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Governments around the world have employed a variety of generous subsidies to help promote and develop clean energy technologies in the hope that they will widely replace dirtier carbon-based power sources. Unfortunately these subsidies have not prevented numerous green technology bankruptcies including the infamous 2011 closure of the California based solar panel producer Solyndra, and these failures have cost taxpayers and private investors billions in lost capital. The green innovation value chain (GIVC) provides a possible framework for determining the diffusion prospects of green technologies through environmental and financial comparisons to conventional alternatives across the separate chain links comprised of manufacturers, distributors, customers, government, and the environment. The GIVC framework is used here to analyze the photovoltaic solar power chain, where financial deficits are found in each link that will need to be reduced or eliminated through technology advancements, subsidies, or changes in market conditions in order to provide the conditions necessary for the technology to achieve mass-market acceptance and positive financial returns.

Keywords: Solar Power, Green Innovation Value Chain, Life cycle assessment, Green Subsidies.

1.0 Introduction

"11 More Solyndras In Obama Energy Program." (*CBS News*, Jan.13, 2012)

The environmental innovation and strategy literatures frequently encourage firms and nations to make strategic commitments towards reducing CO2 and other emissions as a means to not only help the environment, but also increase firm profitability and competitive advantage (Porter and van der Linde, 1995; Porter and Reinhardt, 2007; Unruh and Ettenson, 2010). The assumption that there are profitable and growing markets that are receptive to green technologies is largely based on decades of opinion polls showing a consistent and growing majority of citizens expressing concern for the environment (Nisbett and Myers, 2007). Thus the possibility of higher profits while also helping the environment has spurred private and public sector investments in cleaner power generation to supply the electricity needs of industry and households, with one result being a 30% per annum growth in solar energy capacity over the past 20 years (Solarbuzz, 2010).

Figure 1 about here

Yet the headline from the CBS News story above also highlights the high failure rate of green energy firms that have cost public and private investors billions in lost capital, including investments in recently bankrupted solar panel producers Solyndra, Evergreen, Spectrawatt and Solon (Attkisson, 2012; Hoium, 2012). The large number of recent solar industry failures point to the need for a multi-stakeholder framework covering both the economic and environmental performance of solar technologies, which can be utilized to determine current viability and provide guidance to both private investors and government policy makers. The recent introduction of the green innovation value chain (GIVC) concept offers promise in addressing this need (Olson, 2013a), and the purpose of this article is to illustrate the GIVC concept via a case study of photovoltaic (PV) solar generated electricity and the key stakeholders who comprise each 'link' of the technology's chain. As illustrated in figure 1, the analysis will encompass the relative overall economic and environmental impact of PV solar versus natural gas generated electricity on equipment manufacturers, power companies, electricity customers, governments, and the environment.

2.0 Background

For many years a variety of scholarly literature has encouraged organizations to 'green' their manufacturing, distribution, and products as a strategic path that will provide them and society with both environmental and economic benefits (e.g. Porter and van der Linde, 1995, Porter and Reinhardt, 2007; Unruh and Ettenson, 2010). A literature review of 325 green product development articles, however, found the majority were prescriptive in advocating more manufacturer efforts in developing and launching green products, while only 10% provided empirical support (Baumann, et al. 2002). Furthermore, the empirical proof regarding the economic benefits of 'going green' is often anecdotal, with repeated references to a few well known cases such as Body Shop and the Toyota Prius (Crittenden, et al. 2011; Pujari, 2006; Rehfeld, et al., 2007). Thus much of this pro-green 'supply-side' literature fails to acknowledge any potential tradeoffs for green adopting firms, such as higher costs and weakened competitive position (Ambec and Lanoie, 2008; Palmer et al., 1995).

In contrast, a common theme in green technology adoption studies involving consumers is the presence of a value–action gap between the public's almost universal pro-green attitudes and their much rarer pro-green behaviors. This 'demand-side' value-action gap is widely attributed to the significant sacrifices that green technologies often require of users on conventional attributes such as price, convenience, or quality (Olson, 2013b; Pujari et al., 2003; Rokka and Uusitalo, 2008). While green tradeoffs are acknowledged in the consumer adoption literature, surprisingly few conceptual frameworks and little empirical research take their size and scope into account (Rokka and Uusitalo, 2008; Young et. al., 2010). For example, Roger's popular innovation diffusion theory predicts that innovations offering greater advantages versus current products will experience faster and more widespread adoption (Janssen and Jager, 2002; Rogers, 1995), but does not address the common green technology situation in which lower emission advantages require the acceptance of tradeoffs such as higher price/cost (Olson, 2013b). The Roger's framework is also most often focused on the innovation adoption decisions by end-users, but expectations of poor financial returns are also a major obstacle to the adoption of green technologies by the 'supply-side' firms that will produce and sell them (Ambec and Lanoie, 2008; Wong, Turner, and Stoneman, 1996).

