Environmental, Policy and Social Analysis

of Photovoltaic Technologies

by

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ABSTRACT

Many expect renewable energy technologies to play a leading role in a sustainable energy supply system and to aid the shift away from an over-reliance on traditional hydrocarbon resources in the next few decades. This dissertation develops environmental, policy and social models to help understand various aspects of photovoltaic (PV) technologies.

The first part of this dissertation advances the life cycle assessment (LCA) of PV systems by expanding the boundary of included processes using hybrid LCA and accounting for the technology-driven dynamics of environmental impacts. Hybrid LCA extends the traditional method combining bottom-up process-sum and top-down economic input-output (EIO) approaches. The embodied energy and carbon of multi-crystalline silicon photovoltaic systems are assessed using hybrid LCA. From 2001 to 2010, the embodied energy and carbon fell substantially, indicating that technological progress is realizing reductions in environmental impacts in addition to lower module price.

A variety of policies support renewable energy adoption, and it is critical to make them function cooperatively. To reveal the interrelationships among these policies, the second part of this dissertation proposes three tiers of policy architecture. This study develops a model to determine the specific subsidies required to support a Renewable Portfolio Standard (RPS) goal. The financial requirements are calculated (in two scenarios) and compared with predictable funds from public sources. A main result is that the expected investments to

achieve the RPS goal far exceed the economic allocation for subsidy of distributed PV.

Even with subsidies there are often challenges with social acceptance. The third part of this dissertation originally develops a fuzzy logic inference model to relate consumers' attitudes about the technology such as perceived cost, maintenance, and environmental concern to their adoption intention. Fuzzy logic inference model is a type of soft computing models. It has the advantage of dealing with imprecise and insufficient information and mimicking reasoning processes of human brains. This model is implemented in a case study of residential PV adoption using data through a survey of homeowners in Arizona. The output of this model is the purchasing probability of PV.

Dedicated to Weijun, for his love and support

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It would be difficult to overstate how much I have learned from Prof. Eric Williams, my advisor and how grateful I am to his guidance. From choosing topics, reviewing literatures, collecting data, constructing models, analyzing results and publishing papers, he gave me tremendous support in every step. I appreciate the freedom of choosing topics he gave me and his respect to my idea. The discussions with him have always inspired me. I deeply value his engagement with my work and his huge efforts. Not only the dissertation, almost every aspects of being a graduate student, I owe too much to Eric, such as, financial, emotional and career support he gave. I feel very lucky to be his student. His words and his way of being an advisor will benefit my future life a lot.

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1. INTRODUCTION

1.1 Climate Change and the Third Wave of Energy Transition

In the first decade of the new century, renewable energy related issues have attracted more global attention than before, especially in the context of global warming dilemma. No matter how different people around the world perceive the global warming issue, it is definitely a global topic that has drawn attention of decision makers in an attempt to address it cooperatively. This November Cancun Climate Summit 2010 will be held and provide a platform to discuss climate change and relevant topics. To address climate change problems, implementing low-carbon technologies is inevitable. Although renewable energy is often identified with GHG mitigation, it offers a broader vision. Renewable energy also deals with the issues of sustainability of the human society, such as shifting paradigm of global energy consumption and national energy security.

The existence and development of human society relies on energy supply. When oil prices exploded in the 1970s, economists began to put more research interest on the interrelation between economy and energy. With the falling of the oil price, the academic and industrial interest in energy was diminished until 1990s. At that time, the awareness of environmental changes such as global warming; air and water pollution is getting severe.

Environmental problems are mainly caused by the combustion of fossil fuels for power generation and transportation. Fossil fuels such as coal and natural gas are depletable resources which decrease when the resource is being used and the stock never increases over time.

Fossil fuels are the most widely used energy in the industrial world. Although an inexpensive electricity source, coal combustion emissions cause global warming and air pollution. The technology of clean coal is being improved. But the cost of such technological improvement is still too high to make it competitive and attractive. Oil and natural gas suffer from high and volatile prices which make the supply unstable and insecure.

Besides depletable resources, hydroelectric power represents a significant share of the energy mix in areas that have abundant hydropower. Hydropower is renewable resource which can regenerate when the resource is being used and the stock can increase over time. The hydroelectric power is also inexpensive. However, there are contraversial environmental and societal issues given growing awareness of damages to ecosystems and local cultures caused by dams.

The Hoover Dam created a miracle era in the development of southwest in the history. But it is impossible to replicate the story anywhere else around the world. Even in China, the proposals of large hydroelectric projects face huge protest after the Three Gorges as the awareness of environmental protection of both the central government and citizens is increasing. Also, hydropower resources are constrained.

Besides coal, gas and hydropower, another important energy resource is nuclear power. It provides more than 70% of electricity in some European countries. However, the license expiration date of most the nuclear power plants is 2030. That means aging facilities will need to be replaced, which will require a large amount of investment.

The nuclear power emits next to no air pollution when it is in normal operational condition. It is thus helpful to address issue of global warming. However, it always is controversial after the accidents of Three Miles Island and Chernobyl. The investment is too huge to be independent from long and painful debate of political decision which brings about high risk for the future of nuclear energy. In sum, coal, natural gas, oil, hydropower and nuclear are the conventional energy resources which represent most of the energy supply in current world.

On the other hand, new energy sources such as solar, wind, biomass and geothermal are booming in recent years. Strictly speaking they cannot be considered as “new energy”, because people have used them for a long time in the human history, much earlier than current conventional energy sources. However, with the rising difficulties of conventional energy, “new energy” sources are attracting attention from society. In this work, these new energy including solar, wind, biomass and geothermal are termed as renewable energy though the definition is not restricted. In economy, the solar and wind are actually expendable resource which means the regeneration time is rather small that can be ignored, the biomass and hydro are renewable resources. To make the notation simple, the renewable energy discussed here includes solar, wind, biomass and hydropower.

In recent years, the role of renewable energy as part of the solution to realize more secure and sustainable energy supplies is drawing more and more attention and investment. In 2007, global wind generating capacity has increased 28 percent while solar PV capacity rose 52 percent according to the report of Renewable Energy Policy Network for 21st century. The PV module shipment in the US has increased 15 times from 1997 to 2006 (Energy Information Administration). The production and investment tax credits for renewable energy has been extended to 2016, stimulating enthusiasm in investment and stabilizing the growing renewable energy market. The main economic obstacle for renewable energy is the high price. The main technological obstacle is the low power factor which makes the power supply not reliable and creates a need for backup capacity and storage equipments. Those obstacles are being overcome by technological improvement. The transition from conventional energy to renewable energy is happening; even an energy revolution is being conceived and may happen in the near future, especially in the big context of global economy crisis.

1.2 The First and Second Global Energy Transition

To address the transition to sustainable energy, it would be meaningful and helpful to take a retrospective look at the first and second global energy shifts. From a historical perspective, the Industrial Revolution can be viewed as a response to a concern with the supply of energy. The need for finding substitutes for wood-fuel was being signaled in England though rising prices of wood. The process of substitution of cheap coal for wood is slow because of technical difficulties of extraction and combustion of coal. The energy crisis forced people to find alternative energy. The first global energy shift is from biomass, mainly wood, to coal resources. During the period 1800-1913, coal went from providing around 10% to over 60% of the world's total energy requirements. The second global energy shift is from coal to oil. The share of world energy provided by petroleum rose from 5% in 1910 to around 50% in 1973.

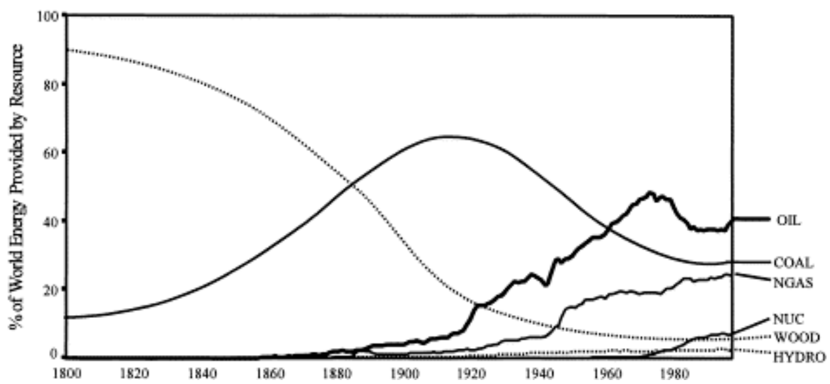


Figure 1-1:World Energy Shift (Podobnik, 1999)

The causes and drivers of the shifts are complex, they are embedded in the context of social, political, economic and technological dynamics. This article will not discuss the first and second energy shifts in detail. However, the concern of political support for coal and oil industries would shed light on the current changing of energy pattern.

At the early stage of coal and oil deployment, promotion and incentives from governmental were significant. By the 1830s, British agencies were subsidizing domestic iron industries, railroad construction, and the operation of steam shipping lines which the coal industry heavily depending on (Headrick, 1981). From 1918 to 1970, U.S. energy tax policy provided subsidies to oil and gas producers allowing a significant amount of deduction of the tax (CRS, 2007).

Looking at contemporary world, energy security and environmental concerns call for the third energy shift. More recent outbreaks of military conflict in the Middle East repeatedly jeopardized the geopolitical and commercial stability of the contemporary world petroleum system. History replicates itself in some ways, but not absolutely in the same way. However there is no doubt that the energy is essential to the development of human society even in the so-called information era. The conventional resources provide energy to power the human society to evolve to current situation. Considering the depletable nature of conventional resources, they would become an obstacle of development in the future. In the long term, it is inevitable to shift from conventional energy to renewable energy to sustain the operation of industry and meet the demand of society, then achieve a relative steady state of societal pattern in term of energy use. In the short term, the shift is a transitional process which has many opportunities and challenges. We are in the third wave of energy transition.

1.3 Booming Renewable Energy Technologies

Many expect renewable energy including solar, wind and bio-fuels to become leading technologies to a sustainable energy supply system and help shifting away from over-reliance on traditional hydrocarbon resources in next few decades.

The production of solar cells has grown at an average annual rate of 37% in the past decade (from 77.6 MWp in 1995 to 1817.7 MWp in 2005), and at an average annual rate of 45% in the past 5 years (from 287.7 MWp in 2000 to 1817.7 MWp in 2005) (Eltawil and Zhao, 2010). Wind energy has been suggested that installed capacity will increase fivefold over the next 10-year period, to exceed 700 GW by 2017, which is possible at current growth rates (Pryor and Barthelmie, 2010).

In 2006, the share of the global energy provided by renewable energy was 18% (REN21, 2010, p9). A closer look reveals that majority is due to traditional biomass and hydro-electric power and a very small remainder can be attributed to "new renewable energy technologies" (Hirschl, 2010). In 2008, only 3% of electricity generation in the United States is provided by renewable energy resources (Sovacool, 2009a).

Despite of the low penetration level of renewable energies worldwide at this moment, aggressive goals are set by lead countries or lead markets. US President Barack Obama calls for doubling renewable energy production by 2012. Denmark plans to produce 60% of its electricity from renewables by 2025. Germany even has the ambitious goal of achieving 100% renewable energy by 2050.

However, optimistic objectives don't guarantee expected outcomes. If we examined backward, something not that optimistic would be revealed. In 1979, former President Jimmy Carter expected renewable power to reach 10% of electricity in the US by 1985 (Sovacool, 2009a). In 1980, the National Research

Council declared that solar energy would account for 38.2% of American electricity supply by 2010 (NRC, 1980). Obviously, those goals or projections were failed to achieve. It is due to economic, social and technological constraints and uncertainties, especially from changing political atmosphere, such as administration rotate.

1.4 Emerging of the Science of Sustainability

Sustainability science has emerged as the interdisciplinary umbrella for addressing human-environment problems (Turner, 2010). The concept was proposed in the late 1980s with the release of Sustainable Development of the Biosphere (Clark and Munn, 1986). After the publication of the Brundtlandt Commission report in 1987, the term "sustainability" became one of the most popular target of policy makers. The Brundtlandt Commission defined sustainable development as a process meeting "the needs of the present without compromising the ability of further generations to meet their own needs" (Brundtland, 1987). Sustainable development encompasses the balancing of economic growth with ecological integrity (Brown and Sovacool, 2007). In academic regime, there are several journals, such as Sustainability Science and Management, Sustainability: Science, Practice and Policy and Current Opinion in Environmental Sustainability emerged to handle the large growth in the array of this research (Turner, 2010). Over the years a wide variety of conceptions of sustainability have been developed (Garrera and Mack, 2010). Renn et al. (2007) have categorized these conceptions according to the number and quality of dimensions. Of these, single pillar concepts are oldest and focus primarily on the impacts on ecology. The second category refers to the three-pillar concepts. These are by far the most popular concepts: they define sustainability as a combination of ecological, economic and social compatibility. There are other dimensions proposed by researchers, such as culture and institutional stability (Renn at al., 2007).

There is a variety of research dealing with energy related sustainability issues. Afgan and Carvalho (2000) have developed the concept of multi-criteria sustainability assessment in regards to sustainability. This approach focuses mainly on technical aspects of energy systems, but also considers the social indicators. Elghali et al. (2007) argue that sustainable energy technologies should meet the well-known three pillar of sustainability: economic viability, ecological performance and social acceptance. Garrera and Mack (2010) develop social indicator set cover four criteria: security and reliability of energy provision; political stability and legitimacy; social and individual risks and quality of life.

This work does not focus on developing the concept of sustainability science, or energy sustainability, or indicators of sustainability. The author's argument is that sustainable energy technologies are critical to achieve the goal of sustainability of ecology, economics and society. So the environmental assessment, economic viability and social acceptance of sustainable energy technologies are three main topics of this dissertation.

1.5 Organization of the Dissertation

The dissertation addresses three questions: (1) how "green" the solar energy technologies (photovoltaic) are (2) how effective the policies (economic subsidies) supporting sustainable energy adoption (3) how acceptable the solar energy technologies (photovoltaic) are to the society. Figure 1-2 shows the structure of the dissertation of three pillars (environmental, policy and social).

Chapter 2 is to answer the first question of how "green" the sustainable energy technologies are using photovoltaics (PV) as case study. PV is an emerging technology converts sunlight directly to electricity which also known as solar electric technology. During the phase of electricity generation, there is no emission or fuel requirement by this technology. But during the phase of manufacturing and distribution of the products, an amount of energy and materials has to be consumed. The consumed energy in the product can be noted as embodied energy which is a widely accepted concept. This chapter is using the methodology of hybrid life cycle assessment to investigate the embodied energy and carbon of multi-crystalline silicon PV from 2001 to 2011.

Chapter 3 is to answer the second question. The market of solar energy has rapid growth in recent years. However, the boom and bust of solar market in Spain and some other countries alert us how ill-designed regulations hurt the industry. So the question of what the healthy regulations are leads me to the second research topic. After a comprehensive review of renewable energy policies in the U.S., I found out an underlying relationship among the policies and then proposed a three-tier architecture. To address this issue, we develop a model to reveal the subsidies required to support the RPS goal based on two key forecasting results: future renewable energy installation and technological experience curve-based cost reduction. The study reveals the mismatches among policy tiers quantitatively and presents an emphasis on the importance of coordinative function among policies.

Chapter 4 is to answer question 3. The related questions are, now that the subsidies for renewable energy push the market adoption, how about the customers' side, what the social acceptance of the technologies is. Generally speaking, social barriers to the adoption of advanced technologies are high cost, high complexity and low familiarity. People tend to describe their opinion toward a technology by the imprecise language from human experience. Such information of human language is difficult to quantify. Is there a possible way to handle the social issues quantitatively? The methodology of fuzzy logic (one of soft computing methods) has possibility to handle the problem of social acceptance. The reason has two folds: one is that it deals with vague and imprecision data; the other is that it manipulates logic reasoning. Researchers have begun to notice its potential to solve social problems in the past few years. This study implements the methodology of fuzzy logic to evaluate social acceptance of distributed solar energy technology (photovoltaics) with the data we collected from the survey of urban homeowners.

Chapter 5 is the summary of the work of Chapter 2,3 and 4. It also talks about the further studies in the future which is the extension of the dissertation.

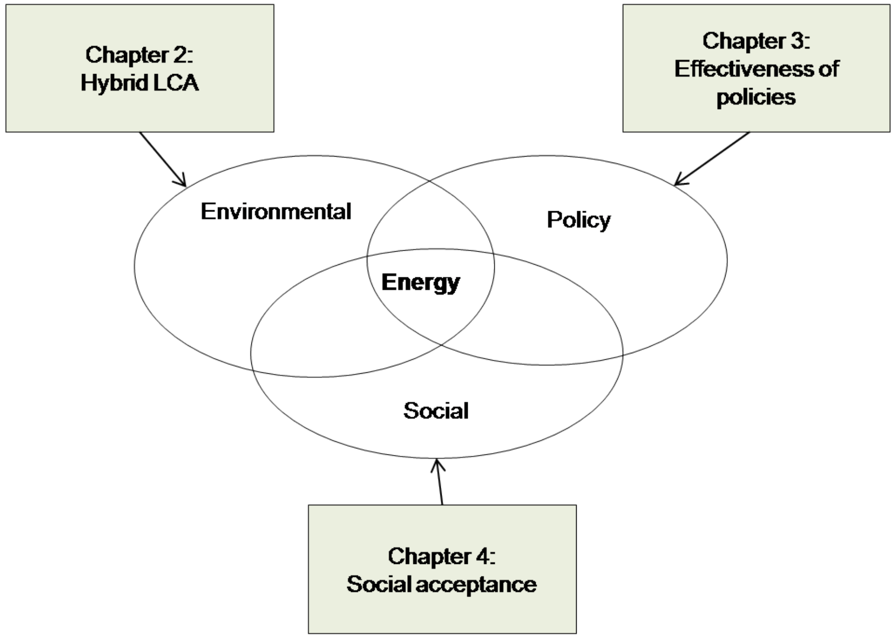


Figure 1-2: Structure of Dissertation—Three Pillars

Research motivations and contributions

Chapter 2:

1. Expanding the boundary of LCA to obtain more accurate results
2. Developing dynamic LCA to investigate technological change of ten years

Chapter 3:

1. Presenting the relationship of renewable energy policies
2. Revealing the mismatch between required investment of achieve targets of renewable energy adoption and available sources

Chapter 4:

1. Presenting the social acceptance of solar electric energy by survey
2. Revealing the adoption potential of renewable energy

CHAPTER

2. DYNAMIC HYBRID LIFE CYCLE ASSESSMENT OF ENERGY AND CARBON OF MULTI-CRYSTALLINE SILICON PHOTOVOLTAIC (PV) SYSTEMS

The first part of this dissertation advances the life cycle assessment (LCA) of PV systems by expanding the boundary of included processes using hybrid LCA and accounting for the technology-driven dynamics of environmental impacts. Hybrid LCA extends the traditional method combining bottom-up process-sum and top-down economic input-output (EIO) approaches. The embodied energy and carbon of multi-crystalline silicon photovoltaic systems are assessed using hybrid LCA. From 2001 to 2010, the embodied energy and carbon fell substantially, indicating that technological progress is realizing reductions in environmental impacts in addition to lower module price.

2.1 Introduction

Many expect photovoltaic (PV) electricity generation to become a leading technology contributing to a sustainable energy supply system. During the operation phase of PV systems, no significant material and energy use or emissions occur. During manufacturing, installation, maintenance and decommissioning, however, energy and emissions are embodied in PV systems, and these should be accounted for. Global PV shipments have grown explosively in recent years, increasing by more than 50% year over the period 2003-2006 (EIA, 2007a). Given the potential macroscopic adoption levels in the near future, it is important to characterize the embodied energy and emissions of PV systems from a life cycle perspective.

Life cycle assessment (LCA) is a powerful tool to evaluate the energy flows over the entire life of a PV system, from silica extraction during manufacturing to end-of-life decommissioning. The embodied energy (also known as the gross energy requirement) and energy payback time (EPBT) are indicators often used to evaluate the energy balance of PV systems. EPBT is defined as the number of years a PV system must operate before it generates sufficient energy to equal the amount it consumed in manufacturing (Alsema, 1998a).

Net energy analysis and life cycle assessments of PV modules and systems have a long history. The earliest literature estimates the EPBT of single-crystalline silicon (c-Si) PV as 11.6 years (Hunt, 1976). In a 1997 study in Japan, the EPBT for c-Si PV was found to be 15.5 years (Kato et al., 1997). EPBT calculations for multi-crystalline silicon (multi-Si) PVs under Southern European radiation (1700 kWh/m^2/yr) have yielded values of of 4-8 years (Alsema et al., 1998b) and 1.5-2.5 years (Alsema, 2005). Stoppato reports various EPBT values for multi-Si PV under different radiation conditions (Stoppato, 2008). Fthenakis and Kim (2008) have performed detailed LCA studies on thin-film PV technologies, especially those based on CdTe. The variation in EPBT results is substantial owing to a combination of factors, such as differences in the sources and years for manufacturing process data, solar radiation conditions, and process boundaries considered. Pacca analyzes the parameters that influence PV LCA results (Pacca et al., 2007). Sherwani presents a detailed review of LCA results for PV technologies including mono-Si, multi-Si, and amorphous-Si PVs (Sherwani et al., 2010). The most up-to-date, publicly available results based on data measured on production lines are from the European CrystalClear project (Alsema et al., 2006b).

