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The road ahead for solar PV power[☆]

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ABSTRACT

Over the past decade, solar photovoltaic (PV) power has experienced dramatic deployment growth coupled with substantial decreases in system prices. This article examines how solar PV power is currently positioned in the electricity marketplace and how that position is likely to evolve in the foreseeable future. We first assess the current cost competitiveness of solar PV in select U.S. locations and industry segments using the levelized cost of electricity (LCOE) metric. This framework enables us to quantify the effects that supportive public policies, time-of-use pricing, and anticipated future technological improvements have on the cost of solar PV. We also build on recent analytical work that has identified circumstances under which it becomes financially attractive to add behind-the-meter batteries to an existing PV solar system. Taken together, our findings suggest that solar power, by itself and in conjunction with low cost storage, is positioned to account for a significant and growing share of the overall energy mix.

1. Introduction

Solar photovolatic (PV) power has long been heralded as an energy source with enormous potential for the electricity sector. Fig. 1 shows that for new deployments, growth rates have been consistently high, particularly over the past decade with annual installation capacity increasing in each successive year. Another 100 GW in new capacity installations were added globally in 2017 to the 300 GW that had already been in place.[1] Globally, solar power now accounts for 6.3% and 1.7% of installed capacity and electricity generation, respectively [5,22].

As solar PV deployments grew rapidly in recent years, the prices of solar systems fell precipitously. To witness, the average sales price of PV modules has declined from about $4 per Watt in 2007 to around $0.35 per Watt by late 2017. A large body of literature has documented reductions in module prices and their underlying manufacturing costs; see, for instance, Swanson [57], Candelise, Winskel, and Gross [9], Sivaram and Kann [55,47]. At the same time, the prices of Balance of System (BOS) components, which comprise inverters, trackers, structural, and electrical components, have also come down significantly with annual reductions in the range of 5 – 7%.

Our objective in this article is to examine how solar PV power is currently positioned in the electricity marketplace and how that position is likely to evolve in the foreseeable future. To do so, we first assess the current cost competitiveness of solar PV in early 2018 and then examine how further technological improvements as well as potential changes in public policy are likely to shape the industry over time. Our analysis of the impact of public policy focuses on the current U.S. environment, though it will become clear that certain findings carry over to jurisdictions that have adopted different policies.

To assess the current cost competitiveness of solar PV in select U.S. locations and industry segments, we first estimate the levelized cost of electricity (LCOE) of the technology. The significance of this widely used metric is that it provides a lower bound on what an investor/developer would have to obtain as average revenue per kilowatt hour, possibly as part of a power purchasing agreement, in order to earn a normal return on investment. By the LCOE criterion, we find that in many parts of the western United States, utility-scale solar systems are currently better positioned than other electricity generation sources, in particular natural gas powered facilities or wind energy. For the commercial and residential segments, across geographies we find that the corresponding LCOE figures are generally below the rates that utilities currently charge their customers, consistent with the recent pace of deployments in these segments of the industry.

Our analysis highlights that any claims about the competitiveness of solar PV power should account explicitly for the policy support mechanisms currently in place. Most important among these is the U.S. federal investment tax credit available to solar facilities. The policy of net metering is another crucial support mechanism that allows

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[1] Of the 100 GW of new capacity added globally in 2017, the U.S. market share is estimated to be about 15%.

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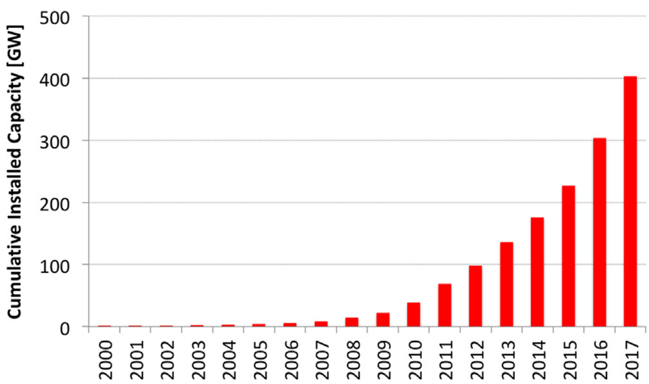

Fig. 1. Cumulative global solar PV capacity installations by end of 2017.

commercial and residential solar customers to obtain credit at the going retail rate for surplus electricity transferred to the grid. Both of these support mechanisms are likely to diminish in the near future. For federal tax incentives, the U.S. Congress has specified a "sliding scale" leading up to the end of 2021. Similarly, many U.S. states are currently debating or implementing restrictions on net metering. These projections naturally raise the question as to what further reductions in solar system prices will be required to maintain the cost competitiveness of solar PV in the face of weakening public policy.