These findings, together with other literature that demonstrates the helpfulness of broad based approaches to understanding innovation adoption, suggest that the evaluation of green technology diffusion prospects requires a multi-stakeholder perspective that encompasses both the supply-side (i.e. suppliers, manufacturers and distributors) and demand-side (i.e. end-users) (Enflo, Kander, and Schon, 2008). Thus the GIVC framework combines the multi-stakeholder approach and emissions focus of life cycle assessment (LCA) with the cost/value aspects of traditional value-chain analysis to consider the tradeoffs facing potential adopting stakeholders, which will in turn influence the green technology's supply and demand. Although neither value chain analysis nor LCA are expressly designed as frameworks for understanding technology diffusion, the following sections demonstrate how the GIVC combines them to overcome the limitations of each as tools for evaluating the adoption prospects of green technologies.

2.1 Value-chain Analysis

Value-chain analysis traditionally focuses on the positive and negative financial implications that activities such as logistics, operations, and marketing/sales can have on the costs and pricing power of a firm's product. The value-chain paradigm is also amendable to modifications that suit the analytic needs of specific areas such as the new product development process or non-manufacturing based firms such as banks (e.g. Hansen and Birkinshaw, 2007; Stabell and Fjeldstad, 1998). Within the environmental arena, Porter and Reinhardt (2007) further suggest a ratio of profits to total emissions as a metric for evaluating the climate impact of each value-chain activity within the firm.

Yet the focus on the value enhancing/detracting activities within a specific firm limits the usefulness of value-chain analysis in the study of green technologies because the approach typically ignores important external stakeholders. For example, green technology frequently needs to satisfy pending or anticipated changes to government environmental regulations and policies (Bauman et al., 2002; Rehfeld, et al., 2007; Taylor, 2006). In part this government 'push' is often seen as necessary to achieve environmental objectives due to customer unwillingness to make green-related sacrifices on economic or quality attributes (Bamberg, 2002; Ginsberg and Bloom, 2003; Wong et al., 1996). Thus without widespread customer demand and/or government push, green technologies may not be seen as good investments by industry and therefore not be made available to displace conventional competitors (Pujari et al., 2003; Pujari, 2006; Wong et. al., 1996).

2.2 Life cycle Assessment (LCA)

By including the financial focus of value chain analysis, GIVC offers a broader perspective than traditional LCA, which typically focuses on environmental impact via the calculation of total emissions through each phase of the product's life cycle from raw material extraction to final use and disposal (Albino et al., 2009, Baumann, et. al., 2002; Hermann et al. 2006). LCA case studies regarding the relative environmental performance of competing green and conventional technologies are often influential in policy and investment decisions, and have become so common that specific ISO operational standards have been developed for conducting them (Hillman, 2008; Finnveden et al., 2009). While LCA is a multi-stakeholder approach, its focus on environmental effects typically ignores the financial implications of the focal technologies, which is a major limitation in terms of evaluating diffusion prospects (Finnveden et al., 2009; Norris, 2001). GIVC analysis relies on LCA for the comparative environment link results, which may come from new or existing LCA studies that are then combined with the financial results from the other links to determine current viability and/or identify any weak links that will limit the green technology's attractiveness to potential adopters.

Another commonality between GIVC analysis and LCA is their systems approach, as they both focus on defining the boundaries between internal and external system/chain elements and the influence of interactions between subsystems/links on the results (Hillman, 2008; Olson, 2013a). An example of an interaction that is possible in both GIVC analysis and LCA, are the rebound effects that can occur when lower emissions are achieved through reduced energy consumption, which encourages greater use of the green technology and a subsequent loss of potential environmental gains (Finnveden et al. 2009; Hillman, 2008; Olson, 2013a). The addition of financial results within GIVC analysis, however, brings another dimension to the link interactions, as favorable economics that increase the likelihood of green technology adoption by any single link, may also positively influence the adoption decisions of other links.

Although attempts have been made to incorporate economic elements into LCA, none have achieved widespread acceptance or consider the cost of green technology adoption from the perspective of all key stakeholders (Finnveden 1999; Finnveden et al. 2009). Instead, the two types of financial analyses most typically utilized in LCA cases are narrower in their scope. The first, sometimes referred to as environmental priority strategies (EPS), focuses on the demand side by estimating the price that citizens are willing to pay for the technology's ability to provide environmental benefits such as improved human health and biodiversity (Finnveden et al. 2009; Steen 1999). The utility of such data, however, is limited without the adoption cost estimates necessary to determine if they are lower than benefit valuations (Norris 2001). The second method is commonly known as life cycle costing (LCC) and involves the calculation of the ownership costs related to technology adoption from the perspective of the buyer/user (Norris 2001), but in focusing only on the costs of adoption for one party it ignore the costs borne by other stakeholders. As will be demonstrated, GIVC analysis incorporates LCC type estimates for calculation of the customer link financial results, and EPS type estimates as a frame of comparison to the relative financial value of the environmental benefits derived by the chain's adoption of the green technology. Thus by focusing on both the environmental benefits and financial costs of technology adoption by all key stakeholders individually and across the entire chain, GIVC analysis is more complete and diagnostic than LCA related approaches as to whether poor financial returns are likely to be an obstacle to the mass-adoption of green technology (Olson 2013a).

