Levelized Cost of Electricity Calculator: A User Guide

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1 Description

The economics of electricity generating facilities is determined by range of parameters including, including upfront investment, operating expenses and capacity factors. The Levelized Cost of Electricity (LCOE) is a metric commonly used to compare the cost competitiveness of alternative electricity generating platforms. Our LCOE calculator seeks to provide a simple, flexible and transparent tool that enables users to quickly determine the LCOE for different generation technologies, segments and geographic locations within the United States.

The generation technologies assessed in this tool include renewable energy sources, in particular solar photovoltaic (PV) and wind power, in addition to fossil fuel power plants including natural gas combined cycle (NGCC) and pulverized coal. For solar PV, our LCOE tool also differentiates segments according to utility scale, commercial and residential installations. The LCOE for each technology-segment combination is determined for a specific U.S. state, where currently the user can choose one from a list of eleven.[1] For each technology-segment combination in a given U.S. state, the default input values for the fourteen components of the LCOE are displayed. The input variables considered are:

- Useful Life
- Tax Depreciation Method
- System Price (Cost of Capacity)
- Investment Tax Credit
- Production Tax Credit
- Capacity Factor
- System Degradation Factor
- Fixed Operation and Maintenance Cost
- Variable Operation and Maintenance Cost
- Fuel Cost

[1] Arizona, California, Florida, Georgia, Iowa, Massachusetts, New Jersey, North Carolina, Oklahoma, Texas and Wyoming.

- Carbon Dioxide Emission Charges (Allowance Cost)
- Emissions Performance (Carbon Intensity)
- Cost of Capital (Discount Rate)
- Effective Corporate Tax Rate

The tool allows each input value to be freely adjusted to recalculate the LCOE, so as to perform a sensitivity analysis relative to the default values.

The remainder of this user document is organized as follows. Section 2 provides instruction on how to use the LCOE tool. Section 3 outlines the data sources that provide the inputs to the default component values. The analytical background and relevant equations are provided in Section 4.

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2 User Manual

The LCOE Calculator is available at:

`http://stanford.edu/dept/gsb_circle/sustainable-energy/lcoe/`

When you load the website of the LCOE Calculator, you see the following page:

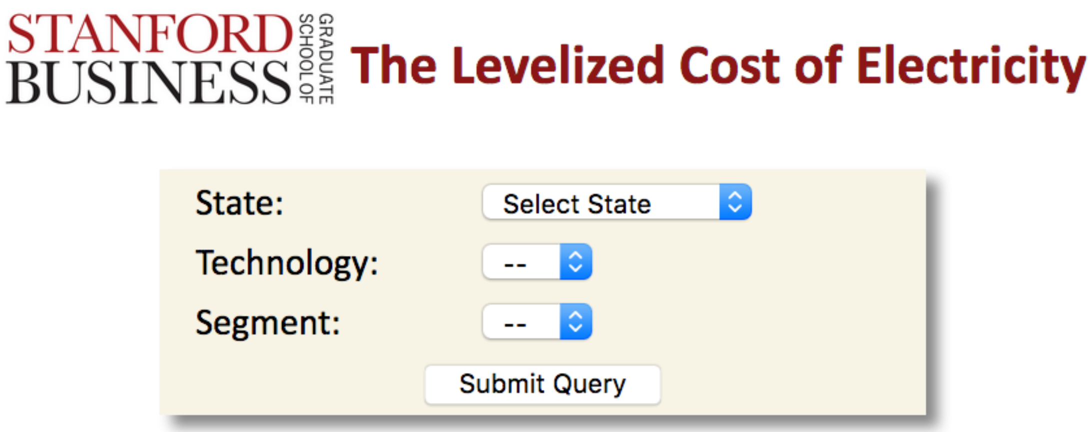

Figure 1: Start page of the LCOE Calculator.

To calculate the LCOE of an energy source, choose a **state**, **technology** and **segment** and click on '**select**'. Example: Select 'California', 'Solar' and 'Commercial'.