Electric power is increasingly priced not on a purely volumetric basis; instead, prices vary according to the time of day and season. Since electricity prices presently are at a premium during the hours of the day when solar PV systems generate their power, time-of-use pricing improves the economics of solar PV systems in the current environment. Our discussion here relies on earlier work that has quantified the magnitude of that synergistic effect. Yet, as the share of solar power in the overall energy mix increases, these synergies are likely to diminish. Furthermore, if some of the predicted scenarios associated with the system net load (i.e. the "duck curve") actually materialize, there may ultimately be a negative complementarity between the prevailing time-of-use prices and the pattern of solar power generation. We examine how such developments may be counteracted by a range of measures, including energy storage and the possibility of sacrificing overall output from a solar PV facility in return for more favorable timing of the solar power.

Battery storage systems are increasingly combined with both residential and commercial solar PV installations. The financial rationale for doing so relies on the potential to avoid paying a premium for electricity during peak pricing hours, and, for commercial users, on the ability to reduce demand charges. Our discussion of combining battery storage with solar PV systems is focused on residential settings where restrictions on net metering effectively yield a price premium for electricity that is self-generated and subsequently self-consumed at later hours of the day. Our analysis identifies conditions that make it financially attractive to add behind-the-meter battery storage to an existing PV solar system. At the same time, our findings suggest that in addition to the price premium, the availability of federal tax credits and state-level investment rebates is critical for economically viable battery deployments in this segment.

The final part of our analysis examines the dynamics of solar PV system prices. For photovoltaic modules, recent literature has argued that observed steep price declines are partially attributable to both intrinsic manufacturing cost reductions and excessive additions of manufacturing capacity.[2] We follow the framework in recent learning curve models to project the long-run unit cost of manufacturing modules by extrapolating from the most recent production volumes. These improvements combined with the expected reduction in balance of system prices have to be weighed against the diminishing federal tax support for solar PV. The resulting dynamic leads us to predict that the LCOE figures will see modest reductions over the next four years, culminating in a negligible increase in 2022 due to the federal investment tax credit reaching its ultimate plateau level of 10% at that point in time. Specifically, we expect the LCOE of utility-scale facilities in California to remain essentially stable despite the anticipated decline in the ITC.

In interpreting our projections for the future, it should be kept in mind that our focus on crystalline silicon PV modules considers only one avenue for future improvements. While crystalline silicon technology dominates the market currently, there also appears to be a tangible chance that other photovoltaic technologies may leapfrog the cost and performance of crystalline silicon based systems in the foreseeable future [54].

One of the contributions of this paper is to provide an up-to-date assessment of the cost-competitiveness of solar PV in the U.S., including recent system price reductions and the recent changes to the U.S. tax code. This change in the tax laws reduces the corporate tax rate to 21% and makes long-term assets eligible for 100% bonus depreciation.[3] As such, our work provides an update and extension to other recent assessments of solar power, such as Ryan et al. [51], Bolinger, Seel, and LaCommare [4], Fu et al. [21] and Lazard [35].

Beyond the inclusion of recent market developments and the new tax law, our analysis provides explicit treatment of the incentives for combined solar PV and energy storage systems. In doing so, we build on studies such as EIA [19] and Lazard [35] by showing the fine-grain impact of the available support mechanisms. Our study also provides a unique assessment of the prospects of solar power, based on the recent dynamics for both module prices and balance of system costs. This quantification goes beyond the recent, more qualitative assessments found in Kabir et al. [30] and Verdolini et al. [58]. Our framework also allows to provide new quantitative forecasts for the competitiveness of next-generation solar facilities.

The remainder of this paper is organized as follows. Section 2 provides a baseline assessment of the current cost competitiveness of solar PV power. Section 3 highlights the impact of public policy, specifically federal tax support and net metering policies at the state level, on the recent growth spurt of solar PV in the U.S. We examine the impact of increased time-of-use pricing on the economics of solar power in Section 4. Section 5 explores the economics of battery storage systems in conjunction with solar PV. The past dynamics of solar system prices and corresponding forecasts for the levelized cost of solar power over the next five years are analyzed in Sections 6 and 7. We conclude in Section 8.

2. Current cost competitiveness of solar PV

Our assessment of the current cost competitiveness of solar PV focuses at first on the Levelized Cost of Electricity (LCOE), a cost concept that is widely relied upon by researchers and energy analysts; see, for instance, Lazard [35], Fu et al. [21] and EIA [19]. This life cycle cost measure is stated in terms of dollars per kilowatt-hour of electricity, accounting for all upfront capital expenditures and subsequent operating costs. The LCOE is interpreted as the break-even value per kWh that a producer would need to obtain in sales revenue in order to justify an investment in a particular power generation facility. A developer who signs a power purchasing agreement (PPA) for a new project will therefore be "in the money" with a new project provided the PPA exceeds the LCOE of the facility.

In aggregate form, the LCOE can be expressed as the sum of three

[2] See, for instance, Candelise, Winskel, and Gross [9].

[3] On December 22, 2017, the 115th U.S. Congress passed HR 1 into law, No. 115–97 "An Act to provide for reconciliation pursuant to titles II and V of the concurrent resolution on the budget for fiscal year 2018.".