Previous LCA studies of PV systems are based on the process-sum method, which constructs energy flows from a bottom-up model of processes in the supply chain. By its nature, the process-sum method implies a degree of cutoff error because of processes that are excluded when materials input-output data are not available. Processes typically excluded from process-sum analysis include:

1) Manufacturing of capital equipment such as module manufacturing machinery,
2) Residual materials such as industrial gases for cell processing, and
3) Services such as management and maintenance.

This study aims to reduce cutoff error by using hybrid LCA, which combines bottom-up process-sum and top-down economic input-output (EIO) approaches (Williams et al., 2010). EIO models describe environmental impacts through a matrix of financial transactions between sectors in (usually national) economies.

When addressing rapidly changing processes and products, LCA studies need to characterize the effects of technological progress (Williams et al., 2010). The prices of PV panels have fallen steadily due to technological progress (Nemet, 2006). However, these falling prices could also signal reductions in the environmental overhead of photovoltaic module manufacturing. Using process-sum LCA, Alsema and deWild (2007) found steadily falling embodied energy and EPBT for c-Si PV panels. In this article we use hybrid LCA to analyze PV module manufacturing from 2001 to 2011, the first dynamic hybrid analysis of which we are aware.

Section 2 describes the hybrid method in detail. In Section 3 we analyze a multi-Si PV system as a case study. In Section 4, results for embodied energy, EPBT, and carbon emissions are presented. In Section 5, the historical and future trends of embodied energy and emissions are analyzed using hybrid LCA.

2.2 Methodology: Hybrid LCA

Assessment of the net environmental impacts associated with delivering a product or service started in the 1970s with net energy analysis (Bullard and Herendeen, 1975), which has since expanded to become a broader field known as LCA. The "life cycle" in LCA refers to the attempt to characterize environmental impacts from cradle to grave, starting from extraction of resources and moving through production of raw materials and parts, assembly, sales, use, and disposal of a product. The main LCA methods are process-sum, EIO, and hybrid. The term "process-sum" denotes the most common form of LCA as delineated by the International Standards Organization (ISO 14040 series). This method is based on a bottom-up model of a supply chain in which each constituent process is described in terms of material inputs and environmentally significant releases or outputs. The inventory compilation method ranges from the simple constituent summing of a supply chain to a matrix formulation that holistically accounts for circularity effects (Heijungs, 1994; Suh and Huppes, 2005). EIO LCA is based on economic input-output tables. Pioneered by Leontief in the 1940s, EIO is a model that describes an economy in terms of financial transactions, inputs and outputs, between sectors (Leontief, 1970). The most detailed IO tables in the U.S. divide the economy into 400-500 aggregated sectors (Henderickson et al., 1998). The completeness and mathematical simplicity of IO tables implies that incorporating higher order flows (e.g., use of steel to produce the iron ore needed to make steel) can be easily accomplished by matrix inversion. Material use in the supply chain or emissions associated with manufacturing a product can be determined by multiplying the supply intensity of the relevant sector by the producer price of the product (Lave et al., 1995).

The bottom-up process-sum LCA method, which is based on facility/site level data, can describe elements in a supply chain precisely, but lack of data leads to cutoff error due to excluded processes. EIO LCA models (Hendrickson et al., 1998), which are based on national sectoral data, are holistic but suffer from aggregation error due to coarse graining of processes. The term hybrid LCA generically refers to any method that combines process-sum and EIO analysis to reduce uncertainty. Several approaches to hybrid LCA exist. The first is the *additive hybrid,* which identifies economic data that covers processes for which materials data are unavailable and is associated with sectors in an EIO model (Bullard et al., 1978). The *economic-balance hybrid* calculates the value added in a materials process model, subtracts this from the total price, and estimates impacts associated with the remaining value using EIO LCA (Williams, 2004). The *mixed-unit hybrid* model constructs a matrix containing both physical and economic quantities (Hawkins et al., 2007). For PV module manufacturing we argue that the additive hybrid method is most appropriate, as it depends on full cost accounting data, which is available for silicon PV manufacturing. The economic-balance method, on the other hand, generates cost-accounting using EIO LCA on a representative product sector. In the U.S., PV module manufacturing is aggregated into a larger semiconductor sector and thus may not be representative. Furthermore, mixed-unit models are data-intensive, and the guesses required to implement the model for PV manufacturing could induce more uncertainty than is gained from a generalized mathematical framework (Hawkins et al., 2007).

Therefore, this study uses an additive hybrid method based on the fundamental equation:

$$E_{Total} = E_P + E_{EIO} \qquad [2\text{-}1]$$

E_{Total} is the total embodied energy of the PV system. E_P is the embodied energy of the PV system from process-sum LCA and can be expressed as the sum of E_{pi}, the energy requirement of the *i*th procedure of manufacturing:

$$E_P = \sum E_{pi} \qquad [2\text{-}2]$$

E_{EIO} is the embodied energy from EIO LCA, which accounts for those components for which relevant economic data (cost, energy intensity, etc.) is available. Let *j* be an index denoting sectors for which such economic data can be obtained, excluding processes already covered in the process-sum piece in equation [2-2]:

$$E_{EIO} = \Sigma\, P_j\, E^{SC}{}_j \qquad [2\text{-}3]$$

P_i is the cost (for example, equipment cost in $/Wp), and $E^{SC}{}_j$ is the energy intensity of the relevant sector in MJ/$. Note that Wp refers to peak-Watts, a standard measure of PV capacity based on the electricity output of a panel when illuminated under standard conditions of 1000 Watts of light per square meter, 25°C ambient temperature, and a spectrum similar to ground-level sunlight.

This additive method differs from previous process-sum studies in the second E_{EIO} term, which describes processes, such as equipment manufacturing, services, and auxiliary materials, for which materials input-output data are not available.

2.3 Case Study: Multi-Si PV System

The embodied energy of PV technology varies substantially among different types of PV modules (mono/multi-crystalline silicon, thin-film). This study uses multi-crystalline silicon as a case study. In future work, the authors will apply the hybrid LCA method to other dominant technologies, especially thin-film PV.

This case study implements hybrid LCA to assess embodied energy, EPBT, and embodied carbon emissions for a multi–Si PV system. The PV system includes the PV modules, inverter, and supporting structure. An inverter is necessary to convert direct to alternating current. Batteries are needed in a standalone PV system but not in a grid-connected system; here we consider a grid-connected system without batteries. The multi-Si PV system is assumed to be 13.2% efficient and installed in the 1700 kWh/m^2/yr radiation. The hybrid LCA base year is 2007 (the process-sum LCA data are adjusted to 2007, and the EIO LCA data are from 2007). Table 2-1 describes the features of the PV system and module, which are assumed from the data collected for this study (deWild and Alsema, 2006a; NREL, 2008).

Table 2-1: Features of the PV System and Module in the Base Year of 2007

PV system features		
	Efficiency	13.2%
	Connection	Grid-connected without batteries
	Installation	Southern Europe
	Life span	System: 30 years Inverter: 10 years
PV module features		
	Poly-silicon purification	Siemens method
	Wafer thickness	200 μm

Step 1: Separating PV system manufacturing into process-sum and EIO LCA

The first step in the hybrid LCA method is to separate the PV system into process-sum and EIO LCA. Previous PV LCA studies focused on process-sum LCA, which covers some parts of the supply chain and excludes others, such as equipment and residual material (industrial gases) manufacturing. EIO LCA should cover the remaining components according to data availability. Figure 2-1 shows the boundaries of hybrid LCA using process-sum and EIO methods in the multicrystalline silicon PV systems case study. In addition, the inverter is analyzed using EIO LCA in this study. Previous studies *(*Alsema and deWild, 2006a; deWild et al., 2006b) have calculated the embodied energy in the inverter (1930 MJ/kW), but the authors indicated in their studies that their results underestimated the real impacts of inverters (deWild et al., 2006b).

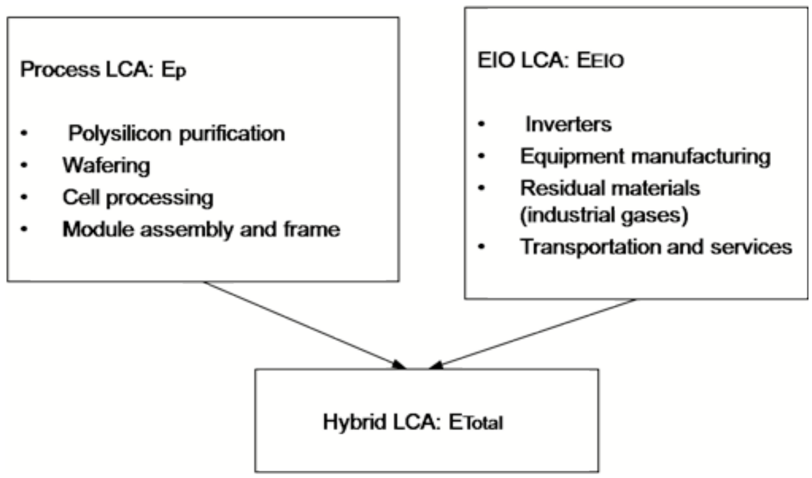


Figure 2-1: Hybrid LCA Boundaries

Step 2: Process-sum LCA to calculate E_P

This step uses process-sum LCA to calculate E_P in equation [2-1]; this section describes the data collection, method and results. Only publicly available process data from published academic studies are used here. As mentioned in the introduction, the most updated and detailed results based on data collection from production lines instead of LCA software or literature reviews are the series of publications from the Crystal Clear project (Alsema, 2005; deWild and Alsema, 2006a; Alsema et al., 2006a,b; Fthenakis and Kim, 2008). The research results are based on data collected from 11 PV companies in Europe and the U.S., mainly between September 2004 and November 2005 (Alsema, 2005). The studies cover processes including silicon mining, poly-silicon production, wafering, cell processing, and module assembly.

Table 2-2 shows the embodied energy in each manufacturing process for multi-Si PV modules (data from Figure 2 of Alsema 2006b). The total embodied energy is around 3300 MJ/m^2, EPBT is 1.8 years, and the embodied equivalent carbon is 32 g/kWh (data from Figures 2, 3, and 4 of Alsema 2006b). The June 2006 paper *(*Alsema and deWild, 2006a) gives higher total energy results (3940 MJ/m^2) than the September 2006 paper. Because "the September's results are based on more updated data," we use these results in our study. From Table 2, the most energy-intensive process is silicon purification and wafering.

This data source assumes wafer thickness to be 285 to 300 μm. However, Alsema emphasizes that "wafer thickness has not been updated yet, although significant changes have occurred." Several reports from the U.S. National Renewable Energy Lab (NREL) indicate that with present technologies, wafer thickness is approximately 200-250 μm (NREL, 2007). Furthermore, the source file we use for EIO analysis indicates that the wafer thickness in 2007 was 200 μm (NREL, 2008). On the basis of this wafer thickness reduction, we adjust the embodied energy in poly-silicon purification from 1700 to 1260 MJ/m^2 and in wafering from 600 to 420 MJ/m^2.

Table 2-2: Process-Sum LCA Results--Embodied Energy Breakdown for a Multi-Si PV Module in 2007

Manufacturing processes	MJ/m2	Notes
Polysilicon	1260	Siemens process

production		
Wafering	420	Adjusted from 600 MJ/m^2 in Alsema 2006b based on the wafer thickness change from 285 to 200 μm
Cell processing	550	
Module assembly	350	Glass thickness 3.6 mm
Frame	150	Aluminum
Module total	2730 MJ/m^2 (20.7 MJ/Wp)	

The E_P result for process-sum LCA on a multi-Si PV module made around 2007 is 2730 MJ/m^2. Converting to energy per Watt of peak output using 1000 W/m^2 irradiation and 13.2% efficiency yields an E_P of 20.7 MJ/Wp.

Step 3: EIO LCA to calculate E_{EIO}

The PV supply chain contains some additive components whose energy requirements are difficult to obtain from process-sum LCA due to the analysis boundary; these include the energy embodied in equipment (such as the poly-silicon purification reactor) and residual materials (such as industrial gases for cell processing). While process data on these components is difficult to find, it is possible to obtain economic data such as cost/price, (we use cost data, deducting profit and tax from price) which makes EIO LCA feasible.

Analysis of Cost data -- P_i

NREL reports detailed economic data in the Manufacturing Cost Model, which is a sub-model of the widely-used Solar Advisor Model (NREL, 2008). The Manufacturing Cost Model was created for U.S. DOE's Solar America Initiative to demonstrate a common accounting framework. It claims that "the model breaks out module manufacturing costs (year 2007) for a representative poly-crystalline module relative to generally accepted accounting principles, supplemented by some of the definitions established in SEMI standard." The model's spreadsheets break down the costs of manufacturing processes, including the costs of equipment, residual materials, sales and management, and shipping. Such publicly accessible data provide the information needed to calculate P_i in equation [2-3] and make our EIO LCA possible.

The total cost of a multi-Si module is 2.3 \$/Wp. Table 3 breaks down this cost.

Table 2-3: Breakdown of Multi-Si PV Module Cost

Multi-Si PV Cost	2007 \$/Wp	Should be accounted for in embodied energy in EIO LCA?
Equipment	0.14	Yes
Labor	0.14	No
Material	0.84	No
Factory overhead	0.187	No
Corporate overhead	1	Partly Yes (see Table 2-4)
Total	2.3	No

Equipment cost comes from the Output Summary, which contains depreciation data. Residual materials cost comes from Supplies, which has data on industrial gases (nitrogen, oxygen, $POCL_3$, and silane). Data on transportation (shipping) and services (sales and management) are modified from Global Assumptions and Corporate Overhead (1\$/Wp in the Output Summary). In Corporate Overhead, sales and management and shipping are considered to contribute to the embodied energy for PV systems as services and transportation; R&D, insurance, and taxes are not accounted for because these components are not very energy intensive. Table 2-4 breaks down the cost of corporate overhead for the PV industry.

Table 2-4: Breakdown of Corporate Overhead Cost for Multi-Si PV Modules

Corporate overhead cost	% sales	2007 \$/Wp	Should be accounted for in embodied energy in EIO LCA?
R&D	0.5%	0.03	No
Sales & Management	2%	0.11	Yes
G&A	5%	0.26	No
Insurance	0.5%	0.03	No
Shipping	4%	0.21	Yes
Taxes	7%	0.37	No
Total	19%	1	

The cost of an inverter is modified from price data from Solarbuzz (Solarbuzz, 2009). The average price for an inverter was 0.71 \$/Wp in 2009. After the reduction of value added from the total price (electric equipment sector data from *BEA 2002* Benchmark IO table), the cost is 0.4 \$/Wp. Because the life span of a PV system is 30 years (from Table 2-1) and the life span of an inverter is 10 years, 3 inverters are required, and the total cost is 1.2 \$/Wp.

Data of energy intensity -- E^{SC}_{j},

After obtaining cost data, the next step is to find the energy intensity of matching sectors. E^{SC}_{j}, values are obtained from the EIO LCA model developed by Carnegie Mellon University (CMU, 2009). This model is free and available to the public.

Calculation of embodied energy -- E_{EIO}

After obtaining cost data for each component and the energy intensity of relevant sectors, the embodied energy of each component can be calculated using equation [2-3]. Using EIO LCA, the total embodied energy in the components is

14.2 MJ/Wp (1870 MJ/m^2 under 13.2% efficiency). Table 2-5 shows the costs of these components, the energy intensity of the relevant sector, and the calculated embodied energy.

Table 2-5: EIO LCA in 2007—Cost, Energy Intensity, and Embodied Energy

Components	Cost 2007 \$/Wp	Energy intensity MJ/\$	Embodied energy MJ/Wp	Relevant sector in the EIOLCA model
Inverters (three)	1.2	5.76	6.91	Miscellaneous electrical equipment manufacturing
Module manufacturing equipment (depreciation)	0.14	7.17	1.00	Semiconductor machinery manufacturing
Residual materials (industrial gases)	0.0023	46.2	0.11	Industrial gas manufacturing
Transportation	0.21	18.8	3.96	Truck transportation
Services (sales & management)	0.11	3.09	0.33	Wholesale trade
Total			12.3 (1624 MJ/m2)	

Step 4-- Combining results to calculate E_{Total}

The results from the process-sum and EIO LCAs can now be combined to estimate the embodied energy of multi-Si PV systems in 2007.

$$E_{Total} = E_P + E_{EIO} = 2730 + 1624 = 4354 \text{ MJ/m}^2$$

2.4 Combined Results: Embodied Energy, EPBT, and Embodied Carbon

The hybrid LCA yields an embodied energy for multi-Si PV systems of 4354 MJ/m2. To calculate EPBT, features such as solar radiation conditions need to be defined; these are listed in Table 2-6. To make our study comparable, the features are the same as in the European process-sum LCA studies we cite (Alsema 2005, Alsema et al. 2006b, deWild and Alsema, 2006a).

Table 2-6: Features Defined for EPBT and Embodied Carbon Calculation

Features and parameters	
PV module efficiency	13.2%
PV system performance ratio	75% (fixed axis)
Solar radiation	1700 kWh/m^2/yr
Electricity to primary energy conversion	11.6 MJ/kWh
Carbon (CO_2 equivalent) embodied in the power grid	520 g/kWh

Table 2-7 compares EPBT and CO_2 emissions for hybrid LCA and process-sum LCA. The hybrid result is larger by approximately 70%. Because of the significant difference when previously excluded processes are included, we argue that it is important to transition toward increasing the use of hybrid LCA. While total carbon emissions for silicon PV are substantially smaller than those for fossil fuels, the difference between the two results is significant if PV is adopted on a large scale. For example, if multi-crystalline silicon-based PV grew to account for 10% of the electricity production in the U.S. (4157 billion kWh in 2007) (EIA, 2010), the difference between the hybrid and process-sum result is 3.3 million tons of CO_2, or 0.13% of national emissions in 2007.

Table 2-7: Hybrid LCA vs. Process LCA—Comparison of Results for a Multi-Si PV System in 2007

	Hybrid LCA	Process LCA
Embodied energy MJ/m^2	4354	2730
EPBT year	2.2	1.4
Embodied carbon g/kWh	32	24

2.5 Historical and Future Trends of Embodied Energy and Emission

The case study discussed in this study focuses on multi-Si PV in the base year of 2007. However, the passage of time will bring many changes. For example, the embodied energy should decrease with improvements in technology. Wafer thickness is projected to decrease to 150 μm by 2011. We assume the embodied energy in poly-silicon (MJ/kg) has not changed obviously. PV efficiencies of 11% in 2001; 12% in 2004; 13% in 2007, and 17% in 2011. We assume the The cost of manufacturing PV modules is also decreasing significantly due to factors such as plant size and module efficiency (Nemet, 2006). Table 2-8 to Table 2-10 list the process, EIO, and hybrid LCA results in three-year increments from 2001 to 2011.

Table 2-8: Process LCA Results from 2001 to 2011

Manufacturing processes MJ/m^2	2001	2004	2007	2011
Polysilicon production	2200	1700	1260	950
Wafering	1000	600	420	320
Cell processing	550	550	550	550
Module assembly	350	350	350	350
Frame	400	150	150	0
Module total	4500	3350	2730	2170
Adjusted from sources	(Alsema, 2000)	(Alsema, 2006a,b)	(Alsema, 2006a,b)	(Alsema, 2006b)

Table 2-9: EIO LCA Results from 2001 to 2011

	2001	2004	2007	2011	Adjusted from Sources
Equipment cost $/W	0.24	0.19	0.14	0.09	(Schaeffer, 2004); (NREL, 2008)
Inverter cost $/W	0.8	0.6	0.4	0.3	(NREL, 2006); (Solarbuzz, 2009)

E_{EIO} MJ/W	19.9	16.1	12.3	10.8

Table 2-10: Hybrid LCA Results from 2001 to 2011

	2001	2004	2007	2011
E_P MJ/m^2	4500	3350	2730	2170
E_{EIO} MJ/m^2	2193	1934	1600	1835
E_{Total} MJ/m^2	6693	5284	4330	4005
EPBT years	4.1	3.0	2.2	1.6
CO_2 g/kWh	60	43	32	23

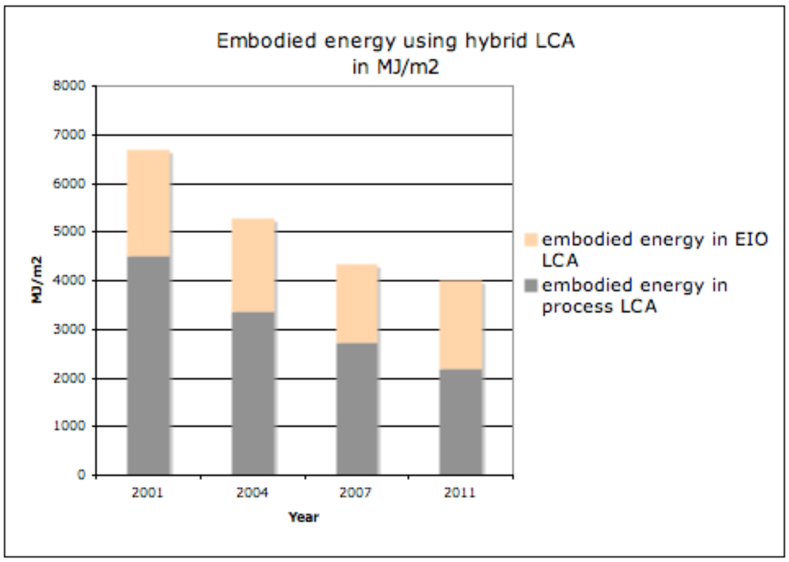


Figure 2-2: Embodied Energy in the Hybrid LCA of a Multi-Si PV System

Figure 2-2 shows that the embodied energy, EPBT, and embodied carbon emission results in hybrid LCA (process-sum plus EIO) are larger than the results in process-sum LCA by 60%. However, the embodied energy decreases by almost 50% from 2001 to 2011.

