COST-REDUCTION STRATEGIES IN THE SOLAR PHOTOVOLTAIC INDUSTRY: ECONOMIES OF SCALE IN SOFT COSTS AND INDUSTRY-LEVEL MODULARITY AS TOOLS TO INCREASE COMPETITION

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by

Benjamin M. Attia

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ABSTRACT

This is an independent research study highlighting scale benefits of soft costs and modularity as strategies for increasing cost-competitiveness in the solar PV industry. On the economies of scale front, an analysis of the implied soft costs over time presents a general trend of a decline in unit costs per watt due to decreasing module costs rather than soft cost declines, suggesting that modularity may be an effective strategy to drive down costs in solar PV project development. To that end, this analysis sought to index the level of modularity present in different US industries to see if the theory held true across the US economy and could be sustained and applied to the solar PV industry. Using a binary probit regression model: this research yielded an index of the level of modularity present in each US industry, as delineated by the NAICS codes, that was based on the following variables: intermediate transport levels, inter-industry interactions, energy intensity of industries, Cost of Goods Sold (as a percentage of All Returns), and level of technology. Energy intensity was found to be insignificant on the regression. The study revealed substantial skewedness in the distribution of index values, with a high concentration of points centered around the low end of the index, followed by a definitely sparsely populated central band, followed by a smaller but yet significant concentration of industries that were highly modular. Many of the modular industries are centered on capital production in a few select sectors. Unfortunately, the North American Industry Classification System data presently available does not capture the renewable energy industry with enough specific detail to be able to draw specific conclusions about the presence of economies of modularity in utility-scale solar PV as originally desired. However, these results represent a powerful framework that

can be replicated to draw solar PV industry-specific conclusions when more detailed energy sector input-output data tables become available in the next 12 to 18 months.

Chapter 1

INTRODUCTION & BACKGROUND OF STUDY

1.1 Introduction

As the energy sector transitions towards increased utilization of renewable energy, power providers are seeking to minimize the costs per kilowatt hour (kWh) of these technologies in order to become cost-competitive with current prices of fossil fuel-generated power. Looming uncertainty in futures markets for coal, oil, and even natural gas, as well as high concentrations of carbon dioxide and other pollutants from energy production using fossil fuel technology have contributed to the rapid increase in demand for clean, renewable energy generation.

Because people are economically rational beings, participation in sustainable development practices must be profitable in the long run. In order for people to adopt new technology or change their behavior, it must be in their own best interest, meaning that renewable energy must be economically profitable, affordable, and sustainable in the long run. In “Soft Energy Paths,” Amory Lovins discusses how even though Midwestern farmers lost 9 tons of soil per acre per year, nobody changed anything because, “at a 10 percent discount rate, soil in fifty years is hardly worth anything” (37, 1976). Lovins argues that that the conceptual framework with which we approach energy is entirely wrong, and that energy efficiency and renewable energy technologies, in addition to the necessity of supplying energy in “appropriate scale and quantity for our range of end use needs” are the key components of the ‘soft’ energy path away from unsustainable and environmentally-damaging practices and toward a sustainable energy future (Lovins, 44, 1976). Even in 1976, Lovins sought to explain the consequences of unsustainable economic growth and a price system that does not value environmental quality. If energy markets were responsible for the environmental costs of their carbon emissions, solar power would have reached grid parity many years ago. An international energy regulation handbook published by USAID (2011) notes that "cost calculations do not monetize environmental costs" (Bjork, et al., 19). However, due to the onset of peak oil and the limited supply of fossil-fuel resources, renewable energy will ultimately become the most economically feasible electricity source because, in many cases, fuel costs are zero, in spite of the fundamental flaws in environmental accounting in place today.

Understanding cost structures in solar markets, especially under different policy environments, is incredibly important in financing new installations efficiently and effectively, crafting policies that promote scale-based cost reductions, and remove technological, institutional, and economic barriers from restricting further capacity increases.

Aside from the carbon emissions reductions and other environmental benefits[1] that come with substituting solar power for fossil fuel generation, solar photovoltaics provide many other significant innate advantages. One such advantage is an elimination of fuel price uncertainty ("Top 5 Reasons"). Because sunlight is free, solar photovoltaic installations are immune to fuel price volatility, allowing electricity costs to be predictable and stable. Further, the time from approval to deployment is much lower than centralized fossil fuel power plants,

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[1] According to Carol Olsen, a researcher at the Energy Research Center of the Netherlands, "Compared with electricity from coal, photovoltaic electricity over its lifetime uses 86 to 89 percent less water, occupies or transforms over 80 percent less land, presents approximately 95 percent lower toxicity to humans, contributes 92 to 97 percent less to acid rain, and 97 to 98 percent less to marine eutrophication" (Powers).

which can take several years to construct and bring online. Wholesale distributed generation projects are ideal for rapid deployment because they “do not require lengthy permitting and construction of costly transmission lines” (“Top 5 Reasons”). Solar photovoltaic implementation has the ability to provide a powerful economic engine in a local setting. By creating green jobs, establishing a supply chain and network of installers, and creating revenue streams for homes and commercial businesses, solar photovoltaic growth can have serious economic benefits (Top 5 Reasons”).

The solar PV industry is a rapidly changing landscape, with plummeting module costs, variable policy environments and incentive structures, a tariff war over Chinese modules, and new financing mechanisms for solar projects, such as Power Purchase Agreements (PPAs), solar leasing, and Property Assessed Clean Energy (PACE) financing. These constantly changing incentive structures create difficulty in long-term valuation of solar projects, but many of these factors show promise of stabilizing in the next few years. The installed cost of solar power has been declining rapidly in the last few years, as total installed capacity has increased dramatically. At time of this writing, there is over 17.5 GW of total solar capacity installed in the United States and the projected growth rate is increasing at a rate faster than any other renewable energy technology (“Solar Industry Data,” SEIA, 2014). Feldman, et al. (2013) summarize the state of the market (at the time of publication):

> In 2011, the median reported installed price of residential and commercial PV systems was \$6.13/W for systems of 10 kW or smaller, \$5.62/W for systems of 10–100 kW, and \$4.87/W for systems larger than 100 kW. The capacity-weighted average reported installed price of utility- scale PV systems (ground-mounted systems at least 2 MW in size) declined from \$6.21/W during 2004–2008 to \$3.42/W in 2011. The drop in installed system prices has resulted from module and non-module cost reductions, but module costs have declined more quickly, thus heightening the PV industry’s recent emphasis on reducing non-module costs (p. 2)

Other factors that have lowered the cost of solar power include various policy incentives as well as technological advancements in efficiency, production processes, and material design. These factors comprise what Verbruggen, et al. (2009) call “disruptive changes” for the implementation of renewable energy.

1.2 Problem Statement

While installations range in size from massive solar farms in the hundreds of megawatts (MW) to just a few kilowatts (kW) of individual roof installations, the industry has yet to settle on the centralized or decentralized implementation model for solar photovoltaics. Some firms have sought to capitalize on the benefits of economies of scale in soft costs by creating utility-scale installations, while others have advocated for grid independence through small residential rooftop installations. Due to global panel manufacturing driving module costs down and evolving incentive and regulatory policies at the state and national levels for renewable technologies in the US, prices in the solar PV market vary dramatically in different states and nations. Solar PV has enormous technical potential, dropping prices, largely favorable policy environment, and characteristics that make the technology highly scalable and modular, but it is not yet fully cost-competitive with traditional carbon-based generation.

1.3 Thesis Statement

The solar industry, government agencies, and other key players in the field must capitalize on the cost-competitiveness gains inherent in the modularity and scalability of solar PV technology inherent in its nature in order to improve efficiency, lower costs, and stimulate investment.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

This literature review[2] seeks to understand the current body of literature in the field as applied two solar PV cost-reduction measures and strategies: scale benefits and learning reductions in soft costs and industry-level modularity. Beginning with scale economies in soft costs, the review will move to a summary of the various scales of system sizes, then to modularity as a general theory and industry-level modularity. The purpose is to understand the perspective of the literature on the source of lower installed costs per watt for larger systems. It is widely understood throughout the literature on PV cost studies that economies of scale exist in this industry, on both the module costs and manufacturing side as well as the soft costs side. Generally, much of the literature agrees that average unit prices on a per peak W_{dc} basis decrease as system size increases. However, in some cases, these scale benefits are exhaustible and reversible, creating situations in which the unit price per watt actually rises as the system size increases.

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[2] This literature review is based in part on exploratory research conducted by the author of this thesis and published for the National Regulatory Research Institute in a white paper entitled "A Review of Cost Comparisons and Policies in Utility-Scale and RooftopSolar Photovoltaic Projects." NRRI 14-05. June 2014.

2.2 Solar Photovoltaic Installed Cost Breakdown

Installed costs per watt of solar PV vary widely across the United States and the globe, depending on a long list of factors which will be explored below. The total installed cost is comprised of module costs, 'balance of system' (BoS) costs, and soft costs. Module costs entail the manufacturing and shipping cost of an individual PV panel. BoS costs include "site preparation and mounting systems, and power electronics gear including inverters, switches and wiring" (Stanton, et al., 2014, p. 15). Last are 'soft costs,' which include "marketing, customer acquisition, siting, permitting, applications, regulatory and contractual transactions, insurance, and property taxes" as well as interconnection, financing and cost of financial capital, installation labor, and variable O&M (Stanton, et al., 2014, p. 15).

In some countries, module costs make up a large percentage of the installed cost of a system, and in others, such as the United States, soft costs dominate the total installed cost by proportion. In 2013, NREL reported that soft costs became the largest piece of the total installed cost, comprising up to 64 percent of the system cost in residential systems, 57 percent of the small commercial price and 52 percent of the large commercial price (Friedman, et al., 2013, p. 2). These estimates are up from a 2010 study that estimated soft costs comprised 47 percent of residential installed costs, and 33 percent of commercial installed costs (Goodrich, James, and Woodhouse, 2012). However, these proportions vary just as much as the cost estimates. One study reports 50 percent variance in soft costs in different states, for both small-sized residential and for commercial systems larger than 100kW, highlighting discrepancies in "market size and maturity, incentive levels, regulatory costs, sales tax, and others" (Feldman, et al., 2013, p. 11). As PV module prices continue to plummet due to economies of scale in manufacturing, improved module conversion rates, and reduced raw-materials costs (Stanton, et al., 2014, p. 13), "the contribution of non-module costs to the cost of solar energy will increase" (Goodrich, James, and Woodhouse, 2012, p. 1). Module prices will likely continue to fall, but the real battle in making solar more cost-competitive will be on the soft cost side.

2.3 Economies of Scale in Soft Costs

The concept of a scale economy is based on the long-run average total cost curve of the firm. As the firm enters the long run, fixed costs are sunk and only variable costs remain at the margin. Therefore, when production expands, the average cost per unit is reduced over the increased output. The increase in production and maintenance of variable costs in factors of production, namely capital, allows the firm to spread sunk, fixed costs on the margin to reduce the cost per unit of output. As Barbose, et al. write, economies of scale in PV projects involve a firm "spreading fixed project and overhead costs over a large number of installed watts and, depending on the installer, through price reductions on volume purchases of materials" (Barbose, et al., 2012). The application of this idea to the production and deployment of solar PV parallels the application of scale economies to the current centralized electric grid and the massive fossil fuel power plants that power it. These monolithic systems face steep scale economies, with enormous upfront capital investment and a very low average cost per unit of energy (kWh), even after fuel costs.

As module prices continue to fall, a larger and larger portion of total system costs will be comprised of soft costs, which are highly dependent on local regulation and incentives and geography and irradiance, which determine factors such as the cost of labor, land, permitting, and grid interconnection. These soft costs are largely fixed, meaning that the dollar-per-watt cost of the system will decline predictably as the system's capacity increases. This phenomenon of economies of scale in soft costs has wide implications for the further driving down of the levelized cost of energy (LCOE) for solar PV-produced electricity. LCOE is "the constant dollar electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors" (MIT 2007, p. 127). LCOE metrics generally incorporate fixed costs, variable costs (fuel and operation and maintenance costs), and financing costs, such as the cost of debt and equity capital (Branker et al., 2011; EIA, 2013a; Namovicz, 2013). However, due to consistently outdated data in this rapidly changing and dynamic industry, these LCOE metrics are often inaccurate or vary widely with other estimates based on location or the age of available costing and pricing data (Goodrich, James, and Woodhouse, 2012, p. 34). Most LCOE studies don't include grid interconnection and integration costs as a cost in LCOE calculations, and when they do, average costs are often used rather than actual costs (Stanton, et al., 2014, p. 13). Other differences noted in the literature include variability by region, project site, quality of equipment, engineering and construction requirements, overhead of the installer, and risk profiles of investors (Feldman et al., 2013, p. 10; Bazilian et al., 2012, pp. 330-332; Goodrich, James and Woodhouse, 2012, p. 34).

Soft costs generally reflect economies of scale because smaller systems have equivalent or even higher costs for components including "customer acquisition, engineering design, permitting and inspections, financing, and contracting" (Stanton, et al., 2014, p. 18). However, Stanton, et al. point out that various government incentive programs are "effectively reducing some of these costs for smaller systems" (2014, p. 18). As system size increases, the general trend is to see greater realized economies of scale in the large residential and commercial scales, but to see diminishing returns to scale as system sizes increase within each market segment. (Feldman, et al., 2012, p. 11) Figure 1 below illustrates this trend of price benefits with increased system sizes. Feldman, et al. argue that larger systems are better able to amortize fixed overhead expenses and "also improve installer efficiencies and drive more efficient supply chain strategies" (2012, p. 12).

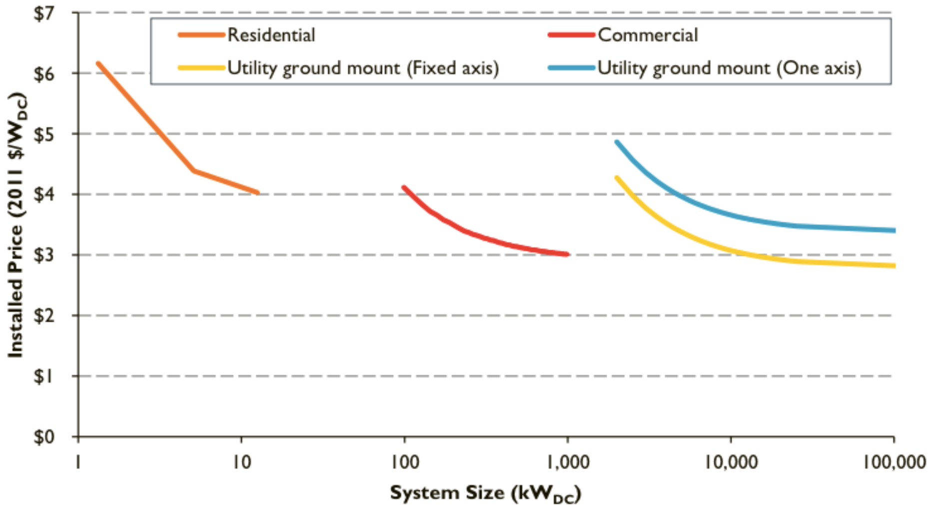

Figure 1: Economy of Scale Benefits by system size, Q4 2011
Source: Feldman, et al., 2012, p. 12

The amortization of fixed costs discussed above is also seen clearly in Figure 2 below. This figure illustrates the 20th/80th percentile ranges for each market sector of the reported price dataset in Feldman, et al. (2012) compared to the modeled bottom-up benchmark price. The figure represents the per-watt cost decline as system size increases, from residential at $6.13/W to commercial at $4.87/W and utility-scale at $3.42/W (Q4 2010 numbers).

