Energy Policy 94 (2016) 264–273

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Climate impacts on the cost of solar energy

Mallory E. Flowers [a,*], Matthew K. Smith [b,*], Ara W. Parsekian [c], Dmitriy S. Boyuk [d], Jenna K. McGrath [a], Luke Yates [c]

[a] School of Public Policy, Georgia Institute of Technology, 685 Cherry St NW, 30332 Atlanta, Georgia
[b] School of Materials Science & Engineering, Georgia Institute of Technology, 771 Ferst Drive, 30332 Atlanta, Georgia
[c] School of Mechanical Engineering, Georgia Institute of Technology, 311 Ferst Drive, 30332 Atlanta, Georgia
[d] School of Chemical & Biological Engineering, Georgia Institute of Technology, 311 Ferst Drive, 30332 Atlanta, Georgia

HIGHLIGHTS

- We integrate local climate into the Levelized Cost of photovoltaic technology.
- Climate dictates panel degradation rates and the impact of temperature on efficiency.
- We compare LCOE under policy scenarios for three technologies in four U. S. states.
- Degradation is highly variable, increasing costs by shortening panel life in many regions.
- Incentives targeting investment are most effective at reducing solar deployment costs.

ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form
5 April 2016
Accepted 11 April 2016

JEL Classification:
Q42
Q43
Q48

Keywords:
Solar Power
Photovoltaics
Levelized cost
Climate
Renewable energy
Silicon PV

ABSTRACT

Photovoltaic (PV) Levelized Cost of Energy (LCOE) estimates are widely utilized by decision makers to predict the long-term cost and benefits of solar PV installations, but fail to consider local climate, which impacts PV panel lifetime and performance. Specific types of solar PV panels are known to respond to climate factors differently. Mono-, poly-, and amorphous-silicon (Si) PV technologies are known to exhibit varying degradation rates and instantaneous power losses as a function of operating temperature, humidity, thermal cycling, and panel soiling. We formulate an extended LCOE calculation, which considers PV module performance and lifespan as a function of local climate. The LCOE is then calculated for crystalline and amorphous Si PV technologies across several climates. Finally, we assess the impact of various policy incentives on reducing the firm's cost of solar deployment when controlling for climate. This assessment is the first to quantify tradeoffs between technologies, geographies, and policies in a unified manner. Results suggest crystalline Si solar panels as the most promising candidate for commercial-scale PV systems due to their low degradation rates compared to amorphous technologies. Across technologies, we note the strong ability of investment subsidies in removing uncertainty and reducing the LCOE, compared to production incentives.

1. Introduction

As the global demand for solar power is growing, the development and deployment of solar photovoltaic (PV) technology is also increasing. Installed PV capacity has grown from approximately 14 gigawatts (GW) in 2008–180 GW in 2014 worldwide (IHS, 2015), indicating that the combined effects of technological innovation, reduced manufacturing costs, and various governmental programs are allowing the systems to become more economically feasible to install. Deployment of PV systems is poised to help meet the growing global energy demand and reduce the detrimental environmental effects of fossil fuel consumption. Despite incentives, solar electricity generation currently accounts for 7 GW, or less than 1% of U.S. electricity production (EIA, 2015; IHS, 2015). Rapid adoption of a renewable energy technology may be possible when it reaches a critical *grid parity*, the tipping point at which the lifetime generation cost of a renewable electricity technology is comparable to the price of electricity generated using traditional resources. Levelized cost of electricity (LCOE) is a common metric used to compare energy generation technologies

---

[*] Corresponding author.
E-mail addresses: MFlowers8@gatech.edu (M.E. Flowers), MKSmith@gatech.edu (M.K. Smith), Ara.Parsekian@gatech.edu (A.W. Parsekian), DBoyuk6@gatech.edu (D.S. Boyuk), McGrathJ@gatech.edu (J.K. McGrath), LYates6@gatech.edu (L. Yates).

http://dx.doi.org/10.1016/j.enpol.2016.04.018
0301-4215/

when considering grid parity (Campbell et al., 2008), though other metrics, including job creation and reliability, are often considered (Baer et al., 2015). The debate over the economic feasibility of solar PV technologies in the current electricity marketplace often involves LCOE estimates for PV technology. Recently, LCOE calculations by Deutsche Bank were used to argue solar PV grid parity had already been achieved across 10 states in the U.S. (Shah and Booream-Phelps, 2015). Quantitative comparisons of energy technologies are essential guides in energy policy design. However, the utility of LCOE estimates is limited by both the completeness of lifetime field studies, the inability of LCOE to account for intermittency, and uncertainty in the future cost of electricity.

