A Countdown towards Solar Power at Grid Parity:
Policy Analysis Based on the Evolution of Price-Performance

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Abstract

The price-performance of solar photovoltaic power generation systems seems to be on the verge of reaching grid parity. With this paper we examine first the effect that government sponsored renewable portfolio standard initiatives will have on the true, i.e. total, cost of solar electricity for consumers and second the degree to which the problem of meeting the consumer demand may become more significant once solar component technology reaches parity with conventional sources of electricity generation. The total costs associated with grid parity include the costs of components technologies for power generation, infrastructure expansion, ancillary services, transmission and distribution. The production costs of photovoltaic power generation systems are on track to drop over time, on the other hand the distribution and allied infrastructure costs can increase owing to daily production variation, grid congestion and long distance transmission loads as the demand for solar power grows. We create a dynamic framework based on the evolution of the total cost for assessing a set of policies that will affect the diffusion of solar power technologies.

Key words: Diffusion, Solar Power, Grid Parity, Infrastructure, RPS, Utility Industry

1. Introduction

> "Reaching 10 percent of our electricity from solar sources by 2025 will require the active participation of utilities along with the support and participation of regulators and solar technology companies."   Ron Pernick, Managing Director, Clean Edge, 2008

The search for cheap and renewable power sources and their efficient distribution have been identified as major opportunities for private sector and governmental bodies while nations are trying to work their way out of current economic doldrums (Friedman 2008). Solar powered Photovoltaic (PV) technology seems to have a promising future amongst renewable power sources because it utilizes distributed but small landmass (Scientific American 2007) and its price-performance seems to be improving dramatically (Soderholm and Sundqvist 2007). While the current installed based for solar power accounts for less than 1% of total electricity

demand, its penetration rate is on path for rapid growth, both in the USA and overseas. One key reason for such growth is the belief that this technology is close to grid parity. The term grid parity signals that price performance of photovoltaic electricity is equal to, or cheaper than grid supplied power from conventional sources. Parity is achieved initially in areas with abundant sun and high costs for electricity.

For an entire nation, or a large geographic region, a countdown towards grid parity is not a straightforward process. The market structure for the power generation and distribution sectors, particularly in the US, is complex. As the above mention quote indicates, we need to examine the role of utilities in the generation and the co-evolution of infrastructure and regulatory issues that will make the delivery of solar power at grid parity a reality. The solar power supply chains have dissimilar configurations across different states in US, with varying types of Renewable Portfolio Standards (RPS), and a variety of ownership stakes and Renewable Energy Credit (REC) sharing arrangements. RPS specifies the fraction of power that must be generated by renewable sources. RECs are tradable property rights to the environmental benefits of generating electricity from renewable energy sources. RECs carry a distinct value that augments the value of the energy created by renewable generation facilities.

Since the energy supply chains are complex in term of governance and cost structure, and incentives are uneven across states, grid parity can mean different things to different stake holders. For instance, a goal of the US Department of Energy's R&D program, working in collaboration with partners such as Abengoa Solar, is to develop technologies that are competitive with conventional energy sources by 2015 (Abengola 2009). Others have claimed that solar power is already at parity (Wynn 2007) in certain regions. This heterogeneity creates room for debate and for multiple policy alternatives. Some relevant policy questions from governmental perspective are: is the RPS strategy followed by various states effective? Might there be a desirable level of RPS that will spur autonomous market growth, social surplus, and allied green house gas (GHG) reductions? Technology suppliers, such as solar panel OEM firms are in a "land grab" mode by trying to establish technology standards in anticipation of a demand boom. However, their investors are worried about fixed costs and the adoption lags for competing technologies such as polycrystalline and thin film based cells. Might there be overinvestment and a capacity glut for the wrong type of technology, as was the case in the telecommunication industry in the past decade? Management at utility firms are mainly concerned about the appropriate levels of investments in generation costs, along with infrastructure bottlenecks, regulatory uncertainties, and the transmission costs that grid parity may lead to. Gaps in the technology suppliers' and utility company's perspectives can provide differing views of grid parity and associated technology diffusion policies.

Owing to improving technologies and volatility in energy prices, the evolution of solar energy capacity is an inherently dynamic problem wherein grid parity ought to be viewed as a tipping point that will spur a large and autonomous growth in demand. *The goal of this paper is to develop a consistent dynamic analysis framework that can be used to assess various policy alternatives that are likely to shape solar technology diffusion.* In this paper, we examine first the effect that government sponsored renewable portfolio standard initiatives will have on the true cost of solar electricity for consumers and second the degree to which this problem of

meeting the consumer demand may become more significant once solar electricity reaches parity with conventional sources of electricity generation. The true or total costs, including the investment in generation capacity, backup infrastructure, along with the transmission and the distribution costs are changing as the market evolves. Hence, there is need for developing a dynamic model that supports policy assessments, both for governments and for individual firms. We offer a set of dynamic hypotheses for developing such a model, illustrate its behavior, and study some of the policy questions raised above by using parameters observed in the California market.

Our results indicate that system dynamics based modeling effort can inform the policy questions along three fronts. First, we identify key constructs and their relationship across a set of loops that isolate the drivers and impediments for solar capacity diffusion. Second, for a simplified model we illustrate how the combined evolution of generation and infrastructure costs make the tipping point sensitive to the gains within the driving and impeding loops. That is, the targeted grid parity date is susceptible to the underlying structure and the manipulation of allied policy variables. Third, we develop a phase plane analysis framework by linking the installed base with at the pertinent price-performance index that we define. We then illustrate how the impact of various drivers and impediments for diffusion can be analyzed within this framework in order to gain policy insights for various stakeholders.

The rest of this paper is organized as follows. In §2, we draw upon evidence from California to describe the underlying technology diffusion issues and isolate the evolution of grid parity within the utility sector as the key behavioral mode that will precipitate large scale and autonomous demand growth. In §3, we identify related literature and develop causal loops involving drivers and impediments for solar technology diffusion. §4 outlines the key constructs, model specification, design of a numerical study and calibration effort. Results are presented in §5. The analysis of a phase plane based framework is outlined in §6 and the implications of the results for California market, and beyond, are discussed. We end this paper by describing the limitations of current work and identify avenues for further development.

2. Solar Power Technology: Evidence on Diffusion in California

The drive to invest in solar electric generation capacity in the U.S. has, to a great degree, been spurred by RPS standards in many states and has been aided by the extension of Investment Tax Credits by the Federal Government and high prevailing commodity prices that have increased the absolute levels of power prices throughout the country, thus making the pass to grid-parity more manageable. The current map of RPS standards is shown in Figure 1. It should be noted that of the 28 states that have formal RPS programs, 20 have specific solar provisions within their RPS initiatives.