3.0 Green Innovation Value Chain (GIVC)

Based on research that finds only small 'extreme green' segments are willing to accept significant tradeoffs in order to 'go green' (Ambec and Lanoie, 2008; Ginsberg and Bloom, 2004; Peattie and Peattie, 2009), a key GIVC assumption for predicting widespread green technology adoption is that it provides ‘win-win-win’ outcomes versus conventional competitors along each link of the chain (Olson 2013a). GIVC analysis further assumes that the long-term viability of the green technology is based on the achievement of attractive financial results with minimal government subsidies, and thus attempts to isolate the business case from any current support to better determine how close the green technology is to standing on its own.

Table 1 about here

The following sections will use GIVC analysis to calculate the financial and environmental attractiveness of electricity generated by PV solar power plants, which is accomplished through a comparison with electricity generated via natural gas turbine generators. Data for the analysis is taken from well-respected government, industry, and academic sources cited throughout the text and focusing primarily on the United States electricity market. As noted in table 1, despite the dramatic recent growth in solar generating capacity, it accounts for less than 1% of U.S. electricity production. In contrast, natural gas generates almost a quarter of U.S. electricity, and is chosen as solar’s conventional competitor because it is projected to be the fastest growing carbon-based fuel source for new electricity generating plants (EIA, 2012; Smil, 2012).

The GIVC links included in the comparative analysis cover all the key demand and supply-side stakeholders that will determine the likelihood that PV solar can become a major source of electricity generation. The links included in the present case are: 1) manufacturing (i.e. solar panels vs. gas-turbine generators), 2) distribution (utility company generated electricity via solar and gas power plants), 3) end-user (i.e. industrial and residential buyers of electricity), 4) government (subsidy supplier), and 5) the environment (CO2 equivalent LCA emissions of solar vs. gas generated electricity). Although other links, such as manufacturer supply chains, could also be included in the analysis, background research suggested that their addition would not materially influence the results, and hence the simplified chain is utilized for reasons of case parsimony.

3.1 Manufacturer Link of the Green Innovation Value Chain

Estimating the 'subsidy free' profitability of PV solar panel manufacturing is difficult due to the fact that industry growth has been largely fueled by generous government subsidies (Bernbaum and Failoa, 2012). Recent reductions in solar subsidies by governments around the globe have led to industry overcapacity and the elimination of profits, which is demonstrated by the over 70% share price reduction since 2008 of two exchange-traded-funds (EFT) tracking the overall solar panel industry (Konrad, 2012). Thus table 2 section 1 estimates zero profits for the solar panel manufacturer link, which is likely optimistic since analysts predict that near-term financial prospects are more likely to be negative than positive on an industry-wide basis (Styles, 2011). In comparison to the solar panel industry, the manufacturers of modern gas-turbine generators enjoy profit margins of approximately 15% (Hinton, 2011). This 15% margin is then multiplied by the typical gas-turbine price of $200,000 per megawatt (MW) of capacity to provide the lifetime profit figure for gas-turbine manufacturers of $30,000 per MW (Nye 2012). Dividing the 999,000 gigawatt hours (GWh) of annual natural gas generated electricity by the 4,119,828 GWh of U.S. natural gas generating capacity yields a 24.2% utilization rate (EIA 2010). Thus combining the 30-year plant life assumed by the U.S. Energy Information Administration (EIA) with a 24.2% utilization rate means that each MW of plant capacity would generate 63,725 megawatt hours (MWh) during its life (EIA 2012). When this figure is divided by the $30,000 lifetime manufacturer profit per MW, the results show a gas-turbine manufacturer profit of $0.47 per MWh versus the $0.00 per MWh estimate for PV solar panel manufacturers. Increased sales volumes would likely improve the financial picture for solar panel manufacturing, but the likelihood of achieving this is highly dependent on PV solar power attractiveness to the links further up the chain.

Table 2 about here

3.2 Distributor Link of the Green Innovation Value Chain

Solar power distributors in this case are the electric utility companies that link together thousands of PV panels to create solar power plants that generate electricity for retail sale. The effort that utilities put into solar generated electricity is dependent on its relative costs and/or profit margins, which are typically poorer than carbon-based electricity due to basic physics and the power conversion limitations of current solar technology (Schlesinger and Hirsh, 2009). Solar energy is dependent on the mass and velocity of solar radiation, which is diluted over 90% by the time it travels from the sun to the earth (Tucker, 2009). The best current PV solar panels typically collect less than 15% of this diluted solar radiation under ideal conditions (i.e. dust-free panels, no-cloud cover, day-time hours), which then goes through a series of power transformations for a further efficiency loss of 12-15% (Smil, 2010, pp. 12-14; Tucker, 2009). This means that solar power plants using current PV technology are limited to approximately 10 watts of power per square meter of panel, although cloudy and short days can reduce this maximum figure by 50% (Smil, 2010, p. 16). For example, Germany's world-leading 25,000 MW of installed solar panel capacity generated 18 terawatt-hours of electricity in 2011 (Bryce 2012). Thus during each 24-hour day during 2011, only 72.1 MWh was generated out of the maximum total capacity of 8,760 (i.e. 24 hours * 25,000 MW = 8,760 MWh or about 1% of maximum theoretical capacity) due to the country's northern latitude and often-cloudy environment. In comparison, modern large gas turbines are currently 60% efficient in converting natural gas energy into electricity, and can generate 5,000 watts per square meter of power plant footprint under virtually all conditions (Smil, 2010, pp. 8-11). These efficiency differences mean a solar plant that can deliver 1,000 MW would require at least 100 square kilometers of space (38.6 square miles) under ideal conditions, while a gas turbine power plant of the same capacity would need 0.2 square kilometers (0.077 square miles).