2.6 Discussion

Consideration of uncertainty is very important to establish LCA as a rigorous and reliable tool to inform decision-making (Williams et al, 2010). Considering the hybrid LCA of PV in this study, we discuss two crucial uncertainties: geographic uncertainty, which relates to the global supply chain, and aggregated uncertainty, which relates to EIO LCA.

The PV industry has spread from a few companies in developed countries, such as Japan, Germany, and the U.S., to a worldwide scale. PV companies are especially popular in developing countries such as China (Hariharan et al., 2008).

This study also incorporates aggregated uncertainty and inaccuracy when using data on various sectors. For example, the cost data we use for the inverter are adjusted from the price data (cost data are hard to find). The calculation of embodied energy in equipment chooses semiconductor machinery manufacturing as the relevant sector; the calculation of embodied energy in transportation uses truck transportation as the relevant sector.

The expansion of system boundaries using additive hybrid LCA was found to significantly increase the life cycle environmental impacts of photovoltaic modules. In a previous study of desktop computers, economic balance hybrid LCA was found to yield significantly higher impacts than the process-sum method (Williams, 2004). These two cases suggest that the hybrid approach could be key in assessing the impacts of a broad range of products and technologies. Future work is needed to develop hybrid methods and to assess when and how to apply them.

Technological progress significantly reduces the environmental impacts of photovoltaic modules. This study only accounted for energy-related flows, but the improved efficiency of modules and reductions in material use are also likely to mitigate other environmental impacts such as land use and chemical consumption and emissions. Technological progress could significantly affect the environmental impacts of renewable energies ranging from other photovoltaic materials to biofuels to wind power. Decisions on the development and adoption of new energy technologies should be informed by the dynamics of environmental impacts. More work is needed to develop methods and explore case studies in order to characterize relationships between technological change and life cycle impacts.

CHAPTER

3. THE COORDINATIVE FUNCTION OF RENEWABLE ENERGY POLICIES—REGULATIONS, FINANCIAL SUBSIDIES AND FUNDING SOURCES

A variety of policies support renewable energy adoption, and it is critical to make them function cooperatively. To reveal the interrelationships among these policies, the second part of this dissertation proposes three tiers of policy architecture. This study develops a model to determine the specific subsidies required to support a Renewable Portfolio Standard (RPS) goal. The model is based on two forecasting assumptions: future renewable energy installation which realizes the RPS goal and experience curve-based cost reductions. The model is applied to the case study of solar energy adoption in the state of Arizona. The financial requirements are calculated (in two scenarios) and compared with predictable funds from public sources. A main result is that the expected investments to achieve the RPS goal far exceed the economic allocation for subsidy of distributed PV.

3.1 Introduction

Many expect renewable energy sources including solar, wind and biofuels to become leading technologies for a sustainable energy supply system and to aid the shift away from over-reliance on traditional hydrocarbon resources in the next few decades. Solar cell production has grown at an average annual rate of 37% in the past decade and 45% in the past 5 years (Eltawil and Zhao, 2010). It has been suggested that the installed capacity of wind energy will increase fivefold over the next 10 years, to exceed 700 GW by 2017, possible if current growth rates continue (Pryor and Barthelmie, 2010).

However, the renewable energy industry growth rate has been falling since 2008, mainly due to the worldwide economic recession. New investment in renewable energy in 2009 was $150 billion down from 2008 plans (REN21, 2010). Some renewable energy industries have experienced severe boom and bust. For example, new PV installations in Spain shot up from 88 MW in 2006 to 2500 MW in 2008 and then fell back to 70 MW in 2009 (Cameron, 2010). The main cause of this cycle is slashed government subsidies. The subsidy policy in Spain is designed such that it is especially vulnerable during an economic downturn (Voosen, 2009).

The estimated government support worldwide for both electricity from renewables and for biofuels totaled $57 billion in 2009, of which $37 billion was for the former. The subsidies to fossil fuels in 2009 was $312 billion (IEA, 2010).

The most recent report from REN21 shows that renewable energy provides 18% of global energy (REN21, 2010, p9). A closer look reveals that most of this renewable energy is traditional biomass and hydro-electric power; only a very small portion can be attributed to "new renewable energy technologies" (Hirschl 2010), such as solar, wind, and geothermal energy.

Despite the current low penetration level of renewable energy worldwide, leading countries and markets have set aggressive goals. US President Barack Obama has called for doubling renewable energy production by 2012

(Garthwaite, 2009). Denmark plans to produce 60% of its electricity from renewables by 2025. Germany even has the ambitious goal of achieving 100% renewable energy by 2050 (Burgermeister, 2009). Developing countries such as China and India also have renewable energy targets. India has proposed that by 2012, 10% of annual additions to power generation should be from renewable energy (Beck and Martinot, 2004); China is aiming for 20% renewable energy by 2020 (ChinaDaily, 2009).

However, optimistic objectives do not guarantee positive outcomes. Indeed, a retrospective look reveals many disappointments. In 1979, former President Jimmy Carter predicted renewable power would provide 10% of electricity in the US by 1985 (Sovacool, 2009a). In 1980, the National Research Council declared that solar energy would account for 38.2% of the American electricity supply by 2010 (National Research Council, 1980). Obviously those goals were not achieved. From 2004 to 2009, the share of global shipments from photovoltaic manufacturers in the U.S. decreased from 10% to 5% (Mints, 2010). Barriers to renewable energy adoption arise due to various economic, social, technological, and policy uncertainties and constraints. Among those uncertainties, renewable energy policy and relevant subsidies play an important role.

The family of renewable energy support policies includes a variety such as Renewable Portfolio Standard (RPS) adopted in the U.S., Feed-in Tariff (FIT) adopted in Germany and Spain, tax and grant subsidies, and R&D support. Several researchers have proposed methods to categorize these policies (Beck and

Martinot, 2004; Sovacool, 2009b; Laird and Stefes, 2009). However, multiple policies must work together to support renewable energy. In particular, RPS (which sets adoption targets), tax credit and rebate programs (which provide financial incentives), and sources of funds (which finances incentive programs) must coordinate with each other to support renewable energy adoption, especially in the mid- to long term.

In previous studies, research on the coordinative functions of renewable energy policies is lacking. In this study, the authors emphasize the relationships between renewable energy policies and present them in a three-tier architecture.

The three policy tiers must be coordinated to support renewable energy adoption. For example, many public utilities offer rebates or similar programs to support solar energy adoption (DSIRE, 2010). To sustain the rebate programs, they need a source of funds. This source is usually money (such as environmental surcharge benefits) collected from ratepayers of the public utility. Having a financial source that is sufficient to support the required rebates is critical to the achievement of RPS goals. Consider the state of Arizona as an example. Its largest public utility, Arizona Public Service Corp (APS), provided rebates for residential solar energy (photovoltaics) at 3 $/W until 2010 July, after which the rebate dropped to 1.95 $/W because the funding source for this program was being depleted (Randazzo, 2010). Meanwhile, the APS 2009 Renewable Energy Compliance report states that despite best efforts the company is failing to achieve the RPS target for distributed renewable energy adoption (APS, 2009). Obviously, there is a mismatch among policy tiers.

Based on our proposed policy architecture, this study builds a model which clarifies the amount of financial subsidies required to support RPS goals. The model uses two key forecasting elements: future renewable energy installation capacity and experience curve-based cost reduction. The model is then employed to analyze the case study of solar energy adoption in the state of Arizona by 2025 under two scenarios: extension or termination of federal tax credits after 2016. Given these and other assumptions, the required subsidies are calculated using the model. As will be seen subsidies are much larger than the amount of funding predicted to be available from public sources.

Section 2 reviews renewable energy support policies and discusses the inter-relationships among them. Section 3 presents the methodology behind the model to calculate the funding required to support renewable energy adoption. Section 4 describes the case study of Arizona and the state's renewable energy policies. It also illustrates the solar energy price trend using an experience curve. Section 5 applies the model to the case study of Arizona. The financial requirements are calculated (in two scenarios) and compared with predicted funding from public sources. Section 6 discusses the problem caused by the mismatch among policy tiers using the case study results. It also explores ways to deal with the problems.

3.2 Three-tier Architecture of Renewable Energy Policies

3.2.1 Literature Reviews of Renewable Energy Policies

A wide variety of policies support renewable energy adoption. Beck and Martinot (2004) summarizes them with three categories: price-setting and quantity-forcing policies, which mandate prices or quantities, such as Feed-in-Tariff (FIT) and Renewable Portfolio Standard (RPS); investment cost reduction policies, which provide incentives in the form of lower investment costs, such as income and property tax credits; and public investments and market facilitation activities, a wide range of public policies that reduce market barriers and facilitate or accelerate renewable energy markets, such as net-metering.

Menz (2005) arranges U.S. policies according to their geographic/administrative scales. The federal government establishes regulations relevant to the electricity market that favor renewable energy, R&D funding, demonstration grants, and financial incentives; state and local policy instruments include financial incentives, rules and regulations, and voluntary measures.

Toke and Lauber (2007) emphasize two financing types to promote renewable energy in Europe. One is the so-called 'market-based' renewable obligation in the UK, which issues renewable energy generators 'renewable obligation certificates' (ROC) and requires electricity suppliers to supply a target portion of their electricity from renewables or suffer penalties. The underlying rationale is that the establishment of a market for the certificates will cause suppliers to make an effort to purchase the cheapest renewable energy. By contrast, in Germany, Spain, and other countries, laws set the prices that renewable electricity generators are paid; this mechanism is called a 'command and control' renewable energy FIT.

Sovacool (2009b) lays out the impediments to renewable energy in financial, political, cultural and aesthetic categories and then details the four most favored policy mechanisms: eliminating subsidies for conventional and mature electricity technologies; pricing electricity accurately; passing a national feed-in-tariff; and implementing a nationwide systems benefit fund to raise public awareness, protect lower income households, and administer demand-side management programs. Sovacool emphasizes that these policy mechanisms must be implemented comprehensively, not individually, if the barriers to renewable energy are to be overcome.

The categorization of renewable energy policies is important to understanding their functions and to designing policies. However, previous studies lack research on the cooperative functions of such policies. For example, RPS is a powerful mechanism for setting an adoption target, but without a proper financial support mechanism, such as a tax credit or rebate program, and a sufficient financial source to fund the support mechanism, it is difficult to achieve the target. Cooperation between relevant policies is critical to renewable energy adoption, especially in the mid- to long term.

3.2.2 Three-tier Architecture of Renewable Energy Policies

In this study we describe levels and relationships between renewable energy policies as a three-tier architecture:

1. Top tier—regulations, rules or guidelines
2. Middle tier—financial subsidy programs
3. Bottom tier—financial source or funds collection

Figure 3-1 shows the three-tier policy architecture and how the tiers work with each other. The top tier (regulation and rules) sets renewable energy adoption targets. To achieve these targets, financial subsidy programs must be set up. For the subsidy programs to function properly, a certain amount of money must be fed into them. The key point of this study is that the three tiers must coordinate with each other to support a successful renewable energy adoption. However, in practice, the design of each tier tends to be isolated. The bottom tier is especially difficult to match to the target of the middle tier, as often insufficient money is available for subsidy programs (the question mark in Figure 3-1).

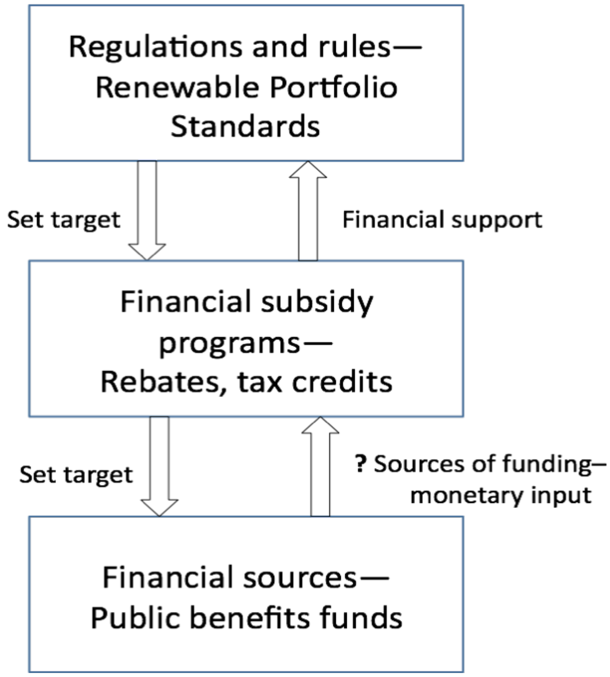


Figure 3-1: Three-tier Architecture of Renewable Energy Policies

A discussion of each policy tier follows:

1. Regulatory policies or guidelines set quantitative adoption targets such as RPS, which has been adopted in 90% of U.S. states (DSIRE, 2010).

No federal-level regulation or rule in the U.S. requires a certain quantity of renewable energy adoption. The most prevailing renewable energy policy at the state level is RPS, which ensures that a minimum amount of renewable energy (such as wind, solar, biomass, or geothermal energy) is included in the portfolios of electricity-generating resources (Yin and Powers, 2010). The renewable electricity can be generated in-state or purchased from other states to meet the requirements, which vary by state (Wiser and Barbose, 2008; Yin and Powers, 2010). For example, California requires 33% by 2020, New York requires 25% by 2013, and Nevada requires 20% by 2015 (Sovacool and Cooper, 2006). Arizona, which is among the states with the most abundant solar radiation, requires 15% by 2025. Many states have specific technology carve-outs or distributed generation set-asides. The popularity of set-asides for solar or distributed energy has increased dramatically in recent years. In 2007 alone, Delaware, Maryland, New Hampshire, New Mexico, and North Carolina created targets with solar or distributed energy carve-outs (Wiser and Barbose, 2008).

2. Financial subsidy programs, which are mainly cost-reduction policies, such as subsidies and rebates, tax credits, accelerated depreciation, etc.

At the federal level, the most effective renewable energy support mechanism is energy tax credits. Although support for tax credits has varied in a cyclic pattern during the past few decades (Medonca et al., 2009), the present atmosphere favors renewable energy. In 2008, tax credits for renewable energy technologies were extended. Investment Tax Credit (ITC) provides a 30% tax credit for renewable energy systems and has no cap (DOE, 2009). Besides tax credits, the federal government has also funded research grants and R&D investment for renewable energy (Herrera, 2009).

At the state level, financial subsidies mainly come from the rebate programs of public utilities, governmental tax credits, and loan programs. Generally subsidies from utilities cover from one-third to half of the cost of renewable energy systems (as discussed in detail later). The Database of State Incentives for Renewables and Efficiency (DSIRE, 2010) provides detailed information on policies in each U.S. state. In California (the most remarkable renewable energy market in the U.S.), for example, utilities have rebate, loan, and grant programs, whereas the state has rebate, grant, loan, and tax credit programs. There are also innovative leasing programs such as the Property Assessed Clean Energy (PACE) program. In Arizona, the main support for renewable energy (especially solar energy) at the state level comes from public utilities.

3. Financial sources, which raise money from “environmental surcharges” and other fees. These surcharges have generally been implemented as volumetric fees, such as a charge per kilowatt-hour collected from all electricity users.

Once collected, these funds can be distributed in various ways (Wiser and Pickle, 1998). In California, from 2002 through 2007, major utilities collected a “public goods surcharge” on ratepayer electricity use to fund renewable energy of $135 million annually, then reduced the collections to $65.5 million annually beginning in 2008 (DSIRE, 2010). Currently, the surcharge is approximately 0.0016 $/kWh in California. In Arizona, APS has a similar program to raise money to promote renewable energy, but the surcharge was only 0.000875 $/kWh prior to 2010 (APS, 2010a). To fulfill the RPS, the surcharge from January 2010 forward is 0.00866 $/kWh (capped at 3.46 $/month) (APS, 2010b). The total amount allocated to support residential renewable energy in 2010 is $44 million (Randazzo, 2010). Other financial sources to fund subsidies include ‘green electricity programs’ that allow customers to buy electricity from renewable energy voluntarily at a higher price than electricity from nonrenewable sources. Options for financing renewable energy installation include subsidies such as rebates, loans and leasing programs. Leasing programs such as PACE are becoming quite popular. PACE financing allows property owners to borrow money to pay for renewable energy installations. The amount borrowed is typically repaid over a period of years via a special assessment on the property. In general, local governments that choose to offer PACE financing must be authorized to do so by state law (PACE, 2010).

It is essential to determine how much money is required to support financial programs that promote renewable energy (the question mark in Figure 3-1).

3.3 Modeling Financial Requirements to Support Renewable Energy Adoption

In this section we lay out a general method to estimate the future requirements for funding of renewable energy subsidies. We first explain the two key methodologies in the model: scenario analysis and experience curves.

Scenario analysis is a common methodology in which researchers assume different growth rates or incentive levels in energy-related policy analysis (Palmer and Burtraw, 2005; IEA, 2006). Scenario analysis has a fundamental philosophy of "if-what", that is, it focuses on what effects or results are if assumptions are true. Several scenarios are proposed based on assumptions about different drivers or variables. The assumptions are subjective and have a certain level of possibility. But as a methodology scenario analysis does not emphasize the subjectivity of assumptions or likelihood of each scenario. The emphasis is on presenting a big picture of multiple causes and their mapped effects.

Experience curve or learning curve applications can be traced back to Wright (1936), who estimated the relationship between total labor hours and cumulative airplane production. Many researchers have used this methodology to evaluate the cost reduction over time with increasing cumulative output of renewable energy products. In this model, the photovoltaic (PV) price is based on forecasting using the experience curve methodology. The most common conclusion drawn using the learning curve or experience curve (Neij, 1997; Nemet, 2006; Papneau, 2006; van Sark and Alsema, 2008; Bhandari and Stadler, 2009) for the PV industry is that with each doubling of cumulative capacity, PV module price decreases to roughly 80% of its previous level. Several learning factors can contribute to such a reduction, including increases in module efficiency and plant size as well as the cost reduction of poly-crystalline silicon. We discuss the history of price reductions in PV technology and the forecasting of prices in detail in Section 4.

From Figure 3-1, we know that policies in the top tier, regulation, often set targets for renewable energy adoption that requires financial support to achieve. Thus, we first develop a timeline of adoption quantities using the particular regulation as guide. For example, we can determine the total required installation capacity to achieve a RPS target. Then, we calculate the total required financial investment using Equation [3-1].

*Required investment ($) = PV Price ($/Watt) * Installation capacity (Watt)*

[3-1]

Financial support programs in the bottom tier have different scales, so we break down the required investment by stakeholder—federal government, public utilities, and customers. Federal government subsidies are in the form of tax credit programs. Public utilities can offer various types of subsidies, but the prevailing one is rebate programs. In addition, the state government covers a part of the investment (because it is a small amount, the calculation will take it into account, but we do not list the equation here). After all these subsidies are factored in, customers pay for the rest of the investment.

The calculation of federal tax credits is denoted as Equation [3-2], utility rebates as Equation [3-3], and customer payments as Equation [3-4].

*Federal tax credit subsidies ($) = X% * renewable energy installation price after utility rebate ($/Watt) * Installation capacity (Watt*)

[3-2]

*Public utility subsidies ($) = Rebate rate ($/Watt) * Installation capacity (Watt)*

[3-3]

Customer payments ($) = Total required investment ($) – utility subsidies ($) – Federal government subsidies ($)

[3-4]

To break down the required investment into government, public utility and customer portions, we have to assume different scenarios. The calculation of required subsidies requires forecasting that embodies several uncertainties, such as existence of federal tax credits after 2016, utility rebate level, cost of renewable technologies, and customers' willingness to pay for renewables. In this scenario analysis, we do not consider the uncertainties in the cost of renewable technologies, and we consider customer acceptance to be constant. Thus, the scenarios we propose here are based on two assumptions about federal tax credits (exist or expire after 2016). For each scenario, we determine the required utility rebate and the funding available from known financial sources.

Finally, a comparison of available and necessary financial sources is presented. This allows us to draw a conclusion about the feasibility of supporting financial subsidies to renewable energy adoption if we assume other factors do not change. We do this by applying the model to the case study of distributed renewable energy adoption in Arizona.

3.4 Case Study of Arizona

3.4.1 Social Context of Arizona and RPS

Solar energy adoption scenarios must be based on the geographic and social context of a region. The average solar radiation in Arizona is 2092 $kWh/m^2/yr$, whereas the average US level is 1800 $kWh/m^2/yr$. Electricity demand is projected to grow at a rate of 30% (APS, 2006) from 80,000 GWh in 2010 to 104,000 GWh in 2020. Electricity is largely produced from conventional resources: coal contributes 39.6%, natural gas contributes 28.5%, and nuclear power contributes 25.4% (EIA, 2007b).

Arizona’s RPS (called the Arizona Renewable Energy Standard) requires regulated utilities such as Arizona Public Service (APS) to obtain 15% of their electricity from renewable resources by 2025 (RES, 2006). Unregulated utilities such as Salt River Project (SRP) also have set goals to obtain 15% of their electricity from renewable resources by 2025 (SRP, 2007). Distributed renewable generation includes biomass or biogas electricity generators, geothermal generators, fuel cells that use only renewable fuels, new hydropower generators of 10 MW or less, solar electricity resources, and wind generators of 1 MW or less (RES, 2006).