The state of California has been one of the leaders in the US in terms of the adoption of Renewable Portfolio Standards (RPS) for the generation of electricity. Studying the California market has relevance for the rest of the country because California is slated to produce over 20% of the nation's solar power and is deemed to be a bellwether state in term

of renewable power technology development and consumption. California's RPS legislation initially required that state's Investor Owned Utilities (IOUs) source at least 20% of their electric generating capacity from renewable sources (solar, wind, biomass, and geothermal) by year-end 2010. The RPS law was subsequently amended to raise the requirement to 33% by year-end 2020. At the time the law was first introduced, renewable sources of electricity already accounted for approximately 10% of California's electric capacity portfolio, with wind and geothermal capacity accounting for most of the existing renewable capacity.
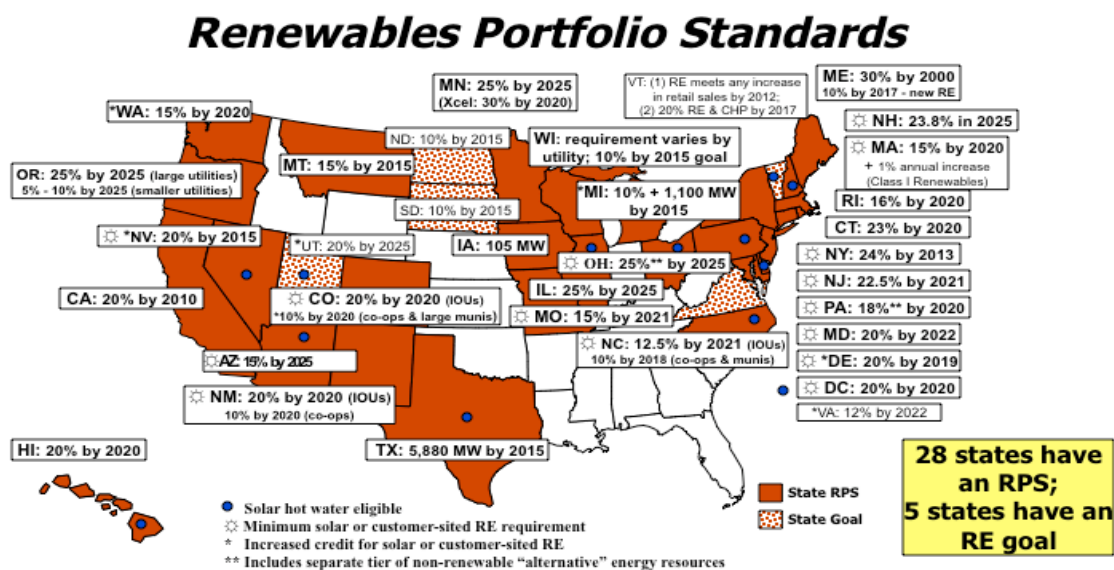

Figure 1: Variation in Renewable Portfolio Standard

The California RPS envisions the addition of over 19,000MW of new renewable energy capacity over the next 10 years with solar accounting for over 5,000MW of that total (CAISO 2007). The state also established the California Solar Initiative, a plan that will result in the addition of 3,000MW of solar electric capacity to the grid. The initial phase of the project envisions 1,750MW added to the grid by 2017, with the balance to be added over the following 10 years (CPUC 2009). These two initiatives combined should result in the addition of 8,000MW of solar capacity on a base of less than 500MW in 2007.

We have tracked publicly announced solar capacity data in California as shown in Figure 2. Based on these data, we identify the adoption by utilities to be the key driver of solar technology diffusion. Both the IOUs and the California Public Utility Commission have identified 2015 as the year that solar electric generation reaches grid parity. The expectation that grid-parity is achieved in 2015 is evidenced by the large number of contracts that have been signed with solar power installations beginning that year. IOU contracts for renewable electricity are signed at terms based on the Market Price Referent (MPR), which is established by calculating the fully-loaded cost of a new natural gas combined cycle generation turbine (CCGT). This analysis also includes the value of different products including base load, peaking, and as-available generation. In 2008 the MPR for a 20-year contract commencing operations in 2015 was set at $0.1329/KWh. This would be the price at which a solar facility

would sell its power during the 20-year life of a contract signed in 2008 and operational in 2015. This compares with an MPR for projects active in 2010 of $0.1139/KWh.
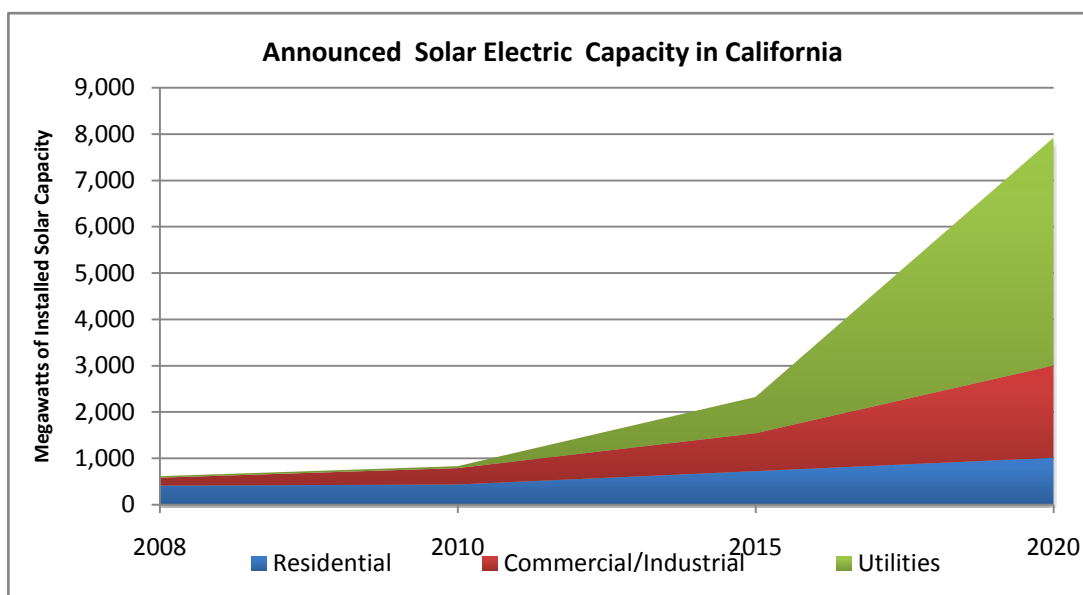

Figure 2: Utilities Will Dominate Solar Capacity Growth in California

It is important to make a distinction between grid-parity in California, the country as a whole, and the states that have RPS programs in place. Because grid parity generally refers to the marginal cost of electricity generation in a given market, that number will be different in each region of the country, as there are significant differences in the types of generation capacity available and in the kind of power plant that provides the marginal source of electricity in each market. While California's grid-parity (or marginal cost of generation) equivalent price is currently in the $0.10/KWh range as established by the MPR, the country's average retail price for electricity has averaged $0.08/KWh over the last five years. California's average retail electricity price has averaged over $0.12/KWh during the same time period. For the purposes of our analysis we have attempted to evaluate the effect of reaching grid parity nationwide, and thus have used a conservative benchmark set at $0.08/KWh.