The sheer size needs of PV solar means land requirements are huge and costly, and typically forces the power plants to be located in less populated areas where the land is cheaper (Schlesinger and Hirsh, 2009). But such remote locations enact their own costs as they typically require lengthy new power lines for transmitting the electricity to population centers, which can incur a further power loss of 5 to 7% (Deodhar, 2011). In contrast, natural gas generating plants can be located close to population centers with relatively minimal disruption of the environment (Evans et al., 2008; Smil, 2010, p. 8-11).

Distributor link profitability is calculated by the following formula: Profit = (revenue from power sales – (cost of power generation + cost of backup power)). The cost of power generation reported in table 2 section 2 utilizes EIA estimates for the levelized cost of generating one MWh of electricity that includes the costs of building, operating and maintaining a power plant during a 30-year life. The EIA predicts a cost of $63.10 per MWh using natural gas and $152.70 for PV solar energy (EIA, 2012). For PV solar, the EIA estimates do not include the $3 to $5 per MWh cost of a conventional power generator backup required to provide customers with a reliable power source when the sun is not shining (St. John, 2012), and thus the mid-point estimate of $4 is added to the PV generation cost in table 2. In the U.S. the average power company customer pays $98.26 per MWh (EIA, 2010), and together with the additional $0.35

per MWh coming from higher fees for green power (see note 3 in table 2) means each MWh of PV generated electricity is sold at a loss averaging $58.09. In contrast, natural gas generated electricity earns a profit of $35.16 per MWh, which means the total financial deficit is $93.25 per MWh for PV solar in the distributor link. Thus solar power gives its distributors negative margins versus natural gas, and will therefore only be attractive to power companies if customer preferences for clean energy allow premium prices to be charged that can make up the losses.

3.3 Customer Link of the Green Innovation Value Chain

Nationwide, U.S. electricity customers that are offered the opportunity to buy green power generated from renewable sources are charged a price premium that averages $1.75 cents per kilowatt-hour (kWh) above the regular price, but only about 2% of homeowners and businesses voluntarily sign up to pay the extra fee (Environmental Leader 2010). This low level of adoption should not be surprising, as solar generated electricity offers no visible advantages to customers versus gas-generated electricity (Pujari, et al., 2003). After all, a home refrigerator or industrial robot will run just as well on ‘dirty’ gas-sourced electricity as from ‘clean’ solar power. Similarly, because buying solar generated electricity from a power company is invisible to outside observers it provides no customer social status via public displays of environmental concern. Furthermore, general consumer indifference to green power provides little opportunity for solar adopting firms to pass the higher costs of ‘greening’ their business processes onto their customers.

Thus the unwillingness of most customers to pay even a small premium for clean electricity means that the extra green power revenue covers only a small portion of solar power’s extra cost to the power company, which forces the remaining customer base to pay higher prices to make up the deficit (Noon, 2012). Solar’s higher costs to the GIVC customer link are presented in table 2 section 3, and assumes the solar power buyer paying the $17.50 per MWh average 'green power' program price premium (Environmental Leader 2010). With 98% of customers not volunteering to pay extra for green electricity, together with the manufacturer and distributor link losses, only attractive government subsidies and/or compelling environmental benefits might make PV solar worthy of each link's financial sacrifices.

3.4 Government Link of the Green Innovation Value Chain

Due to PV solar's negative financial results for the manufacturer, distributor, and customer links, adoption of the current technology is largely dependent on government support that provides compensation for at least some of each link's green sacrifices. Environmentalists and government policy makers typically promote green technology subsidies and supports for three main reasons (Friedman 2008; Hargadon and Kenney 2012; Kahouli-Brahmi 2009; Kerry and Graham 2009). First, they claim that non-green alternatives have an unfair advantage due to their failure to pay for negative externalities in the form of 'free' discharges of greenhouse gases. The second major justification is that relatively new green technologies require 'temporary' start-up subsidies to compete effectively with older conventional technologies that benefit from the accumulated learning and scale effects built over decades of use. The third common rationale for green subsidies is the creation of high value green industries and jobs.