The LCOE Calculator returns the results of the LCOE calculation with all the parameters and cost components. You see the following page:

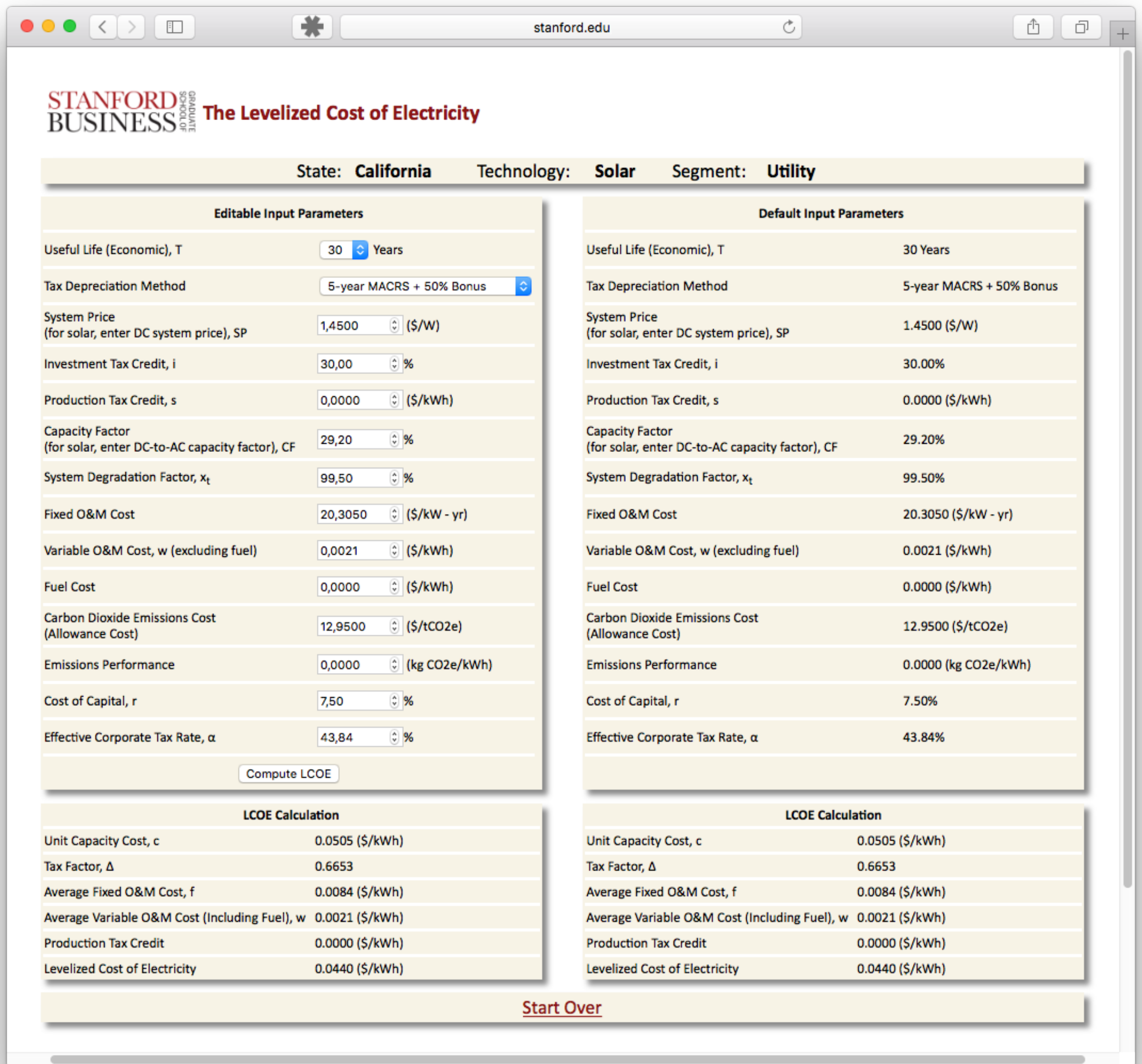

Figure 2: Result and parameter page of the LCOE Calculator.

The page has three distinct areas:

1. the **top bar** shows the initial selections,
2. the **left column** shows the adjustable input parameters and the LCOE, and
3. the **right column** shows the default input parameters and the LCOE.

The collection of input parameters is listed in Section 1. **To test the sensitivity** of the LCOE value to a particular parameter, simply edit its value by **clicking** into the field and **entering** a new value. Then **click** '**Compute LCOE**' to recalculate the results of the left column. The right column allows for a direct comparison of the results.

To choose a different state, technology or segment, **reload** the website or click '**Start Over**'.

3 Data Sources

This section provides details about the data sources used for each of the parameters used in the LCOE calculation.

Useful Life

Generally assumed value across all generation technologies.