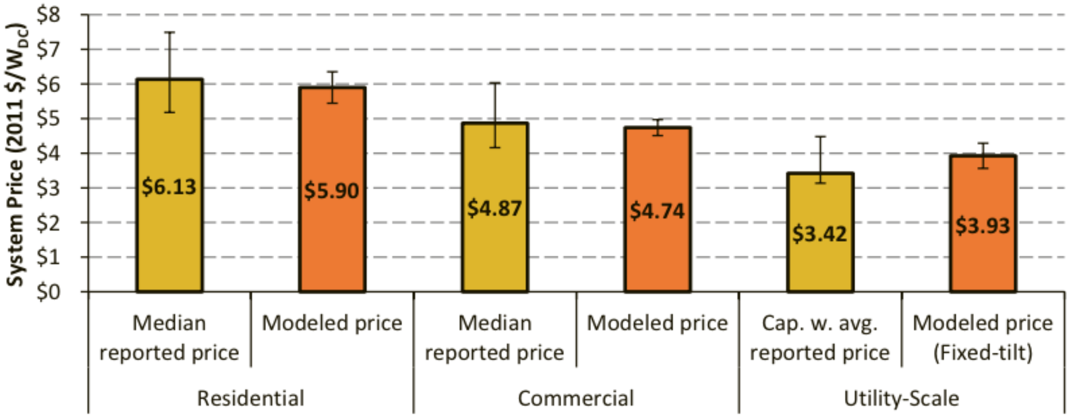

Figure 2: 2011 reported medial (residential/commercial) and capacity-weighted average (utility-scale) prices vs. Q4 2010 bottom-up benchmark prices
Source: Feldman, et al., 2012, p. 14

These scale benefits are felt more acutely in some cost components more than others, as described in the literature, which, likely due to the difficulty of collecting reliable and current data[3], generally disagrees on which soft cost benefits are of the greatest magnitude in scaled applications. For example, Ardani, et al. (2012, p. iv) explain that installation labor and customer acquisition labor "present the greatest potential for cost reductions for residential and commercial PV," while Goodrich, James, and Woodhouse argue that "permitting and regulatory needs, project transactions, and engineering design" costs "will be amortized over a larger system size" (2012, p. 12). These cost amortization benefits also vary across system scales. Goodrich, James, and Woodhouse (2012) report that

> "(a) residential system costs decline by approximately two-thirds as sizes increase from about 2 to 15kW; (b) commercial system costs are much steadier, but still decline by a few percentage points as sizes increase from about 10kW to as much as 1MW; and (c) utility-scale system costs per MW and MWh decline by over half as sizes increase from about 1MW to as much as 100MW" (13).

Seeing these costs from the perspective of the publically owned utilities (POUs), the NRRI study on which this portion of the literature review is based "identified lower costs for utility-scale systems, reflecting economies of scale in engineering, procurement, construction, and operation" (Stanton, et al, 23, 2014). As mentioned previously, these cost gains are due in part to learning rates, technological advances, supply chain management, and other indicators

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[3] "Consider an installer installing a system may not keep track of all those costs specific to an individual project and then has to answer a question about it in a form. Or consider that one installer that does track at least panel costs may use LIFO accounting but another may use FIFO accounting. Also consider that some installers in itemized quotes could roll some margin into equipment costs or that some installers by through distributors and others direct from manufacturers." (Personal Correspondence, March 16th 2015. Justin Baca of the Solar Energy Industries Association.)

of sector growth, as well as to economies of scale as system sizes increases. Figure 3 below represents the declining per-kW costs of different sized systems in California, and shows the scale economies gain between each size, from small residential to utility-scale. As system size increases, average cost per kW decreases dramatically. Additionally, Figure 3 also represents the changing module pricing for solar PV, reflected in the 40 to 60 percent decreases in average system cost for each system size from 2006 to 2013.

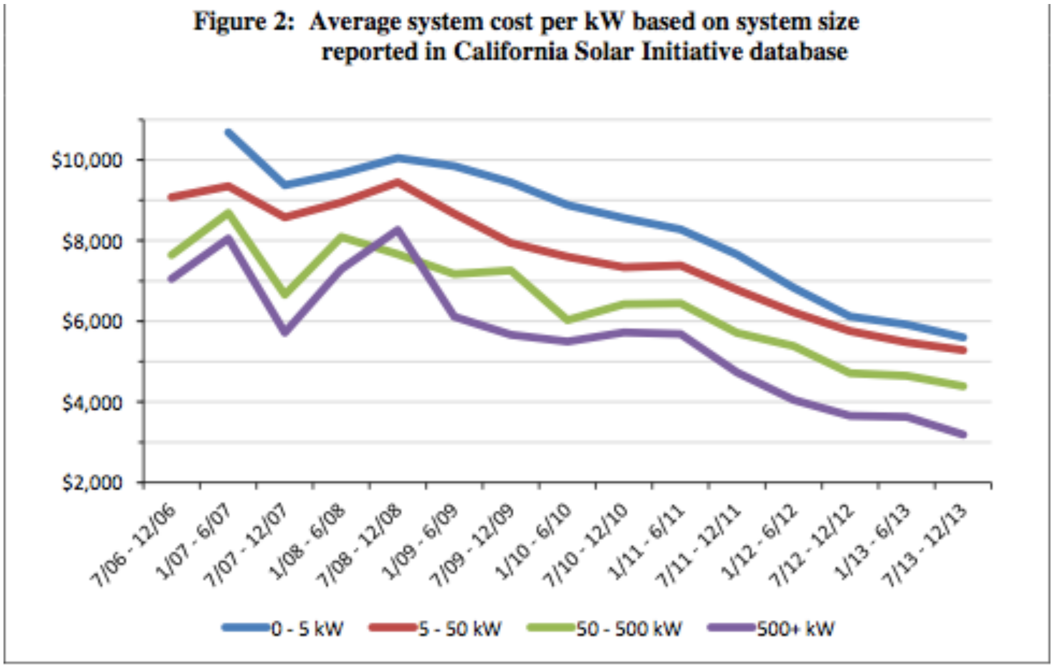


Figure 3: Average System cost per kW based on system size
Source: Stanton, et al., 7, 2014
Data Source: California Solar Initiative

These figures from the Cost Comparisons study represent the general, persistent trend: that larger systems are more cost-competitive on a per unit of capacity and energy produced basis. Goodrich, James, and Woodhouse (2012, p. 12) support this claim, writing that "economy-of-scale benefits are clear, because the fixed costs for ground-mount systems....are amortized over a greater system size." NRRI's study also reviewed data from the consulting firm Lazard, whose estimates for 2015 LCOE differences between utility-scale and rooftop installations have a range magnitude of $153 (2013). This comprehensive review and analysis of relevant academic literature and study of current data suggests a strong presence of scale economies in PV production and installation.

See the following two subsections for a breakdown of these cost benefits in utility-scale installations and residential and commercial scale installations. Generally, the literature agrees that economies of scale allow soft costs to represent a smaller percentage of total costs, and that there are important opportunities to reduce soft costs at every scale in order to make solar PV systems more cost-competitive.

2.3.1 Utility-Scale Installations

Projects larger than 1MW are considered utility-scale in the solar industry. Utility-scale PV projects are a recent phenomenon in the United States, but capacity has been growing rapidly. Mimicking the centralized power infrastructure existent in the United States today, utility-scale solar farms are designed to be built in remote areas on cheap land and transmit the generated electricity over long distances to high-load urban areas. While they do still experience economies of scale, projects of this size often face greater development challenges than smaller projects because they are interconnecting on the front end of the meter and are not rooftop mounted, including “greater environmental sensitivities and more stringent permitting requirements, as well as more interconnection and transmission hurdles” (Bolinger and Weaver, 2012). Additionally, as these installations grow in size, land and transmission and transportation infrastructure needs, as well as financial risk, climb significantly (Appleyard). These additional costs subtract total value from these large systems.

However, utility-scale systems face huge benefits from economies of scale. Ground mounting systems saves about 20 percent of the total system cost, due to standardization of design, bulk purchasing of identical mounts, and labor efficiencies in installation, according to Sinha (2013). According to Feldman, et al. (2013), utility-scale systems also often have lower hardware costs per unit as a result of ground mount standardization, and also benefit from higher average output due to lack of shading and one or two-axis tracking systems typically not present in rooftop solar installations.

Utility-scale systems also provide a financial service to the industry by creating an investment hedge and placing financial risk on large utility corporations' project companies holding the guaranteed Power Purchasing Agreements (PPAs) rather than individual residential consumers (Shepard). Bolinger and Weaver further assert that after a certain point, "the costs of overcoming these incremental challenges may outweigh any benefits from scale economies in terms of the impact on the PPA price" (2012). These PPAs face an added downward pressure on the guaranteed price at the utility-scale level as these projects sell into the grid at wholesale prices rather than the retail prices residential and commercial-scale systems receive through net energy metering policies in 43 states.

Numerous studies have shown that these scale economies in solar photovoltaics diminish rapidly after utility-scale systems reach 5-10 MW (See Bolinger and Weaver, 2012; Carus, 2013; Clarke, 2012), a range one FirstSolar executive referred to as the "sweet spot" (Clarke, 2012). Feldman, et al. report average cost reductions of 22 percent to 26 percent as systems increase in size from 5MW to 185MW (2013, p. 19). However, nearly 75 percent of that cost reduction is realized in the range of 5MW-20MW (Feldman, et al., 2013, p. 19). Howland (2014) concurs, arguing that projects in the 20MW range can be developed without difficulty in regulatory hurdles or siting and can be located more optimally for interconnection into the grid.

2.3.2 Residential and Commercial Scale Installations

Residential and commercial scale installations generally have capacity in the range of 10kW-250kW (though some large commercial installations can be up to 1 MW). This model of distributed generation reduces grid stress and transmission losses by providing power and voltage response near the energy demand, which, according to Farrell, can “defer upgrades to existing infrastructure and open up capacity on existing transmission lines” to support more centralized renewable energy projects, such as coal and combined heat and power plants, gas turbines, nuclear plants, wind farms, hydroelectric dams, and other large-scale forms of generation. Farrell cites additional benefits of this decentralized model of solar implementation, including prevented blackouts, reduced environmental damage, and significant economic growth and job creation, advantages which he concludes contribute $0.22 per watt of added value to decentralized systems.

Despite nearly always having a higher cost per watt than utility-scale projects, residential and commercial solar PV installations realize the strongest economies of scale effects, especially at the smallest system sizes, from 2-10kW (Bolinger and Weaver, 2013; and Feldman, et al., 2013). This is illustrated in Figure 4 below. The slope of the cost curves for small residential is the steepest. Though “substantial variability in installed prices exists within each size range,” installed prices for the “largest commercial systems [are] 38% lower than for the smallest residential systems” (Feldman, et al., 2013, p. 10). Barbose (2012) puts the same cost differential a bit higher at 42 percent between commercial-scale rooftop systems and residential rooftop systems. As shown in Figure 4, these differences were closer to 22 percent in the NREL study titled “Benchmarking Non-Hardware Balance-of-System (Soft) Costs for U.S. Photovoltaic Systems, Using a Bottom-Up Approach and Installer Survey –Second Edition.” The economies of scale benefits in individual soft costs are evident, most notably in “supply chain costs, indirect corporate costs, transaction costs, and installer/developer profit” (Freidman, et al., 2013, p. v).

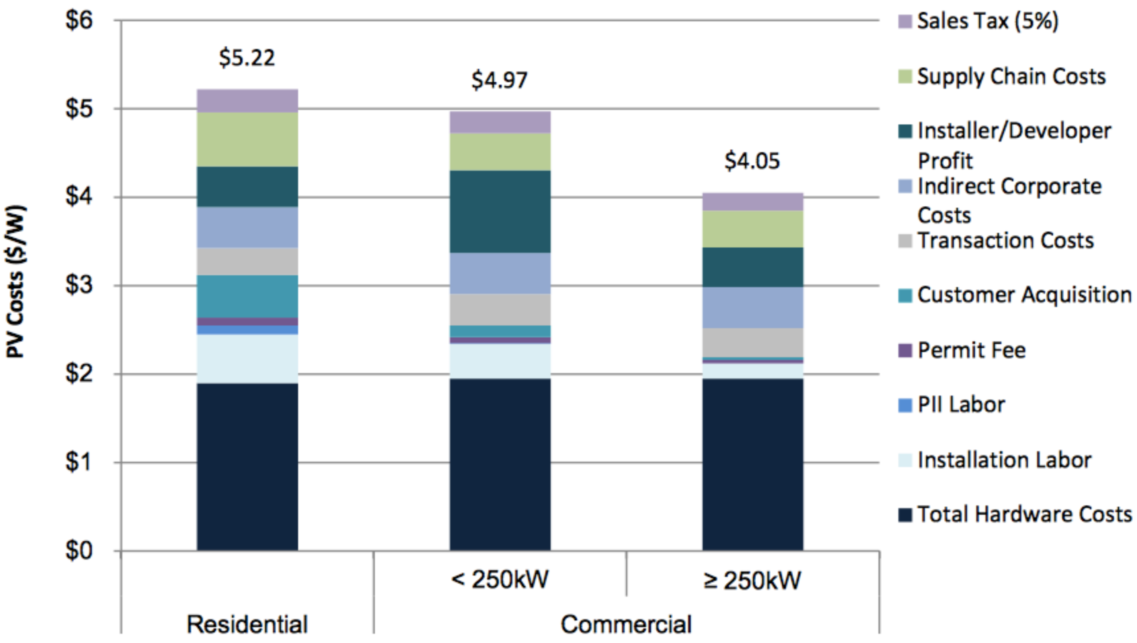


Figure 4: Total PV system price, by sector and system size (first half of 2012)
Source: Friedman, et al., 2013, p. v

As a result of these scale benefits realized by smaller system sizes, Barbose, et al. (2012) report that median system sizes have risen since the proliferation of solar systems implementation in the early 2000s, especially at the low end of the spectrum. Among systems 10 kW or smaller, the long term trend in median system size was a substantial increase, growing from 2.3 kW in 1998 to 5.0 kW in 2011 (Barbose, et al., 2012). In larger system categories, however, the “growth in median system sizes was relatively modest and uneven and is unlikely to have had any material influence on the observed price declines, either over the long-term or within the more recent past, especially given the declining returns to scale at larger system sizes” (Barbose, et al., 2012). These trends represent the ‘elbow’ of the long-run average total cost curve as it decreases with increased output. Past this domain of the curve, costs continue to fall, but at a slower rate, until, in some cases, diseconomies of scale can take over. Farrell posits that commercial-scale systems have captured most total economies of scale, through both lower module costs and lower non-module costs (2012).