Thus from a public policy point of view, government supports should help overcome green technology disadvantages versus conventional alternatives and in so doing create market demand that will cost effectively reduce emissions and create industries to supply the new green markets. These policy aims are reflected by the wide variety of government support for solar energy around the world, which includes research grants, tax credits, feed-in tariff subsidies, and renewable energy mandates for electric utilities. As table 1 shows, in the U.S. these solar subsidies are valued by the EIA at $24.34 per MWh generated, which is almost 100 times higher than the 25 cents per MWh subsidy received by natural gas, creating a $24.09 advantage for PV solar as shown in table 2 section 4. Yet this PV solar support advantage is not generous enough to eliminate the $111.22 PV solar profit deficit from other links, as an $87.13 per MWh natural gas financial advantage remains even after government subsidies are included (see table 2 section 6). Experiences in Europe and the U.S. also suggest that green job creation benefits do little to improve the case for solar power subsidies. For example an analysis of Spanish renewable energy supports (many in the solar power) found that each green job required $800,000 in subsidies and destroyed 2.2 jobs elsewhere in the economy (Alvarez et al. 2009). Similarly, a recent analysis by the U.S. Energy Department found that each permanent green job created by federal loan guarantees to green firms (again many in the solar field) had cost over $5 million (Lawson, 2009).

Thus the economic case for the government support of the PV solar industry is dependent on the economic value of emission reductions from the environment link being higher than the financial cost of achieving them across the other GIVC links. Based on most economic analyses regarding the social, economic, and environmental benefits from a one-ton reduction in CO_2 emissions, PV solar emission reductions versus natural gas should not cost more than $50 per CO_2 equivalent ton, and likely should cost less than $25 (Tol, 2007).

3.5 Environment Link of the Green Innovation Value Chain

The greenhouse gas emissions and other pollutants associated with all phases of the construction, operation, and decommissioning of PV solar and natural gas electricity generating capacity have been the subject of many LCA studies, where comparisons are typically based on CO_2 equivalents per unit of electricity generated (i.e. non-CO_2 pollutants are converted into

CO2 equivalent values). The resulting LCA estimates vary widely due to differing assumptions regarding variables such as power plant efficiency levels, expected plant lifespan, local weather conditions (i.e. sunny hours per day), and needs for power grid investments (i.e. connecting power plant to grid). Hence table 2 section 5 shows that LCA estimates for PV solar range from .032 to .217 CO2 equivalent tons per MWh, while natural gas generated electricity ranges from .385 to .443 tons per MWh (Lenzen, 2008; Sovacool, 2008). These LCA figures are used to calculated the cost effectiveness of PV solar emission reductions using the following formula: (natural gas LCA emissions - PV solar LCA emissions) / (natural gas GIVC profit with & without subsidy - PV solar GIVC profits with & without subsides).

Table 2 section 5 shows the PV solar-induced CO2 equivalent ton reduction per MWh that result from subtracting the LCA estimates. Thus the use of mid-point LCA estimates from each power source results in a CO2 equivalent ton reduction of .29 per MWh, while the best solar estimate versus the worst natural gas estimate is .41, and the worst solar versus the best natural gas is .17. These CO2 equivalent reduction figures are then divided by the $111.22 total PV solar profit deficit, without any government subsidies, to determine the subsidy-free cost per CO2 ton reduction at $384, $271, and $662 respectively (see note 1 in figure 2). When the government link subsidy is included, the PV solar profit deficit is reduced to $87.13, and the cost per CO2 equivalent ton reduction becomes $300, $213, and $519 respectively. All of these CO2 reduction costs are far higher than the $50 (or less) per ton value of the reduction benefits, and suggest a very poor environmental return across the entire PV solar GIVC.

Figure 2 about here

3.6 Summary of the PV Solar Green Innovation Value Chain

This GIVC case analysis reflects current cost and emission projections for PV solar and natural gas generated electricity in the United States, and the results are not supportive of most PV solar investments and subsidies. Although U.S. government subsidies for PV solar are almost 100 times higher than subsidies to natural gas, they are still inadequate to overcome the PV solar profit disadvantages and achieve less than $50 per ton emission reduction costs. As shown in figure 2, achieving emission cost reductions that are less than $50 per ton will require reductions in the PV solar GIVC financial deficits from the current -$111.22 to -$8.40 in the worst case and -$20.50 in best case, which translates into 92% and 82% financial deficit reductions respectively. Thus a key follow-up question is whether foreseeable technology improvements and/or changing market conditions are likely to greatly reduce current PV solar financial deficits, and thereby justify continued private and public investment in the industry.

Although solar panel prices have dropped dramatically in recent years due to growing economies of scale and technology improvements, many analysts attribute the majority of the reductions to overcapacity induced price competition that have eliminated all industry profits and resulted in several high profile bankruptcies (Styles, 2011). Higher solar panel efficiency levels might also reduce the financial deficits displayed in table 2, and experimental panels have been tested that double the energy conversion rates of current panels, but when they become available they will likely be competing with more efficient gas-turbines also under development (Smil 2012). Furthermore, until some cost effective systems can be developed for the storage of excess power generation during the sunniest hours, solar power is unlikely to reach complete parity with natural gas generated electricity due to the need for system redundancy in the form of conventional power plant backups for periods when the sun doesn’t shine (St. John, 2012).