Tax Depreciation Method

Refer to IRS Publication 946 (2016), "How to Depreciate Property".[2]

System Price

For NGCC, wind and utility scale solar, the average of actual system prices is used based on 2015 vintage facilities. Data provided by ABB Velocity Suite Subscription Service.[3]
Since no pulverized coal facilities were constructed in 2015, cost of capacity estimates are from U.S. Department of Energy National Energy Technology Laboratory (NETL) report, titled "Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3" (DOE/NETL-2015/1723).[4]
For commercial and residential scale solar PV, the reported cost of capacity, by segment, for 2015 vintage installations is used. Data provided by GTM Research report titled "U.S. Solar PV Price Brief H1 2016: System Pricing, Breakdowns and Forecasts".[5] Given that values in the GTM Research report are national averages, state differentiation is determined by adjusting cost of capacity using the averaged city cost indexes for a given state, provided by RSMeans Construction Cost Indexes.[6]

Investment Tax Credit

In accordance with IRS rules.[7]

Production Tax Credit

In accordance with IRS rules..[8]

[2]https://www.irs.gov/publications/p946/index.html.
[3]http://energymarketintel.com/velocity-suite/.
[4]https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=729.
[5]https://www.greentechmedia.com/research/report/us-solar-pv-price-brief-h1-2016.
[6]https://www.rsmeans.com/products/books/2017-cost-data-books/2017-construction-cost-indexes-october.aspx.
[7]https://energy.gov/savings/business-energy-investment-tax-credit-itc.
[8]https://energy.gov/savings/renewable-electricity-production-tax-credit-ptc.

Capacity Factor

For utility scale systems (NGCC, coal, wind and utility scale solar), data are provided by an average of actual capacity factors for facilities characterized as "operational" for the full year 2015, as denoted in ABB Velocity Suite Subscription Service.

For commercial and residential scale solar, the annual insolation of a given state is used, as determined by the average of point-estimates of cities provided by PV Watts. [9] This average value is then reduced by incorporating system losses (86%), inverter efficiency (96%) and temperature losses (97%). The result is then divided by 8,760 to arrive at state-specific residential and commercial capacity factors.

System Degradation Factor

For all solar installations, degradation factor baseline values follow Jordan, Wohlgemuth, and Kurtz (2012). Wind degradation factors are derived from statistics provided in the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy report titled: "2015 Wind Technologies Market Report."[10] NGCC and coal facility degradation were provided through expert elicitations.

Fixed Operation and Maintenance Cost

For NGCC, wind and utility scale solar, we rely on an average of actual fixed operating and maintenance costs for 2015 vintage facilities. Only those facilities that were in full operation for 12 consecutive months are used. Data are provided by ABB Velocity Suite Subscription Service.

Since no pulverized coal facilities were constructed in 2015, fixed operating and maintenance costs estimates are based on the National Energy Technology Laboratory (NETL) report, titled "Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3" (DOE/NETL-2015/1723).

For commercial and residential scale solar PV, the reported fixed operation and maintenance costs are based on 2015 vintage installations. Data have been provided by GTM Research report titled "U.S. Solar PV Price Brief H1 2016: System Pricing, Breakdowns and Forecasts". The values in the GTM Research report are national averages. Therefore state differentiation is achieved by adjusting system prices by the state-averaged city cost index provided by RSMeans Construction Cost Index.

[9] http://pvwatts.nrel.gov/.

[10] https://energy.gov/sites/prod/files/2016/08/f33/2015-Wind-Technologies-Market-Report-08162016.pdf.

Variable Operating and Maintenance Costs

For utility NGCC, wind and utility scale solar, the calculator relies on an average of actual variable operation and maintenance costs for 2015 vintage facilities is used. Only those facilities which were in full operation for 12 consecutive months were included. Data inputs are based on the ABB Velocity Suite Subscription Service.

Since no pulverized coal facilities were constructed in 2015, variable operating and maintenance costs estimates are obtained from the US. Department of Energy National Energy Technology Laboratory (NETL) report, titled "Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3" (DOE/NETL-2015/1723).

For commercial and residential scale solar PV, the calculations rely on the reported variable operating and maintenance costs for 2015 vintage installations. Data are provided by the GTM Research report titled "U.S. Solar PV Price Brief H1 2016: System Pricing, Breakdowns and Forecasts." Since values in the GTM Research report are national averages, differentiation by state is achieved by adjusting these costs according to the RSMeans Construction Cost Index.

Fuel Cost

For NGCC and coal facilities, the average fuel costs is obtained from facilities that were characterized as "operational" for full year 2015, as reported in ABB Velocity Suite Subscription Service.