Despite the seemingly American ideal that ‘bigger is always better,’ the countries around the world with the largest renewable energy capacities have met with such great success by incentivizing and installing distributed generation technology, not centralized, utility-scale power. The poster child for solar photovoltaic implementation success, Germany has more than 16GW of solar photovoltaic capacity installed, 80 percent of which is made up of residential rooftop scale systems (Farrell). Section 2.4 discusses Germany’s success in reducing soft costs in solar photovoltaics.

2.4 Germany’s Soft Cost Reductions: A case study

With the largest amount of solar capacity in the world, Germany is a global beacon for the success of solar photovoltaic implementation. Countries with comparatively high installed costs for PV can take a lesson from the German model, which is seeing prices about 50 percent lower than the U.S. on a pre-tax basis, according to Feldman, et al. (2013, p. 25). The Lawrence Berkeley National Laboratory (LBNL) recently released a study investigating cost differences between residential solar systems in Germany and the United States, and largely concluded that the massive price differences are due to differences in soft costs (See Seel, et al., 2014). The report points to factors including market size, system size, length of project development period, and lower hardware component costs and installation labor costs in Germany. Distributed PV systems in Germany come online in 35 days on average (Shahan). It also cites higher customer acquisition costs, marketing and advertising costs, and sales taxes in the US as the culprits to higher installed prices. Soft cost differentials between the United States and Germany are huge, as every category of the soft costs in the US analyzed by LBNL was higher than Germany's, with most by significant margins (Seel, et al., 2013). See Figure 5 below.

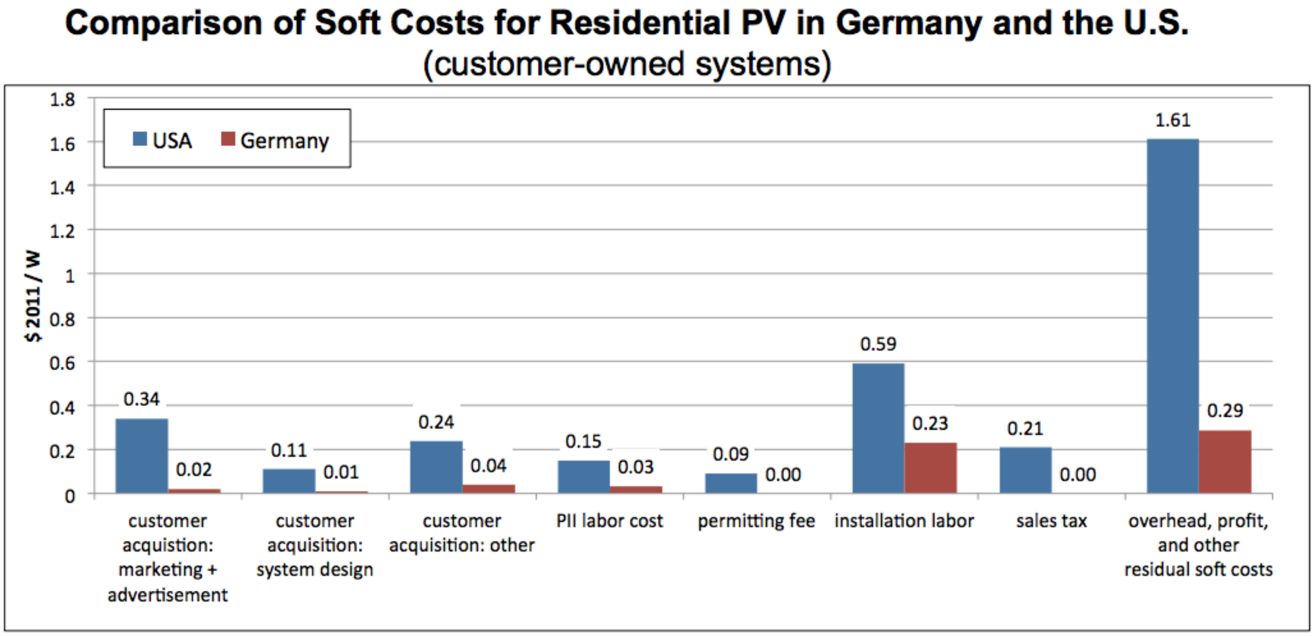
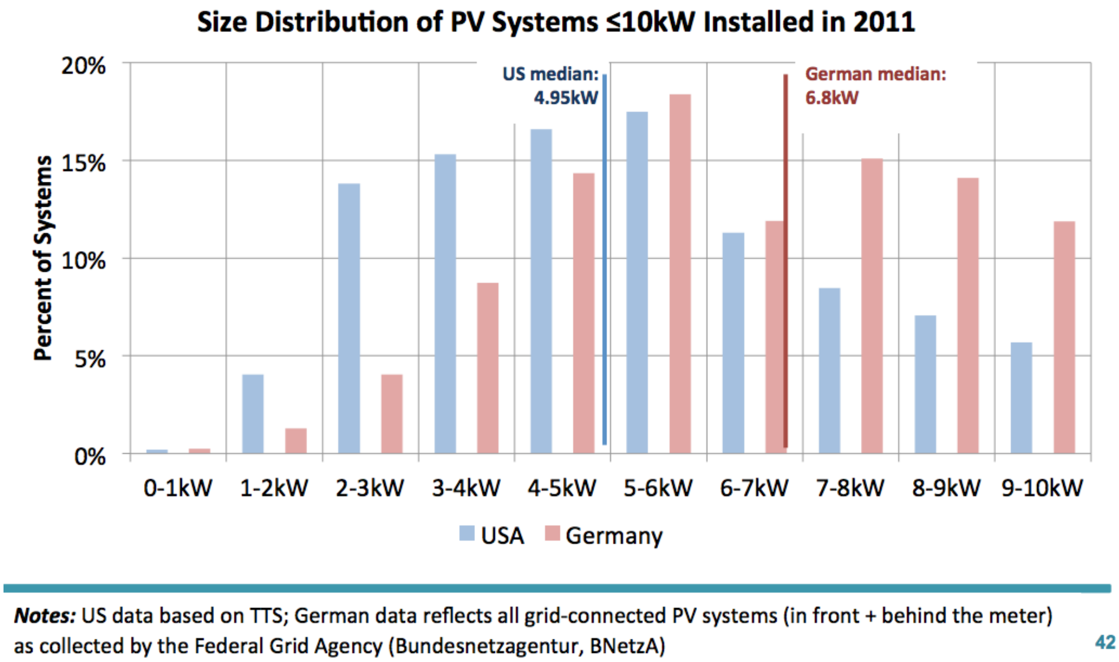


Figure 5: Comparison of Soft Costs for Residential PV in Germany and the U.S.
Source: Seel, et al., 2013

However, it is interesting to note that these cheaper residential installations in Germany are in fact larger than U.S. installations. German median installation size for residential systems under 10kW is 6.8kW, whereas in the United States, the median is 4.95. See Figure 6 below. These larger installations lend a $0.15/W price reduction to Germany's systems (Seel, et al., 2013). The larger size of installations is due in part to the higher population density and lower market fragmentation present in Germany, but a significant portion of this discrepancy is due to differences is policy design, which allow the larger installations to benefit from economies of scale. The German Feed-in-Tariff policy, designed and proposed by Hermann Scheer (Scheer, 2007), provided a huge price differential for renewably-produced energy from behind the meter, and made distributed renewable energy a highly lucrative investment at the expense of the utilities.



Notes: US data based on TTS; German data reflects all grid-connected PV systems (in front + behind the meter) as collected by the Federal Grid Agency (Bundesnetzagentur, BNetzA)

Figure 6: Size Distribution of PV Systems Greater than 10kW Installed in 2011
Source: Seel, et al., 2013

According to Shahan, “Regular declining FiT [Feed-in-Tariffs] and high competition among installers yield pressure for price reductions and lower margins in Germany, while larger incentives, opportunities for higher value-based pricing, and less installer competition allow for higher prices and margins in the U.S.” This and other reductions, according to LBNL, allow the total non-hardware costs for residential photovoltaics in Germany to be $2.70/W lower than in the U.S. (Seel, et al., 2013).

2.5 Literature Recommendations to Reduce Soft Costs in the US

Currently, the literature recognizes that there are soft cost reductions to be made in U.S. solar PV markets. A summary list of recommendations in the current literature can be found in Table 1 below.

Table 1: Essential Literature Soft Cost Reduction Recommendations

Soft Cost Reduction Recommendations	**Source**
'Standardized' systems	Goodrich, James, and Woodhouse (2012, p. 6)
Advanced installation methods, such as unitized construction techniques	Goodrich, James, and Woodhouse (2012, p. iv)
(1) streamlining permitting and interconnection processes (2) developing improved software design tools and databases (3) addressing policy and regulatory barriers (4) streamlining installation practices through improved workforce development and training (5) expanding access to a range of business models and financing approaches (6) developing best practices for considering solar access and PV installations in height restrictions, subdivision regulations, new construction guidelines, and aesthetic and design requirements (7) reducing supply-chain margins through industry growth and maturation	DOE *SunShot Vision Study* (2012, p. 86-87)
(1) Consider policy reforms that enable an a larger residential PV market (2) Simplify PII requirements and regularly decreasing incentives, which drive and follow price reductions and offer a transparent and certain value proposition	Seel, Barbose, and Wiser (2014, p. 225)

These recommendations cover a wide range of soft cost components, but there is a common theme among them that applies to the soft costs side and the production side that has not yet been explored: modularity.

2.6 Modularity

Modularity is the degree to which components of a system can be separated and recombined. When systems are non-decomposable and non-interdependent, they have heightened compatibility with similar systems, allowing the interchange of parts and components, as well as ease of repair and installation (Langlois, 2002). The concept of modularity is parallel with the concept of division of labor among components, where each miniature system operates individually as a part of the larger system, without a dependency or cost component to communicating across a system (Langlois, 2002).

Our current energy system is far from modular; there are hundreds of interconnections and interdependencies between our energy systems today (Lovins and Lovins, 2001). Because many of our energy systems today require auxiliary inputs of different sources of energy, such as a gas furnace requiring an electric igniter or a refinery's production being severely restricted when there is a grid blackout, interruptions in one energy system can lead to interruptions in another system (Lovins and Lovins, 2001). Lovins and Lovins write "any disturbance in the intricately interlinked web of fuel and power supplies can spread out in complex ripple effects at all levels, from primary supply to end use, complicating substitutions and making the initial shortage much worse" (2001). This lack of modularity makes the entire system vulnerable.

Integrating solar technology into other systems is becoming easier and cheaper, with technology innovations such as thin-film wafers and photovoltaic fabrics (Shephard). Additionally, the economies of scale benefits inherent in large installations are supplanted by the innate modularity of photovoltaic panels. Because economies of scale for solar photovoltaics drop off after 5-10 MW, many large solar systems find that balancing land availability and transmission availability prevents the project from capitalizing on the modularity inherent in the technology (Clarke). Modularity in systems design, project development, and other areas can be a highly useful strategy to reduce cost and increase efficiency at multiple points along the value chain when applied to the solar PV industry. Below, this analysis will continue with the concept of modularity and how it is seen in theory, production, cost-reduction applications, and value-added applications. It will then move into theory on what types of characteristics identify modularity and how to model this relationship, followed by a discussion of results and application of the findings. This research will seek to explore further economies of scale and modularity in renewable energy applications, namely soft costs in solar PV implementation, and make policy recommendations for the industry in the context of modularity as a cost-reduction strategy.

2.6.1 Modular Systems Theory

Nearly every system operates independent of other systems and is yet interdependent and interconnected with many others. Each trade relationship, national economic system, central bank, firm, and individual household is an independent system operating in the context of many larger systems. The global financial crisis of 2007 and 2008 demonstrated this contextual and interdependent relationship quite clearly. Herbert Simon describes these complex systems as "made up of a large number of parts that have many interactions…in such systems, the whole is more than the sum of the parts, in the weak but important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole" (Simon, 2003, p. 19). Organizational complexity is, then, a function of the number of parts in a whole as well as the “nature of their interactions” (Simon, 2003, p. 19).

A fundamental way to manage complexity in a large system is to group the elements of a system into a smaller number of sub-systems, as often seen in nature. Simon’s seminal work focused on the decomposability of systems, the concept of reorganizing a complex system into subsystems that can function at a basic level independent of the larger system. Simon offers a parable in which two watchmakers, Tempus and Hora, are both frequently interrupted in their work. “Tempus organized his work in a manner that if he had one watch partly assembled and had to put it down…it immediately fell to pieces and had to be reassembled from the elements” (Simon, 2003, p. 19). Hora, on the other hand, built his watches with “stable subassemblies that could then be put together in a hierarchic fashion into larger stable subassemblies.” (Simon, 2003, p. 19) When Hora was interrupted, he only had to resume from the most recent subassembly. Tempus faced what Simon termed “perpetual incompleteness” in his watchmaking process, while Hora’s modular production process allowed him to separate the production, performance, and success of each subassembly from the others. (Simon, 2003, p. 20) Giving Hora an almost evolutionary advantage in the watchmaking process, “Modularity facilitates the retention and reuse of system parts and enhances the speed, scope, and reach of innovation” (Garud, Kumaraswamy, and Langlois, 2003, p. 2).

The concept of modularity in production processes has been analyzed in industries from Silicon Valley to Detroit. There is a recent shift towards modular systems and even more towards modular products, as firms seek to increase cross-compatibility among products, reduce repair and installation costs, and increase large-scale production. As a measurable concept, modularity is the degree to which components of a system can be separated and recombined. Modularity is also defined by economist Richard Langlois as a “set of principles for managing complexity” (Langlois, 2002, p. 19). Langlois (2002, p. 19) writes that, “By breaking up a complex system into discrete pieces—which can then communicate with one another only through standardized interfaces within a standardized architecture—one can eliminate what would otherwise be an unmanageable spaghetti tangle of systemic interconnections” (2002, p. 19). Likewise, Schilling and Steensma (2001) described modularity as “a situation where ‘a tightly integrated hierarchy’ is supplanted by ‘loosely coupled’ networks of organizational actors” (1149). However, modularity is, at its essence, a process. Baldwin and Clark define modularity as the process of “building a complex product or process from smaller subsystems that can be designed independently yet function together as a whole” (Baldwin and Clark, 2000, 84). Analyzing the laptop computer industry, they argued that modularity is a concept far more widely applicable than was realized in the academic world at the time of publication. Just about everything in the economy, to some degree, is modular, from physical products to firm structure to this thesis. The level of modularity is tied to the level of complexity, but the concept is nearly universal. Modularity is then defined here as the level of decomposability and intercommunication in a process or system observed as a function of its complexity.

The concept of modularity is parallel with the concept of division of labor among components, where each miniature system operates individually as a part of the larger system, without a dependency or cost component to communicating across a system (Langlois, 2002). Applied to production, modular products are comprised of individual components sourced from different resource bases and produced in separate production processes. This facet of modular production allows components to be assembled separately and then combined in the final stage of production, increasing production efficiency and lowering costs. Modular production shapes industrial organization and supply chain dynamics. Firms that produce modular products often source intermediate modules from multiple points on the supply chain and simply guide final assembly. Similarly, as Sanchez and Mahoney (1996) assert, “products design organizations.” In other words, modular products require modular production and non-modular products require non-modular production (63). Modularity in industry organization is an indicator of its level of complexity and increasing the degree of modularity in products and processes will yield efficiency increases and cost reductions.