In the next section we review the literature on technology growth and use this literature to develop a set of dynamic hypotheses associated with the behavioral mode shown in Figure 2.

3. Literature and Hypotheses

3.1 Dynamic Models of Solar Technology Diffusion

There has been a general agreement that the cost of PV has been coming down both at the cell and module levels roughly at a 82% learning curve (IEA, 2001; Söderholm and Sundqvist 2007). Based on module fixed costs, 12% conversion efficiency and 1700 KWh/m2 of

available sunlight energy (US average is 1800 KWh/m2) PV systems have been shown to have *energy payback period* as low as 2 years for poly-crystalline modules (Alsema, 1997). The *economic payback* period for photovoltaic systems, however, varies significantly depending on local electricity prices, installed system costs, and available sunlight energy. Borenstein (2008) offers a comprehensive economic analysis, including timing adjustment, peak lead correction, along with environmental and security externalities to argue that "the high cost of PV has been a major deterrent to technology penetration, and … the actual installation of solar PV systems in California has not significantly reduced the cost of transmission and distribution infrastructure." Another stream of literature (Ott, 2003; Brown and Rowlands 2009) models the transmission and infrastructure costs in terms of localized marginal pricing (LMP), which accounts for congestion effects and transmission losses. We will draw up the learning curve associated with solar power-generation, and include LMP corrections owing to infrastructure congestion while specifying our model in the next section.

Allied system dynamics (SD) literature can be divided into two streams: power generation and infrastructure growth. There has been a long history of examining the dynamics associated with boom and bust in pricing and capacity issues in the electric power industry (Ford 1997). Deregulation and the rising importance of carbon markets have sparked follow-on studies (Dyner and Larsen 2000; Ford 2002, Ford 2005, Ford forthcoming). Similarly, following Saeed (1996) and Wang (1996), there have been several studies that have looked into infrastructure dynamics, see for instance Stapelberg (2007) and Chouri et al (2008). Recently, scholars have examined the co-evolution of a stock of electric vehicles with the growth of supporting infrastructure (Welch 2007; Struben and Sterman 2008) to point out that such infrastructure growth is a necessary condition for the adoption of renewable technologies. Dimitrovski et al (2007) make the case for linking infrastructure (e.g. transmission network) optimization models that yield LMP related insights with SD simulations by building multi-disciplinary models.

We did not find any comparable SD models that examine the co-evolution of generation capacity, infrastructure and LMP in the solar power industry.

Based on this literature review, we develop dynamic hypotheses associated with the behavioral mode in Figure 2 next.

3.2 Growth Drivers: Dynamic Hypotheses

We now describe the mechanisms that can support the growing demand for solar power capacity as shown in Figure 3.

3.2.1 Investment Loop: Loop GL1
Investment in solar generation equipment drives up completion of solar generation capacity that translates into generation experience, and reduces the price-performance owing to learning effects. Reduced price performance increases demand and spurs further investment. This type of rationale for growth has been documented in solar industry (WSJ 2008).

3.2.2 Infrastructure Support: Loop GL2
Investment in generation equipment also drives up investment in infrastructure, such as transmission lines, which with a delay result in larger infrastructure capacity. Such capacity improves price performance, increases demand, and spurs further investment. This type of growth has been advocated by the solar and wind industry associations (SEIA 2009).
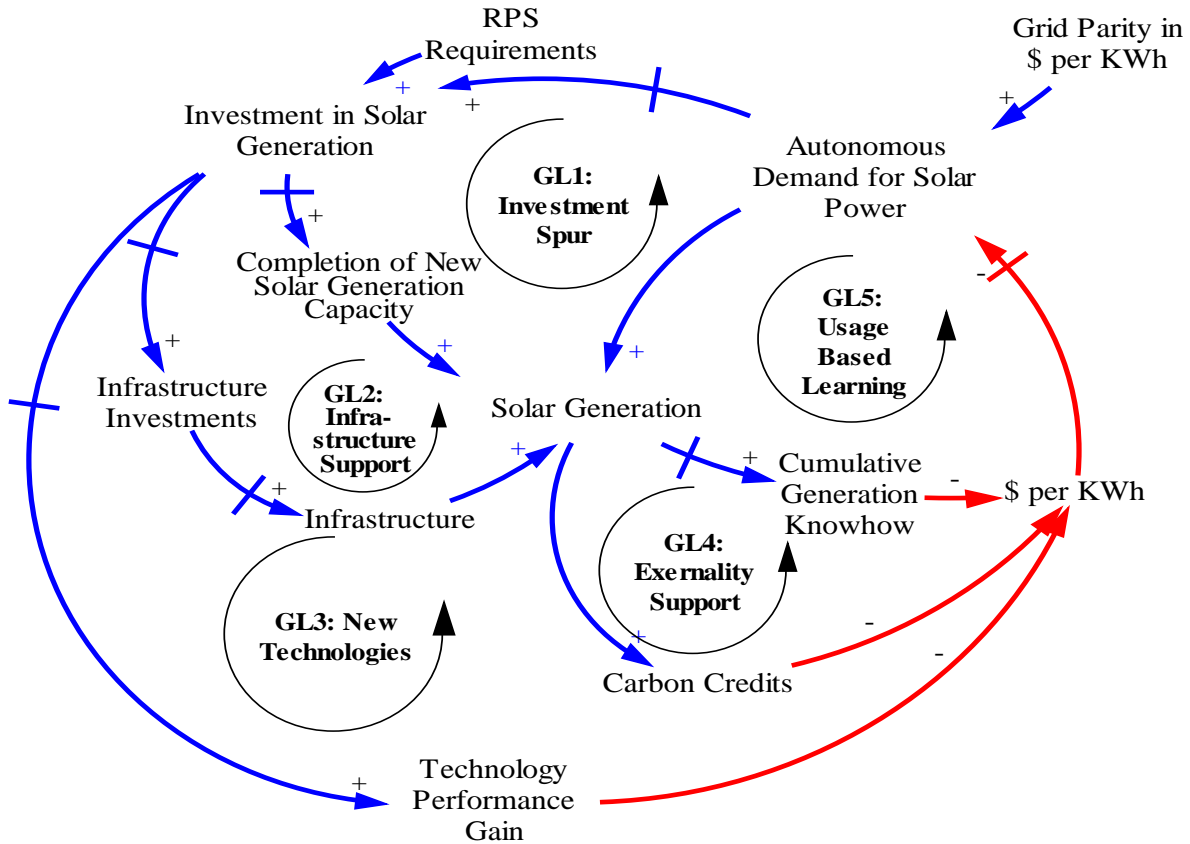