Carbon Dioxide Emission Charges

The California charge is based on the AB 32 California Cap and Trade Program, with the allowance cost for carbon dioxide provided by California Carbon Dashboard.[11] The Massachusetts charges are provided by the Regional Greenhouse Gas Initiative (RGGI).[12]

Emissions Performance (Carbon Intensity)

Carbon intensity estimates were provided by the National Energy Technology Laboratory (NETL) report, titled "Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3" (DOE/NETL-2015/1723).

Cost of Capital (Discount Rate)

[11] http://calcarbondash.org/.
[12] https://www.rggi.org/.

The default calculations assume an identical value across all generation technologies. The cost capital is to be interpreted as a weighted average between the cost of equity and debt.

Effective Corporate Tax Rate

The effective corporate tax rate for each state is the sum of the federal tax rate of 35% and the state specific corporate tax rate, as reported by the Tax Foundation.[13]

[13] https://taxfoundation.org/state-corporate-income-tax-rates-and-brackets-2016/.

4 Analytical Background

The LCOE is a life-cycle cost concept that includes all physical assets and resources required to deliver one kilowatt hour (kWh) of electricity. It reflects the break-even price that must be achieved as **average revenue** to yield a zero-net-present value (NPV) for equity investors.[14] The concept assumes that capacity and fixed operating costs scale proportionally with the size of the facility. Thus investments in power capacity are normalized to 1 kilowatt (kW). Following the notation in Reichelstein and Yorston (2013), the LCOE of a 1 kW facility is given by:

$$LCOE = w + f + c \cdot \Delta, \tag{1}$$

with w as the time-averaged variable cost per kWh, f as the levelized fixed operating cost per kWh and c as the levelized capacity cost of the facility per kWh. Δ is a tax factor that covers the impact of income taxes, the depreciation tax shield and investment tax credits. The cost components are determined by the following parameters:

- SP: system price, the acquisition cost of the generation capacity (in \$/kW),
- W_i: variable operating cost in year i of the generation facility (in \$/kWh),[15]
- F_i: fixed operating cost in year i of the generation facility (in \$/kW),
- γ: discount factor based on the cost of capital r: $\gamma \equiv \frac{1}{(1+r)}$ (scalar),
- T: useful lifetime of the output generating facility (in years),
- CF: capacity factor of the generation capacity (scalar),
- x^{i-1}: system degradation factor in year i (scalar),
- m: number of hours per year: $m = 8,760$.

Since the LCOE represents a break-even price, standard corporate finance theory suggests that if the firm's leverage ratio (debt over total assets) remains constant, the appropriate discount rate is the Weighted Average Cost of Capital (WACC). The capacity factor of the LCOE is the average capacity factor of the generation capacity ignoring intertemporal

[14] C.f. MIT (2007).

[15] The variable operating cost include all costs that depend on the output quantity, such as variable maintenance cost, fuel cost and carbon dioxide emissions cost.

variations. It is a unitless scalar in the range of [0, 1], reflecting environmental or technological factors. The system degradation factor x^{i-1} covers the potential change of output of the generation capacity over time. It is a unitless scalar quantifying the fraction of the initial capacity that is still operational in year i. For notational compactness, denote by $m = 24 \cdot 365 = 8,760$ the total number of hours in a year.

To obtain the levelized capacity cost per kWh, the initial capital expenditure (system price) is 'levelized' across all future hours of energy output that can be obtained from the facility. Specifically, the system price per kW is divided by all hours of production discounted over the useful lifetime:

$$c = \frac{SP}{m \cdot CF \cdot \sum_{i=1}^{T} x^{i-1} \cdot \gamma^i}. \tag{2}$$

The denominator represents the lifetime aggregate output per kW of installed capacity. The levelized operating costs per kWh for fixed and variable operating costs are given as the present value of all costs divided by the aggregate output:

$$f = \frac{\sum_{i=1}^{T} F_i \cdot \gamma^i}{m \cdot CF \cdot \sum_{i=1}^{T} x^{i-1} \cdot \gamma^i}, \tag{3}$$

and

$$w = \frac{\sum_{i=1}^{T} W_i \cdot x^{i-1} \cdot \gamma^i \cdot m \cdot CF}{m \cdot CF \cdot \sum_{i=1}^{T} x^{i-1} \cdot \gamma^i} = \frac{\sum_{i=1}^{T} W_i \cdot x^{i-1} \cdot \gamma^i}{\sum_{i=1}^{T} x^{i-1} \cdot \gamma^i}. \tag{4}$$

