Solar Energy Materials & Solar Cells 154 (2016) 71–77

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Quantitative analysis of the levelized cost of electricity of commercial scale photovoltaics systems in the US

Moon Hee Kang [a,b,*,1], Ajeet Rohatgi [a,c]

[a] University Center of Excellence for Photovoltaics Research and Education, School of Electrical and ComputerEngineering, Georgia Institute of Technology, 777 Atlantic Drive, Atlanta, GA 30332, USA
[b] Korea Institute of Industrial Technology, Center for Nano-Photonics Convergence Technology, 6 Cheomdan-gwagiro 208-gil, Buk-gu, Gwangju, 61012, South Korea
[c] Founder and CTO, Suniva Inc., 5775 Peachtree Industrial Blvd, Norcross, GA 30092, USA

ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form
25 April 2016
Accepted 27 April 2016
Available online 7 May 2016

Keywords:
Photovoltaics
Solar
System cost
LCOE
Commercial scale

ABSTRACT

The levelized cost of electricity (LCOE) of a commercial scale photovoltaics (PV) system is quantitatively investigated. The impact of the system and financial parameters, the installed system cost, solar insolation, system lifetime, system derate losses, module cost, module efficiency, balance of system (BOS) cost, inflation, discount rate, and loan rate, are quantitatively calculated using the System Advisor Model (SAM) from the National Renewable Energy Laboratory (NREL). 3D contour plots are generated to assess the impact of the key system and financial parameters on the LCOE. Calculations show that an installed system cost of 2.8, 2.3, and 2.1$/W can provide an LCOE of ~10¢/kWh (average price of electricity in the US) in Phoenix, Atlanta, and Boston, respectively, for a 30 years system lifetime, 20% system derate losses without investment tax credit (ITC). In addition, contour plots are generated to show what happens to the LCOE if the above parameters change. The study uses reasonable inputs for the current (2015) commercial scale PV system in the US.

1. Introduction

The levelized cost of electricity (LCOE), levelized cost per unit energy produced, is the most important parameter in assessing the cost effectiveness of a PV system. The ultimate goal of a photovoltaics (PV) system is to attain an LCOE equal to or lower than the current market price of electricity in a given location (grid parity). The correct value of the LCOE is dependent on the accuracy of multiple inputs, which makes it challenging to assess the exact value. Darling et al. [1] attempted to calculate the LCOE from the probabilistic distribution of the input parameters and concluded that LCOEs of 9.3, 9.7, and 6.9¢/kWh represent the highest probability for Boston, Chicago, and Sacramento, respectively. They also provided the sensitivity of each key parameter on the LCOE. However, some input parameters cannot be probabilistically distributed. Powell et al. [2] assessed the LCOE from the module fabrication cost reduction and found that a module fabrication cost of 0.50–0.75$/W can provide an LCOE of 6¢/kWh in the US southwest. Breyer et al. [3] calculated LCOE from the PV system experience curve and estimated the time for grid parity through most regions in the world. However, the LCOE is not only a function of the module cost and time but also several system parameters such as the installed system cost, solar insolation, system lifetime, system derate losses, module cost, module efficiency, BOS cost, inflation, discount rate, and loan rate. Therefore, attempts to perform a sensitivity analysis of several system parameters was initially performed in ref. [4], a dissertation [5], and then continued in this paper.

Since accurate assessment of the LCOE comes from correct reflection of the system parameters, our starting input parameters in Table 1 originated from various technical reports [6–8] and the DOE SunShot vision study [9] and the Solar Energy Technologies Program [10–12], and in our study, we varied them to assess their impact on the LCOE. The generated contour plots in this paper help in rapid assessment of the LCOE for a given situation different from the starting input parameters. For a convenient contour plot reading, lower LCOE values are toward blue and higher are toward red. Contour plots provide guidelines for focusing and selecting the best combination of the key system and financial parameters that can lead to a desired LCOE value in a given location. Finally,

* Corresponding author.
E-mail address: moonhee@kitech.re.kr (M.H. Kang).
[1] Current address: Korea Institute of Industrial Technology, Center for Nano-Photonics Convergence Technology, 6 Cheomdan-gwagiro 208-gil, Buk-gu, Gwangju, 61012, South Korea.

http://dx.doi.org/10.1016/j.solmat.2016.04.046
0927-0248/

Table 1
List of reference input parameters used for the LCOE calculations.