Figure 3: Drivers for Solar Capacity Growth

3.2.3 New Technologies: Loop GL3
Investment in capacity attracts efforts by technology suppliers to improve their performance. Better performance increases demand and spurs further investment. This type of growth has been documented in alternative solar technologies, e.g. either polycrystalline or amorphous silicon, that have different conversion ratios and fixed cost structures (see Kazmerski 2007 for a road map on alternative solar generation technologies).

3.2.4 Externalities: Loop GL4
Increased generation creates carbon credits that can be applied to make the technology more cost competitive. Better performance increases demand and spurs further generation. Externality based justification for PV has been studied by a number of economists (Borenstein 2008).

3.2.5 Learning Effects: *Loop GL5*

Even without new investment, over time, experience builds up with the use of generation capacity. Such experience enhances the price-performance and spurs further demand. This type of growth has been documented in solar and other renewable industries (IEA 2000, Soderholm and Sundqvist 2007).

3.3 Impediments: Dynamic Hypotheses

We now describe mechanisms that can deter the demand growth for solar power capacity as shown in Figure 4.

3.3.1 Upfront Cost: Loop IL1

Investment in solar generation drives up the upfront costs in terms of land and component technology acquisitions, such as generators, storage and inverter devices, and degrades the price-performance. This type of impediment to growth has been examined in the solar industry by Bernstein (2008).
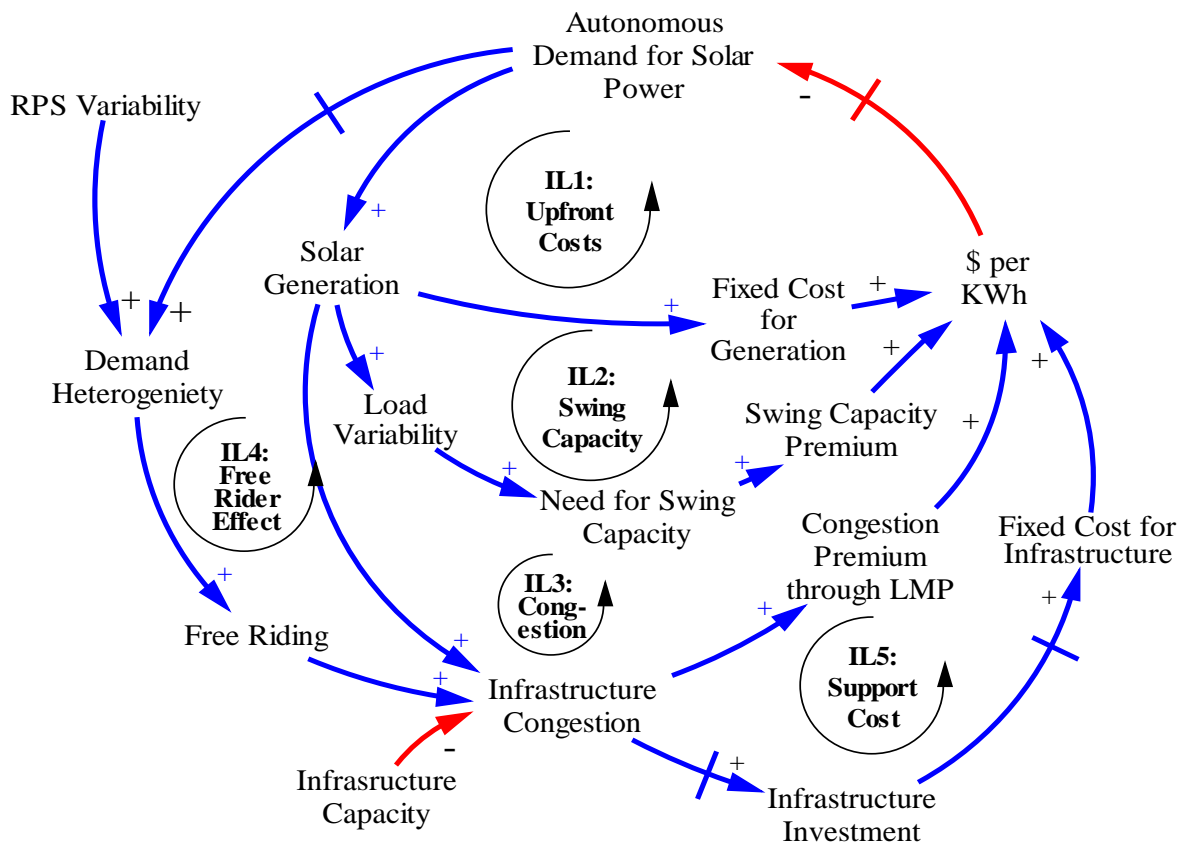

Figure 4: Impediments to Solar Capacity Growth

3.3.2 Swing Capacity: Loop IL2

Demand drives solar power generation. Solar generation drives up load variability and increases the need for swing (i.e. back up) capacity. The cost of this stand capacity degrades price performance. The need for this type of capacity has been documented in distributed system design studies (Whitaker et al 2008).

3.2.3 Congestion: Loop IL3
Demand drives solar power generation. Solar generation drives the need for transmission infrastructure and creates congestion and transmission losses. This creates a congestion premium through LMP that affects price performance and decreases system benefits (Brown and Rowlands, 2009). Allied issues in this regard are transmission losses and access to the infrastructure for export of excess capacity (see White 2004 and Frederic-Bach 2008 for a discussion of excess power capacity exported from Denmark).