Although Arizona has abundant solar radiation, deployment of solar energy technologies remains low. The installation capacity of photovoltaics in Arizona in April 2009 was 14 MW (2.5 MW in 1-5 kW scale), whereas in California it is currently 500 MW (100 MW in 1-5 kW scale) (OpenPV, 2010).

3.4.2 Roadmap of Distributed PV Installation Capacity

To achieve Arizona's RPS goal by 2025, 15% of electricity should be generated from renewable resources, of which 30% should be from distributed renewable resources. Considering the natural resources in Arizona it is reasonable to make the assumption that the distributed renewable energy will come from solar energy. Among distributed photovoltaic installations, while there is no regulatory requirement a presentation by Arizona Commissioner indicates the plan that 50% are to be commercial and 50% residential installations. (Newman, 2010). The annual yield ratio from PV in Arizona is 1.62 MWh/kW assuming a south-oriented PV system with 13% efficiency and system performance ratio of 75% (PVWatt, 2010). Table 3-1 presents the adoption roadmap for renewable energy and distributed photovoltaic generation as well as the installation capacity required by the Arizona RPS.

Table 3-1: Roadmap of Renewable and Distributed Solar Energy Adoption Required by the Arizona RPS

RPS requirement	2010	2015	2020	2025
Percentage of energy from renewables	2.5%	5%	10%	15%
Electricity from renewables GWh	2,800	6,180	13,660	22,620
Distributed PV GWh	280	928	2,730	6,790
Distributed PV capacity MW	172	574	1,690	4,196

The installation capacity of distributed photovoltaic systems (residential scale) required by the RPS is calculated to be 2098 MW. As noted, the 1-5 kW residential scale installation capacity was approximately 2.5 MW in April 2009. Thus, to achieve the goal, the deployment of PV needs to be much faster than it is currently. Such desired explosive adoption of photovoltaic technologies requires political, financial and social support. Subsidies from government and utilities play an important role. However, the huge monetary investment required poses a challenge to reach the RPS deployment goal.

3.4.3 Trend of PV System Price and Experience Curve

According to Equation [3-1], to determine the required investment, the price of the PV system also needs to be estimated. The cost of the PV system mainly comes from the PV module cost and installation cost. Most residential systems are multi-crystalline silicon PV modules. Installation cost includes the cost of inverters, controllers, and other electric components as well as the labor cost for installation and maintenance. Lawrence Berkeley National Laboratory released a report in 2009 summarizing the installed cost of photovoltaics in the U.S. from 1998-2007 (Wiser et al., 2009) that stated, “Among all PV systems in the dataset from nearly 37,000 residential and non-residential PV systems, average installed cost—in terms of real 2007 dollars per installed watt and prior to receipt of any direct financial incentives or tax credits—declined from 10.5 $/W in 1998 to 7.6 $/W in 2007. The overall decline in installed costs is primarily attributable to a reduction in non-module cost, which fell from 5.7 $/W in 1998 to 3.6 $/W in 2007." In addition to reports summarizing practical observations and data collected from PV installations, researchers also have developed empirical models that fit past PV cost reduction trends.

The most common model used to illustrate the relationship between technology adoption and price reduction is the learning curve or experience curve (Neij, 1997; Nemet, 2006; Bhandari and Stadler, 2009). In the PV industry, with a doubling of the cumulative capacity, the PV module price decreases to roughly 80% of its previous level (or the learning ratio is 0.8). However, this rough conclusion is based on empirical data in a relatively long-term observation. A look at the solar industry recently shows that a notable price increase occurred around 2007 because of booming demand and a feedstock shortage (Mints, 2009). However, non-module cost exhibits a consistent downward trend, due to inverter price reduction and accumulation of installation experience.

Two PV installation companies were surveyed about PV system price in November 2009. Both gave the same answer of 6 $/W for the cost of installing a residential PV system in Arizona.

To estimate necessary future investment in PV installation, we must forecast the PV system price, which suffers from uncertainties. The theory of learning curves as applied to PV mainly focuses on PV modules. Although non-module components may have different learning ratios, we assume they are the same as the module learning ratio—0.8 in our calculation. The PV installation capacity projections are based on the targets of the International Energy Agency, which are 118 GW in 2020 and 447 GW in 2030 worldwide (IEA, 2009). The PV price forecasting results are listed in Table 3-2.

Table 3-2: PV System Price Trend from 2005 to 2025

PV system price	2005	2010	2015	2020	2025
2010 $/W	9	6	4	3.5	3

3.4.4 Calculation of Total Required Investment

Using the required PV installation based on the RPS and the PV system price trend, we have calculated the total required investment from Equation [3-1]. As shown in Figure 3-2, the annual investment in 2025 is almost $700 million (assuming the discount rate is zero).

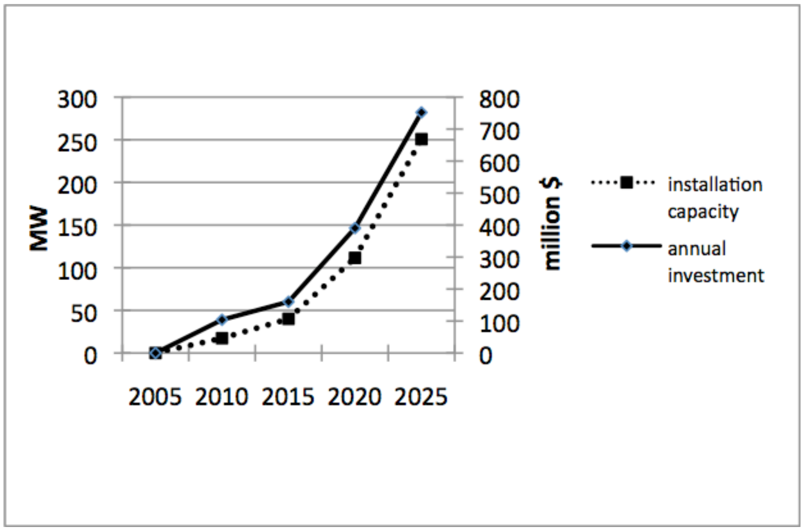


Figure 3-2: Annual Residential PV Installation and Investment to Achieve Arizona's RPS Target

3.5 Breakdown of Required Investment

Several components contribute to the total required investment to achieve the RPS goal, including tax credits from federal and state governments, rebates by public utilities, and purchases by customers. Thus government, utilities, and customers are considered the three stakeholders in the PV adoption process. In this section, we break down the investments by the three stakeholders.

3.5.1 Renewable Energy Policy at Federal, State and Utility levels

At the federal government level, the Investment Tax Credit (ITC) covers 30% of the investment in a PV installation after rebates from utilities, as shown in Equation [3-2]. ITC has been extended to 2016. It should be noted that when calculating the 30% tax credit, it is not the total investment but the investment after rebates from utilities. Equation [3-2] in the section of Methodology also indicates that.

At the state government level subsidies include the Arizona Income Tax Credit of 25%, which is capped at $1000; the Arizona Solar Device Sales Tax Exemption; and accelerated depreciation.

At the utility level rebates are provided. Arizona Public Service (APS) provides a 1.95 $/W rebate for residential PV systems, and Salt River Project (SRP) provides 2.15 $/W.

Table 3-3 summarizes subsidies by level for residential PV systems in Arizona.

Table 3-3: Incentives for Residential PV Installation

Incentives for residential PV installation			Data sources
Federal level			
	Federal Tax Credit	30% (capped at $2000 until 1/1/09, then uncapped)	SEIA Guide to federal tax incentives for solar energy DOE website (http://www.energy.gov/taxbreaks.htm)
State level			
	Arizona Income Tax Credit	25% (capped at $1000)	Arizona Solar Center website (http://www.azsolarcenter.com/econ.html)
	Arizona Solar Device Sales Tax Exemption and accelerated depreciation	No state sales tax	Arizona Solar Center website (http://www.azsolarcenter.com/econ.html)
Utility level			
	APS rebate	$1.95 per installed DC watt	APS website (http://www.aps.com/main/green/choice/choice_2.html)
	SRP rebate	$2.15 per installed DC watt (up to $13,500)	SRP website (http://www.srpnet.com/environment/earthwise/solar/)

Next we show an example calculation that breaks down the investment in a residential PV system in Arizona. For example, a 4 KW residential polycrystalline silicon PV system costs 6 $/KW. The total cost is $24,000. Table 3-4 shows the investment breakdown before and after 2010 July, when APS reduced its rebate level from 3$/W to 1.95 $/W.

Table 3-4: Breakdown of Investment for a 4 KW PV System before and after 2010 July in Arizona

4KW * 6 $/Wp	Before July 2010	After July 2010
Total cost $	24,000	24,000

Federal ITC $	3,600	4,860
State Income Tax Credit $	1,000	1,000
Utility rebate $	12,000	7,800
Installed price after incentives $	7,400	10,340

3.5.2 Two Investment Breakdown Scenarios Considering Different Subsidies

From a short review of renewable energy history in the U.S., especially tax credit policies, the establishment and expiration cycle is clear. In 1992, the Energy Policy Act provided a PTC (Production Tax Credit) for renewable technologies. In 1999 the PTC expired, causing a 93% drop in wind development the following year. The PTC also expired in 2001 and 2003, resulting in drops larger than 70% in 2002 and 2004 (AWEA, 2007). The inconsistent policies for renewable energy have created boom and bust cycles, making it difficult to obtain financing for projects (Wiser, 2007).

Table 3-5 presents a brief timeline of federal energy policies to illustrate their history.

Table 3-5: Federal Energy Policies in the U.S. from 1970 to 2008

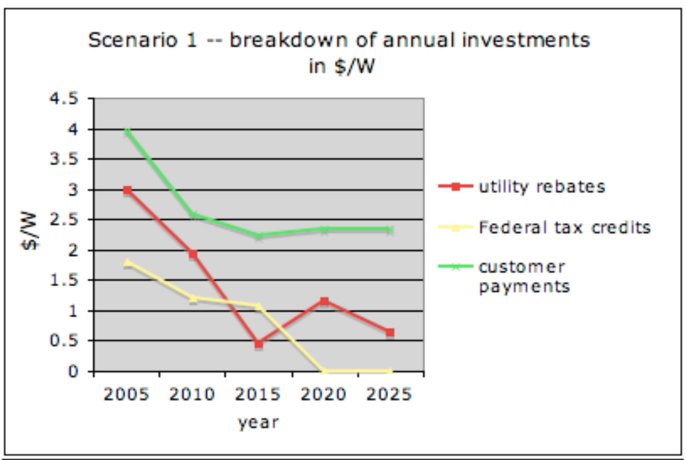
Year	Energy policy
1918-1970	Tax credits promote the oil and gas industries
1978-1990	Public Utility Regulatory Policies Act (PURPA)
1978	Tax credits for renewable energy established
1985	Tax credits expire
1992	Production Tax Credit (PTC) reestablished
1999 2001 2003	PTC expired
2005	Investment Tax Credit (ITC) established
2008	ITC extended to 2016

In 2008, tax credits for renewable energy technologies were extended. PTC received a one-year extension and ITC an eight-year extension. The ITC provides a 30% tax credit for renewable energy systems and has no cap (DOE, 2009). In addition to tax credits, the federal government also provides grants and R&D investment for renewable energy technologies (Herrera, 2009). Clearly the political atmosphere today favors renewable energy. However, it is difficult to predict whether PV tax credits will continue after 2016. Thus, we propose two scenarios:

Scenario 1—federal tax credit is not extended after 2016

Scenario 2—federal tax credit is extended after 2016

In Scenario 1, we assume that subsidies from federal tax credits are not extended after 2016 and that payments from customers do not change obviously after 2010. The utilities have to subsidize the rest of the investment.



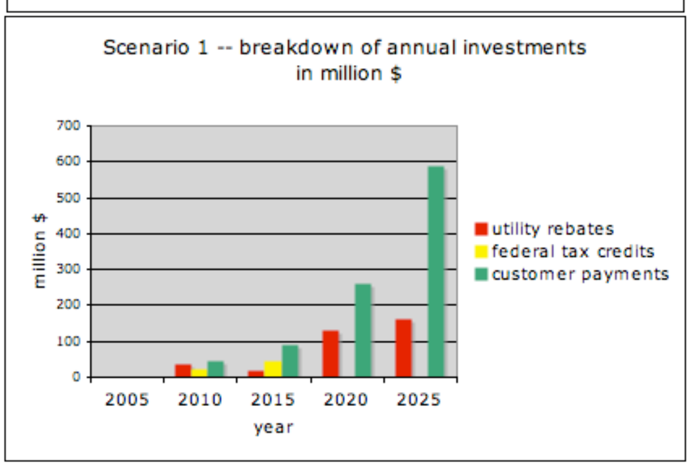
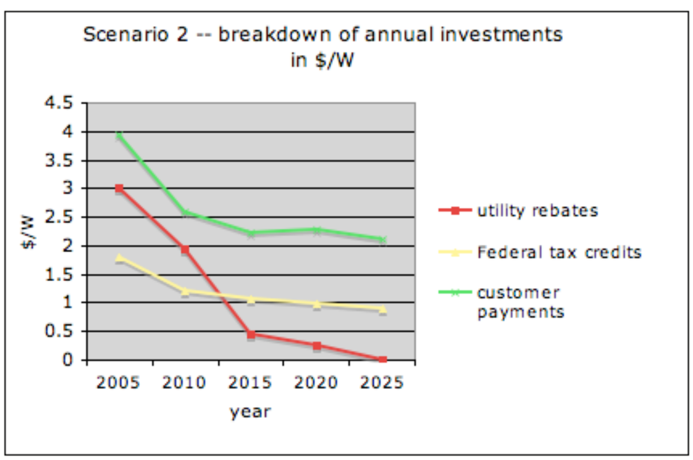


Figure 3-3: Scenario 1—Breakdown of Investments in PV by Utility Rebates, Federal Tax Credits and Customer Payments

Figure 3-3 shows the trend of this breakdown through 2025. In Scenario 1, the level of federal tax credits steadily decreases from 2010 through 2016, when it drops to zero. If customer payments do not change obviously, the public utility financial support programs must have sufficient subsidies to make up the difference. APS provided 3$/W to buy down the PV system cost before 2010 July, then reduced the rebate to 1.95 $/W. Because the PV system cost decreases, the rebate level can be reduced to 0.45 $/W by 2016. However, if the federal tax credit is not extended, the rebate must increase again to 1.15$/W in 2020.

In Scenario 2, we assume that federal tax credits are extended after 2016. If customer payments do not change after 2010, then utilities must subsidize the rest of the investment.



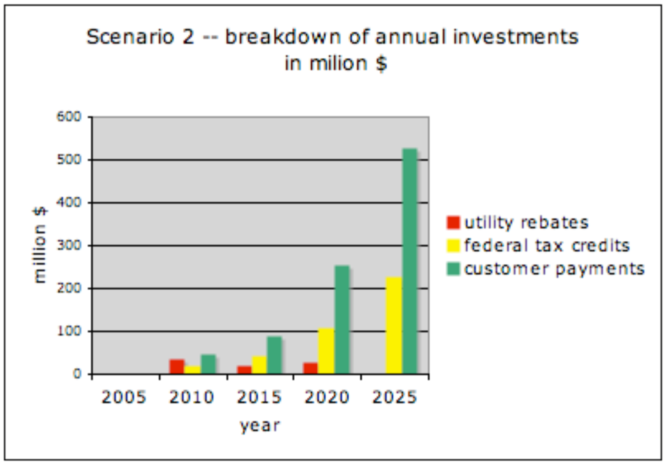


Figure 3-4: Scenario 2—Breakdown of Investments in PV by Utility Rebates, Federal Tax Credits and Customer Payments

Figure 3-4 shows the trend of this breakdown through 2025. The federal tax credit level remains at 30%, and the amount steadily decreases from 2010 through 2025. If customer payments do not change, then public utility financial support programs must have sufficient subsidies. Because the PV system cost is decreasing, the rebate level can be reduced to 0.45 $/W by 2015, 0.25 $/W by 2020, and zero after 2025.

3.5.3 Comparison Between Required Subsidies and Predicted Financial Sources

In last section, we discussed the breakdown subsidies per Watt of PV. To explore the relationship between required monetary input and predicted financial sources, it is necessary to know the subsidies to the PV installation at macro-scale (in this case study, it is the state of Arizona). Using Equations [3-2] and [3-3] and the PV installation roadmap based on RPS, total subsidies in the form of utility rebates are calculated in both scenarios and shown in Figure 3-5.

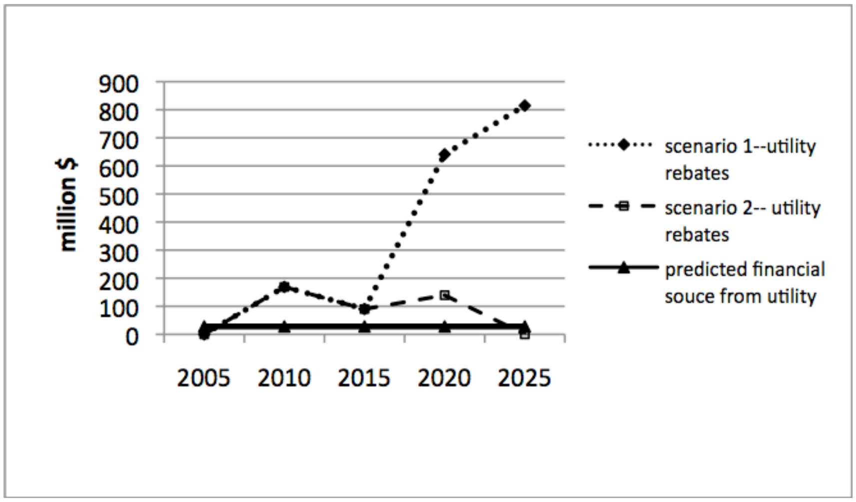


Figure 3-5: Comparison Between Required Rebates and Predicted Funding

In scenario 1, the amount of required rebates from utilities to achieve the RPS target explosively increase from $170 million (year 2010) to $800 million (year 2025). In scenario 2, the amount is between around 100 to 200 million from 2010 to 2020.

The predicted financial source cannot support the necessary rebates in either case. In 2008, APS collected $41.4 million from public benefit funds to support renewable energy (APS, 2009), much less than needed.

From the analysis of the three-tier architecture of renewable energy policies in previous section, which is essential to support renewable energy adoption is to make sure the policies function cooperatively. Specifically, whether there are sufficient financial funds to feed into rebate programs is worth questioning, especially because the analysis in this section shows a gap between required subsidies and sources of funds (the question mark in Figure 3-1 is 'probably NOT' in this case).

3.6 Conclusion

Although this case study uses data from Arizona, it parallels the situation in many states. In the analysis of the three tiers of policies with RPS at the top, clearly the policies themselves are inherently isolated from each other. RPS offers no guidelines about how to design the financial support or subsidy tiers. Rebate programs do not include mechanisms to collect sufficient funds to support them. This is why a utility can set a generous rebate level at the beginning and then reduce it suddenly and dramatically. APS has argued that it reduced its rebate level suddenly because the distributed renewable energy market is overheated (Randazzo, 2010). But APS also stated in its annual compliance report that the distributed renewable energy target of RPS has not been achieved because of customers' lack of acceptance.

The authors' point of view is that the true problem is that renewable energy policies have not been designed to work with each other well. If governments want renewable energy to reach a certain level of adoption (as RPS requires), relevant financial sources should be developed that are sufficiently supportive. If there are no sufficient financial sources, no matter how attractive the target is, the program will inevitably fail.

The support mechanisms of Feed-in Tariff (FIT), in contrast, require not only a particular subsidy level (premium price from renewable generators) but also pass the cost of subsidies to all consumers. Although this mechanism also suffers shortcomings and criticisms, its ability to ensure sustainable financing is notable. While we do not take the stance that FIT is a better policy, we argue that renewable energy policy options should be considered and evaluated with the objective of providing stable financial support.

A system stable over reasonable time scales promotes confidence in renewable energy adopters. To make renewable energy policies stable, explicit analysis of how each tier of policies coordinate with each other is needed.

CHAPTER

4. ANALYSIS OF SOCIAL ACCEPTANCE OF DISTRIBUTED SOLAR ENERGY USING FUZZY LOGIC MODEL

Social acceptance plays a role in the adoption of residential photovoltaic and other renewable energy technologies. Even with subsidies there are often challenges with social acceptance. The third part of this dissertation originally develops a fuzzy logic inference model to relate consumers' attitudes about the technology such as perceived cost, maintenance, and environmental concern to their adoption intention. Fuzzy logic inference model is a type of soft computing models. It has the advantage of dealing with imprecise and insufficient information and mimicking reasoning processes of human brains. This model is implemented in a case study of residential PV adoption using data through a survey of homeowners in Arizona. The output of this model is the purchasing probability of PV. It also quantifies the sensitivity of purchasing probability to the perception variables.

4.1 Introduction

One of the barriers to the adoption of renewable energy technologies has been their relatively higher cost. The policy-supporting mechanisms are designed to promote renewable energy. In U.S. multi-level policies and regulations are supporting the adoption from federal and state governments, as well as public utilities. The cost of electricity generated from solar electric system—photovoltaic

(PV) is still higher than the one from power grid (around 0.1-0.15 $/kWh). In Table 4-1 we calculated that before subsidies, the electricity cost (levelized cost) from photovoltaic is around 2 to 2.5 times higher than electricity from power grid. However, after subsidies, more than half of the installation cost of PV is covered.

