Computing the Levelized Cost (B R¢/kWh [US ¢/kWh]) of Solar Electricity Generated at Grid Connected Photovoltaic (PV) Generating Plants

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Abstract

A simple worksheet (spreadsheet) has been designed to compute the levelized cost (in B R¢/kWh [US ¢/kWh]) of grid connected PV generated electricity. A previous version of this paper was presented at the American Solar Energy Association's SOLAR FORUM 2001(Stavy, 2001). This paper presents an updated version of this levelized cost worksheet for a new international audience in Brazilian Reals (B R$). The paper first reviews the technical, financial and economic basis underlying the worksheet. The technical analysis involves the physical life and electric production of the PV plant. The financial and economic analysis involves using financial annuities to cost account for the capital recovery (depreciation and amortization) of the initial capital and for the financial expense (interest and return on equity) of using the initial capital through out the predicted physical life of the PV plant. The cost accounting also involves computing the plant's yearly fixed and variable operating and maintenance expenses. The paper then analyzes, in more depth, the specific inputs (capacity-W_P, capital cost-B R\$/W_P [US \$/W_P], efficiency, physical life, solar radiation, capital recovery method, interest rate, return on investment, tax adjustments, fixed and variable operating and maintenance expenses) used in the worksheet. Near the end of this paper is a printed copy of the "Levelized Cost Worksheet for a 1 kWp PV Electric Generating Plant". The worksheet has benchmark values in B R$ for a model solar electric plant located in Rio de Janeiro, Brazil and in US $ for a model solar electric plant located in Chicago, IL.

1. GENERAL PRINCIPLES

1.1. The Cost of Generating Capacity

Electric power plant capacity is measured in kW; electric energy is measured in kWh and its cost is priced in B R¢/kWh [US ¢/kWh for US retail residential customers]. The efficiency of a power plant is measured as the percent of the fuel (i.e. natural gas, coal, sunlight) that is converted into electric energy.

The cost of electricity from a fossil power plant consists of the plant's operating and maintenance costs, the fuel cost, fuel waste disposal costs and the recovery of the capital invested in the plant.

A PV electric plant generates electricity by converting solar energy (i.e. sunlight or solar radiation) into electric energy. The fuel is free but the technology (the PV power plant) to convert the solar energy into electric energy is not free; it has a capital cost.

A PV electric power plant has a physical life. At the end of its physical life the plant will no longer be able to generate electricity. During its physical life, while the power plant is generating energy, the capital cost of the plant must be recovered. The recovery of the capital cost of the plant is called the depreciation (amortization) of the plant. The yearly depreciation expense is the yearly capital recovery and is a major cost of generating PV electricity.

Until recently, many US college introductory economic textbooks stated that sunk costs (the capital cost of the PV plant) were irrelevant. This is not correct. The capital cost of a PV electric generating plant is relevant and must be recovered. The capital cost of currently operating regulated US nuclear and fossil fuel electric generating plants are now called stranded costs instead of sunk costs. Stranded costs are very relevant to US electric industry deregulation policy makers (Stavy, 1970-97).

In addition to the recover of the capital (<u>the capital cost</u>), the plant must pay for the <u>cost of the capital</u> (for using the capital). If borrowed money is used to buy the plant, the cost of borrowing the capital is called interest. If plant owners have used their own money to buy the plant, the cost of using the owner's money is called the return on investment (ROI). The cost of capital (ROI and interest) is expressed as a percent.

There are various authorities (i.e. US federal income tax, European generally accepted accounting, Brazilian regulatory, etc.) and methods (straight line, sum of the years digits, double declining balance, etc.) that can be can be used to compute the yearly depreciation of a power plant.

This paper uses the levelized cost method of depreciation. This method computes one constant yearly payment (the capital amortization) for both the cost of capital and the capital cost (depreciation) of the power plant over the physical life of the plant. The first year's payment is almost all the cost of capital, while the last year's payment is almost all the capital cost. This implies that it is in the later years of its life that the PV plant incurs most of its loss in generating capacity and, therefore, its depreciation should be the greatest.

The levelized cost method can be thought of as a financial annuity. The principal is the capital cost of the PV plant instead of the amount borrowed. The number of years is the physical life of the plant instead of the number of years of the annuity. The annuity interest rate is the cost of capital and is a blended rate for both the interest and the ROI. The annual payment is the yearly capital amortization.