The last component of the LCOE is the tax factor Δ that quantifies the financial effect of income taxes, the depreciation tax shield and investment tax credits. While depreciation and interest on debt reduce a firm's taxable earnings, the debt tax shield is already included. if the cost capital is interpreted as the WACC. The depreciation tax shield is determined by the effective corporate income tax rate and the allowable depreciation schedule. The U.S. tax code currently grants an investment tax credit (ITC) for some renewable energy sources. It reflects a dollar-for-dollar subsidy that is deducted from the income taxes an investor otherwise owes.[16] The tax factor incoporates the following parameters:

- ITC: investment tax credit (in %),

[16] C.f. U.S. Department of Energy (2016a), Comello and Reichelstein (2016).

- α: effective corporate income tax rate (in %),
- d_i: allowable tax depreciation rate in year i (in %),
- δ: capitalization discount for depreciation purposes.[17]

The assumed useful life for tax purposes is usually shorter than the economic lifetime. Therefore, the tax depreciation rate is zero ($d_i = 0$)) in those years. Following the notation in Comello and Reichelstein (2016), the tax factor is given by:

$$\Delta = \frac{1 - ITC - \alpha \cdot (1 - ITC \cdot \delta) \cdot \sum_{i=1}^{T} d_i \cdot \gamma^i}{1 - \alpha}. \tag{5}$$

The tax factor is increasing and convex in the tax rate α. Without an ITC, it is greater than 1 and bound above by $1/(1 - \alpha)$. Furthermore, an accelerated tax depreciation schedule reduces Δ due to the time value of money. Specifically, if the tax code were to allow for a full depreciation in the first year ($d_0 = 1$ and $d_i = 0$ for $i > 0$), the tax factor would equal 1. With tax credits, Δ can fall below 1.

For wind power, the U.S. tax code currently grants the production tax credit (PTC). It also reflects a dollar-for-dollar subsidy in terms of a fixed premium per kWh of produced electricity that is deducted from the income taxes otherwise owed by the investor.[18] Since the PTC is commonly granted for less than the useful life of the asset for tax purposes, we denote by T^0 as the duration of the PTC. We denote by Δ^o the tax impact of the PTC. It can be derived from the NPV as follows:

$$\Delta^o \equiv \frac{\sum_{i=1}^{T^0} \gamma^i}{(1 - \alpha) \cdot \sum_{i=1}^{T} x^{i-1} \cdot \gamma^i}. \tag{6}$$

To integrate the PTC into the LCOE calculation, it can be shown that an investor will break-even in terms of discounted cash flows if the average sales revenue per kWh is exactly equal to the following LCOE measure:

$$LCOE = w + f + c \cdot \Delta - PTC \cdot \Delta^0. \tag{7}$$

[17] The current tax code of the U.S. states that an investor claiming a 30% ITC can only capitalize 85% ($= 1 - 0.3 \cdot 0.5$) of the system price for depreciation purposes.
[18] C.f. U.S. Department of Energy (2016b).

Glossary Of Terms

Abbreviations

Abbreviation	Description
LCOE	Levelized cost of electricity
ITC	Investment tax credit
kW	kilo Watt
kWh	kilo Watt hour
NPV	Net present value
NGCC	Natural gas combined cycle
PTC	Production tax credit
PV	Photovoltaic
WACC	Weighted average cost of capital

LCOE Parameters

Parameter	Description	Unit
Greek		
α	Effective corporate income tax rate	%
δ	Capitalization discount for depreciation purposes	-
Δ	Tax factor, overall effect of corporate income taxes	-
Δ^0	Tax impact of the production tax credit	-
γ	Discount factor: $\gamma = 1/(1+r)$	-
Latin		
c	Capacity cost of the generation facility	\$/kWh
CF	Average capacity factor of the generation capacity	-
d_i	Allowable tax depreciation in year i	%
f	Time-averaged fixed operating cost	\$/kWh
F_i	Fixed operating cost in year i	\$/kW
ITC	Investment tax credit	%
$LCOE$	Levelized cost of electricity	\$/kW
m	Number of hours per year	*hours*
r	Interest rate, weighted average cost of capital (WACC)	%
PTC	Production tax credit	\$/kWh
SP	System price, the acquisition cost of the generation capacity	\$/kW
T	Useful life for economic purposes	*years*
T^0	Duration of the production tax credit	*years*
w	Time-averaged variable operating cost	\$/kWh
W_i	Variable operating cost in year i	\$/kWh
x^{i-1}	System degradation factor in year i	%

References

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