Table 4-1: Levelized Cost of PV System before and after Subsidies

	2010	2015	2020	2025
Levelized cost of PV ($/kWh)	0.232	0.165	0.148	0.131
Levelized cost of PV with subsidies ($/kWh)	0.063	0.055	0.058	0.058

However, even with very generous subsidies, the adoption situation of distributed PV is not optimistic. Arizona Public Service (APS)—one of the largest public utilities in the U.S. states in their 2008 annual report (APS, 2009) stated that "despite the company's best effort to encourage customer participation in incentive programs, APS fell short of the distributed energy requirement of 50,580 MWh by a total of 33,256 MWh." It seems like the utilities and governments have tried their best to stimulate the adoption of distributed renewable energy. But why the adoption level is still low? Many researchers have argued that the barriers of social and cultural relevant issues are critical (Wustenhagen et al., 2007; Zoellner et al., 2008; Sovacoool, 2009a,b; Claudy et al., 2010). If those barriers are not well perceived, the adoption of renewable energy is hard to be successful.

Most of existing studies qualitatively illustrated the social acceptance of the renewable energy adoption (Wustenhagen et al., 2007; Sovacool, 2009a,b). Some other studies quantitatively analyze the relationship of social acceptance and demographic characteristics (such as age, gender, educational level and etc) using statistical tools (Zoellner et al., 2008; Claudy et al., 2010). However, the attitudes of society towards the renewable energy technologies (such as social familiarity of the technology, environmental awareness) are difficult to quantitatively analyze. This study attempts to evaluate the social acceptance of distributed solar energy using a quantitative methodology—fuzzy logic. The fuzzy logic is good at using linguistic value rather that numerical value to describe a problem. Some pioneers have attempted to implement this engineering-based methodology into energy related interdisciplinary study (Kaminaris et al., 2006; Doukas et al., 2007).

In Section 2, we present a literature review of social acceptance of renewable energy adoption. In Section 3, we illustrate the design of survey and the analysis of the results (such as purchasing probability) using logistical regression model In Section 4, we present the methodology of fuzzy logic and the reason we implement it. In Section 5, we apply the fuzzy logic model to the handle the data from the survey. In Section 5, the analysis of the results using fuzzy logic model are presented. There is a discussion section in Section 6.

4.2 Literature Review: Social Acceptance of Renewable Energy Adoption

No matter researchers, policy decision-makers or industrial investors in this field are attempting to figure out the adoption roadmap of renewable energy technologies and the relevant challenges and opportunities. Especially the adoption of solar energy is highly dynamic. The cost of PV modules is fluctuating, policy of incentives is unstable, technology seems to have breakthrough quite often. Those dynamic phenomenon are countless, some are technological, some are social, others are political. Some have instant and intensive impact, others have continual and modest impact. To understand the underlying knowledge of those phenomenon, it is meaningful to categorize them. Previous literatures from other researchers provided insightful knowledge.

The article presented by (Wustenhagen et al., 2007) introduces the issue on social acceptance of renewable energy innovation. It is a collection of best papers at an international research conference. By summarizing the points of view towards social acceptance. The paper presents three dimension of this concept, namely socio-political, community and market acceptance. In term of market acceptance, it emphasis the role of consumers has changed to investors when distributed energy is adopted. The ownership of the renewable energy devices, such as solar panels becomes a question.

Sovacool in his insightful article (Sovacool, 2009a) asked a question that "if renewable power systems deliver such impressive benefits, why do they still provide only 3% of national electricity generation in the United States?" After 181 interviewing with a diverse array of stakeholders, he presented a comprehensive network of impediments from technological, social, political, regulatory, and cultural aspects which he termed as socio-technical. He found that social or cultural barriers are critical, such as, utility operators reject renewable resources because they are trained to think only in terms of big, conventional power plants.

Sovacool in another article (Sovacool, 2009c) discovered the cultural impediments to renewable technologies by conducting interviews at more than 82 institutions. The study finds that the apparent disconnect between how electricity is made and how it is socially perceived perpetuates public apathy and misinformation about it; also that deeply held values related to consumption, abundance, trust, control and freedom shape American attitudes toward energy. Psychologists and economists, for instance, have observed the following: people hold a strong preference for the status quo, and once familiar with a particular energy product, it attains higher value (conflicting with the view that people will invest in changing their lifecycles if it maximizes self interest).

Other researchers such as Medonca (Medonca et al., 2009) analyzed in more detail about the adoption of renewable energy in Denmark and the U.S. He also brought the term "innovative democracy" which reflects the healthy renewable energy situation in Denmark. Because not only the aggregated number is impressive, 20% of electricity from wind energy, more important thing is 80% of wind turbines are owned by households in a way of cooperatives, that means residents get most of the benefits from investing to renewable energy. The success of renewable energy adoption is not only to achieve how many percent is from renewables by building large scale of wind or solar farms, but to make it more beneficial (both environmental and economic) to residents. However, large scale adoption of residential renewable energy technologies face the social and cultural constraints that centralized one may not face.

A research lead by National Renewable Energy Lab (Farhar and Coburn, 2000) interviewed more than 3000 single-family in Colorado about the questions of installing PV system on their roof-top. In the question of favorability of PV system, score is 7.5 (full score is 10). In the question of familiarity of PV system, score is 3.2. The survey also shows that the first concern of benefits from PV installation is long-term energy cost savings. The most important outcome of this survey is that the main barriers of PV adoption are residents are not willing to install it until they know more information about PV system (how they work, how they save electricity bill, what other users experience is). Electricity is so easy and cheap to use. It is even hardly to notice the existence of power grid. Why should costumer choose a complicated product that is might help them to save money, except a tiny amount of tree-huggers?

This concern brings me back to Roger's classic technology adoption model which discusses social acceptance including the consideration of technology's relative advantage, complexity and triability. Mallett (Mallet, 2007) explains the solar water heater adoption in Mexico City using this model and emphasis the importance of cooperation of participants.

Tsoutsos et al., (2005) summaries the barriers as: technological factors, government policy and regulatory framework, cultural and psychological factors, demand factors, production factors, infrastructure and maintenance, undesirable societal and environmental effects, economic factors. Among cultural and psychological factors, he mentioned that unfamiliarity with the new technologies and possible failures or bad examples (broken or run-down wind turbines) lead to skepticism.

Besides those qualitative research mentioned above, there are several quantitative analysis towards social acceptance of renewable energy.

Zoellner et al., (2008) investigated the public acceptance of residents toward renewable technologies in Germany using the statistical regression methodology. The regression analysis of the data shows the economical estimation of the technology appears to be the strongest predictor for a reported acceptance. Other factors include procedural justice, reliability estimation, risk evaluation, etc. Those factors also show somewhat positive relationships with the acceptance of renewable technologies.

Claudy et al., (2010) assessed the consumer awareness towards distributed renewable energy in Ireland also using the statistical regression methodology. It revealed the relationship between consumer awareness and demographic variables, such as gender, internet access, age, household size, employment status. It found out that men, older people, educated people, full employed people were significantly more likely to have heard of such technologies and have higher awareness of renewable energy technologies.

4.3 Survey of Customers' Perceptions toward Solar Panels

4.3.1 Survey Design and Questions

In September 2010 a survey was developed to identify the social perceptions to solar electric power technology (photovoltaic or solar panels) in

Phoenix Metropolitan Area, Arizona, U.S. A pilot-study was conducted to verify the questions. The study was distributed by a professional market research company. The survey targeted to the group of homeowners who are in the panel of "pro-green energy". As a "green" technology, solar panels are more likely to diffuse among people who have higher environmental concern. However, since this technology is still in the early adoption stage, the percentage of adoption among households is less than 1%.

The survey has collected 487 completed responses, among them, 454 are non-adopters, 21 are adopters (have installed grid- connected PV); others are PV adopters but their houses do not use electricity from power grid and PV system is in a off grid connection mode (their purchasing motivation is considered to be different with grid power customers, so in this study their responses are not included for analysis).

The questionnaire was designed in two parts. One part is for early-adopters, the other part is for non-adopters. The questions in each part are designed to be equipotent. Take the question of asking perceived cost for example, the question for the adopters is "Before you purchased them, did you think that solar panels would save you money over the years you would own them?"; and the question for the non –adopters is "Do you think that solar panels would save you money over the years you would own them?".

From literature review, we notice that among the barriers, other than higher cost, the convenience of using power grid electricity and lacking of familiarity of the solar panels are other important barriers. For example, customers do have to worry about the operation and maintenance (O&M) of power plants; but if they install solar panels, they have to take charge of O&M, at least, to call professionals to address the problems. So in the survey we design the question about maintenance to understand this issue.

For the complete questionnaire, see the Appendix A.

4.3.2 Descriptive Results From the Survey (Demographic variables and Perception variables)

For the demographic variables, this study examines age, income, educational level. Table 4-2 shows the descriptive statistics of the demographic variables.

Table 4-2: Descriptive Statistics of Demographic Variables

Demographic variable		Mean	Standard deviation	T	Sig. (2-tailed)	Means' difference is significant or not (at the 95% level)?
Age	Adopter	58.36	10.67	2.012	0.056	No
	Non-adopter	53.51	12.94			
Income	Adopter	5.20[A]	1.91	0.731	0.472	No
	Non-adopter	4.88[A]	1.86			
Education	Adopter	3.25[B]	1.65	-0.109	0.914	No
	Non-adopter	3.19[B]	1.67			

[A]: scaling from 1-10 (low to high), for detail, see Figure 4-1
[B]: scaling from 1-5 (low to high), for detail, see Figure 4-1

Since the two samples are highly unequal, so the t-test may not be robust in this case. The frequency distribution of the demographic variables are shown in Figure 4-1 to present a visualized description.

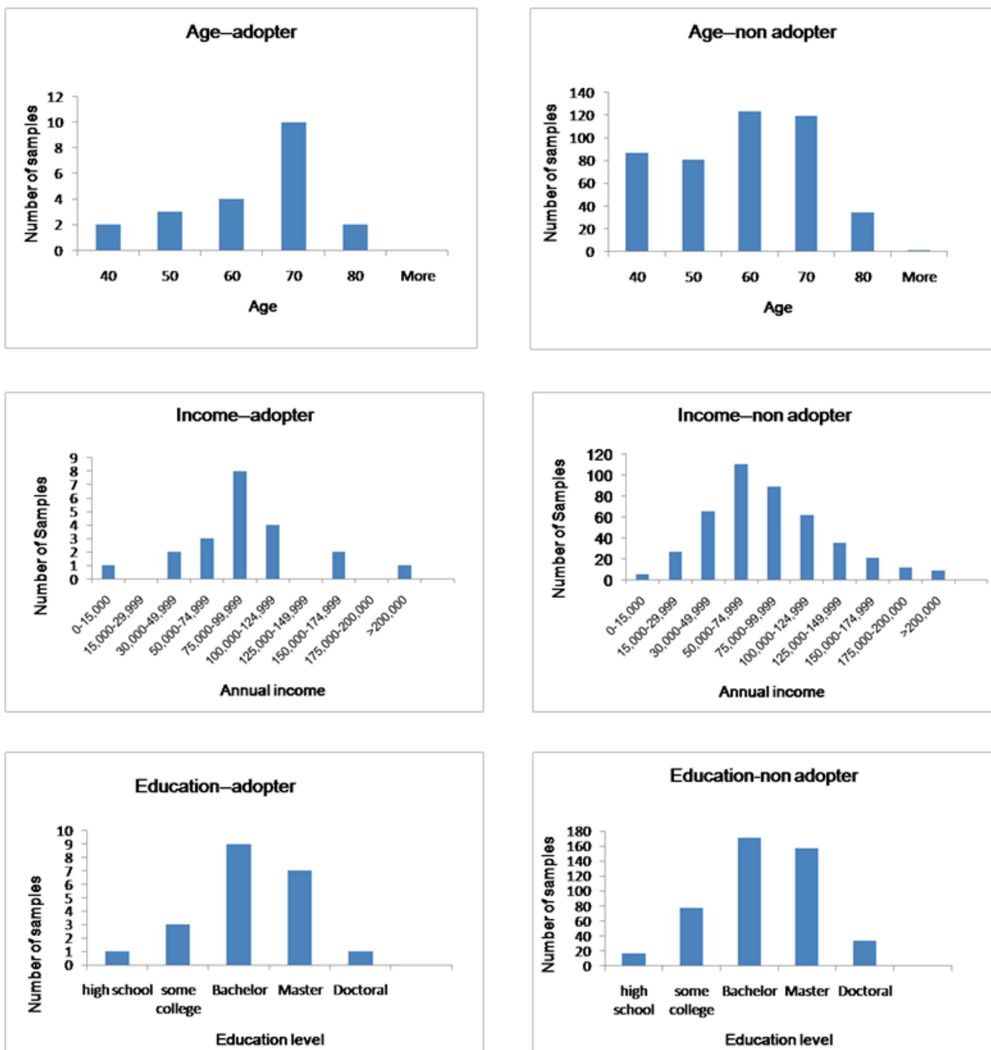


Figure 4-1: Frequency Distribution of Demographic Variables

The survey has asked a question about "How much would the following factors affect your decision to purchase solar panels?" For adopters, the question is "How have the following factors affected your decision of purchasing solar panels?" The factors included the rankings by non-adopters and adopters are listed in Table 4-3.

Table 4-3: Rankings for the Affecters of Purchasing

	Non adopters	Adopters
Cost of solar panels	1	2
Amount of time to break even investment	2	3
Environmental benefits	3	1
Maintenance requirement	4	5
How long I would stay in the same house	5	4
Convenient loan program	6	7
Solar panel aesthetics on my rooftop	7	6

The frequency distribution of the other variables are shown in Figure 4-2 to present a visualized description.

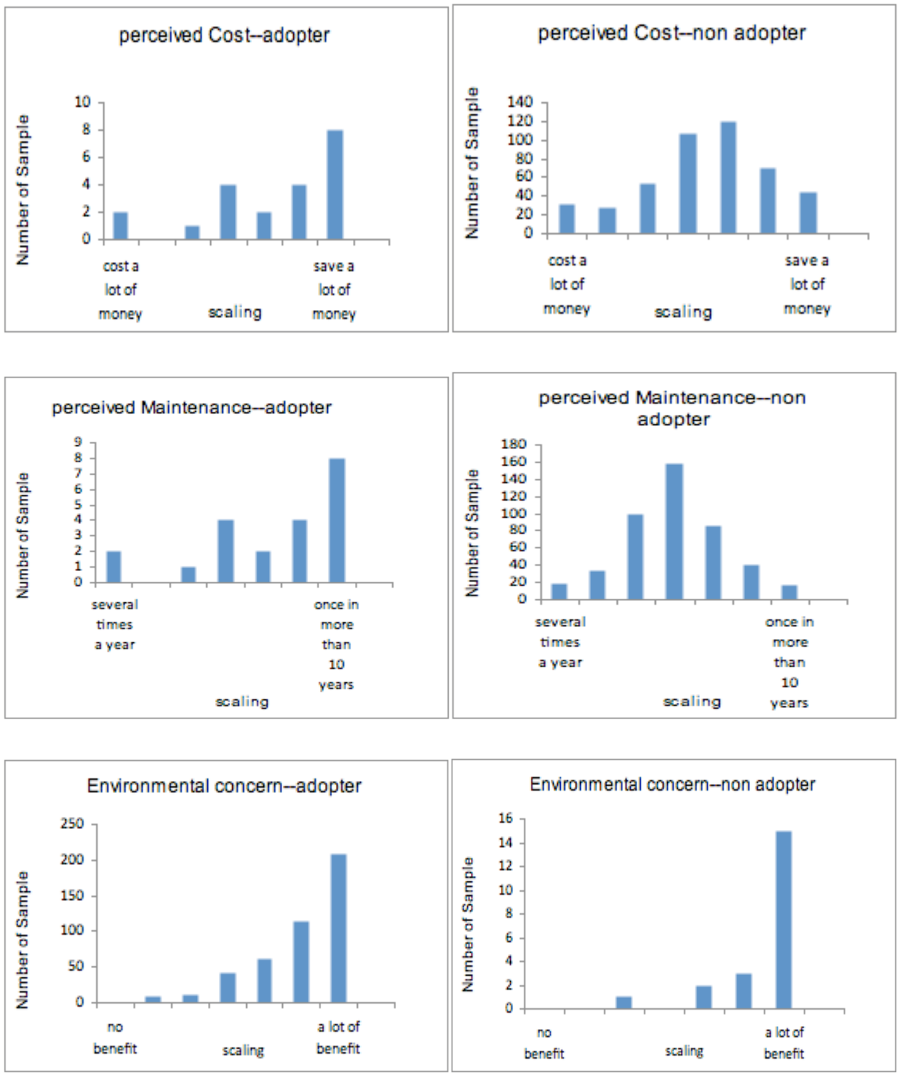


Figure 4-2: Frequency Distribution of Perception Variables

From the statistical test of survey results (Table 4-4), we can notice that the social aspects of customers such as perceived cost of solar panels, perceived maintenance requirement, and environmental concern are significantly different between early adopters and non-adopters. We call them perception variables in this study. Table 4-5 shows the relevant questions of each variable and the scaling of them. In the questions, the scaling is from 1 to 7. In order to handle the data using mathematical models (both regression model and fuzzy logic model), the scales are stretched linearly to a new one (0 to 10).

Table 4-4: Descriptive Statistics of Perception Variables

Perception variable		Mean (weighted scaling)	Standard deviation	T	Sig. (2-tailed)	Means' difference is significant or not (at the 0.05 level)?
E (Environmental concern)	Adopter	7.66	2.81	2.316	0.030	Yes
	Non-adopter	6.20	2.96			
C (perceived Cost)	Adopter	2.09	1.89	-4.009	0.001	Yes
	Non-adopter	3.82	2.65			
M (perceived Maintenance requirement)	Adopter	1.64	2.02	-4.890	0.000	Yes
	Non-adopter	3.86	2.29			

Table 4-5: Relevant Questions of Each Variable and Scaling Explanation

Perception variable		Questions	Scaling (1-7)	Stretching scales linearly (0-10)
E	Adopter	How much do you think solar panels benefit environment	1: No benefit 7: A lot of benefit	0: No benefit 10: A lot of benefit
	Non-adopter	How much do you think solar panels benefit the environment?		
C	Adopter	Before you purchased solar panels, did you think that solar panels would save you money over the years you would own them?	1: Save a lot 7: Cost a lot	0: Save a lot 10: Cost a lot
	Non-adopter	Do you think solar panels would save you money		

		over time?		
M	Adopter	Before you purchased solar panels, how frequently did you think solar panels would require maintenance from professionals?	1: Once in more than 10 years 7: Several times a year	0: Once in more than 10 years 10: Several times a year
	Non-adopter	How frequently do you think solar panels would require maintenance from professionals?		

The questions in Table 4-5 are designed to understand the perception of each variable, such as "how do you think the solar panels can benefit environment?" However, they do not reveal the effects of the variable on customers' (potential) decision making process. To understand such effects, a question of "How much the factors affect your decision to purchase solar panels?" is designed. From, the responses of the survey, adopters consider environment benefit is the most important factor of their decision making (the mean value is 5.81 higher than non adopter's 5.45); while for non-adopters, cost is the most important factor. Table 4-6 shows the mean values for each variable.

Table 4-6: Effects of the Perception Variables on Decision Making

Perception variable		Mean value of the answers ("How much the factors affect your decision to purchase solar panels?" 1: Not affect, 7: Greatly affect)
E	Adopter	5.81
	Non-adopter	5.45
C	Adopter	5.25
	Non-adopter	6.26
M	Adopter	5.42
	Non-adopter	4.38

4.3.3 Logistic Regression Model

To analyze relationship between dependent variable and several independent variables, the regression models are widely used. The dependent variable in this study is binary (0 or 1, not purchase or purchased). The logistical regression model is implemented for analysis (Claudy et al., 2010). Table 4-7 shows the coefficients of each variable and the significance of them.

Table 4-7: Logistical Regression Analysis of Purchasing Activity

Perception variable	Coefficient	Sig. (P value)
E	0.154	0.072
C	-0.190	0.118
M	-0.524	0.000
Constant	-2.237	0.004

The purchasing probability (Prob) can be expressed using Equation.4-1 and 4-2.

$$Prob = \frac{e^y}{e^y + 1} \quad [4\text{-}1]$$

$$y = -2.237 + 0.154 \times E - 0.019 \times C - 0.524 \times M \quad [4\text{-}2]$$

The purchasing probability can be calculated using the equations and is shown in figures of probability distribution (Figure 4-3).