For such a widely applicable concept, modularity has a relatively thin base for peer-reviewed academic literature directly on the subject. However, there is much to be said about modularity in industrial organization in the context of other fundamental economic theories. The literature focuses itself on these areas and applies these concepts towards the construction of a modular systems theory.

According to Langlois (2002), clearly defined property rights are critical to creating modular systems. Boldly citing the work of groundbreaking economists Adam Smith and Ronald Coase in this area, Langlois asserts that property rights and ownership of decision-making rights can inherently modularize social and economic interaction. In fact, Langlois considers Adam Smith to be the first economist to suggest modular organization in production, based on his discussion of the division and specialization of labor and diminishing marginal productivity in *The Wealth of Nations*. Langlois writes of Smith:

> “We can think of Adam Smith’s ‘obvious and simple system of natural liberty’ (1976) as among the earliest proposals for how a complex modern society might be made more productive through a modular design of social and economic institutions. In separating mine from thine, rights of private property modularize social interaction, which is then mediated through the interface of voluntary

> exchange, all under the governance of the systems architecture of common law (19-20, 2002)."

Another early proponent of property rights is Armen Alchian, who defines a system of property rights as, "a method of assigning to particular individuals the authority to select, for specific goods, any use from a non-prohibited class of uses" (Alchian, 1973, p. 26). The authority to classify and organize economic activity to ones liking and net benefit, is, in essence, the ability to modularize. As a result, resources, goods, and services are funneled efficiently through the economy. Langlois agrees, arguing, "the creation of 'new' rights and the re-bundling of existing rights are really manifestations of the same underlying process of modularization, re-modularization, and sometimes even de-modularization" (2002, p. 27). Ultimately, however, clear definition of property rights is most critical for internalizing externalities. Without clearly defined property rights, Garrett Hardin's Tragedy of the Commons is likely to occur in the resource extraction phase of the modularized production process (Hardin, 1968, p. 1245). These externalities are of course "subject to the costs of setting up and maintaining the rights as well as to other considerations, notably the presence of economies of scale" (Langlois, 2002, p. 28). However, firms often find themselves in a non-modular organizational structure within an economy, and therefore "arise as islands of non-modularity in a sea of modularity," creating more externalities (Langlois, 2002, p.34).

Another common theme within the literature is the necessity of decomposability of systems as a pretext for modularity. Recall Simon's parable of the watchmakers, in which he offers decomposability as a necessary requirement for modularity. Simon (2003, p. 19) considers decomposability "a prescription for human designers and as a description of the systems we find ready-made in nature." Without decomposability, systems will be resigned to the frustrated progress and "perpetual incompleteness" of Tempus's watchmaking procedures.

Langlois also argues for decomposability as a criterion for modular systems. When systems are decomposable, he argues, they have heightened compatibility with similar systems, allowing the interchange of parts and components, as well as ease of repair and installation (2002, p. 22). On the other hand, in non-decomposable systems, the successful operation of any given part is likely to depend on the characteristics of many other parts throughout the system" (Langlois, 2002, p. 21). D.L. Parnas, a computer scientist who made some highly pertinent observations about programming that have since been applied to the concept of modularity, argued that modular systems are not automatically decomposable, "since one can break the systems into modules whose internal workings remain highly interdependent with the internal workings of other modules" (Parnas, 1972, p. 1056). Parnas's essential point is that modules within systems ought to operate independently of the other modules, with limited interaction between modules. However, on the other hand, Langlois notes that decomposable systems inherently do poorly in identifying and correcting errors, because they are each contained in individualized systems. Non-decomposable systems raise the cost of missing or poorly functioning parts, which raises the incentive to make sure that each part is of high quality. (2002, p. 24)

Another critical facet of modular systems is non-interdependence, meaning that sub-systems are functional and independent of each other as they function within a larger system. Especially in large modular systems, Parnas (1972) argues that the organizer's goal ought to be to minimize interdependencies and intercommunication among the modules. By doing so, transaction and communication costs are minimized and the systems maintain their independence. He writes:

> If knowledge is hidden or encapsulated within a module, that knowledge cannot affect, and therefore, need not—must not—be communicated to other parts of a system. Under this scheme, every module "is characterized by its knowledge of a design decision which it hides from all others. Its interface or definition was

> chosen to reveal as little as possible about its inner workings (Parnas, 1972, p. 1056)

He argues that, although modular systems are difficult to design, by reducing interdependencies and therefore communication costs, firms can reap the benefits of specialization and the division of labor more easily (2002, p. 23). Using the Japanese auto industry as an example, he makes the point that non-decomposable modular systems stimulate learning-by-doing benefits because they "highlight bottlenecks and inconsistencies" and raise the incentive to produce higher quality components (2002, p. 24).

Every process is, to some degree, modular. However, especially in production, the modularity of a product will often yield a resulting firm design that is also modular. Sanchez and Mahoney contend that products design organizations, not the other way around. This means that non-modular products lead to non-modular organizations, whereas modular products call for modular organizations. In a sense, however, this is a variant on what the mainstream economics of organization has long believed: "production processes design organizations" (1996, p. 63). If this is true, then firms are essentially non-interdependent confluences of modules of production processes, property rights, and ownership of decision-making rights.

Glen Hoetker argues that organizational modularity has multiple advantages for firms and that product modularity has a quantifiable, causal relationship to organizational modularity (Hoetker, 2006, p. 513). Firms can outsource, reselect and switch suppliers, and engage in 'modular innovation,' in which "firms improve their end product by incorporating improvements in various components of the product, which may occur at different rates for different components," with ease (Hoetker, 2006, p. 502). After studying the notebook computer industry, Hoetker's argument for modularity's advantages was to "provide empirical evidence on the impact of product modularity on the ease with which a firm can reconfigure its own organizational design." (Hoetker, 2006, p. 513) This was in contrast to Baldwin and Clark, who argued that product modularity pushed firms away from hierarchal structures (2006, p. 88). Hoetker also establishes that modularity is not a "monolithic" concept, meaning that loosely coupled, configurable networks and moving out of hierarchy are separate phenomena and that one can exist without the other." (Hoetker, 2006, p. 514) Schilling and Steensma (2001, p. 1149) described modularity as "a situation where 'a tightly integrated hierarchy' is supplanted by 'loosely coupled' networks of organizational actors." Hoetker disagrees, asserting that "loosely coupled, configurable networks and moving out of hierarchy are separate phenomena and that one can exist without the other." (Hoetker, 2006, p. 514) These arguments ultimately lead to the same end: that ultimately, modular outputs demand modular inputs, and that the trait of modularity is applicable among all stages of the production process, and that this property of modular systems can have huge efficiency benefits for firms.

Modularity is, as previously mentioned, a nearly universal concept. Along this vein, firms are finding that transforming their organizational structures yields similar efficiency increases to those experienced in modular production. In its greater universality than originally thought, Baldwin and Clark argued "a growing number of industries are poised to extend modularity from the production process to the design stage" (Baldwin & Clark, 2000, p. 85). In doing so, business planners and designers apply these concepts to firms' organization, achieving modularity by splitting it into its components (in a nearly ironic modular fashion): visible design rules and hidden design parameters. The visible design rules consist of architecture to define module boundaries, interfaces that describe the intercommunication of the modules, and standards for measuring individual module performance. The hidden design parameters are decisions that do not affect the design beyond the local module and are not communicated to the modules in an organization (Baldwin and Clark, 2000, p. 88). In light of the changing business environment and the trends toward modular organization, companies are shifting to become one of two types: either an architect of an organization with the motive to create products made up of modules or a designer of modules that conform to the architecture of other firms (Baldwin and Clark, 2000, p. 88). This observation has wider implications for vertical integration, production and supply chain analytics, and even questions of labor and employment.

It is evident that modular structures of organization come with large increases in efficiency for a firm. Likewise, the modular structure gives full rein to the economic benefits of specialization, the division of labor, and marginal productivity of labor. Langlois and Robertson (1992) argue for demand side benefits and supply side benefits of modular organization. On the demand side, the largest benefit is the "ability to fine-tune the product to consumer needs and therefore blanket the product space more completely" (297). On the supply side, firms have the "potential for autonomous innovation, which is driven by the division of labor and provides the opportunity for rapid trial-and-error learning" (297). Langlois and Robertson (1992) suggest that innovation in modular systems can lead to "vertical and horizontal disintegration, as firms can often best appropriate the rents of innovation by opening their technology to an outside network of competing and cooperating firms" (298). They further assert that increasing consumer demand and the importance of achieving scale economies in production emphasizes the benefits of modular organization.

However, as economists famously love to say, there is no such thing as a free lunch. Baldwin and Clark (1997) note that modular systems are much more difficult to design than comparable interconnected systems, and that without a thorough knowledge of the inner workings of the production process, the modules will function poorly together as an integrated whole (86). In addition, redesigning an entire firm's structure can be costly, and maintaining independent modules often incurs a high communications cost (Langlois, 2002, p. 20). In many cases, the benefits of modularization may not be worth the cost, especially when the system is in an environment where adaptability is unnecessary (Langlois, 2002, p. 23). It is important to note that, just like any economic problem, societies (and the economic actors within them) will only willingly incur the cost of an action if it is exceeded by its benefit. Economist Yoram Barzel gives an analogy:

> Economists have been well aware that the modular design of property rights comes at a cost, and that societies (and the economic agents within them) will want to pay that cost only if it is worth the benefit. Restaurant owners do not assert their full property rights over the salt they offer customers, but instead place the salt "in the public domain." Even though this destroys the patron's incentive to husband salt, any inefficiencies are dwarfed by the transaction costs of monitoring and charging for the use of the salt (Barzel, 1989, p. 66).

However, notice that architectural innovation doesn't always imply a change in the firm's "visible design rules" (Sanchez and Mahoney, 1996, p. 65). For example, LEGOs and TinkerToys are classic examples of modular systems designed for architectural innovation (65). For those firms that have positive net benefits from investing in a modular structure, there are efficiency gains, management benefits, and lower costs in store for them. For the other types of industries where modular organization provides negative net benefits, firms will remain non-modular and non-decomposable.

Ultimately, firms that provide modular goods or services will become more modular in their internal organization, in the production process, and in their supply chain management.

Firms that provide non-modular products or whose costs of changing the architecture are too high will remain non-modular.

Chapter 3

RESEARCH METHODOLOGY

3.1 National Regulatory Research Institute Economies of Scale Analysis Methodology

The National Regulatory Research Institute issues white papers on various topics relevant to the regulatory space in electricity and telecommunications markets. The research behind these white papers generally provides an extensive literature review, as well as relevant, objective analysis of existing data on the subjects of the white papers.[4] The purpose of the Cost Comparisons study was to understand why PV costs tend to be lower for larger scale systems. In order to conduct this research objectively, our team collected data from the California Solar Initiative (CSI) working data set ("Current CSI Working Data Set," 2015). Because it is by far the most comprehensive and accurate solar project database, and because California is home to a large share of all US PV installations (about 40% of all installations in 2013), the CSI data set was used as a representation of the entire U.S. market (Feldman et al., 2013; Kann et al., 2013). California leads the nation in renewable energy innovation in a variety of categories, so these results are useful conclusion to draw to imply what lies ahead in other states. Currently, data on state-level soft cost breakdowns is not available, so this portion of this study works on the idea of implied soft costs by seeking to approximate the implied soft cost difference between total installed cost and module costs. To create the model for this analysis using the CSI data, the

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[4] The purpose of the organization's research is to serve state utility regulators by providing "the analytical framework and practical tools necessary to improve their public interest decision-making" (Stanton, et al., p. i). As a result, the original analysis I conducted for the Cost Comparisons study was objective in its conclusions. This research is independent of that analysis and not objective and does not in any way represent the views or positions of the National Regulatory Research Institute or any of their affiliates.

author first cleaned the data set of systems that had not yet been completely installed and systems with no installed date listed. After cleaning, the dataset contained 141,786 observations. The data set in use was last updated on March 15, 2015. Then, to estimate total installed cost per watt, nameplate capacity of each system was divided into the total cost of the system. The capacity factor of solar PV, which hovers just above 25 percent (EIA, 2015) also affects these measures indirectly because nameplate capacity is much higher in actuality than true capacity. In order to estimate module prices, the author intended to use Navigant Consulting's Global Module Price Index, used by NREL and LBL to estimate module prices and generally considered the most reliable index of these commodity prices available. However, unfortunately, the data set is proprietary and very expensive, so this study estimates these numbers. The Navigant index yearly averages from 1998-2008 are available via the Environmental Protection Agency ("Renewable Energy Cost Database," EPA), and there is a similar, reputable module pricing index called SolarBuzz ("SolarBuzz Module Price Index"), which provides monthly data from March 2011 to March 2012. These 22 data points were plotted on a scatter plot, with each month in the years 1998-2008 reporting the same average annual data. Though the observations from the CSI database do not begin until 2007 when the CSI incentive programs were initiated, all data was included to strengthen the accuracy of the regression. A 6th-order polynomial trendline was fitted to the data, and the predicted y values for each month were reported. In order to make comparisons, the average total installed cost per watt observations were converted to monthly data. This was done by writing an array formula to average the cost per watt of all the projects in the dataset for each month. Lastly, by subtracting the estimated global module price index from the monthly averages of installed cost for the CSI observations from 2007-2012, the model yielded the implied soft costs remainder.

3.2 Modularity Research Process: Towards a Quantifiable Modular Industry Theory

This study seeks to index and quantitatively define the level of the once-obscure and generalized concept of modularity across a large sample of 305 industries in the United States economy with the purpose of drawing conclusions about cost-reduction strategies for the solar PV industry. Based on a battery of variables, the index will categorize industries based on their level of modularity, and can give an indication of which industries could experience efficiency increases if they became more or less modular based on their scores on the index. To create this model, the research team began with some of the industries accepted in the literature to be modular, and investigated what common characteristics they possessed that made them modular. Applying this knowledge to all industries, the team created a list of variables believed to be significant factors in the level of modularity of a firm to be incorporated into the model.

Modular industries are generally focused on final assembly, rather than transformation of raw resources. Rather than being involved in first stage extraction or processing, modular firms source intermediate components or services from other firms and assemble them into final products. This assembly-based production process is generally labor-intensive rather than capital-intensive, although that is changing more and more with scale economies and capital technology advancements. As a result, modular industries are likely to have low energy intensity, which is energy use per dollar of output. A classic example of this is the computer industry, in which firms like Apple, Dell and Hewlett-Packard assemble processors, LCD screens, track pads, and hard drives, each of which is a module in and of itself, into modular laptop and desktop computer systems. These systems are modular because each of these components operates independently of other systems in the computer, yet within the larger context of the entire system. In contrast, non-modular firms, such as steel mills, paper mills, and food processing companies, are likely to have a high level of energy intensity, as these industries generally transform raw materials into first stage intermediate goods in their production processes, and transformative production is often energy intensive.

