ($ / kWh)
param cf := 0.018;          # unit cost of fossil tech($ /kWh)
param cng := 0.106;        # unit cost of nat. gas ($ /kWh)

#initial cost of solar tech          # cost when x=0 (i.e. at start)
param capUnit := 0.6e+9;          # one unit of xp (base experience in kWh)
param gamma := 0.8;              # learning rate, doubling x multiplies cost by gamma
param pwr := log(gamma)/log(2); # actual exponent
param x_0 := 0;                  # starting experience

### 2. variables #####

## 2.a model variables

# output quantities
var qf {0..nh} >=0, :=0.1; # fossil
var qpv {0..nh} >=0, :=0.1; # PV
var qng {0..nh} >=0, :=0.1; # NG

# state variables
var x {0..nh} :=0; # cumulative output for pv (experience)
var z {0..nh} :=0; # cumulative emissions

# PV Cost
param cpv_0 := 0.265;# cost when x=0 (i.e. at start, $/kWh)

## 2.b "intermediate computation" variables
# cost of new tech:

var cpv {i in 0..nh} = cpv_0*((x[i]/capUnit)+1)^pwr;

```

```

# discounted emissions
var g {i in 0..nh} = exp(-a*i*h) * ( bf*qf[i] + bng*qng[i] + bpv*qpv[i] );

# consumer surplus
var Q {i in 0..nh} = qf[i] + qng[i] + qpv[i]; #total output

var S {i in 0..nh} =

(if sigma=1.0 then

    exp(b*i*h)*S0*log(Q[i])

else

    exp(b*i*h*sigma) * S0 * Q[i]^(1-sigma) / (1-sigma)
);

# Formulas used:
# demand  $p(q) = S0/q^\sigma$ 
# growth  $p(q,t) = p(q/\exp(b*t))$ 
# surplus  $S(q,t) = \int p(q,t) dq = \dots$ 

# time  $t=i*h$ 

# discounted welfare
var welf {i in 0..nh} = delta^i*(S[i] - (cf * qf[i]) - (cng * qng[i]) - (cpv[i]*qpv[i]) );

##### 3. Constraints shared by all discretizations #####

subject to

# emissions constraint
con_ZT: z[46] <= Zmax*(1-Zred);

# fuel mix constraint
coal {i in 0..nh}: qf[i] = Q[i]*0.5;
#pv: x[49] = Q[49]*0.32;

```

```
## objective and the rest of constraints
## are in discretization-specific files
## ( Z_EE.mod, Z_EI.mod, Z_Tr.mod)
## that are loaded from run file
```