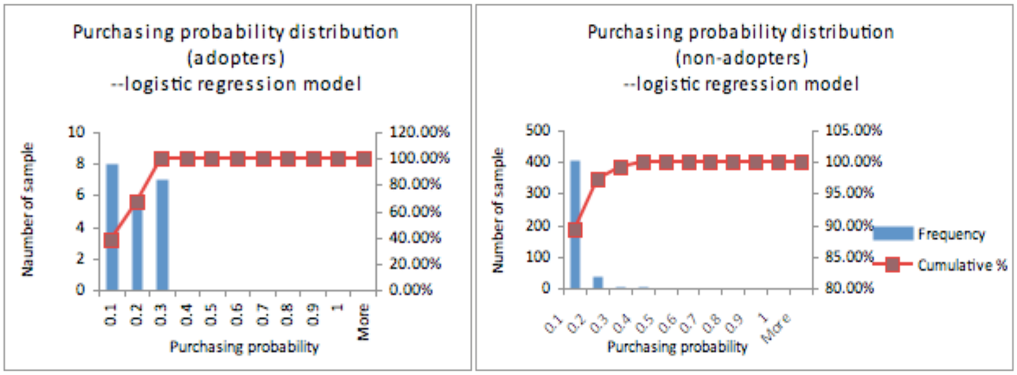


Figure 4-3: Purchasing Probability Distribution Using Logistic Regression Model

The regression analysis can hardly show the reality of purchasing activities in this study. The ideal value of purchasing probability for adopters should be 100%, and for non-adopters should be 0%. The distribution figure of adopters (right figure) shows that their purchasing probability fall into the range from 0 to 30%. The result is far away from reality (that adopters have already purchased). The logistic regression model is not valid enough to describe or predict customers' purchasing activities. There are several reasons for this invalidity. One possible reason would be the samples of adopters and non-adopters are different in numbers severely. Another reason would be, some of the independent variables are not significantly correlated to dependent variables. An alternative model is required to implement.

4.4 Model of Fuzzy Logic

4.4.1 Why Use Fuzzy Logic

To understand the social acceptance to technologies, it is not easy to carry out a controlled experiment to obtain precise data and the problem is not easily to be expressed in a formula and to achieve an exact solution. To quantitatively address this issue, it is helpful to use the tool of soft computing, which is good at dealing with complex system with uncertain information. It includes: neural networks, probability (Bayesian) networks, fuzzy logic, expert system, knowledge-based system, genetic algorithm and etc. The concepts and methodologies are originally from computer science however are applying to various disciplines, such as medicine, biology, social science and management.

The existing literatures state the social aspects in a qualitative way. Others related economical estimation and demographic characteristics to social acceptance in a quantitative way. However none of them have analyzed these social aspects to social acceptance in a quantitative way. To forecast the future adoption of renewable energy technologies, it is worthwhile to quantify those social aspects in a logic and reasonable way. It is difficult. It is a complex issue, some aspects are easy to be quantified, such as cost of PV system; others are not easy to be quantified, such as familiarity of PV system. We can describe the cost as 1 $/W or 2 $/W, but we can only describe familiarity using language like "I think I feel familiar with solar panels" or "I'm not sure with solar panels". Such statement can be defined using linguistic variables, which are critical in methodology of Fuzzy logic to describe imprecision human knowledge (Doukas, et al., 2007).

Before we begin to introduce methodology of Fuzzy logic, we would start with a simple example to demonstrate how Fuzzy logic works and why we choose it for this study. To simplify the problem of PV adoption, it becomes to examine whether a target family is willing to install PV system on their rooftop (because PV adoption can be considered as the aggregated behavior of each consumer).

If there are only two factors determines the acceptance of consumers: cost and familiarity of PV system. It is reasonable to draw the logic analysis below.

Table 4-8: Simplified Social Acceptance of Solar Energy Reasoning

Acceptance of solar energy		Cost	
		Cheap	Expensive
Familiarity	Familiar	Yes	Not sure
	Not familiar	Not sure	No

However, the "familiar or not familiar" or "cheap or expensive" boundary is fuzzy instead of crispy, different people have different understanding. The reasoning of acceptance of the solar panels is based on human knowledge and experience. This knowledge and experience suffer from ambiguous concepts. Fuzzy logic provides the mathematical tools to handle such imprecise description instead of precise one; and linguistic variables instead of numerical variables.

For example, cost of PV system ranges from 1 $/W to 10 $/W, traditional logic will treat it like 1-5 $/W considered as cheap, 5.1-10 $/W considered as expensive. But in fuzzy logic, it treat this problem as 1 $/W is 1-degree-cheap, 4 $/W is 0.75-degree-cheap, something like that. The degree-of-cheap can be denoted as membership function. Figure below shows the membership function of cost.

Why to implement fuzzy logic in the study of social acceptance to renewable energy adoption?

1. Social acceptance study involves imprecise description form human experience and knowledge. For example, “some consumer believes PV system is hard to maintain; some others consider it is easy to maintain”. Either “hard” or “easy” is vague and imprecise description. Also the information obtained from survey or interviews are impossible to reflect the complete decision-making process.

While, fuzzy logic is designed to handle the imprecision and insufficient information system.

2. Most of the existing studies of social acceptance are qualitative analysis. However, in some case, quantitative analysis is necessary to make, for example, to forecast the adoption potential of a certain technology quantitatively.

While, fuzzy logic is a methodology of quantitative variables and mathematical operations.

3. The existing quantitative studies focused on statistically revealing the relevance between demographic characters (such as age, income) and social acceptance and renewable energy, however, fail to explain the logic reasons of that relevance.

While, the methodology of fuzzy logic is mimicking the logic inference process of human being and can reasons how the multiple social characteristics (such as familiarity of renewable energy technology and environmental aware) relates to social acceptance.

4.4.2 Basic Concepts of Fuzzy Logic and Literature Review

The term fuzzy logic has been used in two different senses. In a narrow sense, fuzzy logic refers to a logical system that generalizes classical two-valued logic for reasoning under uncertainty. In a broad sense, fuzzy logic refers to all of the theories and technologies that employ fuzzy sets, which are classes with unsharp boundaries (Yen and Langari, 1999). The idea of fuzzy sets was born in 1964 by Lofti A. Zadeh, a professor of electrical engineering and computer science. Even though there was strong resistance, scholars and scientists in a wide variety of fields—ranging from engineering to sociology have been exploring this methodology. During the past decades, especially after 1990, fuzzy logic has been implemented broadly in the field of engineering, from fuzzy control to fuzzy model identification. After he proposed the concept of fuzzy logic more than 40 years, Professor Zadeh, in the article stated "Fuzzy logic may be viewed as an attempt at formalization/mechanization of two remarkable human capabilities. First, the capability to converse, reason and make rational decisions in an environment of imprecision, uncertainty, incompleteness of information, conflicting information, partiality of truth and partiality of possibility-in short, in an environment of imperfect information. And second, the capability to perform a wide variety of physical and mental tasks without any measurements and any computations. (Zadeh, 2008).

The core methodology of fuzzy logic is based on four concepts: (1) fuzzy sets: sets with smooth boundaries; (2) linguistic variables: variables whose values are both qualitatively and quantitatively described by a fuzzy set; (3) possibility distributions: constraints on the value of a linguistic variable imposed by assigning it a fuzzy set; (4) fuzzy if-then rules: a knowledge representation scheme for describing a functional mapping for a logic formula that generalized an implication in two-valued logic.

There are several existing researches are trying to implement fuzzy logic to address energy issues.

Kaminaris et al., (2006) assessed three renewable energy technologies (PV, wind, small hydro of their life cycle cost, emissions and etc using fuzzy logic to aid decision making. However, he didn't emphasis on the risks or dynamics of the projects. And the variables and membership functions are also not effective or sufficient to capture the features of sustainability and resilience.

Chedid et al., (1999) presents a fuzzy multi-objective linear programming approach to solve energy resource allocation problem. The objectives include minimizing cost, maximizing efficiency, maximizing the use of local resources and etc. It is mainly in the rural area and most of the electricity consumption can be powered by local resources, such as wood and solar thermal.

Doukas et al., (2007) uses multi-criteria decision making and linguistic variables (fuzzy logic) to evaluate power generation technologies. It also develops several improved methods based on weighted operator and realizes them by computer programming.

However, these existing research have analyzed the features of power system in a static way and not considering the risks and resilience of the system.

Medina and Morero, (2007) evaluates risks in Colombia electricity market using fuzzy logic considering regulatory risk, electric risk and social-political risk. However, his focus is merely on electricity cost (how risks affect cost), and the risks are very Colombia-based.

Phillis and Andriantiatsaholiniaina (2001) evaluate the vague concept—sustainability measuring ecological indicators and human indicators. In the aid of fuzzy logic, it combines all indicators to an overall measure. The output of this model is a degree of sustainability of a certain country.

4.5 Application of Fuzzy Logic to Social Acceptance (Purchasing Probability) of Solar Energy

After introduction of fuzzy logic and literature reviews of the energy relevant application of this methodology, we will describe the problem of social acceptance and the solving method using fuzzy logic step by step.

4.5.1 Problem Identification and Variables

The problem we are attempting to solve is to evaluate the social acceptance of distributed solar energy using fuzzy logic by interpreting the results from the survey we conducted. From the Section of Survey of customers' attitude toward solar energy, we know there are several perception variables of customers such as Environmental concern (E), perceived Cost of solar panels (C), and perceived Maintenance requirement (M) are significantly different between early adopter (N1 samples) and non-adopter (N samples).

We define these two groups as:

A(N1)—Early-adopters

B(N)—Non-adopters

Each sample has its own characteristics, the functions (they are called membership functions) denoted as:

A_i {E,C,M}, $i \in (1,N1)$

B_j {E,C,M}, $j \in (1,N)$

Perception variables:

E--Environmental concern,

C--perceived Cost of solar panels,

M--perceived Maintenance requirement

4.5.2 Fuzzy Logic Model Structure

The purpose of the evaluation is to figure out the purchasing probability (prob) of distributed solar energy among the non-adopters, denoted as: Bj {prob}

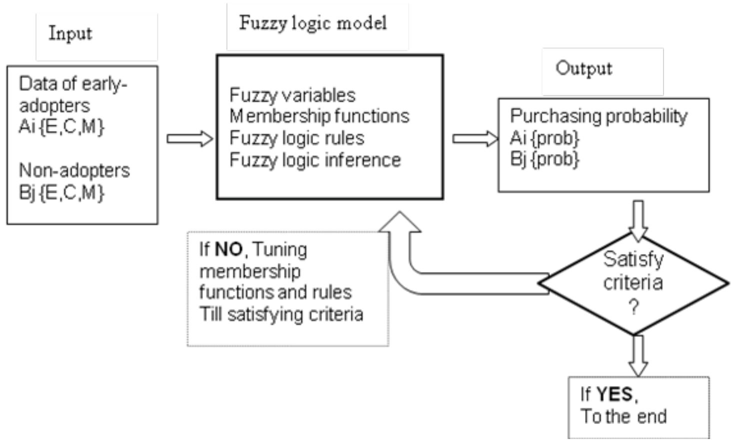


Figure 4-4: Fuzzy Logic Inference Model for Purchasing Probability Analysis

Figure 4-4 illustrates the flow of fuzzy logic methodology. The inputs are survey data from adopters and non-adopters. The outputs are the evaluation of purchasing probability for each sample. The model is constructed by fuzzy logic inference which will be discussed in detail step by step. Similar as other mathematical models, the methodology provides a structure of models. To validate the model, parameters and rules have to be tuned to satisfy certain criteria. The criteria are important to control the modeling process. Only if the criteria are satisfied, the model is validated to implement. Otherwise, parameters and rules are kept tuning.

The model can be presented as:

A_i {prob}= Fuzzy logic inference (A_i {E,C,M}), $j\in(1,N1)$

B_j {prob}= Fuzzy logic inference (B_j {E,C,M}), $j\in(1,N)$

4.5.3 Fuzzy Sets and Membership Functions

A set in classical set theory always has a sharp boundary. Fuzzy set is a set with smooth boundary. For example, if the cost of PV system is $20,000, we can say it is high, and $5,000 is low; however, the cost $10,000 is somewhat high or low. A fuzzy set is thus defined by a function that maps objects in a domain of concern to their membership value in the set. Such function is called the membership function. The membership function of a fuzzy set A is denoted as μ_A, and membership value of x in A is denoted as $\mu_A(x)$. The most common shapes of membership functions are triangular and trapezoidal ones, which are practiced effectively and efficiency among the community of fuzzy logic.

In this study for each variable E,C,M; the fuzzy set can be {Low, Middle, High}. The shape of membership functions can be triangular or trapezoid. How to understand the membership functions? Taking the perceived maintenance requirement (M) of solar panels for example, we assume

If M is less than 2, Then we consider it as low

If M is higher than 7, Then we consider it as high

If M is between 2 and 7, Then we consider it as somewhat low and somewhat high (it can be defined using membership function).

We now translate this human language to fuzzy logic.

MatchingDegree (M, Low) = $\mu_{Low}(M)$

MatchingDegree (M, Middle) = $\mu_{Middle}(M)$

MatchingDegree (M, High) = $\mu_{High}(M)$

So, for example

If M=1; Then

MatchingDegree (1, Low) = $\mu_{Low}(1) = 1$;

MatchingDegree (1, Middle) = $\mu_{Middle}(1) = 0$;

MatchingDegree (1, High) = $\mu_{High}(1) = 0$;

If M=2.4; Then

MatchingDegree (2.4, Low) = $\mu_{Low}(2.4) = 0.5$;

MatchingDegree (2.4, Middle) = $\mu_{Middle}(2.4) = 0.5$;

MatchingDegree (2.4, High) = $\mu_{High}(2.4) = 0$;

If M=8; Then

MatchingDegree (8, Low) = $\mu_{Low}(8) = 0$;

MatchingDegree (8, Middle) = $\mu_{Middle}(8) = 0$;

MatchingDegree (8, High) = $\mu_{High}(8) = 1$;

The membership functions in this study are shown in Figure 4-5.

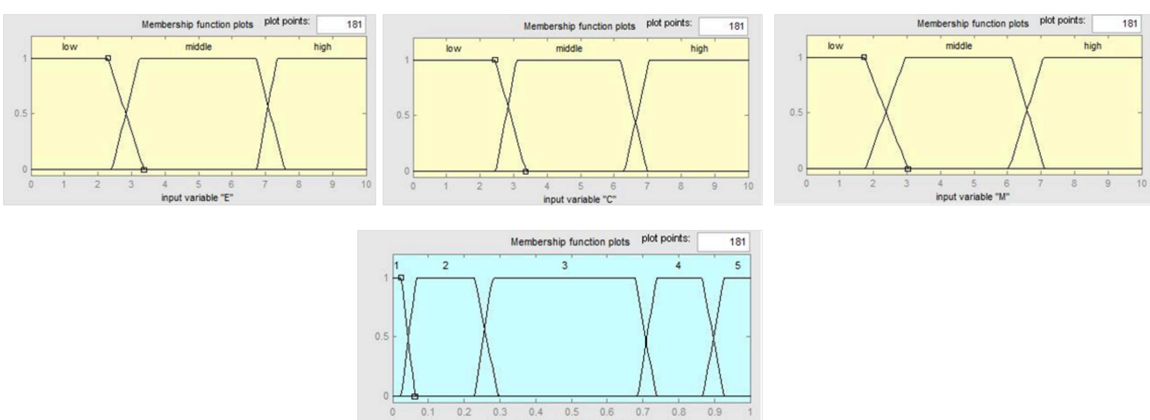


Figure 4-5: Membership Functions of Variables: E, C, M and Probability

4.5.4 Fuzzy If-Then Logic Inference

After the fuzzy variables and membership functions have been defined. The next step is to define If-Then logic inference.

For example, if the relative cost of solar panel is low, the familiarity of solar panels is high, the moving frequency is low and environmental awareness is high, then the acceptance of this technology is considered to be high logically.

To translate this reasoning into fuzzy logic:

IF E is High, AND C is Low, AND M is Low,

THEN Probability is Very high (5).

IF E is Middle, AND C is Low, AND M is Low,

THEN Probability is Somewhat high (4).

IF E is Low, AND C is Low, AND M is Low,

THEN Probability is Neutral (3).

IF E is Low, AND C is High, AND M is Low,

THEN Probability is Somewhat Low (2).

IF E is Low, AND C is High, AND M is High,

THEN Probability is Very Low (1).

.

.

.

Because the fuzzy set of each variable has 3 values {high, middle, low}, and there are 3 variables (E, C, M), so there are 27 (3*3*3) combinations. We also should define the probability into similar way:

{100%, 75%; 50%; 25%; 0%} = {5,4,3,2,1}

Table 4-9 shows the rules of fuzzy logic reasoning which have been tuned for validity.

Table 4-9: Rules of Fuzzy Logic IF-THEN Inference

	IF	AND	AND	THEN
	E	C	M	Probability
1	high	low	low	5
2	middle	low	low	4
3	low	low	low	3
4	high	middle	low	4
5	middle	middle	low	3
6	low	middle	low	3
7	high	high	low	3
8	middle	high	low	2
9	low	high	low	2
10	high	low	high	3
11	middle	low	high	2
12	low	low	high	1
13	high	middle	high	2
14	middle	middle	high	1
15	low	middle	high	1
16	high	high	high	1
17	middle	high	high	1
18	low	high	high	1
19	high	low	middle	4
20	middle	low	middle	3
21	low	low	middle	2
22	high	middle	middle	3
23	middle	middle	middle	2
24	low	middle	middle	2
25	high	high	middle	2
26	middle	high	middle	1
27	low	high	middle	1

The steps of methodology mentioned above have defined the functional operations of fuzzy logic. The function of fuzzy logic reasoning is like the engine, now we fuel the input data into the engine to make it run.

For a fuzzy system whose final output needs to be in a crisp form, a step is needed to convert the final combined fuzzy conclusion into a crisp one. This step is called the defuzzification. There are two major defuzzification techniques: (1) the Mean Maximum (MOM) method and (2) the Center of Area (COA) (Yen and Langari, 1999, p44).

4.5.5 MATLAB Programming and Tuning of Rules

In this study, a software toolbox in MATLAB is implemented: Fuzzy logic Toolbox, especially, Fuzzy Inference System (FIS) editor. It provides default parameters of membership functions (the shapes are chosen by modelers). The membership functions are shown in Figure 4-5. In this study, the parameters are not tuned because the default ones can satisfy the criteria. In practice, models usually choose to tune rule first then membership functions. The criteria for validating the model is to make the difference of mean values of the two groups maximized. By adjusting the membership functions and rules, modelers have accumulated expertise of modeling. After that, a maximized difference of 30% is achieved.

4.6 Results and Analysis

The results of purchasing probability distribution after model validation are shown in Figure 4-6. We must notice that comparing with the one using logistic regression model, the results from fuzzy logic model represent reality in a much more proper way. The peak of the purchasing probability distribution of adopters is at 100%, for non-adopters, it is at 20%. The difference between mean value of the probability is 30%.

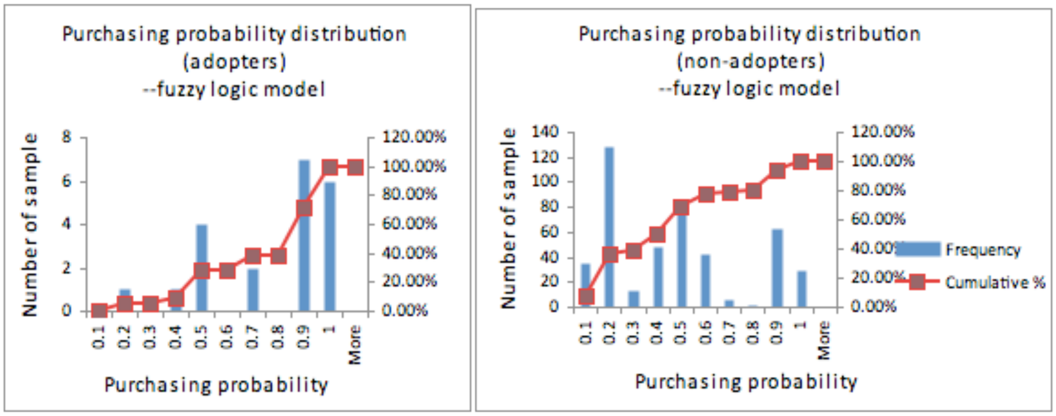


Figure 4-6: Purchasing Probability Distribution Using Fuzzy Logic Model

There is a 3-D graph shown in Figure 4-7 of purchasing probability of both adopters and non-adopters with the variables. The three variables represent the X,Y,Z axis and the size and color of the scattering dots represent the probability (the larger and lighter the dot, the higher the probability).

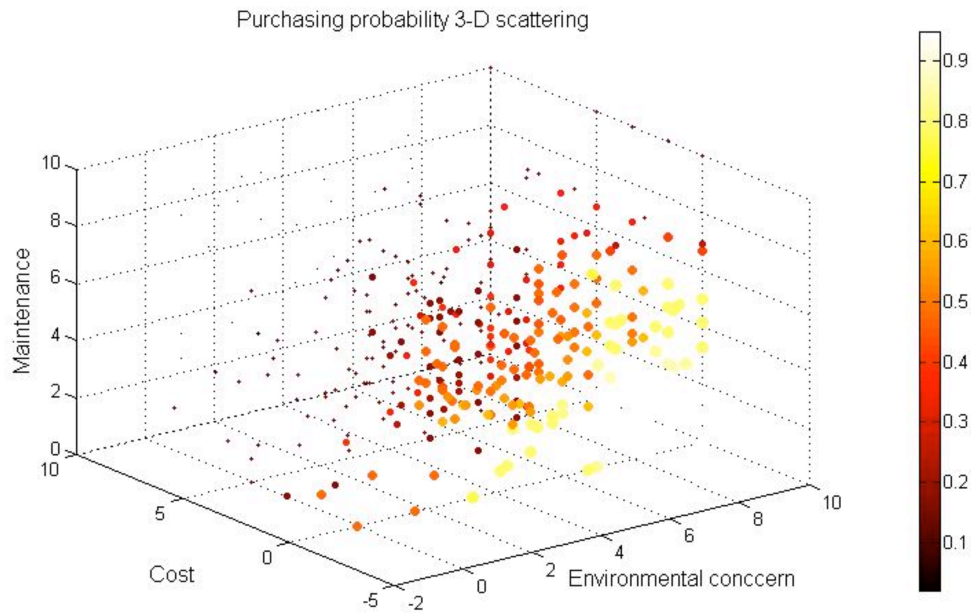


Figure 4-7: 3-D Purchasing Probability Scattering Using Fuzzy Logic Model

To understand the sensitivity of the purchasing probability to variables, 2-D graphs can help to observe the gradients (Figure 4-8). Discontinuous change of purchasing probability (thresholds, stacking) may reflect the decision making process but need more work to prove.