Higher than anticipated solar power costs have led many countries such as Germany, Spain, Italy, and the UK to dramatically reduce their industry support, yet even a continuation or expansion of generous solar subsidies may not be enough to protect industry profits from hydraulic fracturing (a.k.a. fracking) technology that has unleashed vast new natural gas supplies. As a result, the U.S. price of natural gas has been reduced from $15 per thousand cubic feet in 2005 to less than $2 in 2012, with consequent dramatic reductions in the price of gas-generated electricity (Smil, 2012). The lower gas prices have also had a dramatic negative impact on most PV solar financial projections, because they have previously assumed ever-rising prices on carbon-sourced electricity that would reduce current solar cost disadvantages (Brady, 2012).

The GIVC case analysis shows that the largest part of PV solar's total financial deficit comes from the high relative cost of PV solar power generation, and lower cost natural gas only magnifies this disadvantage. This would suggest that PV solar investments and subsidies should focus primarily on R&D that might lead to quantum leaps in solar panel efficiency and dramatically lowered hardware and energy storage costs that could ultimately provide the attractive financial returns that would spur widespread adoption of this clean energy source (Hargadon and Kenney, 2012, Lomborg, 2011). Yet most government support for the PV solar industry, including tax breaks, loan guarantees, price guarantees, and renewable mandates have been used to encourage and/or force solar hardware manufacturing and power plant construction using uncompetitive technology (Lipton and Krauss, 2011). For example, the government loan guarantees provided to solar panel producer Solyndra were allocated to the construction of a new plant for the mass-production of the firm's cylindrical shaped panels, which were expected to be less expensive and more efficient than conventional flat panels (Leonig and Stephens, 2011;

Wald, 2011). The subsequent bankruptcy was in large part due to the failure of the new panels to achieve the hoped for advantages, yet even if the Solyndra panels had attained their theoretical levels of performance and cost, they would have offered only incremental improvements over previous panel designs. Thus even under best case scenarios, commercializing Solyndra's design would have had very little impact in closing the PV solar's current financial gaps with natural gas generated electricity that might wean the industry off government subsidies anytime soon.

Lowering the cost of PV solar is also the key to increasing customer preference for solar power, because otherwise the technology offers no non-green benefits, such as lower energy consumption, that might make it worth a price premium. Yet until there is a cost savings associated with the adoption of PV solar, the lack of benefits also means that rebound effects are less likely to be an issue because lower costs will not encourage the increased electricity consumption that would lead to reductions in expected environmental benefits (Hermann, Kroeze and Jawjit, 2006). On the other hand, more widespread customer adoption of PV solar could create other sources of environmental degradation, such as the loss of farmland and wildlife habitat caused by the large footprints of PV solar power plants (Miller, 2013). Thus future LCA and GIVC studies of the industry will need to include any such emerging externalities, as well as the effects of technical advances, which might impact the relative environmental and financial attractiveness of PV solar.

4.0 Discussion and Conclusion

A comparison of PV solar power with more widely adopted green technologies from a variety of industries, such as hydroelectricity, video-conferencing, e-books, and LED TVs, provides a number of lessons that are relevant to the overall discussion of green technology diffusion. First, none of these more popular green technologies relies on system redundancy for reliability, which eliminates an important financial handicap versus conventional technologies. Second, all the more widely adopted green technologies also provide non-green user benefits compared to conventional alternatives. For example, hydroelectricity is generally less expensive than carbon-fueled sources, and video-conferencing is faster, cheaper, and more convenient than traditional business travel (Biello, 2009; Morgan, 2010). LED TVs provide the highest picture quality and use less electricity than other screen technologies, while e-books can be purchased instantly online to eliminate a lengthy trip to a bookstore (Olson 2013b; Owen 2012). Thus these more successful green technologies all provide a ‘demand-side’ reason for the customer link to adopt them, which in turn makes them more financially attractive to the ‘supply-side’ links in their GIVC chains without the need for government subsidies. This is important because only green technologies that widely displace conventional alternatives can potentially have a significant positive impact on the environment (Pujari et al., 2003). The PV solar case and these more successful green technologies also illustrate the systems perspective of GIVC analysis, as changes in public policy, relative technology performance, or market conditions that effect one link are likely to also increase or decrease the relative attractiveness of the green technology throughout the rest of the chain.

This case also illustrates the importance of applying GIVC analysis to other green technologies and markets, particularly in cases where they have achieved smaller than hoped market success to determine where the problem(s) are before committing major investments as a shareholder, manager, customer, or government policy maker. Analysis that finds financially unattractive propositions at each link using reasonable assumptions, should serve as a warning regarding the green technology’s low likelihood of widely displacing conventional alternatives. On the other hand, analysis for some green technologies might show poor financial returns for only one or two links in the chain, in which case targeted investments by industry and/or government might significantly reduce or eliminate the deficit and dramatically improve diffusion prospects.