3.2.4 Free Rider Effect: Loop IL4
Variability in RPS will lead to relatively lower investments in solar technologies in some states. For instance, Figure 2 shows that the state of West Virginia has no RPS standard in place as of now. These states do not have the incentives to pick up a share of the upfront investments in the renewable infrastructure. This will drive up infrastructure costs, add to the congestion, and degrade price performance.

3.2.5 Support Cost: Loop IL5
Demand drives solar power generation. Solar generation drives the need for transmission infrastructure. This also requires creation of market clearing mechanisms and support services. These costs and the potential infrastructure congestion drive investments and degrade price performance, which in turn decreases demand.

In the next section, we describe the structure of a simulation model that has been set up to examines the behavioral mode associated with the growth of the announced solar capacity generation and allied LMP issues in California.

4. Analysis

4.1 Model Structure

Our formal model involves two sectors: generation and infrastructure. For clarity, we chose to associate only one major loop with each sector: a reinforcing loop based on a learning curve effect that drives down the cost of solar power generation components such as the PV panels, and a balancing loop associated with rise in congestion costs when the demand for the solar power infrastructure will rise. We will address the implications of ignoring some of the alternative loops while discussing our results in §6.

Figure 5 lays out the structure of our model. It involves the co-evolution the solar generation capacity and the infrastructure capacity sectors in the utility industry. Each sector comprises of an aging chain (Sterman, 2000) that tracks the investment, completion rates and installed capacity. The investment level in each sector is driven by announced investments made by utility firms to meet the RPS standard. Autonomous demand is introduced after the grid parity price-performance is achieved.   Key parameters (e.g. the time to complete a new infrastructure project) and their calibration settings are specified in the next section. The installed solar capacity is used to compute the cumulative solar power generation.
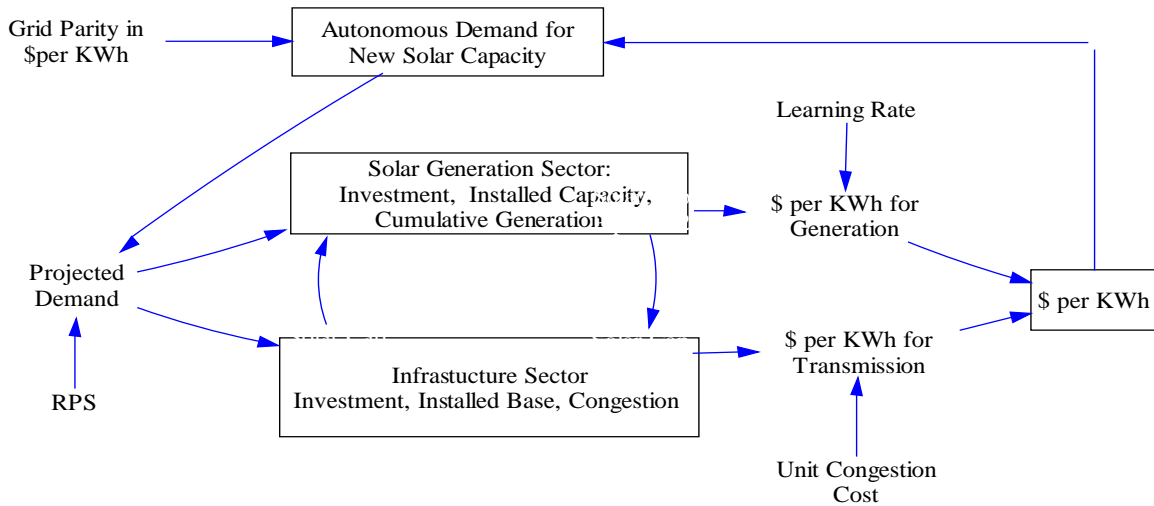
Figure 5: Model Sectors

Learning curve in the solar generation technologies (IEA 2001) is used to specify the following relation:

$/KWh for Generation = Initial $ per KWH *(Cum Solar Generation/
    Initial Generation Capacity)^α   (1)

$$\alpha = \ln(\text{Learning Rate})/\ln(2) \qquad (2)$$

Learning rate is a sensitivity analysis variable. It is set to 0.82 in the base case. The installed solar generation capacity and the available infrastructure capacity are used to compute the congestion fraction:

Congestion Fraction = max(0,(Generation Capacity –
    Transmission Capacity*Smart Grid Correction))/(Transmission Capacity)   (3)

Smart grid correction (SGC ≥ 1) is a sensitivity analysis variable whose default value is set to unity.

$/KWh for Transmission = LMP Adjustment Fraction * Unit Congestion Cost   (4)

Congestion fraction is converted into the LMP adjustment fraction based on a lookup table. This lookup table has been established based on Brown and Rowlands (2009), and normalized with respect to congestion fraction. Unit congestion cost is a variable used for sensitivity analysis (UCC ≥ 1) .

Change in $ per KWh = (($ per KWh for Generation + $ per KWh for Transmission)- $ per KWh) / Time to Adjust Price-Performance   (5)

Autonomous Demand = AD if $ per KWh $\leq$ Grid Parity   (6)

4.2 Parameters

The simulation model has been set up to run over a 30 year planning horizon starting in 2009. After the system reaches grid parity, the autonomous demand is assumed to take up 10% of installed capacity. Based on a calibration process that tracks the evolution of Figure 2, and the ranges specified in the literature, the following parameters have been selected:

> Initial $ per KWh = 0.15
> Grid Parity = $0.08 per KWh
> RPS Driven Investment in Generation= 550 MW/ Year
> RPS Driven Investment in Infrastructure= 250 MW/ Year
> AD = 800 MW/year
> Time to Completion New Generation Capacity = 2 Years
> Time to Completion of New Infrastructure Capacity = 4 Years
> Time to adjust price-performance = 0.25 Year
> Initial Generation Capacity =500 MW
> Initial Generation Capacity in Pipeline = 300 MW
> Initial Infrastructure Capacity = 500 MW

We offer the following two caveats regarding our calibration effort. We have selected nominal values and ranges (see §4.3) for parameters based on data reported in the literature. However, we did not test the fit of the installed capacity against a real data set, because our model structure does not account for all the relevant feedbacks. Instead, we select reasonable parameters and use the simulation process to compare the relative performance of various policies under this simplified model structure.

Second, the general problem of applying learning rates on a regional problem (California) is that the PV learning of rate of the industry is not entirely endogenous to California. It is partly exogenous, as the learning rate of the industry depends on the total globally installed cumulative capacity. This means that the cost of PV will be less responsive to the Californian RPS policy than anticipated in the model (see endnote i). It will be possible to build a broader calibration effort, but California based results could be extended to broader settings suitable adjustments to the learning rate index. We leave such adjustment as future work.