Technology-intensive products are often produced in modular processes. Langlois and Robertson (1991) show that the level of modularity and the level of technology used in an industry can be positively correlated. Further, Sanchez and Mahoney (1996) concluded that products, and therefore production processes, design and shape organizations. Because most examples of modular industries yield products that utilize high levels of technology, this analysis hypothesizes that the modularity of an industry will have a positive relationship to the level of technology in the industry and in the output.

Because modular firms often source intermediate components from different facilities or firms, they often interact with other industries and firms in order to purchases goods or contract services. As a result, this analysis expects modular firms to have greater inter-industry interactions than non-modular firms. This form of economic activity can be measured by the value of goods or services transacted between each industry and all others.

On a similar vein, sourcing components from other facilities and firms is expected to be correlated with greater transportation and shipping costs. Buying intermediate components and input services from around the world based on resource availability, cost of labor, and existing infrastructure, many modular firms allocate a large portion of expenditures towards shipping and transportation costs in order to move the components to one place where they can be assembled into the complete product. Therefore, this analysis also expects transportation costs to be positively correlated with the level of modularity in a firm.

Lastly, this sourcing of intermediate components bears a cost. Because firms incur transaction costs, unit costs, and other types of costs by sourcing components from multiple other firms along the supply chain, modular firms producing many individual modules will likely pay greater proportions of their revenues towards intermediate firms along the supply chain. This analysis also expects that the proportion of revenues spent on intermediate goods and services to be higher, and that it will be positively correlated with the firm's level of modularity.

Each of these characteristics improves product and production process efficiency in a variety of ways. Modular design has increased efficiency by giving way to economies of scale benefits in production. Instead of using one continuous process to produce each component of the final product, modular systems allow for separate and simultaneous mass production of components, followed by final assembly later. In this way, firms are able to reap the economic benefits from scale in production processes. Additionally, the modular system can allow the individual production processes to function independently, with little centralized control and more autonomy among each process, creating an internal profit motive among each process, driving efficiency increases and innovation.

Modular products also provide benefits of specialization and the division of labor. Many modular firms contract external firms to produce components efficiently and with specialized expertise. In this way, specialization of labor benefits allow a firm to lower costs and focus on increasing efficiency in the final assembly stage. Specialization of labor provides resource efficiency and output increases, diversification of the economy into new fields and sectors, and ultimately increases the point of diminishing marginal productivity. This type of economic activity across industries and among groups of firms is indicative of modular production.

3.2.1 Modularity Regression Variables and Final Equation

This model is composed of variables that represent the theorized characteristics of modular industries introduced above. Each variable contains either an exact data match or a proxy variable that simulates the effects of an un-quantified phenomenon. The observations for each variable are industries in the United States economy, delineated by the 2007 North American Industry Classification System (NAICS) codes, which divide the U.S. economy into industries by grouping firms with similar products and services together. All of the data for the independent variables was calculated from the U.S. Bureau of Economic Analysis's 2007 Industry-by-Industry Direct Requirements table, with the exception of the "Cost of Goods Sold as a percentage of All Returns" variable, which was calculated using Returns of Active Corporations data from the Internal Revenue Service published in 2010. Each of the independent variables included in the regression analysis is introduced and briefly discussed below.

Intermediate Transport (INTTRANSPORT)

The intermediate transport variable is a representation of a firm's transportation costs associated with sourcing components from contracted firms or geographically displaced areas of production. As stated above, this analysis expects this variable to be positively correlated with modularity. The variable, INTTRANSPORT, represents part of the cost of intermediate demand, and is calculated by summing each industry's interactions with the transportation sector: Air Transportation (NAICS: 481000), Rail Transportation (NAICS: 482000), Water Transportation (NAICS: 483000), Truck Transportation (NAICS: 484000), Transit and Ground Passenger Transportation (485000), and Warehousing and Storage (493000). This sum was calculated for each industry, serving as a proxy to represent each industry's costs of transportation of intermediate goods.

Inter-Industry Interactions (INTIND)

Because the production processes of modular industries are generally assembly-focused, the level of significant activity with other industries is also a factor in modularity. As a result, using similar data from the Bureau of Economic Analysis for Industry-Industry Total Requirements will also enhance the model. Therefore, using a count variable, INTIND, to quantify the number of inter-industry interactions on the Direct Requirements Table can represent the level of significant inter-industry interactions. Only those interactions of each firm above a 0.005 threshold of significance were included in the count, in order to exclude the effects of miniscule, common, or non-indicative interactions, such as a CEO of a non-modular firm purchasing an executive jet, or a non-modular firm's purchase of printer paper, staples, or toilets. This discrete variable is measured in integer values.

Energy Intensity of Industries (ENGINT)

As stated, because most non-modular industries have transformative production processes, they generally have a high energy input per dollar of output. This analysis expects this energy intensity metric to be negatively correlated with the level of modularity in firms. The ENGINT variable is the sum of each observation's interactions with each of the following industries: Oil & Gas Extraction (NAICS: 21100), Coal Mining (NAICS: 212100), Drilling Oil & Gas Wells (NAICS: 213411), Other support activities for mining (NAICS: 21311A), Electric Power Generation, Transmission, and Distribution (NAICS: 221100), and Natural Gas Distribution (NAICS: 221200). The model seeks to measure total energy input per dollar output, and to avoid omitted variable bias, the variable must include all energy sources, not just the Electric Power Generation, Transmission, and Distribution industry, as it does not encapsulate all forms of energy or all forms of distribution. The data include the renewable and specifically solar energy sectors within these classifications, but the proportion is indiscernible from the data.

Cost of Goods Sold as a percentage of All Returns (COGSPCTRET)

Modular firms often face a larger level of intermediate demand, as they source modules from other firms and industries. The COGSPCTRET variable represents the amount of a firm's total cost that is comprised of intermediate goods. This metric is included to represent the effect on a firm's revenue and balance sheet of buying up intermediate modules to comprise their final product. The variable is taken as a percentage of each industry's total returns, to normalize the values to the size of the industry. Modular industries are expected to have a higher Cost of Goods Sold as a percentage of total returns value, and input industries that create the intermediate products, or industries that engage in transformative production processes are expected to have a low COGS value. These data were gathered from the United States Internal Revenue Service (IRS), which classifies industries differently than the NAICS code classifications this analysis used as its observations. As a result, the data is an approximation in which similar industry classifications were manually matched, more specific classifications were assigned the data from the more general classification, and 83 industries were excluded from the analysis because of a lack of a suitable match in this data set. However, the industries that were excluded were clearly non-modular and as a result did not greatly affect the results of the regression, and the number of observations is still greater than 300 (exactly 305).

Level of Technology (TECHLEVEL)

The model includes a variable for the level of technology in an industry, TECHLEVEL. Langlois and Robertson (1992, p. 21) qualitatively theorized that the level of technology of a firm is positively correlated to the level of modularity present. In the limited pre-existing literature on the subject, most all of the industries used as examples for modularity are high-technology industries. Looking at each industry's use of electronic components will be a sufficient indicator of this effect. This measure will be quantified by inter-industry interaction with NAICS3344: semiconductors and electronic components.

Modularity [Binary] (MODULARITY)

The dependent variable in this model is a binary dummy variable for Modularity. Beginning with a list of industries used as examples of modularity, this 1,0 variable seeks to classify each industry as modular or non-modular, and subsequently construct the probability model that will become the modularity index.

Final Regression Equation

This analysis yields the following model (*Eqn. 1*):

$$MODULARITY = \beta_0 + \beta_1 INTTRANSPORT + \beta_2 INTIND + \beta_3 ENGINT + \beta_4 COGSPCTRET + \beta_5 TECHLEVEL + \mu_i$$

This equation represents a multivariate regression called a linear probability model with a binary dependent variable, MODULARITY, which represents whether a firm is considered 'modular' or 'non-modular.' Because the dependent variable is binary, fitting a line to a (1,0) distribution for the dependent variable is interpreted as a predicted probability. It is these predicted probabilities from which the Modularity Index is derived, and from which policy recommendations can be made. In these types of models, the intercept (β_0) is usually meaningless in terms of interpretation. The other beta coefficients are representative of a change in the probability that MODULARITY= 1 associated with a unit change in one of the independent variables. Likewise, the predicted values from the population regression are a representation of the probability that the binary dependent variable MODULARITY=1, given the values of the independent variables. Unfortunately the linear probability model can yield predictions of probabilities either below zero or greater than one, results which are impossible. The probit and logit models are non-linear regression models specifically designed to constrain binary dependent variables. Based on the cumulative probability distribution functions, which constrain p values to between 0 and 1, the probit and logit models are used to model non-linear probability functions. In the probit model, the beta coefficient represents a z score on the cumulative standard normal distribution. Therefore, interpreting the beta coefficients in a probit model requires computation of the predicted probability on the normal distribution. The maximum likelihood method produces efficient (minimum variance) and consistent estimators, and is normally distributed in large samples, which allows for statistical testing.

Chapter 4

RESULTS AND ANALYSIS

4.1 Results and Analysis of Modularity Index

This analysis tested linear probability, probit models, the logit model, and the changes that result when using the maximum likelihood method. After comparing estimation outputs from the statistical package EViews8 for each of these combinations, the research team decided to rest on the probit model with maximum likelihood estimation as the best representation of the relationship modeled in *Equation 1*. Here, the beta variables have been replaced by their estimated coefficient values (*Eqn. 2*):

$$\begin{aligned} MODULARITY \\ &= 1 - @CNORM(-3.88847047737 * INTTRANSPORT - 0.239934927189 \\ &* INDINT + 1.10922939083 * ENGINT + 1.72834741056 * COGSPCTRET \\ &+ 48.6602959821 * TECHLEVEL - 3.00945182967) \end{aligned}$$

This equation represents the model with the substituted coefficients for each beta. The coefficients in this equation represent the z-scores for each of the variables' effects of the 'success' of the dependent variable. The 1-@CNORM transformation converts these to probabilities. Below is the complete regression estimation output:

Table 2: Regression Estimation Output 1 (Before Significance Testing)

```
Dependent Variable: MODULARITY
Method: ML - Binary Probit (Quadratic hill climbing)
Date: 05/23/14   Time: 11:16
Sample: 1 305
Included observations: 305
Convergence achieved after 7 iterations
QML (Huber/White) standard errors & covariance
==========================================================================
       Variable        Coefficient   Std. Error   z-Statistic     Prob.
==========================================================================
   INTTRANSPORT          3.888470     0.746515     5.208834      0.0000
        INDINT          -0.239935     0.066241    -3.622133      0.0003
        ENGINT           1.109229     0.830057     1.336329      0.1814
    COGSPCTRET           1.728347     0.529169     3.266156      0.0011
     TECHLEVEL           48.66030     13.85727     3.511536      0.0004
           C            -3.009452     0.516996    -5.821036      0.0000
==========================================================================
McFadden R-
squared                  0.510499   Mean dependent var       0.196721
S.D. dependent var       0.398173   S.E. of regression       0.263910
Akaike info criterion    0.524757   Sum squared resid        20.82495
Schwarz criterion        0.597943   Log likelihood          -74.02537
Hannan-Quinn
criter.                  0.554030   Deviance                 148.0507
Restr. deviance          302.4523   Restr. log likelihood   -151.2262
LR statistic             154.4016   Avg. log likelihood     -0.242706
Prob(LR statistic)       0.000000
==========================================================================
Obs with Dep=0                245   Total obs                     305
Obs with Dep=1                 60
==========================================================================
```

There are a few important things to note about the estimation output. This regression corrects for heteroskedasticity using the Hubert/White adjustment. At an α level of 0.05, all of the variables appear to be significant, except for ENGINT, which carries a p-value of 0.1814. Homoscedasticity cannot be assumed in the data, because the dependent variable is binary, so Wald Test restrictions were placed on each variable to calculate F-statistics to test for significance. After each restricted F-statistic was calculated in EViews using the Wald Test, each independent variable was tested for significance. All variables were found to have a significant effect on the probability of success for the dependent variable, except for ENGINT.[5] Therefore, as seen in Table 3, the output was re-estimated without the energy intensity (ENGINT) variable. See Table 3 below for the new estimation output.

This regression has eliminated the statistically insignificant variable, ENGINT. As in the first estimation output, the research team adjusted the standard errors and co-variances according to the Hubert/White correction. All of the variables appear significant with respect to the dependent variable, as all p-values are significant at the α level of 0.05. All variables were also found to be significant effectors on the dependent variable using the Wald Test. TECHLEVEL is the only independent variable with a large standard deviation, though it is not large relative to the coefficient.

---

[5] See Appendix B.

Table 3: Regression Estimation Output 2 (After Significance Testing)

```
Dependent Variable: MODULARITY
Method: ML - Binary Probit (Quadratic hill climbing)
Date: 05/23/14   Time: 11:59
Sample: 1 305
Included observations: 305
Convergence achieved after 7 iterations
QML (Huber/White) standard errors & covariance
=========================================================================
      Variable        Coefficient   Std. Error   z-Statistic     Prob.
=========================================================================
  INTTRANSPORT         3.707191     0.784258     4.727004       0.0000
     INDINT           -0.194512     0.083425    -2.331567       0.0197
   COGSPCTRET          1.718568     0.511019     3.363023       0.0008
   TECHLEVEL           46.04389     12.56054     3.665757       0.0002
       C              -2.885572     0.456481    -6.321347       0.0000
=========================================================================
McFadden R-
squared                0.501415    Mean dependent var     0.196721
S.D. dependent var     0.398173    S.E. of regression     0.262129
Akaike info criterion  0.527207    Sum squared resid      20.61351
Schwarz criterion      0.588196    Log likelihood        -75.39906
Hannan-Quinn
criter.                0.551601    Deviance               150.7981
Restr. deviance        302.4523    Restr. log likelihood -151.2262
LR statistic           151.6542    Avg. log likelihood   -0.247210
Prob(LR statistic)     0.000000
=========================================================================
Obs with Dep=0              245     Total obs                   305
Obs with Dep=1               60
```

Because this is a ML- binary probit model, the coefficients are representative of z-scores corresponding to probabilities on a cumulative normal distribution. The z-statistic column in the regression output is for a test of the hypothesis that the coefficients are actually 0.

As a result of this analysis, we can see that each of these variables has a highly significant effect on the dependent variable. The McFadden R-squared value for the estimated regression is 0.501415, which means that the independent variables in the regression explain 50.14 percent of the variation in the dependent variable. Though this value is not exceptionally high, the regression is a strong representation of the current academic level of understanding about the abstract concept of modularity and its traits, especially given the narrow base for past peer-reviewed academic literature on the subject. The mean of the dependent variable MODULARITY is 0.196721, which represents accurately the 60 observations which contain MODULARITY=1 out of the 305 total observations included. The standard deviation of the dependent variable is 0.398173, which is large for a mean of 0.196. However, this is expected from a binary dependent variable, as the variability is over a (1,0) plane. The standard error of the regression is 0.262129. This value is also reasonable given the binary nature of the dependent variable. With binary models, the estimation output is often not telling of the actual relationships initially, however, the signs of the coefficients are an initial measure of the relationships between the variables. INTTRANSPORT, COGSPCTRET, and TECHLEVEL all have positive beta coefficients, indicating that the probability of MODULARITY in an industry increases when one of these variables increases, holding all else constant. Likewise, INTIND has a negative beta coefficient, meaning that, ceteris paribus, the probability of MODULARITY decreases with an increase in INTIND. See Appendix A for the full index.