Local climate effects on solar PV system lifetime are commonly assumed negligible in the LCOE assessment (Darling et al., 2011). This assumption is in contradiction to numerous studies investigating the impact of temperature and humidity on the panel power production efficiency and panel operational life (Jordan et al., 2012). Variations in local climate conditions are observed to alter the degradation rate of PV devices, and thereby yield significant changes in the total cost of energy produced. Here, we expand the calculation of LCOE for commercial-scale solar PV systems (production capacity >1 MW) by incorporating the effects of climate conditions on device lifetime and power output. We compare performance of traditional crystalline silicon and thin-film (amorphous) silicon PV technologies. These technologies are selected based on their prevalence in the market, ease of comparability, and the availability of data from existing field studies for PV performance and degradation rates.[1] Analysis is conducted based on prevalent climate conditions for Atlanta, GA, Boston, MA, Phoenix, AZ, and Portland, OR. This set of geographical locations allows us to compare PV electricity costs in humid subtropical (Atlanta), humid continental (Boston), desert (Phoenix), and maritime (Portland) climates, to demonstrate the dependence of the LCOE on climate conditions. These areas also correspond to köppen climate zones (see Fig. 1) defined on the basis of temperature and moisture and our results are generalizable to other global regions.

We show that degradation rates dramatically impact costs across climates. Additionally, we consider the impacts of existing and proposed investment and production incentive programs for commercial solar PV on lowering the firm's cost of technology deployment in each of the four states. Incentives occurring at the time of installation are most effective at reducing the firm's cost of deploying solar. This analysis concludes with recommendations for policymakers, noting which forms of incentives are most effective at reducing costs, and which climates are best suited for photovoltaic production.

2. Background

A LCOE estimate takes into account the total costs and amount of electricity produced over the lifetime of a power plant to determine the overall lifetime cost per kilowatt-hour of electricity produced. Initial capital investments and accruing maintenance costs are discounted over the lifetime of the technology. Solar PV levelized cost calculations are typically performed over a time frame of 20–30 years, consistent with most manufacturer's estimates of panel life based on limited data, and assuming a panel has expired once its output reaches 80% of original production. This is consistent with most warranties, which typically only extend to 80% of original production (McCabe, 2011). For example, a manufacturer may place a warranty for the first 25 years of the panel life, and replace modules as needed if they sufficiently degrade before that time. Assuming the original firm that manufactured the panels is still in business and honoring their original warranty, manufacturers would be responsible for the cost of panel replacement. Hence, the variability in panel life from region to region may be incurred to the manufacturing firm as an uncertain expense, but is also of importance to the utility, because the panels are only protected from failure over the warranty lifetime and may not be protected at all if the manufacture is no longer in business at the time of failure. In addition, it is in the best interest of the utility to select panels with the lowest relative degradation rate in a given climate, as reduced degradation rates may increase panel lifetime well past the manufacture warranty. With a better understanding of panel degradation rates and subsequent deployment costs, lower prices could be achieved in some regions.

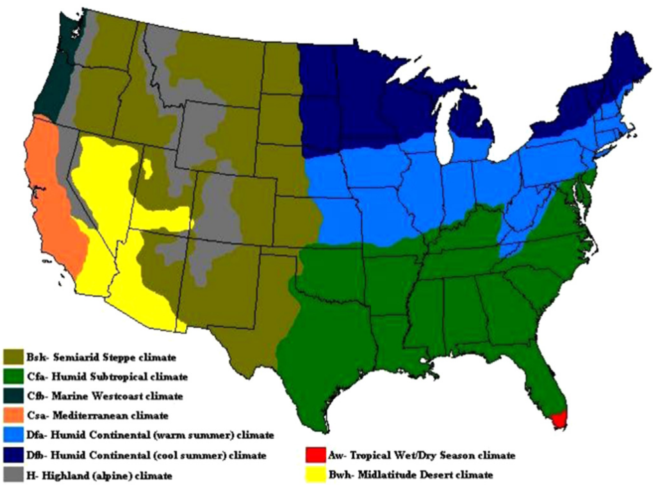

Fig. 1. Climate zones for the United States. Available from: http://upload.wikimedia.org/ wikipedia/commons/5/57/Climatemapusa2.PNG.

Recent studies have investigated the LCOE of solar PV with a focus on approaching grid parity (Darling et al., 2011; SunPower, 2015). Past estimates are often limited not only by uncertainties in degradation rate and module-level efficiency temperature-response, but also by unclear relationships between these parameters and technology and climate conditions. Though climate-specific factors have traditionally been omitted or assumed to be constant across technologies, some values do appear throughout the literature: Capital costs for each panel type are based on available market data, and we draw on existing LCOE literature to select representative values for operations and maintenance costs, residual values, and discount rates. For climate and climate-impact data, which have no foundation in the LCOE literature, we conduct a meta-analysis of engineering field studies to determine appropriate degradation and efficiency values for each panel type in each climate (see Section 4).

First, annual operations and maintenance costs are nontrivial, contrary to the pervasive tendency to label photovoltaic technology as indefinitely self-sustaining. Much of the cost of solar power is embedded in upfront capital, but to avoid significant efficiency losses from soiling and component failure, regular maintenance is typically required. Maintenance activities include module cleaning, panel wiring, and inverter and grid repairs and can significantly contribute to the operating costs of a commercial PV system. Lawrence Berkeley National Laboratory estimates these “soft costs” of solar between \$20–40/kW annually (Bolinger and

---

[1] Although PV technology based on cadmium telluride (CdTe) represent a commercially salient technology, limited field studies inhibit inclusion in this analysis. A recent review of PV field degradation rates by Jordan et al. (2016) revealed only a handful of field studies on CdTe PVs, with highly variable results. By comparison, the same report identified dozens of studies on each of the included silicon-based technologies.