4.3 Design of Numerical Experiment

Increasing the learning rate (LR) reduces the loop gain on the generation loop. Increasing unit congestion cost (UCC) increases the loop gain on the LMP cost loop. Increasing SGC allows us to test the entire range of LMP lookup table by reducing congestion and decreasing the loop gain on LMP costs. Increased RPS level allows us to test the interactions caused by gain in experience and along with gain in the LMP-congestion loop. Therefore, in order to observe the variation of outcome variable, and to run relevant extreme condition tests, we change the following parameters systematically:

Learning Rate (LR): range 82% - 86.1%, in 10 incremental steps.
Unit Congestion Cost (UCC): range 1.0- 2.0, in 10 incremental steps.

Smart Grid Corrections (SGC): range 1.0 to 2.0, in 10 incremental steps.
RPS Level = 550 MW/year to 750 MW/year in 10 incremental steps.

5. Results

For the purpose of comparison, we have constructed an installed capacity index by normalizing the installed capacity with respect to the initial capacity (500 MW).Similarly, we have used a price-performance index with respect to the grid parity price-performance ($0.08 per KWh) while presenting the price-performance results.

5.1 Base Case and Sensitivity Analysis

The base case simulation, as shown in Figure 6, indicates that the total price performance index reduces monotonically while the installed base rises over a thirty year time span. Consistent with the behavioral mode shown in Figure 2, the installed capacity index exhibits an increase in the slope after the price performance index reaches unity. However, because of a delayed capacity ramp up set up by the aging chain structure, we observe that the capacity index ramps up slowly yielding a tipping region starting with the year 2021.

Our results tend to delay the onset of the post grid parity period, compared to predicted values, because we include the LMP costs while computing the price performance index, and we set the grid parity price performance at $0.08 per KWh, rather than $0.13 per KWh.
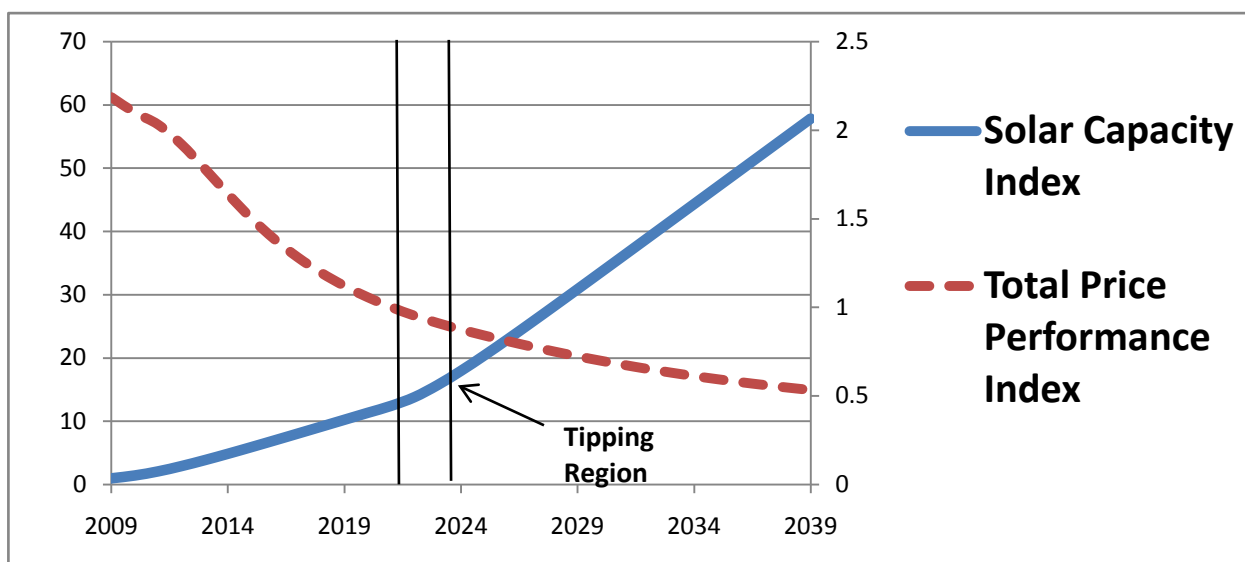

Figure 6: Evolution of Capacity and Price-Performance in the Base Case

The learning rate controls the gain of the reinforcing loop that improves the price performance index. Reported rates for learning for solar generation technologies vary between 82%-86%. We examine the sensitivity of our results by varying learning rates in Figure 7. This figure indicates that reducing the learning rate from base case by 5% (i.e. fractional cost reduces by

a factor of 0.861 instead of 0.82, when generation experience is doubled) will delay the onset of grid parity from 2021 to 2029.
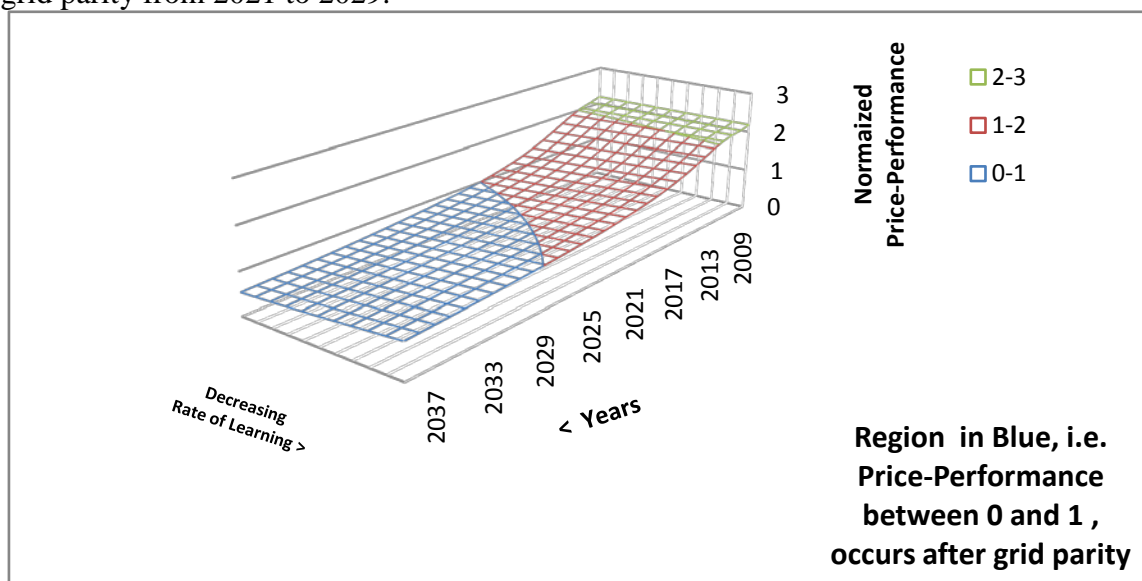