A conventional US home mortgage owed by a homeowner for a set number of years with a constant interest rate and a constant monthly mortgage payment is a common example of a financial annuity. The amount borrowed is the principal. The monthly payment consists of an amount to pay the monthly interest on the previous month's principal balance outstanding and an amount to reduce the principal. The first year's payment is almost all interest; while the last year's payment is almost all principal.

Until recently, PV power plant capacity was stated in watts (W_p) of peak (maximum) power; now with larger (>1 kW_p) plants, capacity is starting to be quoted in kW_p. It is still usual to quote the PV capital cost in B R$/$W_p$ [US $/$W_p$], even thought the electric industry standard is B R$/$kW_p$ [US $/$kW_p$].

PV panels usually are between 50 and 60 percent of a grid connected PV plant's total capital cost. The plant's other costs (balance of system-BOS) include inverters (to convert DC current to AC), the panel rackets, the wiring and controls, the installation, engineering design and project development. The larger the installed capacity, the lower the capital cost B R$/$W_p$ [US $/$W_p$].

The lower the capital cost of a PV plant, the lower the cost of solar electricity. An increase in the efficiency of manufacturing a PV plant (mostly increasing the manufacturing efficiency of panels but also the BOS components) would reduce the capital cost of the plant. A 50% reduction in the cost of a PV plant will, as a rule of thumb, reduce the cost of PV electricity by 50%.

There are standard test conditions and procedures (Committee E44 on Solar, Geothermal and Other

Alternative Energy Sources,1997) for measuring the power output (W_p) and efficiency of a PV panel. PV manufacturers' product specifications state the solar panel's power output and efficiency.

I estimate that the published operating efficiencies (percent of sunlight converted to electric energy) of currently manufactured PV panels to be from 8% to 15%. This means that at standard test conditions (1 kW/m^2) with a 10% efficient panel, a $1m^2$ (10.764 ft^2) PV panel will produce 100 W of power. At 10% efficiency, to get 1kW of power requires 10 m^2 (115.863 ft^2); at 15% efficiency, it would require 6.67 m^2 (71.752 ft^2).

A 50% increase in a panel's efficiency (10%→15%) reduces the panel surface area by 33.3%. If the surface area itself is valuable, with 15% efficient panels, the same surface will produce 50% more energy than 10% efficient panels. To get a 33.3% reduction in the cost of electricity requires that the 15% efficient panels also have a reduction in their capital cost that is equal to 33.3%. In summary, for a PV plant with a specific capacity (for example 5 kW_p), the surface dimensions (m^2, ft^2) of the PV array depends on the efficiency of the panel but the energy output (kWh) depends on the solar radiation level.

A PV plant's BOS components, including modern inverters, usually have operating efficiencies of over 90%. It is also the case that with the BOS components that increases in operating efficiencies do not reduce the cost of PV electricity unless accompanied by proportional reductions in the BOS capital costs.

1.2. Operating and Maintenance Cost

To compute the cost of electricity from a PV plant, we also have to know the yearly cost to operate and maintain the plant as well as the capital costs.

Compared to fossil power plants, a grid connected PV plant has a very low operating and maintenance cost, no fuel costs, no fuel waste disposal costs and very high capital costs. A fossil fuel power plant has a fuel (coal, natural gas, oil) cost, fuel waste disposal cost, operating and maintenance cost and the capital costs.

At a PV plant, the energy conversion efficiency is related to the surface dimensions of the PV array, while at a fossil generation plant, energy conversion efficiency (i.e., Joules [BTU] of fuel converted to kWh of electricity) is directly related to the cost of electricity. A 100% efficient coal fired plant would convert 100% of the J in the coal into kWh of electricity. A 60% combined cycle gas turbine plant will have half the fuel cost of a natural gas plant with 30% efficiency.

Modern grid connected inverters have "microchip" control centers (for voltage, amperage, disconnect, etc.) that allow the PV plants to operate themselves at almost no cost. The inverter automatically meters, controls and stores the record of the PV plant operation. With data-links to the inverter, the PV plant can even be remotely supervised.

There are no operating parts at a PV plant, unless a plant has the PV panels on solar trackers to follow the sun. Some PV plants use solar trackers to capture more sunlight than fixed panels would. Maintenance consists of the periodic inspection and cleaning of the wires, panels and connections. The panel's surfaces must be cleaned to make sure that the forecasted amount of sunlight reaches the cells. The inverter has to be physically inspected and tested to make sure that it is operating efficiently. The projected operating and maintenance (O & M) costs for a model plant should be budgeted from the cost accounts of currently operating PV plants of the same capacity and type.