In order to generate fitted values for the dependent variable, the industries were assigned a classification of ‘modular’ (1) or ‘non-modular’ (0). After the research team ran the analysis, they were able to compare the expected values with the observed values that were assigned to each industry. Table 2 shows the two-way contingencies between expected and observed values in the dependent variable:

Table 4: Two-way Contingencies for Observed and Expected Values in the Dependent Variable

	Expected Value=1	Expected Value= 0
Observed Value=1	0	59
Observed Value=0	40	206

Performing a Chi-Square Test for Two-Way contingencies is not possible with this binary dependent variable because the Chi-Square test statistic cannot be computed, as it would require division by zero. However, Table 4 does give an indication of the power of the index.

The purpose of this analysis is to index industries based on their level of modularity. The fitted values for the estimated regression were interpreted to serve as an index for the level of modularity observed in each of the observations. The complete index for all 305 industries in the sample may be referenced in Appendix A. The index shows that there is a large gap between the highly non-modular firms and the modular firms. Over 75 percent of the observations returned a fitted value below 0.2, 5 percent of the observations fall between the 0.2 and the 0.5 ranges on the index, and 20 percent of the observations are above 0.5 on the index. The distribution of the fitted values is therefore highly skewed to the left. This gap in the index may be due in part to the variables that compose the model and in part to the nature of the U.S. economy. A great many industries exhibit little to no indication of modularity in their production processes or organization, and it is important to note that the efficiency increases associated with modularity will only be experienced by firms with modular output. As a result, among the 305 industries in the sample, the model identified only 60 as modular, and of those 60, only 17 of the probabilities were significant at the 0.05 level. These industries included: Aircraft manufacturing, electronic computer manufacturing, electro-medical and electrotherapeutic apparatus manufacturing, and motor vehicle electric and electric equipment manufacturing, to name a few. 12 of the 17 statistically significant ‘successes’ have an index value of 1.000, indicating a perfect probability. Many of these industries strongly exhibit most, if not all of the categories, but some, such as ‘Semiconductor and related device manufacturing,’ likely have perfect probabilities because they were the example industries many of the basic theories for modularity rest on.

4.1.1 Internal and External Validity

The study is largely valid both internally and externally. After a comparison of many models, including linear probability, probit, logit, and maximum likelihood effects, the research team chose the non-linear binary probit model, which was the best fit the data. The index results also show that the functional form was appropriate, as the distribution was concentrated near the 0 and 1 extremes, as the cumulative normal distribution represents as well. In addition, the battery of models that were tested all represents the types of data used in regressions in which the dependent variable is binary. OLS estimators or Two-stage Least Squares regressions would not be appropriate for this model, nor logarithmic transformations of the dependent variable, because taking the logarithm of a binary variable would simply switch the ‘success’ and ‘failure’ of each observation, because log(1) = 0 and log(0) = 1. This evidence eliminates the possibility of a misspecification of the functional form bias.

The sample for this regression is 305 of the 388 industries in the United States economy, as classified by the Bureau of Economic Analysis’s 2007 NAICS codes. The 83 industries that are excluded from this analysis were stricken from the data set when the Cost of Goods Sold as a percentage of All Returns data, which divided industries by IRS codes, aligned poorly with the NAICS codes used in the data from all of the other variables. However, while this could technically lead to some form of sample selection bias, the sample included all U.S industries for which complete data was available.

An argument can always be made for omitted variable bias, though because modularity is an un-quantified phenomenon, it is often difficult to prove causality and more difficult still to discern indicator variables of modular behavior in industries. The regression estimation originally intended to include data on the segmentation of industries, as a proxy for modular organization of firms, but complications prevented this data from being included in the final regression equation. It is likely that there are other effects that were not included in the independent variables of the regression, but were instead contained in the error term. However, for what the academic community currently knows and theorizes about modularity and its indicators, the model is valid in terms of its variables in its approach to the study of industry-level modularity.

There is no evidence of simultaneous equation bias in the regression, as there is no correlation across the equals sign. Because the dependent variable is binary and in this case, was estimated based on a literature review and rough set of criteria, there is no correlation or causality from the error term to the independent variable, and thus no simultaneous equation bias in this regression.

There is also no evidence of a measurement error, as all of the data was gathered from the U.S. Bureau of Economic Analysis and the U.S. Internal Revenue Service. While the research team cannot provide detailed information on the primary gathering of data, these data were calculated from tax information from the 2007 fiscal year. The only anticipated measurement error may originate in falsified tax records from individual firms, but even these data discrepancies are not likely to be noticeable in the aggregate of the entire United States economy.

Externally, the study holds high validity as well. Although the United States economy is much more diversified and advanced than so many other nations, nearly every decentralized market economy creates an inherent profit motive, driving efficiency increases and innovations. Especially in other diversified and developed economies, the results of this analysis are highly applicable. However, even in developing economies, even those that may be largely based on subsistence agriculture, these principles of modularity still hold true in many less diversified industries. Further, most of the industrial production in developing economies is controlled by multinational corporations from developed countries, whose products are more likely to be modular and whose production processes are therefore more likely to be modular.

4.2 Results from Analysis in Solar PV Cost Study

The results of this analysis yield solar PV industry-specific results with cost-reduction implications. The model built to estimate module prices from the two indices is shown in Figures 7 and 8 below. These figures show the decline in module prices over time, from $4.63 in early 1998 to $4.04 in early 2007 and down to $2.41 in mid 2012. These predicted values, while not the most directly accurate measures of actual module prices, give a significant estimation of the module prices that occurred in the period observed. These predicted values also likely do not accurately represent the polysillicon price spike that occurred in 2005-2009.

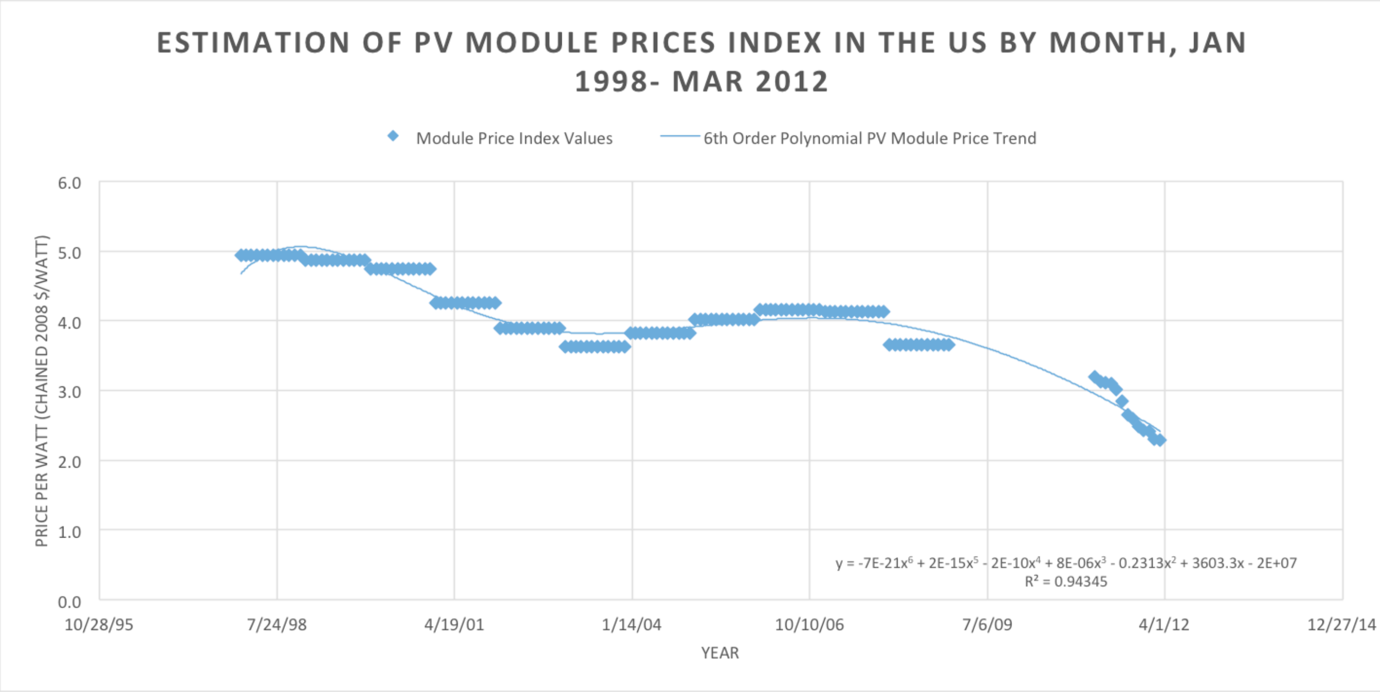

Figure 7: Estimation of PV Module Prices Index in the U.S. by Month, Jan. 1998-Mar 2012

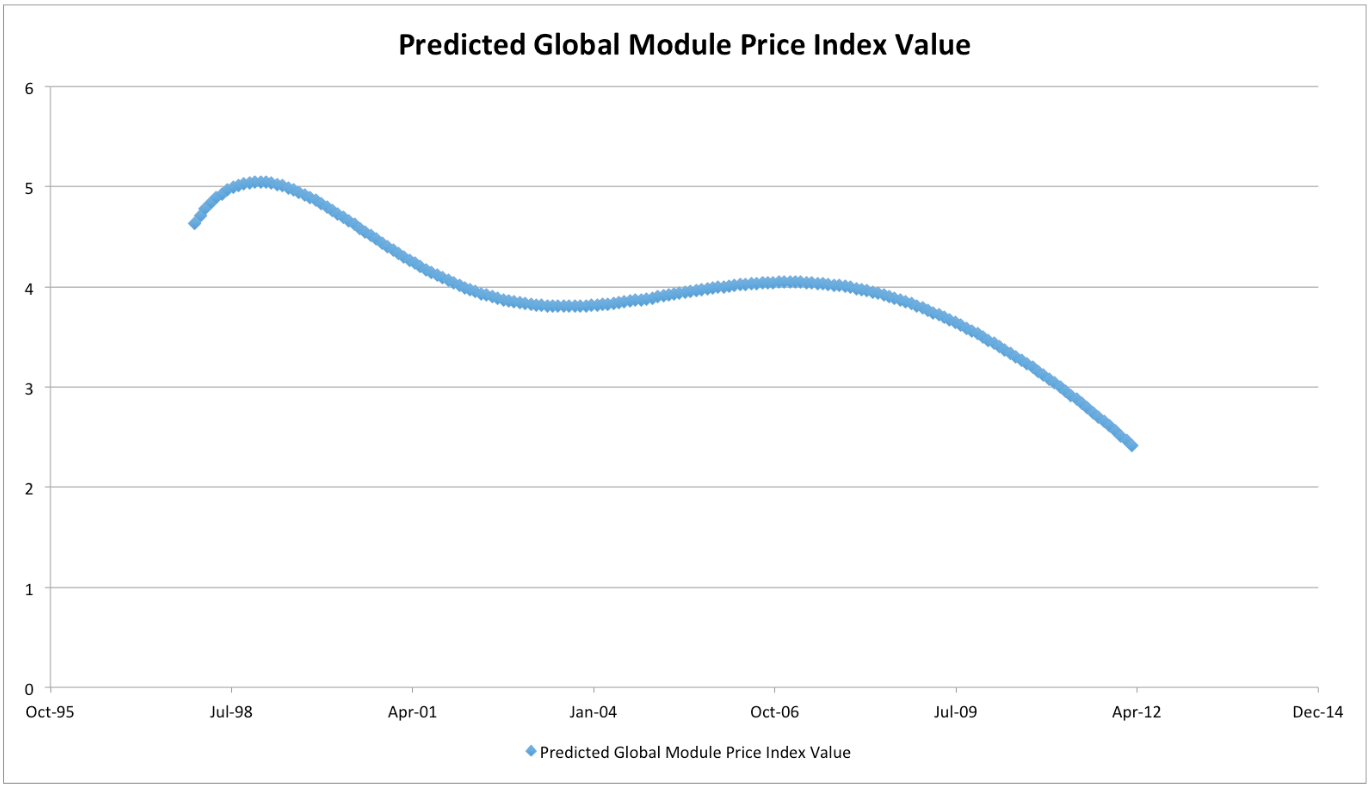

Figure 8: Predicted Global Module Price Index Value by month

These monthly module price values, along with the monthly average installed prices from the California Solar Initiative database were used to calculate implied soft costs. These average installed prices are represented in Figure 9 below.

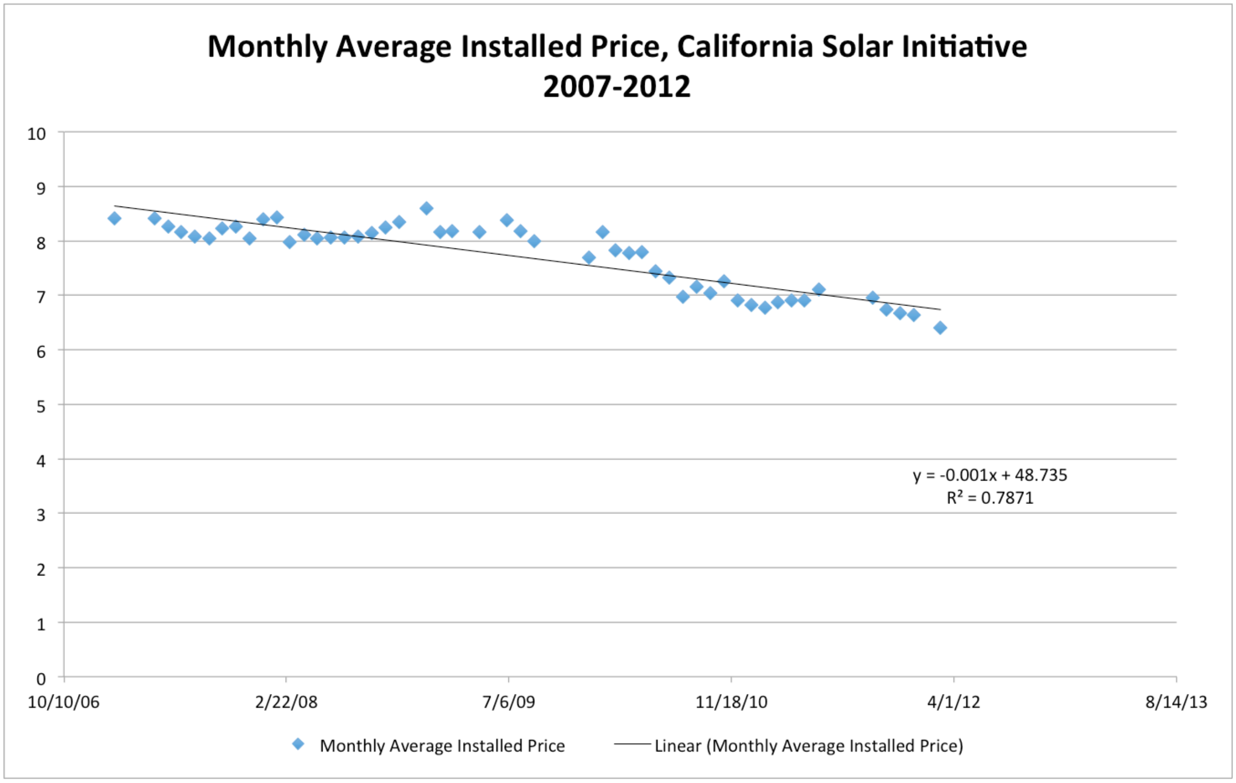

Figure 9: Monthly Average Installed Price, California Solar Initiative (2007-2012)

Figure 9 shows the decline in average total installed price per W_{dc} in California from 2007 to 2012, which encapsulates all costs. The shallow slope of the linear regression fit to the data represents the slow decline in installed cost, which likely indicates a strong lack of cost-reduction on the soft costs side.