Figure 7: Sensitivity Study – Effect of Learning Rates on Grid Parity
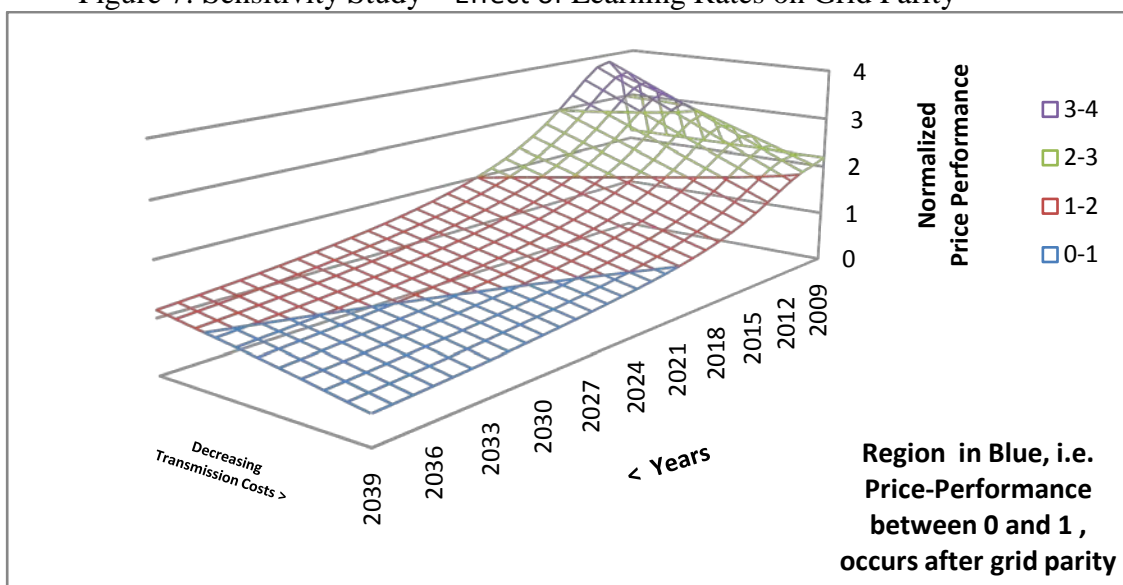

Figure 8: Sensitivity Study – Effect of Transmission Cost on the Grid Parity

LMP correction, due to transmission costs, controls the gain of the balancing loop that affects the price performance index. In the base case LMP correction is set at $0.015 per KWh, with peak congestion at 56%. It is possible for this cost to more than double in the extreme condition, when the congestion level rises. We examine the sensitivity of our results to the transmission cost index in Figure 8. Increasing transmission costs by 70% will ensure that the total price performance index will not dip below the grid parity threshold till 2039 (i.e. the system will not reach grid parity during the entire 30 year planning horizon).

Consistent with intuition based on queuing theory, price-performance degrades severely when congestion fraction approaches unity. We apply a smart grid correction to increase the infrastructure capacity. A 10% correction reduces the congestion from 56% to 52%. The payback from smart grids (or distributed storage technologies) will be much larger, if the congestion in localized markets gets severe.

Finally, we have tested the effect of raising RPS levels. A 10% increase in the RPS level without improved infrastructure increases the installed base more rapidly. However, it also increases the congestion level. In the net, these effects balance each other and the total price performance and the onset of grid parity does not change materially.

5.2 Phase Plane Plot

We present a phase plane plot for the base case in Figure 9 by linking the installed capacity index with the total price-performance index. We also plot the two components, the generation and transmission performance, to illustrate their respective contribution. Since the price performance index has been normalized with respect to the grid parity, the values of the total index below unity represent the post grid parity region. The stock of installed capacity is out of phase with the price-performance index because this index is driven by the stock of cumulative generation. Phase plane plots have been used to track the S-Curve of diffusion of hybrid vehicle technologies (Struben and Sterman 2008). Plotting the inverse of price performance (in KWh per $), and introducing additional structure to create diminishing return, will yield a similar S-Curve for our study. We have chosen to plot the grid-parity ($ per KWh) because it is the commonly used metric for tracking technology diffusion in the electric power industry.
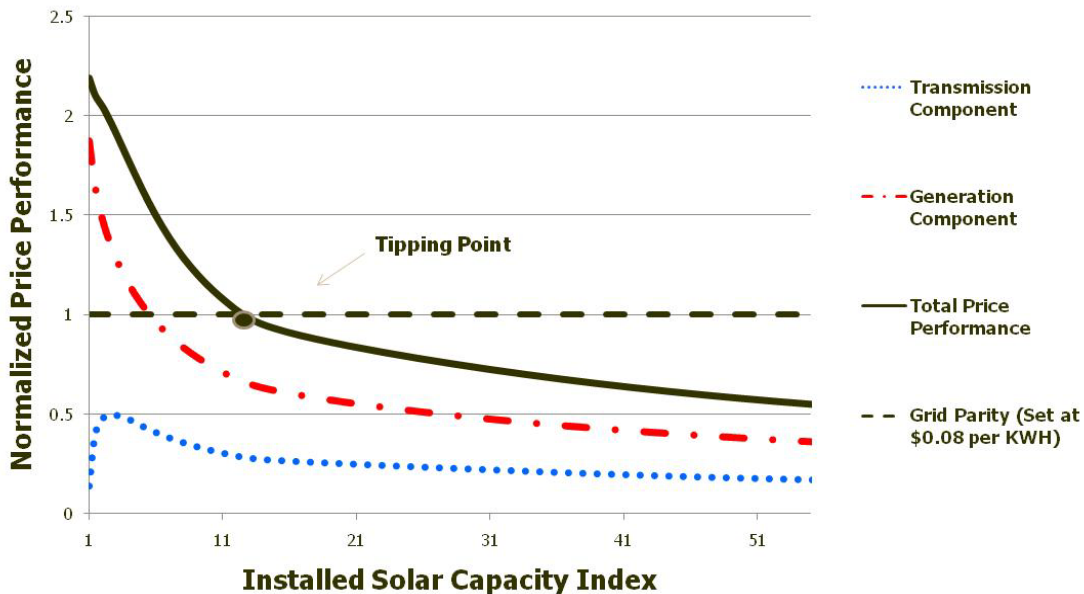

Figure 9: Phase Plane Diagram

For the base case, this diagram shows that grid parity is achieved when the installed solar capacity reaches 12.5 X current installed capacity in California. It also shows that a bulk of the savings in price-performance come from reduction in the unit cost of generation.