The worksheet computes the fixed (a function of the kW_p of capacity) and variable (a function of the kWh generated) O & M costs. The worksheet combines both of the PV plant's O & M costs.

1.3. Annual kWh of Electricity Generated

Forecasting the kWh of electricity that a PV plant will generate each year is required in order to compute the B R¢/kWh [US ¢/kWh] cost of solar electricity. To forecast the kWh per year generated by a PV plant, it is required to know the plant's availability, capacity factor and capacity.

The availability of a power plant is the percent of time in the year that the plant is available to operate. 100% availability would be 24/7/365 or 8,760 hours a year. 100% availability means that there is no time when the plant is shut down for repairs and maintenance. 90% availability is a good rule of thumb for a utility sized fossil fuel plant. I estimate that a gird connected PV plant should have 95% availability. The worksheet assumes that the PV plant is available 100% of the time. This means that there is no time when the plant is shut down for repairs and maintenance.

A PV plant is an intermittent source of energy. It requires sunlight to operate. Even if one assumes that the PV plant is available to operate 100% of the time, it can not run at 100% of capacity. 24 hours of sunlight a day, 365 days a year, will give a 100% capacity factor.

The extraterrestrial solar energy reaching the earth (i.e., at a space station on a PV panel orientated perpendicular to the sunlight, while the space station is in the sun) is a constant 1.37kW/m^2. As all readers know, that due to the atmosphere and the variation in the weather, latitude, season, elevation and geography, the solar radiation at difference locations on the earth's surface is not the same. A full sun on earth is 1 kW/m^2. A full sun hour is 1 kWh/m^2/hr.

The solar radiation reaching a particular plant location must be known in order to predict the PV plant's electric output. A specific site might require site specific radiation measurements. A good <u>first approximation</u> of a US plant location's daily solar radiation can be made at a reasonable cost by using the *U.S. Solar Radiation Resource Maps* located on the web (Marion & Wilcox, 2000). This solar atlas is based on published solar radiation data in the US *National Solar Radiation Data Base (NSRDB). Version 1.1* (Marion & Wilcox ,1994)

Actual and statistically inferred (modeled) solar radiation data from United States meteorological stations has been developed and analyzed. From the solar radiation maps, the map user can get the average daily solar radiation (kWh/m^2/day) on a yearly or monthly basis, at a specific geographic location for different standard PV panel orientations. I have chosen the standard NSRDB flat collector facing the sun (south in the Northern Hemisphere; north in the Southern Hemisphere) with a tilt equal to the plant's latitude.

The maximum radiation occurs when the panel is tilted at the same latitude as the plant's location. For a Rio PV plant which is at latitude 22° 43' South, the tilt should be North 22° 43'. For a Chicago PV plant which is at latitude 41° 78' North, the tilt should be South 41° 78'.

The solar map shows that, on a <u>yearly</u> basis, with the above titled flat plate collector, the maximum average daily solar energy for Chicago is 5 kWh/m^2/day. July, in Chicago, has a maximum daily average of 6 kWh/m^2/day. January has a maximum daily average of 3 kWh/m^2/day.

The worksheet computes the capacity factor as a percent of 24 full sun hours. To get the capacity factor for the Chicago PV plant, the worksheet divides the 5 by 24 to get 20.83%. On the worksheet, the capacity factor stays constant the entire life of the plant.

I have not been able to find Brazilian solar radiation maps which show the average daily solar radiation on a yearly or monthly basis, at specific Brazilian locations for different standard panel orientations. I have used Key West, Florida (24° 33' North) as a proxy for Rio's latitude of 22° 43' South. 6 kWh/m^2/day is the <u>yearly</u> maximum average daily solar energy for Key West. July for Key West [January for Rio], has a maximum daily average of 7. January for Key West [July for Rio], has a maximum daily average of 6. Since Rio is closer to the equator than Key West, I adjusted the proxy 6 to 6.5. The worksheet divides 6.5 by 24 to get a 27.08% capacity factor.

The worksheet does not allow the user to change the capacity of the PV plant. The worksheet PV plant has a standardized capacity of **one** kilowatt (kW_p). This makes both the worksheet and the solar electricity cost computation easier. Data from actual plants of varying capacities can be put on the spreadsheet because the capital cost of a PV plant is usually quoted in B R$/$W_p$ [US $/$W_p$].

The worksheet assumes that there is no inflation over the physical life of the plant. This is a reasonable assumption, since most of the plant's costs are capital costs that do not rise with inflation.