Given the relatively low market penetration of many other green technologies, such as electric cars, biofuels, and wind power, critical questions should be raised about the realism of case parameters when GIVC analysis suggests highly profitable results among all or most of the chain links. As with any tool, the quality of the analysis and resulting conclusions is dependent on its appropriate use, and when dealing with green technologies there may be strong pressure to be 'politically correct' and create pro-green scenarios that show only the best possible financial and environmental results. Thus it is important that comparison parameters are not chosen based on a desire to support pro-green (or anti-green) biases that hinder objective financial and environmental assessments. Such biases might include unrealistic assumptions about development costs, product life, profit margins, adoption speed, government subsidies, and use of theoretical or ideal performance values rather than 'real world' values. Unrealistic GIVC link assumptions are likely to be most problematic when dealing with totally new green technologies that do not have well-established performance and cost data available. Yet even in the case of new technologies, the analysis displayed in figure 2 demonstrate that GIVC analysis can provide useful investor and policy-maker guidance by determining the maximum size of the financial gaps across the links that will provide economically justified environmental benefits versus existing competitors. Thus realistic and objective financial and environmental GIVC scrutiny can help stakeholders to focus limited resources on green technologies that are likely to achieve the attractive financial and environmental returns that will increase their chances of widespread adoption.

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Table 1

U.S. market data for PV Solar Power and Natural Gas Generated Electricity

	PV solar	natural gas	Gas % of PV solar
US Share of Electricity generation 2010 (1)	0.03%	24%	80000%
US Government Subsidies: $ per MWh (1)	$24.34	$0.25	1%
US Power generation cost: $ per MWh (1)	$152.70	$63.10	41%
US retail price: $ per MWh (1,2)	$115.76	$98.26	85%

(1) source: U.S. Energy Information Agency (EIA 2010)

(2) source: EIA 2010 + avg. U.S. green power premium (Environmental Leader 2010)

Table 2

PV Solar Green Innovation Value Chain Results

		PV solar	natural gas	solar vs. gas (1)	
Section 1: Manufacturer Link	$ Profit per MWh (2)	$0.00	$0.47	-$0.47	
Section 2: Distributor Link	$ Revenue from power sales per MWh (3)	$98.61	$98.26		
	$ Cost of power generation per MWh	-$152.70	-$63.10		
	$ Cost of backup power per MWh	-$4.00			
	$ Profit Total per MWh	-$58.09	$35.16	-$93.25	
Section 3: Customer Link	$ Green Program Fee per MWh (4)	-$17.50	$0.00		
	$ Profit Total per MWh	-$17.50	$0.00	-$17.50	
Section 4: Government Link	$ Value per MWh of Government Supports	$24.34	$0.25	$24.09	
Section 5: Environmental Link				0.29	Mid-point
	CO2 equivalent emission tons per MWh (5)	.03 to .22	.39 to .44	0.41	PV best case
				0.17	PV worst case
Section 6: All Links	$ Profit per MWh throughout chain without subsidies (6)	-$75.59	$35.63	-$111.22	
	$ Profit per MWh throughout chain with govt. subsidies (7)	-$51.25	$35.88	-$87.13	

Notes: Unless otherwise indicated the source data is from the EIA. (1) Column values based on PV solar column figure – natural gas column figure, negative figures indicate PV solar deficit vs. natural gas generated. (2) sources: Styles, 2011; Nye, 2012. (3) PV solar revenue based on: (98% non-green power subscribers * $98.26) + (2% green power subscription rate * $17.50 green power price premium). (4) source: Environmental Leader, 2010. (5) sources: LCA estimates from Lenzen, 2008; Sovacool, 2008. (6) sum of Profit Totals from sections 1 to 3. (7) same as note 6 + section 4 value of subsidies.