Using these two metrics, the implied soft costs remainder was calculated, and is shown in Figure 10.

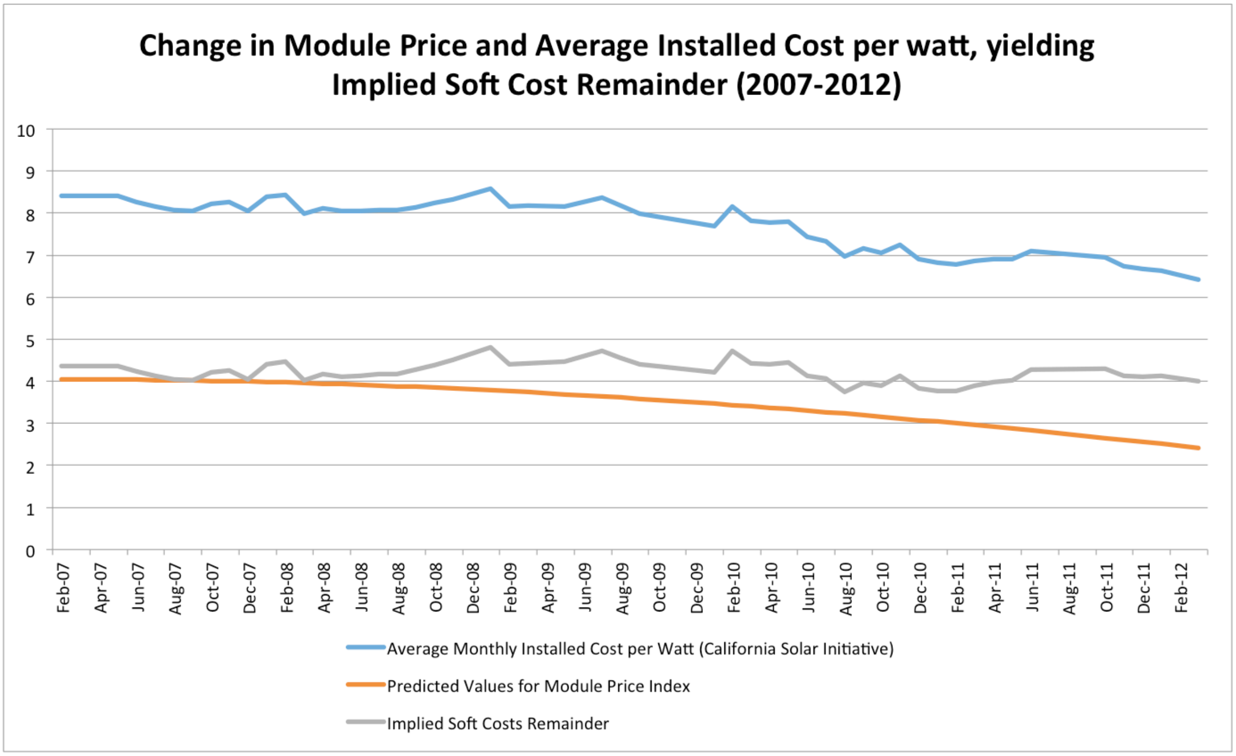

Figure 10: Change in Module Price and Average Installed Cost per Watt, yielding Implied Soft Cost Remainder (2007-2012)

As is evident in Figure 10, the implied soft costs remainder (seen in grey in the figure), changes only 8.4 percent over a five-year period, from $4.36 in early 2007 to $3.99 in March 2012, while module costs declined over 40% from $4.04 to $2.41 in the same time period three years ago at time of this writing. This analysis inevitably begs a solution to soft cost reductions, which this report suggests may lie in modularity.

Chapter 5

KEY FINDINGS & APPLICATION

5.1 Modularity Index Findings in Solar PV

The goal of this research was to make recommendations to the renewable energy industry, namely solar PV, as well as policymakers, to use the principles of modularity to increase production efficiency, lower hard costs, and hasten grid parity. However, because of the nature and level of detail of the data, this analysis does not allow any valid conclusions to be directly drawn about modularity in solar or any other renewable energy source, as the industry data does not differentiate renewable energy from other energy sources. While the data set comes from the highly trustworthy Bureau of Economic Analysis's 2007 Direct Requirements Table data and the Internal Revenue Service data, the NAICS code classifications do not provide enough detail in the way they classify industries in the energy sector. This may be due in part to the fact that this data is from 2007, before the taking off of the solar PV industry after the American Recovery and Reinvestment Act (ARRA) in 2009. It may also be due in part to the relatively small market share of renewables in the energy sector in 2007. Regardless, this lack of detail prevented detailed analysis on the renewable energy market.

Although the data was not specific enough to perform or support a quantitative conclusion about the solar PV industry, a few key assumptions can allow us to speculate based on the parallel results of similar industries. The author theorizes that the solar PV industry is highly modular, and that it ought to reflect this within the regulatory and economic frameworks surrounding this industry. The characteristics of each of the significant independent variables likely apply to some extent to the solar industry, and if this assumption holds, then the solar industry could experience major price reductions and reach grid parity much faster. By modularizing large-scale photovoltaic panel production, installation, and even solar PV financing, the industry could experience economies of scale benefits at every stage of the production process.

These variables are also highly relevant to the types of costs (both module costs and BOS costs) present in the solar PV industry and studied by the team at NRRI. This study lays out a methodology and a framework that quantifies industry-level modularity, which to my knowledge, has never been done before. When the BLS industry input-output tables are updated, they will use the NAICS codes to divide industry, and the 2013 NAICS codes include breakdowns for different renewable energy technologies, including solar PV. As the renewable energy industry booms, the powerful framework for this new and uncharted analysis provided by this study will be highly useful to determine how to make solar more modular and further drive down costs.

5.2 Application to other U.S. Industries

Applied to other industries in the U.S. economy, however, the modularity index allows the research team to easily identify modular and non-modular industries, make strong recommendations regarding production process efficiency increases to modular industries, and improve policy and financial incentives surrounding these modular industries. Treating modular industries differently within regulatory environment by eliminating taxes on intermediate demand, using tax break incentives to encourage firms to form geographic industry clusters, as happened when the Delaware state government lured the Wilmington

Chrysler plant and its subsidiary industries to the state with tax incentives and cost-reduction possibilities. Modular industries face variable market conditions, as they depend on many other firms to source, transform, transport, and assemble final products, and are, to a special extent, at the mercy of energy prices in their regions. By understanding their place within regulatory and economic contexts, modular firms can transform their production processes and their organization in order to drive prices down and increase market efficiency.

By recognizing and studying industries that were not anticipated to be deemed modular, and industries that were expected to be more modular than they are, the author has drawn some conclusions regarding the manifestations of modularity in the economy. A large proportion of the equipment manufacturing industries, including transportation equipment manufacturing, small electrical appliance manufacturing, aircraft and engine parts manufacturing, office machinery manufacturing, and many of the computer, semiconductor, and electronics industries, are considered modular, as well as much of the transportation sector and the communications hardware sectors. An important conclusion is that nearly every industry considered modular by the index is involved in capital production. A plurality of these industries exist to fill other industries' capital needs, rather than to offer consumer goods or services. However, modular industries like home appliance manufacturing, electronic computer manufacturing, and motor home manufacturing do exist to produce final consumer goods.

5.3 Soft Costs Analysis

As Figure 10 above indicates, this analysis suggests that the declines in installed costs that occurred during the time period for which this data is valid are the result of declines in module prices rather than reductions in soft costs. The lack of a decline in soft costs is largely due to the inefficiencies in policy, law, financing, and learning rates in the industry. Policy implications made here must be qualifies by remembering that the installed cost data set was specific to the state of California. While California is the leading state in solar PV installations and represents some of the most innovative and progressive solar policies in the nation, any comments above about policy relative to the analysis must be qualified by noting that the data does only represent one state of 50. Some of these cost reduction sources, such as learning curve improvements, will come naturally with time, but there are some of these inefficiencies that do not represent natural changes.

The concept of modularity applied to industries has already been defined and demonstrated above, but, as an indication of the powerful nature of the concept, it is important to note the implications it may have on the soft cost side as well. Modular policies and finance mechanisms that are easily customizable, have standardized and interchangeable parts, and are able to operate independently as parts of a whole could have enormous impacts on the industry that have not yet been realized.

Chapter 6

RECOMMENDATIONS AND IMPLICATIONS FOR FURTHER RESEARCH

6.1 Recommended Soft Cost Reduction Measures

The results of this study indicate that there are a variety of measures related to economies of scale and modularity in the solar PV industry that could be taken in order to reduce costs on the soft cost side and the project development side. Utility-scale solar installations have lower soft costs overall because they are amortized over a larger system size, but that does not mean that the industry ought to solely pursue utility-scale solar. There are different regulatory and financial structures when on opposite sides of the meter that affect the profitability of energy projects. Distributed, rooftop PV sells into the grid at retail prices, while utility-scale solar farms sell into the grid at wholesale prices. This discrepancy can make some large-scale projects not financially viable where they otherwise would be if they were selling at retail prices. However, especially in emerging market nations, utility-scale solar makes much more sense because wholesale prices are much higher and land and labor are generally much cheaper. Especially in countries such as South Africa with nationalized utilities, companies like Eskom that struggle with system reliability can benefit much more from the increased capacity of utility-scale solar. Additionally, rooftop residential and commercial scale solar without storage is difficult to implement in places without net metering policy, which most emerging markets do not have. In the United States, rooftop solar has enormous potential because of new and innovative financing mechanisms such as power purchase agreements and solar leases. The inherent modularity characteristics defined and quantified in the study can help the solar PV industry drive costs down further by changing system design, racking, and installation processes to be more inherently modular in nature. Additionally, creating streamlined permitting and interconnection processes, standardized financing, and ‘plug and play’ systems which connect independent modules quickly and securely, but operate in parallel circuits. The modularity inherent in PV systems at all scales has enormous potential to drive down costs.

6.2 Implications and Recommendations for Further Study

In the future, modularity will be at the center of discussions regarding efficiency increases and cost-reduction. In order to expand the breadth of understanding among economists in the academic community, further study is recommended on the subject. Perhaps updating the data in this model using the anticipated 2010 Direct Requirements table from the Bureau of Economic Analysis, along with the 2010 NAICS codes, which also redesign the industry classifications based on the changes in the United States economy and delineate a variety of renewable technology industries, including solar PV. Further, perhaps including new indicators of modularity that become theorized as the field of study expands. Two potential ideas to explore are segmentation data and number of inputs into a final good or service. Further, in the future, the research team hopes to request the U.S. Energy Information Administration or the U.S. Department of Commerce to gather data that are more detailed on the renewable energy industry in a specially requested study in order to draw the initially desired conclusions.

Chapter 7

CONCLUSION

Plummeting PV module prices have caught the attention of individual homeowners, as well as firms in developing countries, especially where power is not readily available or reliable. According to the Navigant study, “new annual installations of solar PV will double from 35.9 gigawatts (GW) new capacity in 2013 to 73.4GW in 2020” and these new installations could generate up to $134 billion in industry revenue in the same timeframe (Gauntlett and Lawrence, 2013). Over half of this new capacity is expected to be utility-scale (in the developed world) by 2020, despite many nations, including Germany and China, having financial incentives that point towards investments in rooftop residential solar. As prices continue to fall, global solar dependency could reach up to 34 percent by 2050 (Farrell).

Especially with the looming crisis of peak oil and other shortages of fossil fuel technology, the implications of this renewable energy shift reach beyond environmental and economic benefits. The political implications of the end of the United States’ dependence on foreign oil and the decline of the Organization of Petroleum Exporting Countries (OPEC) cartel are profound, and the societal benefits of net metering and decreased environmental damages and pollution increase total welfare significantly.

The effects of economies of scale are mainly seen in soft cost differentials in the United States, mainly realized by systems reaching 5-10 MW. Because these costs see the most effect of economies of scale, policy impacts and economic markets need to open in order to accommodate the streamlining of photovoltaic production.

Modularity is the degree to which components of a system can be separated and recombined, a huge advantage solar photovoltaics have in both production as well as integration into the grid. Modularity is a largely undiscovered phenomenon that represents huge potential efficiency increases in production processes, firm organization, and even bureaucracy and government. It is the level of decomposability and intercommunication in a process or system observed as a function of its complexity. Modularity is, in essence a process of managing complexity, and can be seen to some degree in nearly every process, good or service. Modularity is a function of the ability for something to be separated and recombined, as an individual unit in the context of a larger whole. These results can be used to make policy recommendations for the purposes of encouraging modular production in industries with modular output in order to reduce costs and increase efficiency by capturing the benefits of economies of scale at each stage in the production process.

Once solar PV reaches grid parity, investors, firms, and consumers will have no economic incentive to choose investment in any technology besides in green energy, before factoring in the economic benefits of decentralization, energy security benefits, no fuel price volatility, and environmental benefits as well. When countries can reach grid parity, they will be able to value environmental quality at no additional cost, shattering the Kuznets Curve relationship, because the pretense that environmental quality is a luxury good will no longer hold, at least in the energy sector.

The benefits of economies of scale in soft costs and modularity in the solar PV value chain are critically important to driving solar PV technology to cost competitiveness and grid parity in U.S. markets.