A 1 kW_p plant with 100% availability and a 100% capacity factor will generate 8,760 kWh/year. This is 1 kWh/hr times 8,760 hr/year. The Rio PV plant with a 27.08% capacity factor will generate 2,372 kWh/year while the Chicago PV plant with a 20.83% capacity factor will generate 1,825 kWh/year. The worksheet assumes that the solar electricity generated each year stays constant through out the life of the plant.

1.4. Computing the Cost of Solar Electricity

After the worksheet computes the yearly kWh that the solar plant generates (Section 1.3), it computes the yearly plant amortization using the plant's capital cost (Section 1.1), interest rate and physical life. The worksheet computes the cost B R¢/kWh [US ¢/kWh] of the solar electricity by dividing the yearly amortization by the kWh of electricity generated. Computing the cost is actually a little more detailed than this because the worksheet adds the fixed and variable O & M costs (Section 1.2) to get the complete cost of generating the solar electricity.
The BR¢/kWh [US ¢/kWh] computed is considered a levelized cost (Stavy, 2002; Wiser 1996) because there is a constant capital recovery.

2. THE ORGANIZATION OF THE WORKSHEET

I will go over the worksheet with benchmark input values for two model PV plants; one assumed to be here in Rio [in B R$] and one assumed to be in Chicago [in US $]. Changing the input values on the actual Excel worksheet causes different values to be computed on the output lines.

2.1. Capital Cost Section

On Line 1, for Chicago, the Capital Cost is US $4.00/$W_p$. Since I have a US PV benchmark cost, the worksheet converted the US $4.00/$W_p$ to B R$9.32/$W_p$ using the Thursday, 12/27/01 exchange rate [B R$2.3310=US$ 1.00] as reported in the 12/28/01 *Wall Street Journal* (Stavy, 1999).

On Line 2, the worksheet computes the Capital Cost in B R$/$kW_p$ [US $/$kW_p$]. This is Line 1 times 1,000. B R$9,324/$kW_p$ and US $4,000/ kW_p are the values computed.

2.2. Yearly Operating and Maintenance Costs

On Line 3, the Annual Fixed Operating and Maintenance Cost is entered as a percent of the Capital Cost-$/kWp, Line 2. 2% is the benchmark value entered on Line 3.

On Line 4, the Chicago Variable Operating and Maintenance Cost is entered in US ¢/kWh. A quarter of a US cent per kWh is entered, that is 0.25. One US cent would be 1.00. The worksheet converted the US 0.25¢/kWh to B R 0.58¢/kWh.

If the Chicago plant generates 1,825 kWh (Line 10), the total O & M cost of $84.56 would consist of $4.56 in variable cost (1,825 times $0.0025) plus $80 in fixed costs (Line 12).

This worksheet does not consider taxes. Taxes are an additional expense and would add to the cost of the solar electricity generated. Real estate taxes would add to the fixed O & M cost while income taxes and value added [sales] taxes would increase the variable O & M cost.

2.3. Capital Recover Computation

On Line 5, the Physical Life of the PV plant in Years, is entered. 25 years is the value entered. Solar panels are guaranteed for 20-25 years. 25 years is a reasonable benchmark.

If the Chicago PV plant continues to operate after its 25 year projected physical life, the cost of electricity would be reduced by 83.9%. The benchmark Total Levelized Cost (Line 16) would go from US 28.78 ¢/kWh, to US 4.63 ¢/kWh (the sum of the fixed [US 4.38 ¢/kWh] and variable [US 0.25 ¢/kWh] O & M cost). Plant amortization represents 83.9% of Chicago's 28.78 ¢/kWh levelized cost.

On Line 6, the Interest Rate, as a percent, is entered. 10% is the benchmark value entered. I have made the interest rate, 10% which is, from my experience, in the "ballpark" for internationally financed power plants. Local values can differ.

On Line 7, the worksheet computes the Capital Recovery Factor-CRF. 0.1102 is the CRF value computed. The CRF is the annual payment computed for an annuity having $1.00 as the principal amount borrowed, a loan period of 25 years (Line 5) and an interest rate of 10% (Line 6).

2.4. Capacity and Energy Generated

On Line 8, the Full Sun Hours per day are entered. The value for Rio is 6.5; for Chicago it is 5.0. On Line 9, the worksheet computes the Capacity Factor percent.

On Line 10, the worksheet computes the kWh of Energy Generated per Year by a 1 kW_p PV plant. For Rio the value computed is 2,373 kWh; for Chicago it is 1,825 kWh.