6. Discussion

6.1 Policy Analysis Implications

There are multiple sets of stake-holders in the solar power adoption process: government, end consumers, developers of new solar technologies, utilities and infrastructure firms. As mentioned earlier in this paper – grid parity is a desirable and somewhat abused construct. We know of at least one supplier (First Solar, 2009) that claims to have achieved parity already. Other, especially governmental bodies have announced grid parity targets (Abengoasolar 2008). Our study has not been designed to be a predictive exercise. Instead, we make simplifying assumptions to illustrate that the evolution of true price-performance will be sensitive to choice of technology growth and policy parameters. Hence, grid parity that accounts for all hidden costs may be more elusive than what appears in the trade press. Based on the analysis thus far, we summarize the implications of our findings as follows:

(i) Generation Technologies: It is clear, as shown in Figure 3, that solar generation technologies must become more cost competitive over time in order to improve the total price performance of utility driver solar energy options. Failure to innovate on this front will delay widespread diffusion of solar power. This type of improvement requires both governmental support (e.g. tax credits for R&D) and private sector commitment (e.g. capital investments). We also note that there are multiple technologies competing for the big prize, namely the autonomous demand for solar power generation. In that sense the second problem (i.e. the size of the market after grid parity) is critical for attracting additional investment in utility scale solar generation technologies. The suppliers who set the technology standards within the utility industry are likely to win this prize. However, the current version of our model does not address the standard setting and technology transitions issues. We identify that as an area for further work.

(ii) Transmission Infrastructure: Our analysis shows that growth of solar power will enhance congestion and burden the price performance. Power transmission infrastructure and transmission losses have not improved considerably, when compared with generation technologies, over the past few decades in the US. Our analysis shows that even a 10% improvement in infrastructure technologies (e.g. smart grids and/or distributed storage) can reduce the peak congestion considerably. The current version of our model does not address the spatial heterogeneity and transmission load issues linked with smart grids. We identify that as another area for further work.

(iii) RPS: Our work assumes that RPS will drive much of the diffusion, by putting utilities into the drivers' seat in terms of installed capacity ownership. For the set of parameters wherein the model was tested, increasing RPS level by 10% will not enhance the diffusion rate of solar technologies, unless there is a corresponding investment in infrastructure. On

the other hand, as shown in Figure 1, there is a large variation in RPS requirements in the US. The current version of our model does not address the RPS heterogeneity and free rider issues. We identify that as another area for further work.

6.2 Phase Plane Analysis with Multiple Loops

We have limited the model structure to two major loops – reinforcing learning effects that reduce the unit cost of generation, and balancing effects that raise the LMP correction owing to infrastructure congestion. Notice that even though the LMP correction is only a small fraction (18.5%) of the grid parity price-performance, it affects the tipping point by nearly doubling the installed capacity requirement.

This analysis can be repeated after introducing additional loops from §2 into the model structure. Sizeable levels of investment (Loop GL1) in generation capacity due to RPS-type mandates will speed up the learning and shift the tipping point to the left hand side of Figure 9. Similarly, new technologies (loop GL5 – e.g. going from crystalline to thin films) will create a technology transition along the learning curve that might delay the grid parity, but that could be very attractive for autonomous demand growth. Externalities (Loop GL4) such as GHG levels and allied RECs could be priced by raising the level of grid-parity price that will also shift the tipping point to the left hand side of Figure 9. Similarly, impediments such as build up of swing capacity (IL2) and free rider effect (Loop IL5) from states that do not call for solar RPS in proactive manner will increase the transmission component and shift the tipping point to the right hand side of Figure 9. It is also possible to conduct formal analysis of the tipping process for a reduced form model (Repenning 2000).

6.3 Summary, Limitations and Future Work

This paper describes an initial attempt at modeling the co-evolution of generation and infrastructure growth in the solar power sector. We argue that the key driver for solar power generation in the US will be the RPS mandate that requires a commitment on part of the utilities to deploy a significant amount of resources to renewable power. Solar technologies are attractive candidates for utilities in this context, when they reach grid parity. However, there are several different mechanisms that support and hinder the diffusion of solar power. Within this context, a phase plane based comparison of the results offers a tidy tool for policy assessment.

We offer the following caveat regarding our modeling and calibration effort. We use reasonable parameters and deploy simulation findings to compare the relative performance of various policies under a simplified two-sector structure. This study has not been set up to reproduce the time series for growth and test its fit against a real data set. Future work ought to test the findings against available time series data with careful econometric tests.

We also limit the analysis of diffusion to an aggregate model of the infrastructure sector. We model the infrastructure for an entire state as single stock. That is, the current model structure does not differentiate between centralized versus distribute generation. We also ignore the variations across the rest of the country. Extent to which PV loads will increase infrastructure

costs, when they are built in a distributed manner, is not addressed in the current formulation. For instance, if PV is built centralized, a rise in LMS is understandable. However, grid costs and LMP tariffs can even benefit PV generation. That is, PV can be seen as a "negative" consumer, for a fraction of the time, reducing the net demand for a consumer and lowering distribution costs. While the relevant basis of the wholesale cost for the utility sector seems to be the long run marginal price for CCGT, residential (or retail) PV consumers can accrue additional savings, both on their electricity costs and their energy dependent grid tariff.[i] It is also possible for the RPS mechanisms in selective states to mandate that their utilities follow a distributed rather a centralized generation model. Similarly, we have not explored alternative tariff structures, alterative service offerings and allied contracting options. Such analyses require disaggregation of our infrastructure sector, and detailed modeling of allied storage, metering and smart grid type of capabilities. We identify these modeling efforts, followed by data collection and policy analyses as logical extensions of our work.

Systems engineering and market clearance studies of alternative energy technologies are authoring novel types of load optimization, pricing and contract theory models around the challenges associated with the power grid (Dimitrovski et al 2007). System dynamics methodology can complement such modeling developments by facilitating a phase plane based assessment of the price-performance evolution under various types of policy options that have been described in our study.

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[i] We gratefully acknowledge that the framing of these issues, and the need for additional work, was brought to our attention by an anonymous referee during the review process.