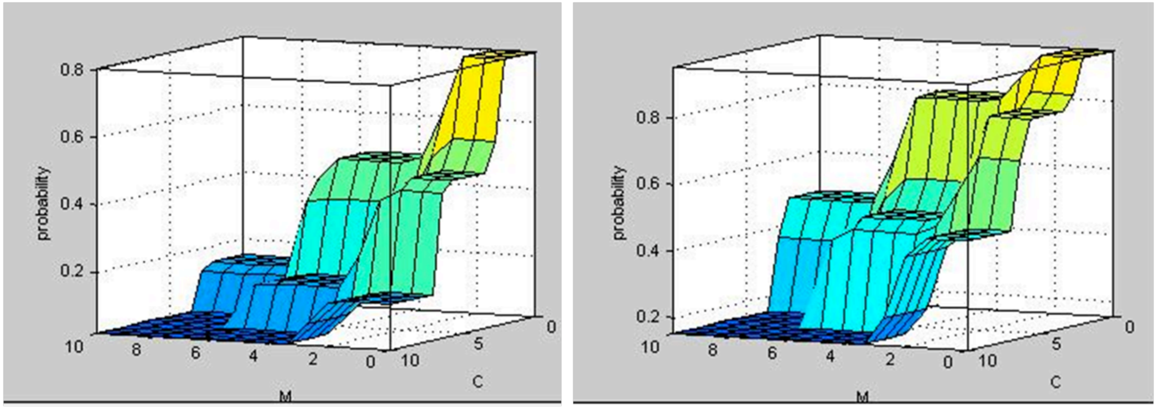


Figure 4-8: 2-D Purchasing Probability with the C and M variance

(left: E is 6, right: E is 8)

The purchasing probability distribution not only tells us the pattern of adoption. It also provides insights to investigate the adoption potential in the future. For example, then mean value of the purchasing probability of adopters is 0.72; while for non-adopters, it is 0.42. So it is arguable to state that 0.72 can be a future target for non-adopters if we consider the adoption process be a dynamic one. Of course, the target here is not set by individual customers. It can be guide for policy design.

Obviously, to achieve 0.72 (adopters' mean value), from this model, there are three ways: to increase E, decrease C or decrease M (Figure 4-9).

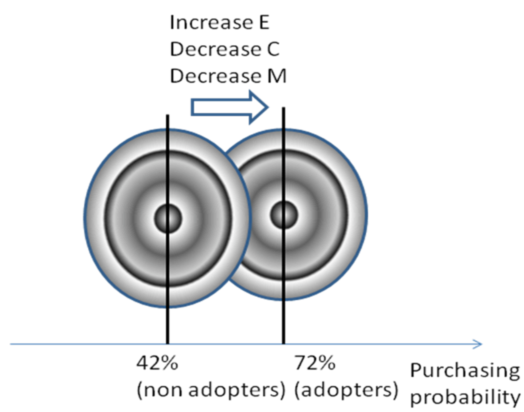


Figure 4-9: Purchasing Probability of Adopters and Non-adopters

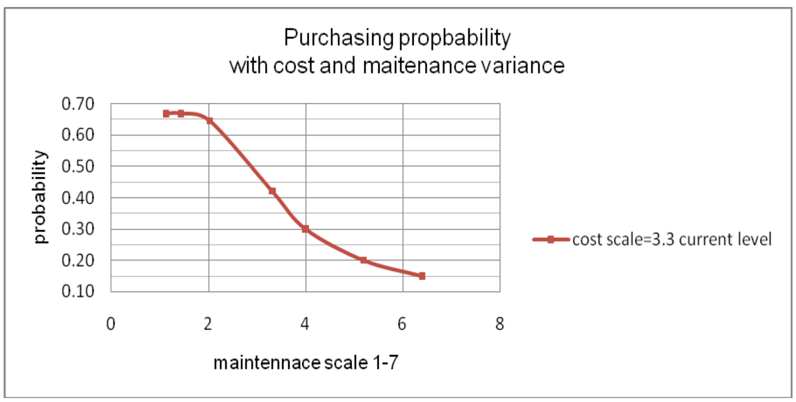


Figure 4-10: Purchasing Probability with Variance of M (Keep C Constant)

Decreasing C means to lower solar panels cost (assuming electricity rate keep constant). Decreasing M means to lower the maintenance requirement of solar panels. We need to notice that the variables here are perceived the cost or maintenance requirement. They are highly depending on customers' knowledge to the products. For example, the mean value of the perceived cost of non adopters is 3.3 (1-7 scales after weighted). That means they have optimistic attitude to cost-benefit of solar panels (benefit is higher than cost, equal at 4). In reality, the payback time of PV is around 21 years (the life time is 25 years). So the benefit is higher than cost, but not too much, the customers' perception can basically reflect the reality. However, the mean value of perceived maintenance requirement is 3.3 (requiring professional maintenance around once in 5 years). In reality, the maintenance requirement from professionals are once in 10 years (replacing inverters). There is huge potential for providing customer knowledge of maintenance to reduce M.

5. CONCLUSIONS

The first part of this dissertation advances the life cycle assessment (LCA) of photovoltaic modules by expanding the boundary of the included processes using hybrid LCA and accounting for the technology-driven dynamics of embedded energy and carbon emissions. Hybrid LCA is an extended method that combines bottom-up process-sum and top-down economic input-output (EIO) methods. In 2007, the embodied energy was 4,354MJ/m^2 and the energy payback time (EPBT) was 2.2 years for a multi-crystalline silicon PV system under 1700 kWh/m^2/yr of solar radiation. These results are higher than those of process-sum LCA by approximately 60%, indicating that processes excluded in process-sum LCA, such as transportation are significant. Even though PV is a low carbon technology, the difference between hybrid and process-sum results for 10% penetration of PV in the U.S. electrical grid is 0.13% of total current grid emissions. Extending LCA from the process-sum to hybrid analysis makes a significant difference. Dynamics are characterized through a retrospective analysis and future outlook for PV manufacturing from 2001 to 2011. During this decade, the embodied carbon fell substantially, from 60 g CO_2/kWh in 2001 to 21 g/kWh in 2011, indicating that technological progress is realizing reductions in embodied environmental impacts as well as lower module price.

Although the PV technologies are proved to have less environmental impacts, they are suffered from higher cost. To promote the adoption, governments establish regulations and provide subsidies.

The second part of the dissertation proposes three tiers of policy architecture: the top tier includes regulatory policies such as the Renewable Portfolio Standard (RPS); the middle tier is composed of financial support mechanisms, such as tax credit and rebates; and the bottom tier comprises policies that provide funding sources, such as Public Benefit funds. Such funds usually are collected from ratepayers of a public utility. Financial source must be sufficient to support the required subsidy if regulatory goals are to be achieved. However, researchers have often neglected the bottom tier. To address this issue, this research develops a model to reveal the subsidies required to support the RPS goal based on two key forecasting results: future renewable energy installation and experience curve-based cost reduction. The model is applied to the case study of solar energy adoption in the state of Arizona by 2025. The required installation capacity of distributed PV is targeted to 4200 MW by 2025, the price of the distributed PV system is forecasted to be 3 $/W. The annual investment in 2025 is almost $700 million (assuming the discount rate is zero). The financial requirements are calculated (in two scenarios) and compared with predictable funds from public sources. In scenario 1, the amount of required rebates from utilities to achieve the RPS target explosively increase from $170 million (year 2010) to $800 million (year 2025). In scenario 2, the amount is between around 100 to 200 million from 2010 to 2020. The predicted financial source cannot support the necessary rebates in either case. In 2008, APS collected $41.4 million from public benefit funds to support renewable energy, much less than needed. The study reveals the mismatches among policy tiers quantitatively and presents possible solutions.

The subsidies from the governments and utilities push down the cost of solar energy technologies. However, at customers' side, there are other social barriers for the adoption of solar energy.

To reveal the customers' attitude to solar energy, the survey was designed and distributed to homeowners of Phoenix, Arizona. There are many variables affect customers' decision making process of purchasing solar panels. The survey shows the top three variables are perceived cost (C), perceived maintenance requirement (M) and environmental concern (E). Here we identify them as perception variables. The statistics test show them are significantly different between adopters and non-adopters. To investigate the relationship between purchasing probability and the perception variables, statistic regression model is the most common tool to use. However, in this case, as we discussed, the model is not suitable. We develop a model of fuzzy logic inference and implement it to this case. The results show that the fuzzy logic inference model can reflect the reality and be validated. The purchasing probability distribution of adopters and non-adopters are the output of the model. To understand how the variables affect customers' decision making process, a sensitivity study is presented. For example, one of possible outcomes from the model can be, if we keep the cost constant, how the maintenance affects the purchasing probability. By providing enough information, the perceived maintenance has potential to decrease, so the purchasing probability has potential to increase from 40% to 63% from the model. However, if a higher purchasing probability is pursued, the efforts to increase environmental concern or decrease cost must be made.

6. LIMITATIONS AND FUTURE WORK

Understanding the limitations of research is important to help make future improvements. Generally speaking, limitations can come from methodology, data, and research scope. The limitations of each aspect involve uncertainties and caveats of explanation of results. In this section I discuss the main limitations of each chapter in this dissertation (three research topics).

In Chapter 2, the methodology is hybrid LCA combining process and economic input-output (EIO) LCA. A main uncertainty of EIO LCA is the aggregation uncertainty. Aggregation uncertainty arises from coarse graining of processes into sectors of EIO table. For example, the Miscellaneous Electrical Equipment sector used to describe inverter manufacturing aggregates many types of equipment. Also, the calculation of the embodied energy in transportation considers the Truck transportation as the only mode.

The process LCA assumes the technology of poly-silicon purification is Siemens method. However, the UCC-Fluidized Bed Reactors (FBR) for silicon deposition has been improved in recent years. It is very difficult to find data describing the share of solar grade silicon produced by different purification technologies. The embodied energy of silicon purification process using FBR is much lower than Siemens methods. It is worthwhile to incorporate the technology progress of silicon purification methods into LCA study.

Other than methodology limitations, in Chapter 2, the research scope is also limited to the case study of multi-Si PV. It is the mainstream PV products (more than 90% market share). For other types of PV technologies, such as thin film, which have quite different manufacturing and operation procedures, are making more market share, it is necessary to assess the environmental impacts of them in further study. Not only the embodied energy and carbon have environmental impacts, the impact from material flow, such as Cadmium (using in thin film PV) cannot be ignored.

The development of renewable energy manufacturing in developing countries, especially China, India and Brazil, is remarkable. The geographical structure of the supply chain has shifted dramatically which entails many uncertainties. Taking the embodied carbon for example, since more and more purified silicon is manufactured in China, and electricity in China is relatively carbon intensive, the embodied carbon must be higher for products made in developed countries. The study of this dissertation does not consider such geographic dynamics. In further study, a comparison of embodied energy in the products of different countries will be made.

Technological progress significantly reduces the environmental impacts of photovoltaic modules. This study only accounted for energy-related flows, but the improved efficiency of modules and reductions in material use are also likely to mitigate other environmental impacts such as land use and chemical consumption and emissions. Technological progress could significantly affect the environmental impacts of renewable energies ranging from other photovoltaic materials to biofuels to wind power. Decisions on the development and adoption of new energy technologies should be informed by the dynamics of environmental impacts. More work is needed to develop methods and explore case studies in order to characterize relationships between technological change and life cycle impacts.

In Chapter 3, one important assumption of the calculation of future investment requirement is the progress ratio of PV learning curve keeping constant. Since the price has significant impact on investment forecasting, more than one scenario of price reduction (various learning ratio) will be considered in future work.

Also, as a research topic, Chapter 3 raises a question of insufficient financial support, however, does not discuss the solutions. To promote the adoption robustly, there are two possible solutions which I want to propose in future work. One is to enact laws, such as a Feed-in Tariff; another is to set market tools, such as a carbon tax. It would be helpful to compare market-based policies with command and control-based policies for example in Germany and China. It is also interesting to understand how countries are racing in the battle of energy and trying to win out using various tools.

In Chapter 4, I discussed the relationship between the purchasing probability and the three variables. However, there are many other variables affecting customers' attitude, for example, the survey shows moving plan, appearance of solar panels, financial programs and regulation from Homeowner Association are among the factors affecting customers' attitude. In the future, a more advanced fuzzy logic model can be developed to include more variables. The fuzzy logic inference model provides an alternative solution to address the social issue of technology adoption. However, due to its characteristics of dealing with imprecise and insufficient information, it has potential to implement in domain of social science.

One important caveat in the study of Chapter 4 is data limitation-- that the sample for adopters is relatively small (the adoption of PV is in early adoption stage). To validate the model and provide policy implications, a larger sample is required by undertaking a larger survey study. The contributions of this study is to explore the applicability of soft computing model to social acceptance issues, and discuss *potential* policy implications. To make concrete policy suggestions, more work is needed in the future, from to improve data (larger sample) and methodology (more refined model).

REFERENCES

Aggan, N.H., Carvalho, M.G., 2000. Sustainable Assessment Method for Energy Systems. Kluwer Academic Publisher, Boston.

Alsema, E., 1998a. Energy requirements of thin-film solar cell modules—a review. Renewable and Sustainable Energy Reviews 2 (4), 387-415.

Alsema, E., Frankl, P., Kato, K., 1998b. Energy payback time of photovoltaic energy systems:present status and prospects. Presented at 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, 6-10 July, 1998.

Alsema, E., Nieuwlaar, E., 2000. Energy viability of photovoltaic systems. Energy Policy 28, 999-1010.

Alsema, E., 2005. The real environmental impacts of crystalline silicon PV modules: an analysis based on up-to-date manufacturers data. Presented at the 20th European Solar Energy Conference, Barcelona 6-10 June 2005.

Alsema, E., de Wild-Scholten, M.J., 2006a. Environmental impacts of crystalline silicon photovoltaic module production. Presented at 13th CIRP intern. Conf. on Life Cycle Engineering, Leuven, Belgium, 31 May-2 June 2006.

Alsema, E., de Wild-Scholten, M.J., Fthenakis, V.M., 2006b. Environmental impacts of PV electricity generation-a critical comparison of energy supply options. Presented at the 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4-8 September 2006.

Alsema, E., de Wild-Scholten, M.J., 2007. Reduction of the environmental impacts in crystalline silicon photovoltaic technology – an analysis of driving forces and opportunities.. Presented at Material Research Society Fall 2007 Symposium, Boston, USA, 26-30 November 2007.

Arizona Depart of Economic Security, 2006. Population Projected by Demographic Cohort-component Population Model, March.

Arizona Public Service, 2007. 2007-2016 ten-year Plan, January.

Arizona Public Service, 2009. 2008 Renewable energy standard compliance report, 2009 April

Arizona Public Service, 2010a. Retrieved June 2010, from http://www.aps.com/my_community/Solar/solar_34.html

Arizona Public Service, 2010b. Retrieved June 2010, from www.aps.com/_files/rates/RES.pdf

American Wind Energy Association, 2007. PTC fact sheet. Retrieved June 2007, from http://www.awea.org/pubs/factsheets/PTC_Fact_Sheet.pdf

BEA, 2002. Retrieved June 2010, from http://www.bea.gov/industry/iotables/

Beck, F., Martinot, E., 2004. Renewable energy policies and barriers. Encyclopedia of Energy 5, 365-383.

Bhandari, R.; Stadler, I., 2009. Grid parity analysis of solar photovoltaic system in Germany using experience curves. Solar Energy 83, 1634-1644.

Brown, M.A., Sovacool, B.K., 2007. Developing an energy sustainability index to evaluate energy policy. Interdisciplinary Science Reviews 32/4, 335-349.

Brundtland, G., 1987. Our Common Future: the world commission on the environment and development. Oxford University Press, Oxford.

Bullard, C., Herendeen R., 1975. The energy cost of goods and services. Energy Policy 3, 263-278.

Burgermeister, J., 2009. Germany: the world's first major renewable energy economy. Retrieved March 2010, from http://www.renewableenergyworld.com/rea/news/article/2009/04/germany-the-worlds-first-major-renewable-energy-economy.

Byrne, J., Hughes, K., Rickerson, W, Kurdgelashvili, L., 2007. American policy conflict in the greenhouse: Divergent trends in federal, regional, state, and local green energy and climate change policy. Energy Policy 35, 4555-4573.

Cameron, A. 2010. Spanish PV after the crash. Retrieved July 2010, from http://www.renewableenergyworld.com/rea/news/article/2010/04/spanish-pv-after-the-crash

Chedid, R., Mezher, T., Jarrouche, C., 1999. A fuzzy programming approach to energy resource allocation. International Journal of Energy Research 23(4), 303-317.

ChinaDaily, 2009. China eyes 20% renewable energy by 2020. Retrieved March 2010, from http://www.chinadaily.com.cn/china/2009-06/10/content_8268871.htm

Clark, W.C., Munn, R.E., 1986. Sustainable Development of Biosphere. Cambridge University Press, Cambridge.

Claudy, M.C., Michelsen, C., O'Driscoll, A., Mullen, M.R., 2010. Consumer awareness in the adoption of microgeneration technologies: an empirical investigation in the Republic of Ireland. Renewable and Sustainable Energy Reviews, In Press

CRS, (2007). Congressional Research Service, Energy tax policy: history and current issues.

CMU, 2009. Economic input-output life cycle assessment. Carnegie Mellon University. Retrieved June 2010, from http://www.eiolca.net/

Department of Energy, 2009. Consumer energy tax incentives. Retrieved March 2010, from http://www.energy.gov/taxbreaks.htm

deWild-Scholten, M. J., Alsema, E., 2006a. Environmental Life Cycle Inventory of Crystalline Silicon Photovoltaic Module Production - Excel file, ECN. Retrieved June 2010, from http://www.ecn.nl/docs/library/report/2006/c06002-LCI_data-cSiPV-pub-v1.xls

deWild-Scholten, M. J., Alsema, E., Horst, E.W. ter., 2006b. A Cost and Environmental Impact Comparison of Grid-Connected Rooftop and Ground-Based PV Systems, 21st European Photovoltaic Solar Energy Conference, Dresden, WIP-Renewable Energies, Munich, Germany, p. 3167-3173.

Doukas, H. C., Andreas, B. M., & Psarras, J. E., 2007. Multi-criteria decision aid for the formulation of sustainable technological energy priorities using linguistic variables. European Journal of Operational Research 182(2), 844-855.

DSIRE, 2010. Datebase of State Incentives for Renewables and Efficiency. Retrieved March 2010, from http://www.dsireusa.org/

Elghali, L., Clift, R., Sinclair, P., etc, 2007. Developing a sustainability framework for the assessment of bioenergy systems. Energy Policy 35, 6075-6083.

Eltawil, M. A., Zhao, Z., 2010. Grid-connected photovoltaic power systems: Technical and potential problems—A review. Renewable and Sustainable Energy Reviews 14(1), 112-129.

Energy Information Administration, 2007a. Form EIA-63B, "Annual Photovoltaic Module/Cell Manufacturers Survey." 2007. Retrieved June 2010, from http://www.eia.doe.gov/cneaf/solar.renewables/page/solarreport/solarpv.html

Energy Information Administration, 2007b. EIA State Electricity Profiles: Arizona Electricity Profile. November, 2007. Retrieved July 2009, from http://www.eia.doe.gov/cneaf/electricity/st_profiles/arizona.html

Energy Information Administration, 2010. Electric Power Annual 2007: A Summary. Retrieved June 2010, from http://www.eia.doe.gov/bookshelf/brochures/epa/epa.html

Engelenburg, B. C., Rossum, T. F., 1994. Calculating the energy requirements of household purchases- A practical step by step. Energy Policy 22(8), 648-656.

Farhar, B., Coburn, T., 2000. A market assessment of residential grid-ties PV systems in Colorado. NREL technical report, 2000, September.

Fthenakis, V.M., Kim, H.C., Alsema, E., 2008. Emissions from photovoltaic life cycles, Environ. Sci. Technol. 42(6), 2168-2174.

Garrera, D.G., Mack, A., 2010. Sustainability assessment of energy technologies via social indicators: results of a survey among European energy experts. Energy Policy 38, 1030-1039.

Garthwaite, J., 2009. How realistic is Obama's goal to double clean energy by 2012? Retrieved March 2010, from http://earth2tech.com/2009/01/09/how-realistic-is-obamas-goal-to-double-clean-energy-output-by-2012/.

Hariharan, G., Sato, S., Liu, C., 2008. Solar cell supply chain. Asia Pacific Equity Research by JPMorgan. 2008 report.

Headrick, D. The Tools of Empire: Technology and European Imperialism in the Nineteenth Century. Oxford University Press, New York, 1981

Heijungs, R., 1994. A generic method for the identification of options for cleaner products. Ecol. Econ. 10, 69-81.