Parameter	Unit	Value
Array size	kW	100
Operation and maintenance	%	0.5% of total installed system cost (ex. 11 $/kW yr, 8$/MWh yr at 2.2$/W PV system at Atlanta, GA)
System derate losses	%	20
Availability	%	97
Temperature coefficient	%/°C	−0.45
Shading and Snow		None
Annual system power degradation	%	0.5
System lifetime or Analysis period	yr	30
Tracking		Fixed South-facing latitude tilt (Tilt=Latitude) (Phoenix: 33.43°N, LA: 33.93°N, Atlanta: 33.65°N, Boston: 42.37°N)
Installed system cost	$/W	2.2
Inflation	%	2.5
Nominal discount rate	%	10.7
Real discount rate	%	8
Federal/state tax	%	28/7
Net salvage value	%	0%
Loan term	yr	10
Loan rate	%	7
Debt fraction	%	50
Federal and state depreciation		5-yr MACRS
Investment tax credit	%	0

*System derate losses include wiring, mis-match, soiling (dust), shading, AC to DC (inverter), and DC to DC (transformer) losses.
*Availability: Assuming 10 days system down per year for maintenance.
*Net salvage value: Estimated resale value of a PV system at the end of system lifetime.
*Depreciation: Decrease in value of project assets over the analysis period. Depreciation reduces federal and state taxable income.
*MACRS (Modified Accelerated Cost Recovery System): Current tax depreciation system in the US.
*5-yr MACRS: MACRS depreciation schedule offered by the federal government and some state. using a five-year life and half-year convention. This tax deduction, expressed as a percentage of the total installed system cost, applies to the first five years of the project life as follows: 20%, 32%, 19.2%, 11.52%, 11.52%, and 5.76% [13].
*Economic (Inflation, discount rate) and tax parameters represent long term average and current value in US, respectively [6].

model calculations are extended to show the installed system cost required in different regions in the US to attain grid parity.

2. Results and discussion

2.1. Levelized cost of electricity of a PV system

The LCOE is defined as the cost per unit of energy produced over the entire life of a system [13–15].

$$\mathrm{LCOE} = \frac{\text{Lifetime money spent}}{\text{Lifetime energy produced}} = \frac{\sum_{0}^{n} C_n}{\sum_{1}^{n} E_n}$$

where C_n is the annual cost and E_n is the annual electricity generation. By definition, C_n is equal to the product of the LCOE and E_n in that year [13,16].

$$C_n = E_n \times \mathrm{LCOE}$$

The annual cost (C_n) consists of the annual payment for the installed system cost and its financing and annual operation and maintenance (O&M) costs [17]. Therefore, the annual cost takes into account the input parameters such as inflation, the discount rate, taxes, loans, etc.

The installed system cost consists of the module and BOS costs, and the BOS cost is composed of wiring and mounting hardware, installation labor, inverters, permitting and commissioning, engineering/design, site preparation, grid connection, management, sales tax, installer margin, overhead, insurance, etc [9,18]. Wiring and mounting hardware and installation labor are referred to as an area-related BOS cost because they depend on the area or the number of modules. The sum of other costs, consisting of inverter, permitting and commissioning, engineering, design, site preparation, grid connection, management, sales tax, installer margin, overhead, and insurance, are referred to as fixed or indirect BOS cost because it is independent of the area or the number of modules [15].

Electricity generation (E_n) is determined from the capacity factor. Capacity factor is the ratio of actual output and potential full capacity output.

$$E_n = \text{Capacity factor} \times 24 \times 365$$

Therefore, the capacity factor of a PV system can be defined from the solar insolation and system derate loss. The derate loss includes wiring, mismatches, soiling (dust), shading, AC to DC (inverter), and DC to DC (transformer) losses [19].

$$\text{Capacity factor} = \frac{\text{Daily insolation}}{24} \times (1 - \text{Derate}) \times \left[1 + \gamma(\text{Temp} - 25\ ^\circ\text{C})\right]$$

where γ is the temperature coefficient of the module, which accounts for the energy output loss when modules operate at higher than the room temperature.

Accurate assessment of the LCOE involves consideration of the time value of money [15–17,20]. The time value accounts for the impact of the opportunity cost of money during the time that one waits for a return on an investment. The discount rate (DR) is used to calculate the time value of money by converting the future value into the present value. The discount rate is influenced by a variety of factors, such as the rate of return, interest rates, risk premium, and income. Including the time value, lifetime money spent can be re-written as [13,16]

$$\text{Lifetime money spent} = \sum_{0}^{n} \frac{C_n}{(1+DR)^n} = \sum_{1}^{n} \frac{E_n \times LCOE}{(1+DR)^n}$$

The discount rate is nominal or real when it includes or exclude inflation, respectively [16]. As annual cost (C_n) includes the impact of inflation, the nominal discount rate is used in the left side of the above equation [13,16]. The right side can be chosen depending on whether the LCOE is real or nominal. Therefore, a real LCOE is an inflation-adjusted value while a nominal LCOE is not. A real LCOE is appropriate for long-term analysis because it accounts for many years of inflation over the project lifetime, while a nominal LCOE is appropriate for short-term analysis [13,16].

$$\text{Real LCOE} = \frac{\sum_0^n \left[\frac{C_n}{(1+DR)^n}\right]}{\sum_1^n \left[\frac{E_n}{(1+DR_{real})^n}\right]}$$

$$\text{Nominal LCOE} = \frac{\sum_0^n \left[\frac{C_n}{(1+DR)^n}\right]}{\sum_1^n \left[\frac{E_n}{(1+DR)^n}\right]}$$

where DR is the nominal discount rate, and DR_{real} is the real discount rate. The relation between DR and DR_{real} is

$$DR_{\text{real}} = \frac{1+DR}{1+\text{Inflation}} - 1$$