Chapter 8

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Appendix A

INDEX OF MODULARITY IN U.S. INDUSTRIES

Appendix A: Index of Modularity in U.S. Industries

Fitted Index Values	Industry Classifications
0.000044	Lessors of nonfinancial intangible assets
0.00113	Civic, social, professional, and similar organizations
.000017	Real estate
.000025	Monetary authorities and depository credit intermediation
.000042	Legal services
0.00016	Couriers and messengers
0.00018	Accounting, tax preparation, bookkeeping, and payroll services
0.00021	Other retail
0.00043	Commercial and industrial machinery and equipment rental and leasing
0.00045	Insurance carriers
0.00052	Management consulting services
0.00053	Radio and television broadcasting
0.00062	Employment services
0.00067	Motor vehicle and parts dealers
0.00106	Accommodation
0.00115	Management of companies and enterprises
0.00125	Services to buildings and dwellings
0.00144	Automotive equipment rental and leasing
0.00146	Nondepository credit intermediation and related activities
0.00174	Business support services
0.00193	Spectator sports
0.00212	Scenic and sightseeing transportation and support activities for transportation
0.00213	Computer systems design services
0.00220	Limited-service restaurants
0.00246	Wholesale trade
0.00271	Consumer goods and general rental centers
0.00275	Custom computer programming services
0.00281	Copper, nickel, lead, and zinc mining
0.00290	Other crop farming
0.00291	Office administrative services
0.00302	Forestry and logging
0.00327	Full-service restaurants
0.00336	Biological product (except diagnostic) manufacturing
0.00344	Support activities for agriculture and forestry

0.00348	Iron, gold, silver, and other metal ore mining
0.00358	Specialized design services
0.00359	Animal production, except cattle and poultry and eggs
0.00360	Environmental and other technical consulting services
0.00379	Oilseed farming
0.00409	Residential mental retardation, mental health, substance abuse and other facilities
0.00430	Waste management and remediation services
0.00437	Dry-cleaning and laundry services
0.00449	Fruit and tree nut farming
0.00467	Nursing and community care facilities
0.00492	Pipeline transportation
0.00551	Hospitals
0.00563	Offices of physicians
0.00597	Newspaper publishers
0.00634	Pharmaceutical preparation manufacturing
0.00672	Food and beverage stores
0.00672	Other personal services
0.00675	Medical and diagnostic laboratories
0.00696	Advertising, public relations, and related services
0.00741	Offices of dentists
0.00744	Internet publishing and broadcasting and Web search portals
0.00757	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and
0.00815	Data processing, hosting, and related services
0.00820	Medicinal and botanical manufacturing
0.00824	General merchandise stores
0.00829	Grantmaking, giving, and social advocacy organizations
0.00832	Marketing research and all other miscellaneous professional, scientific, and technica
0.00839	Gambling industries (except casino hotels)
0.00881	Vegetable and melon farming
0.00886	Performing arts companies
0.00905	Offices of other health practitioners
0.00990	Motion picture and video industries
0.01045	Nonresidential maintenance and repair
0.01088	Cable and other subscription programming
0.01093	Religious organizations
0.01140	Amusement parks and arcades
0.01150	Dairy cattle and milk production
0.01178	Other ambulatory health care services
0.01179	News syndicates, libraries, archives and all other information services
0.01202	Museums, historical sites, zoos, and parks
0.01219	Grain farming
0.01284	Soap and cleaning compound manufacturing
0.01289	Facilities support services
0.01306	Wired telecommunications carriers
0.01332	Greenhouse, nursery, and floriculture production

0.01386	Distilleries
0.01428	Personal care services
0.01510	Outpatient care centers
0.01512	Other amusement and recreation industries
0.01523	Other nonmetallic mineral mining and quarrying
0.01559	Death care services
0.01564	All other food and drinking places
0.01641	Fishing, hunting and trapping
0.01654	Travel arrangement and reservation services
0.01815	Book publishers
0.01832	Oil and gas extraction
0.01832	Water, sewage and other systems
0.01877	Tobacco product manufacturing
0.01902	Home health care services
0.01939	Poultry and egg production
0.02001	Petrochemical manufacturing
0.02138	Directory, mailing list, and other publishers
0.02179	Stone mining and quarrying
0.02228	Other support services
0.02257	Periodical Publishers
0.02258	Flavoring syrup and concentrate manufacturing
0.02352	In-vitro diagnostic substance manufacturing
0.02405	Sound recording industries
0.02426	Sugar and confectionery product manufacturing
0.02534	Machine shops
0.02549	Veterinary services
0.02638	Software publishers
0.02927	Electric power generation, transmission, and distribution
0.02952	Ferrous metal foundries
0.02984	Sawmills and wood preservation
0.03032	Investigation and security services
0.03215	Printing
0.03222	Plate work and fabricated structural product manufacturing
0.03307	Other petroleum and coal products manufacturing
0.03444	Ball and roller bearing manufacturing
0.03511	Petroleum refineries
0.03746	Primary smelting and refining of copper
0.03777	Turned product and screw, nut, and bolt manufacturing
0.03949	Automotive repair and maintenance
0.04279	Plastics material and resin manufacturing
0.04409	Pesticide and other agricultural chemical manufacturing
0.04490	Primary smelting and refining of nonferrous metal (except copper and aluminum)
0.04518	Paint and coating manufacturing
0.04598	Nonferrous metal foundries
0.04651	Surgical and medical instrument manufacturing

0.04871	Valve and fittings other than plumbing
0.04923	Apparel manufacturing
0.04978	Paperboard container manufacturing
0.05095	Animal (except poultry) slaughtering, rendering, and processing
0.05117	All other forging, stamping, and sintering
0.05118	Other basic organic chemical manufacturing
0.05192	All other chemical product and preparation manufacturing
0.05249	Coating, engraving, heat treating and allied activities
0.05291	Urethane and other foam product (except polystyrene) manufacturing
0.05306	Soybean and other oilseed processing
0.06182	Other plastics product manufacturing
0.06219	Paperboard mills
0.06226	Dental equipment and supplies manufacturing
0.06263	Iron and steel mills and ferroalloy manufacturing
0.06271	Fertilizer manufacturing
0.06340	Paper mills
0.06379	Fruit and vegetable canning, pickling, and drying
0.06649	Bread and bakery product manufacturing
0.06734	All other food manufacturing
0.06970	Fats and oils refining and blending
0.07069	Toilet preparation manufacturing
0.07081	Copper rolling, drawing, extruding and alloying
0.07354	Leather and allied product manufacturing
0.07413	Fluid milk and butter manufacturing
0.07463	Cheese manufacturing
0.07600	Synthetic rubber and artificial and synthetic fibers and filaments manufacturing
0.07652	Other support activities for mining
0.07672	Clay product and refractory manufacturing
0.07688	Snack food manufacturing
0.07749	Veneer, plywood, and engineered wood product manufacturing
0.07986	Plastics bottle manufacturing
0.08165	Synthetic dye and pigment manufacturing
0.08166	Seasoning and dressing manufacturing
0.08245	Polystyrene foam product manufacturing
0.08313	Cookie, cracker, pasta, and tortilla manufacturing
0.08327	Other computer related services, including facilities management
0.08403	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and all
0.08482	Plastics packaging materials and unlaminated film and sheet manufacturing
0.08564	Fabric mills
0.08740	Asphalt paving mixture and block manufacturing
0.08869	Cement manufacturing
0.08970	Speed changer, industrial high-speed drive, and gear manufacturing
0.09088	Crown and closure manufacturing and metal stamping
0.09119	Other animal food manufacturing
0.09470	Glass and glass product manufacturing

0.09518	Wet corn milling
0.09589	Dry, condensed, and evaporated dairy product manufacturing
0.09841	Frozen food manufacturing
0.09888	Residential maintenance and repair
0.09914	Coffee and tea manufacturing
0.09933	Steel product manufacturing from purchased steel
0.10123	Industrial gas manufacturing
0.10219	Motor vehicle metal stamping
0.10330	All other wood product manufacturing
0.10476	Pulp mills
0.10653	Breakfast cereal manufacturing
0.10672	Hardware manufacturing
0.10713	Other concrete product manufacturing
0.10785	Breweries
0.10981	Tire manufacturing
0.11018	Custom roll forming
0.11108	Natural gas distribution
0.11531	Plastics pipe, pipe fitting, and unlaminated profile shape manufacturing
0.11968	Seafood product preparation and packaging
0.12223	Power and communication structures
0.12315	Ophthalmic goods manufacturing
0.12533	Alumina refining and primary aluminum production
0.12540	Rubber and plastics hoses and belting manufacturing
0.12545	Lime and gypsum product manufacturing
0.12665	Ornamental and architectural metal products manufacturing
0.12792	Coal mining
0.12840	Other fabricated metal manufacturing
0.12928	Ice cream and frozen dessert manufacturing
0.13114	Other aircraft parts and auxiliary equipment manufacturing
0.13270	Other rubber product manufacturing
0.13603	Satellite, telecommunications resellers, and all other telecommunications
0.13608	Flour milling and malt manufacturing
0.13637	Cutlery and handtool manufacturing
0.13680	Fabricated pipe and pipe fitting manufacturing
0.13703	Commercial structures, including farm structures
0.13723	Millwork
0.13823	Support activities for printing
0.13827	Manufacturing structures
0.13829	Poultry processing
0.13897	Textile and fabric finishing and fabric coating mills
0.14474	Laminated plastics plate, sheet (except packaging), and shape manufacturing
0.14555	Other industrial machinery manufacturing
0.14647	Spring and wire product manufacturing
0.14802	Other basic inorganic chemical manufacturing
0.15005	Paper bag and coated and treated paper manufacturing

0.15376	Fiber, yarn, and thread mills
0.15377	Adhesive manufacturing
0.15390	Soft drink and ice manufacturing
0.15636	Concrete pipe, brick, and block manufacturing
0.15679	Ready-mix concrete manufacturing
0.16360	Ammunition, arms, ordnance, and accessories manufacturing
0.16733	Printing ink manufacturing
0.16997	Secondary smelting and alloying of aluminum
0.17107	Dog and cat food manufacturing
0.17137	Single-family residential structures
0.18325	Other textile product mills
0.18467	Surgical appliance and supplies manufacturing
0.18637	Railroad rolling stock manufacturing
0.18729	Metal can, box, and other metal container (light gauge) manufacturing
0.19505	Other nonresidential structures
0.19571	Other motor vehicle parts manufacturing
0.20096	Sanitary paper product manufacturing
0.20627	Metal tank (heavy gauge) manufacturing
0.21126	Aluminum product manufacturing from purchased aluminum
0.21801	Mechanical power transmission equipment manufacturing
0.22311	Farm machinery and equipment manufacturing
0.22740	All other converted paper product manufacturing
0.22973	Health care structures
0.23478	Motor vehicle steering, suspension component (except spring), and brake systems m
0.23543	Office furniture and custom architectural woodwork and millwork manufacturing
0.23993	Construction machinery manufacturing
0.24036	Multifamily residential structures
0.24068	Asphalt shingle and coating materials manufacturing
0.24824	Mining and oil and gas field machinery manufacturing
0.25283	Motor vehicle gasoline engine and engine parts manufacturing
0.26172	Stationery product manufacturing
0.26729	Air purification and ventilation equipment manufacturing
0.27242	Other residential structures
0.27497	Power boiler and heat exchanger manufacturing
0.27666	Highways and streets
0.27802	Curtain and linen mills
0.28262	Plumbing fixture fitting and trim manufacturing
0.28380	Photographic services
0.29129	Motor vehicle seating and interior trim manufacturing
0.30867	Carpet and rug mills
0.31014	Educational and vocational structures
0.31662	Drilling oil and gas wells
0.33930	Wineries
0.34101	Motor vehicle body manufacturing
0.36264	Motor vehicle transmission and power train parts manufacturing

0.36390	Travel trailer and camper manufacturing
0.37936	Truck trailer manufacturing
0.38218	Other engine equipment manufacturing
0.47098	Air conditioning, refrigeration, and warm air heating equipment manufacturing
0.47606	Lawn and garden equipment manufacturing
0.54591	Plastics and rubber industry machinery manufacturing
0.57773	Motor home manufacturing
0.60849	Ship building and repairing
0.63155	Rail transportation
0.67078	Heavy duty truck manufacturing
0.67492	Small electrical appliance manufacturing
0.68162	Institutional furniture manufacturing
0.69409	Vending, commercial laundry, and other commercial and service industry machiner
0.70283	Air transportation
0.70595	Heating equipment (except warm air furnaces) manufacturing
0.76396	Wireless telecommunications carriers (except satellite)
0.77873	Truck transportation
0.79154	All other transportation equipment manufacturing
0.79994	Automobile manufacturing
0.81318	Aircraft engine and engine parts manufacturing
0.81319	Office machinery manufacturing
0.81561	Warehousing and storage
0.82216	Semiconductor machinery manufacturing
0.83303	Boat building
0.87196	Photographic and photocopying equipment manufacturing
0.90740	Transit and ground passenger transportation
0.91364	Water transportation
0.93910	Light truck and utility vehicle manufacturing
0.95152	Household cooking appliance manufacturing
0.98591	Propulsion units and parts for space vehicles and guided missiles
0.99672	Aircraft manufacturing
0.99685	Guided missile and space vehicle manufacturing
0.99919	Optical instrument and lens manufacturing
1.00000	Electronic computer manufacturing
1.00000	Computer storage device manufacturing
1.00000	Computer terminals and other computer peripheral equipment manufacturing
1.00000	Telephone apparatus manufacturing
1.00000	Broadcast and wireless communications equipment
1.00000	Other communications equipment manufacturing
1.00000	Audio and video equipment manufacturing
1.00000	Other electronic component manufacturing
1.00000	Semiconductor and related device manufacturing
1.00000	Printed circuit assembly (electronic assembly) manufacturing
1.00000	Electromedical and electrotherapeutic apparatus manufacturing
1.00000	Search, detection, and navigation instruments manufacturing

1.00000	Motor vehicle electrical and electronic equipment manufacturing

Appendix B

F-TEST OF EACH VARIABLE WITH WALD RESTRICTIONS The research team ran F-tests using Wald restrictions on each of the variables to determine their significance on the dependent variable. All tests have an alpha value of 0.05:

VARIABLE: INTTRANSPORT

Ho: $\beta_1=0$
Ha: $\beta_1\neq0$
Fcrit: @qfdist(0.95, 1, 299)= 3.87275
Fstat: 27.13195
Decision Rule: If Fstat > Fcrit, reject Ho.
Decision: Reject Ho: INTTRANSPORT makes a significant difference.

VARIABLE: INDINT

Ho: $\beta_2=0$
Ha: $\beta_2\neq0$
Fcrit: @qfdist(0.95, 1, 299)= 3.87275
Fstat: 13.11985
Decision Rule: If Fstat > Fcrit, reject Ho.
Decision:Reject Ho: INDINT makes a significant difference.

VARIABLE: ENGINT

Ho: $\beta_3=0$
Ha: $\beta_3\neq0$
Fcrit: @qfdist(0.95, 1, 299)= 3.87275
Fstat: 1.785774
Decision Rule: If Fstat > Fcrit, reject Ho.
Decision: Fail to Reject Ho: ENGINT makes **no** significant difference on the regression output.

VARIABLE: COGSPCTRET

Ho: $\beta_4=0$
Ha: $\beta_4\neq0$
Fcrit: @qfdist(0.95, 1, 299)= 3.87275
Fstat: 10.66777
Decision Rule: If Fstat > Fcrit, reject Ho.
Decision: Reject Ho: COGSPCTRET makes a significant difference.

VARIABLE: TECHLEVEL

Ho: $\beta_5=0$
Ha: $\beta_5\neq0$
Fcrit: @qfdist(0.95, 1, 299)= 3.87275
Fstat: 12.33088
Decision Rule: If Fstat > Fcrit, reject Ho.
Decision: Fail to Reject Ho, TECHLEVEL makes a significant difference