Henderickson, C.T., Horvath, A., Joshi, S., Lave, L.B., 1998. Economic input-output models for environmental life-cycle assessment. Environ.Sci.Technol 32 (4), 184A.

Herrera, T., 2009. Path to $3B in stimulus funds revealed to renewable energy developers. Retrieved March 2010, from http://www.greenbiz.com/news/2009/07/10/3b-stimulus-funds-renewable-energy-rules

Hirschl, B., 2010. International renewable energy policy—between marginalization and initial approaches. Energy Policy, In Press, Corrected Proof.

Hoff, T.E., 2006. Photovoltaic incentive design handbook. U.S. National Renewable Energy Laboratory report, December.

Hunt, L.P., 1976. Total energy use in the production of silicon solar cells from raw materials to finished product. Proceedings of IEEE photovoltaic specialty conference 347-351.

IEA, 2006. International Energy Agency, Energy Technology Perspectives -- scenarios and strategies to 2050.

IEA, 2009. International Energy Agency, PV roadmap targets viewing. Retrieved March 2010, from http://www.iea.org/papers/2009/PV_roadmap_targets_viewing.pdf

IEA, 2010. International Energy Agency, World Energy Outlook 2010.

ISO (International Standards Organization), 1997. ISO 14040 - Environmental management - Life cycle assessment - Principles and Framework.

Kaminaris, S. D., Tsoutsos, T. D., Agoris, D., Machias, A. V., 2006. Assessing renewables-to-electricity systems: A fuzzy expert system model. Energy Policy 34(12), 1357-1366.

Kato, K., Murata, A., Sakuta, K., 1997. Evaluation of the life cycle of photovoltaic energy system considering production energy of off-grade silicon. Solar Energy Mater. Solar Cell 47 (1), 95-10.

Laird, F.N., Stefes, C., 2009. The diverging paths of German and United States policies for renewable energy: Sources of difference. Energy Policy 37, 2619-2629.

Lave, L., Cobas-Flores, E., Hendrickson, C., McMichael, F., 1995. Using Input-Output Analysis to Estimate Economy-Wide Discharges. Environ.Sci.Technol 29(9), 420A-426A.

Leontief, W., 1970. Environmental Repercussions and the Economic Structure: An Input-Output Approach. The Review of Economics and Statistics 52 (3), 262-271.

Mallett, A., 2007. Social acceptance of renewable energy innovations: the role of technology cooperation in urban Mexico. Energy Policy 35, 2790-2798.

Medina, S., Moreno, J., 2007. Risk evaluation in Colombian electricity market using fuzzy logic. Energy Economics 29(5), 999-1009.

Mendonca, M.; Lacey, S.; Hvelplund, F., 2009. Stability, participation and transparency in renewable energy policy: Lessons from Denmark and the United States. Policy and Society, 27, 379-398.

Menz, F.C., 2005. Green electricity policies in the United States: case study. Energy Policy 33, 2398-1410.

Mints, P., 2009. Module pricing rational or just plain nuts. Retrieved March 2010, from http://www.renewableenergyworld.com/rea/news/article/2009/09/module-pricing-rational-or-just-plain-nuts

Mints, P., 2010. The PV industry's black swan. Retrieved in March 2010 from http://www.electroiq.com/index/display/photovoltaics-article-display/3108489888/articles/Photovoltaics-World/industry-news/2010/march/the-pv_industry_s.html

National Research Council, 1980. National Research Council, Energy Choices in a Democratic Society. National Academy of Sciences, Washington, DC.

Neij, L., 1997. Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology. Energy Policy 25(13), 1099-1107.

Nemet, G.F., 2006. Beyond the learning curve: Factors influencing cost reductions in photovoltaics. Energy Policy 34(17), 3218-3232.

Newman, P., 2010. Feed-in Tariff docket at Arizona Corporation Commission. Presented at Energy and Environment Conference, Arizona, February 2010.

Hirschl, B., 2010. International renewable energy policy—between marginalization and initial approaches. Energy Policy, In Press, Corrected Proof

NRC, 1980. National Research Council, Energy Choices in a Democratic Society. National Academy of Sciences, Washington, DC

NREL, 2006. U.S. National Renewable Energy Laboratory, A review of PV inverter technology cost and performance projections. Navigant Colnculting Inc. NREL/SR-620-38771, January, 2006.

NREL 2007. U.S. National Renewable Energy Laboratory, National solar technology roadmap: wafer-silicon PV. NREL/MP-520-41733, June, 2007.

NREL 2008. U.S. National Renewable Energy Laboratory, SAM Public Cost Model Version 1.0. Retrieved June 2010, from https://www.nrel.gov/analysis/sam/cost_data.html

OpenPV, 2010. Retrieved in March 2010, from http://openpv.nrel.gov/share

PACE, 2010. Retrieved in July 2010 from http://solarfinancing.1bog.org/pace-program-solar-financing/

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

Palmer, K., Burtraw, D., 2005. Cost-effectiveness of renewable electricity policies. Energy Economics 27, 873-894.

Podobnik, B., 1999. Toward a sustainable energy regime: A long-wave interpretation of global energy shifts. Technological Forecasting and Social Change 62(3), 155-172.

Papineau, M., 2006. An economics perspective on experience curves and dynamic economies in renewable energy technologies. Energy Policy 34, 422-432.

Pillis, Y., Andriantiatsaholiniaina. L., 2001. Sustainability: an ill-defined concept and its assessment using fuzzy logic. Ecological Economics 37, 435-456.

Pryor, S. C., Barthelmie, R. J., 2010. Climate change impacts on wind energy: A review. Renewable and Sustainable Energy Reviews 14(1), 430-437.

PVWatt, 2010. Retrieved March 2010, from http://rredc.nrel.gov/solar/codes_algs/PVWATTS/version1/

Randazzo, R., 2010. APS moves to reduce solar rebates. Retrieved in July 2010 from http://www.azcentral.com/news/articles/2010/04/03/20100403aps-solar-rebate.html

REN21, 2010. Renewable Energy Policy Network for the 21st Centrury. Renewables global status report, p. 9.

Renn, O.,Dreyer, M., Schweizer, P., Kinke, A., 2007. Uben den gesellschaftlichen umgang mit unsicherheit. Munchen. Okom.

RES, 2006. Arizona Renewable Energy Standard Summary, 2006

Schaeffer, G.J., Alsema, E., Seebregts, A., 2004. Learning from the Sun, analysis of the use of experience curves for energy policy purposes: the case of photovoltaic power. Final report of the Photex project. ECN-C-04-035. August, 2004.

Sherwani, A.F., Usmani, J.A., Varun., 2010. Life cycle assessment of solar PV based electricity generation systems: a review. Renewable and Sustainable Energy Reviews 14(1), 540-544.

Solarbuzz, 2009. SolarBuzz online database. Retrieved June 2010, from http://www.solarbuzz.com/InverterPrices.htm

Sovacool, B.K., Cooper, C., 2006. Green means ‘go?’—A colorful approach to a U.S. national renewable portfolio standard. The Electricity Journal 19(7), 19-32.

Sovacool, B. K., 2009a. Rejecting renewables: The socio-technical impediments to renewable electricity in the United States. Energy Policy 37, 4500-4513.

Sovacool, B. K., 2009b. The importance of comprehensiveness in renewable electricity and energy-efficient policy. Energy Policy 37, 1529-1541.

Sovacool, B.K., 2009c. The cultural barriers to renewable energy and energy efficiency in the United States. Technology in Society 31, 365-373.

Salt River Project, 2007. Annual Report.

Stoppato, A., 2008. Life cycle assessment of photovoltaic electricity generation. Energy 33 (2), 224-232.

Suh, S., Huppes, G., 2005. Methods for life cycle inventory of a product. Journal of Cleaner Production13, 687-697.

Turner, B.L., 2010. Vulnerability and resilience: coalescing or paralleling approach for sustainability science? Global Environ. change doi: 10.1016/j.gloenvcha.2010.07.003

Toke, D., Lauber, V., 2006. Anglo-Saxon and German approaches to neoliberalism and environmental policy: the case of financing renewable energy. Geoforum 38, 677-678.

Tsoutsos, T., Stamboulis, Y., 2005. The sustainable diffusion of renewable energy technologies as an example of an innovation-focused policy. Technovation, 25, 753-761.

Williams, E., 2004. Energy intensity of computer manufacturing: Hybrid assessment combining process and economic input-output methods. Environ.Sci.Technol 38 (22), 6166-6174.

Williams, E., Weber, C., Hawkins, T., 2009. Hybrid Approach to Managing Uncertainty in Life Cycle Inventories Journal of Industrial Ecology 15(6), 928-944.

Wiser, R., Pickle, S., 1998. Financing investments in renewable energy: the impacts of policy design. Renewable and Sustainable Energy Reviews 2, 361-386.

Wiser, R., 2007. Wind power and the production tax credit: an overview of research results, testimony before the senate finance committee, March 29, 2007.

Wiser, R., Barbose, G., 2008. In: Renewable portfolio standards in the United States- A status report with data through 2007. Lawrence Berkeley National Laboratory report.

Wiser, R., Barbose, G., Peterman, C., 2009. Tracking the sum: the installed cost of photovoltaic in the U.S. from 1998-2007. Lawrence Berkeley National Laboratory report.

Wustenhagen, R., Wolsink, M., Burer, M.J., 2007. Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy 35, 2683-2691.

van Sark, W., Alsema, E., 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.

Voosen, P., 2009. Spain's solar market crash offers a cautionary tale about feed-in tariffs. Retrieved March 2010, from http://www.nytimes.com/gwire/2009/08/18/18greenwire-spains-solar-market-crash-offers-a-cautionary-88308.html

Yen, J., Langeri, R., 1999. Fuzzy logic: intelligence, control, and information. Prentice Hall, New Jersey.

Yin, H., Powers, N., 2010. Do state renewable portfolio standards promote in-state renewable generation? Energy Policy 38, 1140-1149.

Zadeh, L.A., 2008. Is there a need for fuzzy logic? Information Sciences 178, 2751-2779.

Zoellner, J., Schweizer-Ries, P., Wemheuer, C., 2008. Public acceptance of renewable energies: results from case studies in Germany. Energy Policy 36, 4136-4141.

APPENDIX A:

SURVEY FOR THE STUDY OF SOCIAL ACCEPTANCE OF

DISTRIBUTED SOLAR ENERGY

1. For homeowners

This page is ONLY for whom DOESN'T have solar panels installed for home.
If you have solar panels installed for home, please go to next page.

1. How old is(are) the homeowner(s) in your household?

Person 1 __________

Person 2 __________

2. How many people live in your household?

____

3. What is your household's annual income?

- ◯ <15,000
- ◯ 15,000-29,999
- ◯ 30,000-49,999
- ◯ 50,000-74,999
- ◯ 75,000-99,999
- ◯ 100,000-124,999
- ◯ 125,000-149,999
- ◯ 150-174,999
- ◯ 175,000-200,000
- ◯ >200,000

4. What is the highest educational level attained by the homeowner? (If there are multiple homeowners, then choose the highest)

- ◯ High school
- ◯ Some college
- ◯ Associate's Degree
- ◯ Bachelor's Degree (or equivalent)
- ◯ Some graduate school
- ◯ Master's or other professional degree
- ◯ Doctoral PhD, MD, or JD

5. As homeowners, in how many years do you plan to move to a newly purchased household?

- ◯ 0-4 years
- ◯ 4-8 years
- ◯ 8-12 years
- ◯ 12-16 years
- ◯ 16-20 years
- ◯ 20-25 years
- ◯ >25 years
- ◯ no plan

6. How often do you come across information about solar panels?

- ◯ Very often
- ◯ Often
- ◯ Sometimes
- ◯ Rarely
- ◯ Never

7. To your knowledge, solar panels do the following:

- ◯ Convert sunlight directly to electricity
- ◯ Convert sunlight to heat, then to electricity
- ◯ None of the above
- ◯ Have no idea

8. How frequently do you get information about solar panels from the following sources?

	Never	Rarely	Sometimes	Often	Very often
Public utilities	◯	◯	◯	◯	◯
Solar companies	◯	◯	◯	◯	◯
Friends/acquaintances	◯	◯	◯	◯	◯
TV programs	◯	◯	◯	◯	◯
Internet	◯	◯	◯	◯	◯
School/lectures	◯	◯	◯	◯	◯
Seeing actual solar panels	◯	◯	◯	◯	◯

Other sources (please specify)

____

9. Do you plan to purchase solar panels at some point in the future?

- ◯ Yes
- ◯ No
- ◯ Not sure

10. Do you think that solar panels would save you money over time?

	Cost a lot of money						Save a lot of money
They would	◯	◯	◯	◯	◯	◯	◯

11. How frequently do you think solar panels would require maintenance from professionals?

	Several times a year						Once in more than 10 years
They require	◯	◯	◯	◯	◯	◯	◯

12. How much do you think solar panels benefit the environment?

	No benefit						A lot of benefit
They have	◯	◯	◯	◯	◯	◯	◯

13. How visible would you prefer solar panels to look?

	Discreet/minimalist						Very obvious
I prefer	◯	◯	◯	◯	◯	◯	◯

14. I have not yet purchased a solar panel because:

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
I don't know enough about it	◯	◯	◯	◯	◯
Initial cost is too expensive	◯	◯	◯	◯	◯
It won't save enough electricity to be worth the expense	◯	◯	◯	◯	◯
I won't live here long enough to make it worth the expense	◯	◯	◯	◯	◯
It will make my house look unattractive	◯	◯	◯	◯	◯
It will take too much effort to maintain	◯	◯	◯	◯	◯
It won't work as advertised	◯	◯	◯	◯	◯
It doesn't benefit environment	◯	◯	◯	◯	◯
I don't know anyone who has one	◯	◯	◯	◯	◯

Other (please specify)

15. How much would the following factors affect your decision to purchase solar panels sometime in the future?

	Not affect						Greatly affect
The cost of solar panels	○	○	○	○	○	○	○
Maintenance requirements	○	○	○	○	○	○	○
Amount of time to break even on my investment	○	○	○	○	○	○	○
Environmental benefits	○	○	○	○	○	○	○
How long I would stay in the same house	○	○	○	○	○	○	○
Solar panel aesthetics on my rooftop	○	○	○	○	○	○	○
Convenient loan program	○	○	○	○	○	○	○

Other (please specify)

____

16. How much money would you be willing to pay each month in order to subsidize solar energy for everyone?

- ○ <1 dollar
- ○ 1-3 dollars
- ○ 3-6 dollars
- ○ 6-10 dollars
- ○ >10 dollars

17. I would be likely to purchase solar panels if the longest it takes to break even on my investment (pay back time) is:

- ○ < 3 years
- ○ 3-4 years
- ○ 5-6 years
- ○ 7-8 years
- ○ 9-10 years
- ○ > 10 years

18. I would be likely to purchase solar panels if the cost of electricity rises by:

- ○ 0< 40% (from $.10/kwh to $.14/kwh)
- ○ 40-80% (from $.14/kwh to $.18/kwh)
- ○ 80—150% (from $.18/kwh to $.25/kwh)
- ○ 150-300% (from $.25/kwh to $.4/kwh)
- ○ > 300% (more than $.40/kwh)

2. For early adopters of solar panels

This page is ONLY for whom has solar panels installed for home.
If you DON'T have solar panels for home, please answer questions on the previous page (if you have finished them, please scroll to the bottom of this page, click NEXT, and then click DONE on the next page).

1. How old is(are) the homeowner(s) in your household?

Person 1

Person 2

2. How many people live in your household?

3. What is your household's annual income?

- ◯ <15,000
- ◯ 15,000-29,999
- ◯ 30,000-49,999
- ◯ 50,000-74,999
- ◯ 75,000-99,999
- ◯ 100,000-124,999
- ◯ 125,000-149,999
- ◯ 150-174,999
- ◯ 175,000-200,000
- ◯ >200,000

4. What is the highest educational level attained by the homeowner? (If there are multiple homeowners, then choose the highest)

- ◯ High school
- ◯ Some college
- ◯ Associate's Degree
- ◯ Bachelor's Degree (or equivalent)
- ◯ Some graduate school
- ◯ Master's or other professional degree
- ◯ Doctoral PhD, MD, or JD

5. As homeowners, in how many years do you plan to move to a newly purchased household?

- ◯ 0-4 years
- ◯ 4-8 years
- ◯ 8-12 years
- ◯ 12-16 years
- ◯ 16-20 years
- ◯ 20-25 years
- ◯ >25 years
- ◯ no plan

6. Do you have solar panels installed and generating electricity for your home?

- ◯ Yes
- ◯ No

7. How are your solar panels connected to power grid?

- ◯ On-grid (grid connected)
- ◯ Off-grid

8. How many years has it been since you purchased the solar panels on your current home?

	<1 year	1-2 years	2-3 years	3-5 years	5-7 years	7-10 years	> 10 years
I've had them for	◯	◯	◯	◯	◯	◯	◯

9. What is the size of the solar panels?

	<2 kW	2.01-3 kW	3.01-4 kW	4.01-5 kW	5.01-6 kW	6.01-7 kW	>7 kW	Don't know
They are	◯	◯	◯	◯	◯	◯	◯	◯

10. To your knowledge, solar panels do the following:

- ◯ Convert sunlight directly to electricity
- ◯ Convert sunlight to heat, then to electricity
- ◯ None of the above
- ◯ Have no idea

11. How frequently did you use the following sources while researching your solar panel purchase?

	Never	Rarely	Sometimes	Often	Very often
Public utilities	◯	◯	◯	◯	◯
Solar companies	◯	◯	◯	◯	◯
Friends/acquaintances	◯	◯	◯	◯	◯
TV programs	◯	◯	◯	◯	◯
Internet	◯	◯	◯	◯	◯
School/lectures	◯	◯	◯	◯	◯
Seeing actual solar panels	◯	◯	◯	◯	◯

Other sources (please specify)

12. Before you purchased them, did you think that solar panels would save you money over the years you would own them?

	Cost a lot of money						Save a lot of money
I thought they would	◯	◯	◯	◯	◯	◯	◯

13. Accounting for both the cost of the initial purchase and subsequent savings, do you think that solar panels have saved you money over time?

	Cost a lot of money						Saved a lot of money
They have	◯	◯	◯	◯	◯	◯	◯

14. Before your purchased them, how frequently did you think solar panels would require maintenance from professionals?

	Several times a year						Once in more than 10 years
I thought they would require	◯	◯	◯	◯	◯	◯	◯

15. How frequently do your solar panels require maintenance from professionals?

	Several times a year						Once in more than 10 years
They require	◯	◯	◯	◯	◯	◯	◯

16. How much do you think solar panels benefit the environment?

	No benefit						A lot of benefit
They have	◯	◯	◯	◯	◯	◯	◯

17. How visible would you prefer solar panels to look?

	Discreet/minimalist						Very obvious
I prefer	◯	◯	◯	◯	◯	◯	◯

18. How have the following factors affected your decision of purchasing the solar panels?

	Not affect						Greatly affect
The cost of solar panels	○	○	○	○	○	○	○
Maintenance requirement	○	○	○	○	○	○	○
Amount of time to break even on my investment	○	○	○	○	○	○	○
Environmental benefits	○	○	○	○	○	○	○
How long I would stay in the same house	○	○	○	○	○	○	○
Solar panel aesthetics on my rooftop	○	○	○	○	○	○	○
Convenient loan program	○	○	○	○	○	○	○

Other (please specify)

19. How much money would you be willing to pay each month in order to subsidize solar energy for everyone?

- ○ <1 dollar
- ○ 1-3 dollars
- ○ 3-6 dollars
- ○ 6-10 dollars
- ○ >10 dollars

20. When you purchased your solar panels, how did you pay for them?

- ○ Paid the system up front
- ○ Took out loan
- ○ Rent the system
- ○ A mix of two
- ○ Don't remember

21. If you have any question or comment, please let us know.
To exit the survey and get credits, please click DONE on the next page.

APPENDIX B:

APPROVAL DOCUMENT FROM UNIVERSITY SUBJECTS INSTITUTE

REVIEW BOARD (IRB)

ASU Knowledge Enterprise Development

Office of Research Integrity and Assurance

To:	Eric Williams ERC
From:	Mark Roosa, Chair Soc Beh IRB
Date:	09/10/2010
Committee Action:	**Exemption Granted**
IRB Action Date:	09/10/2010
IRB Protocol #:	1008005404
Study Title:	Attitudes Toward Solar Energy

The above-referenced protocol is considered exempt after review by the Institutional Review Board pursuant to Federal regulations, 45 CFR Part 46.101(b)(2) .

This part of the federal regulations requires that the information be recorded by investigators in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects. It is necessary that the information obtained not be such that if disclosed outside the research, it could reasonably place the subjects at risk of criminal or civil liability, or be damaging to the subjects' financial standing, employability, or reputation.

You should retain a copy of this letter for your records.

APPEDIX C:

PERMISSION FOR USING DOCUMENTS CONTAINING PAPERS WHERE

THE STUDENT IS THE FIRST LISTED CO-AUTHOR

Coauthor (Dr. Eric Williams) has granted his permission to use the papers as the chapters in this document.

Chapter 2: Zhai P., Williams E. (2010). Dynamic hybrid life cycle assessment of energy and carbon of multicrystalline silicon photovoltaic systems, Environmental Science and Technology 44(20), 7950-7955.

Chapter 3: Zhai, P., Williams, E. (2010). The coordinative function of renewable energy policies—regulations, financial subsidies and funding sources. Energy Policy, under review.