Figure 1: Green Innovation Value Chain

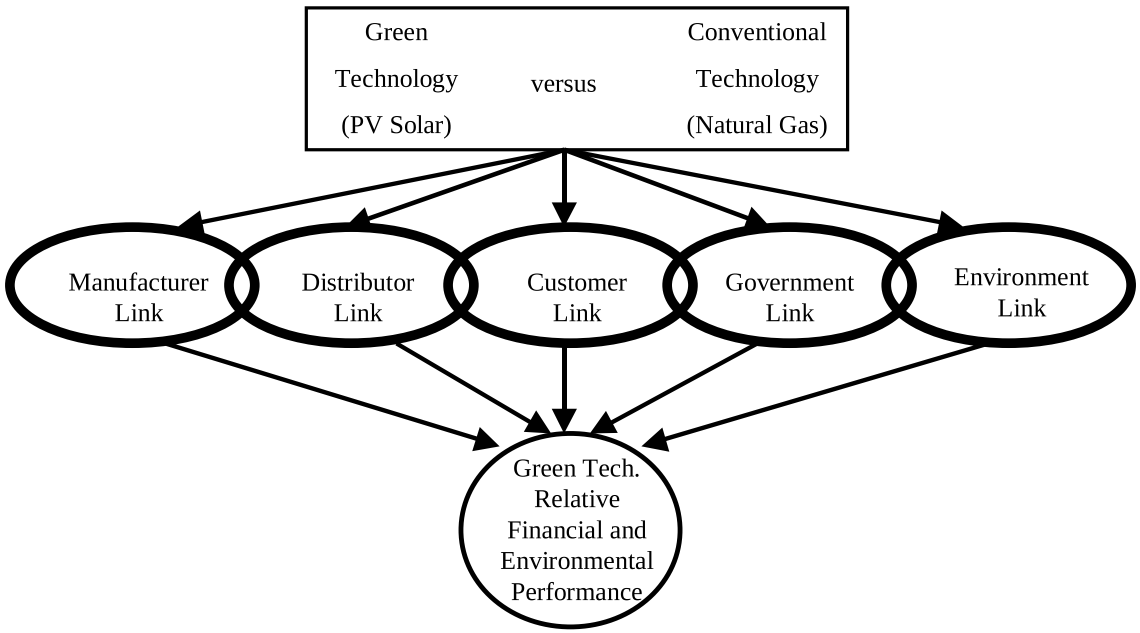
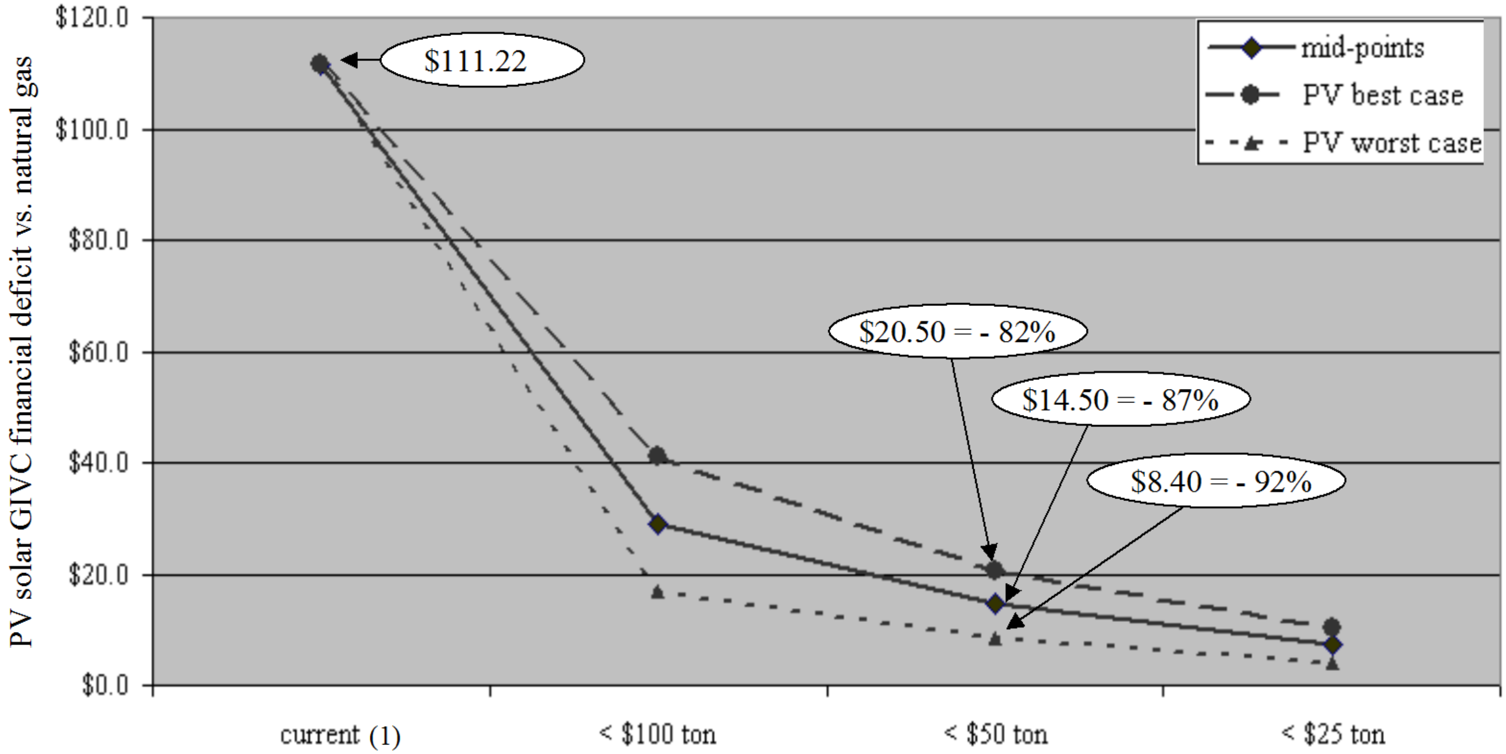


Figure 2:

PV Solar financial deficit required to achieve CO2 equivalent cost per ton reductions



Cost per ton of PV Solar related reductions in CO2 equivalent emissions vs. natural gas

(1) Current subsidy-free cost per ton reduced is $271 (PV best case), $384 (mid-points), $662 (PV worst case), with govt. subsidy the respective figures are $213, $300, $519