2.5. Annual Levelized Cost

On Line 11, the worksheet computes the Annual Amortization in B R$/1$kW_p$ [US $/1$kW_p$] of capacity by multiplying the CRF (Line 7) by the Capital Cost (Line 2). The Rio computed value is B R$ 1027.21; the Chicago computed value is US $ 440.67.

On Line 12, the worksheet computes the Annual Fixed Operating and Maintenance Cost in $/1kWp of capacity by multiplying the Annual Fixed O & M Percent (Line 3) by the Capital Cost (Line 2). The Rio computed value is B R$ 186.48; the Chicago computed value is US $ 80.00.

On Line 13, the worksheet computes the Annual Levelized Cost in $/kWh of electric generated. The worksheet does this by first adding the Annual Amortization (Line 11) to the Annual Fixed Operating and Maintenance Cost (Line 12). The worksheet then divides this sum by the kWh of

Energy Generated Per Year (Line 10). The Rio computed value is BR$ 0.5116; the Chicago computed value is US $ 0.2853.

2.6. Total Levelized Cost Computed

On Line 14, the worksheet transfers the Annual Levelized Cost from Line 13 and converts it from $/kWh to ¢/kWh. B R$ 0.5116 becomes B R ¢ 51.16; US $ 0.2853 becomes US ¢ 28.53. The worksheet transfers to Line 15, the B R 0.58 ¢/kWh and US 0.25 ¢/kWh Variable O & M Cost entered on Line 4 above.

On Line 16, the worksheet arrives at the Total Levelized Cost of BR 51.74 ¢/kWh [US 28.78 ¢/kWh] by adding the BR 51.16 ¢/kWh [US 28.53 ¢/kWh] on Line 14, the Annual Levelized Cost, to the B R 0.58 ¢/kWh [US 0.25 ¢/kWh] on Line 15, the Variable O & M Cost.

3. THE WORKSHEET WITH BENCHMARK NUMBERS

Levelized Cost Worksheet for 1 kWp Grid Connected PV Electric Generating Plants Sited in Rio de Janeiro and Chicago

Line		Capital Cost	Rio	Chicago
1.	Input	Capital Cost-B R$/$W_p$ [US $/$W_p$]	$9.32	$4.00
2.	computed	Capital Cost-B R$/$kW_p$ [US $/$kW_p$]	$9,324	$4,000
		Yearly Operating Cost		
3.	Input	Annual Fixed O&M-% of Line 2-PV Capital Cost	2.00%	2.00%
4.	Input	Variable O&M- B R¢/kWh [US ¢/kWh]	0.58	0.25
		Capital Recovery Computation		
5.	Input	Physical Life of PV Plant In Years	25	25
6.	Input	Interest Rate-%	10.0%	10.0%
7.	computed	Capital Recovery Factor-CRF	0.1102	0.1102
		Capacity & Energy Generated		
8.	Input	Full Sun Hours-per day	6.5	5.0
9.	computed	Capacity Factor-%	27.08%	20.83%
10.	computed	Energy Generated per Year-kWh/kW_P	2,373	1,825
		Levelized Annual Cost		
11.	computed	Annual Amortization-B R$/$kW_p$ [US $/$kW_p$]	1,027.21	440.67
12.	computed	Annual Fixed O&M-- B R$/$kW_p$ [US $/$kW_p$]	186.48	80.00
13.	computed	Annual Levelized Cost- B R$/kWh [US $/kWh]	0.5116	0.2853
		Total Cost Calculated		
14.	transfer	Annual Levelized Cost-¢/kWh Line 13 above converted from $ to ¢.	51.16	28.53
15.	transfer	Variable O & M cost-¢/kWh from Line 4 above	0.58	0.25
16.	14 +15 =	Total Levelized Cost- B R¢/kWh [US ¢/kWh]	51.74	28.78

4. EXAMPLES OF THE EFFECT OF CHANGING THE CHICAGO BENCHMARK INPUT VALUES ON THE OUTPUT RESULTS

If the Capital Cost (Line 1) is reduced from US $4/$W_p$ to US $2/$W_p$ (50% reduction), while none of the other input values are changed, the worksheet computes that the Levelized Cost is reduced from US 28.78¢ to 14.51¢/kWh (49.58% reduction).

US $5.3/$W_p$ is the published (Mortensen, 2001) average nominal value, for 39 US grid-connected systems installed in 2000. If the Capital Cost (Line 1) is increased from US $4/$W_p$ to US $5.3/$W_p$ (32.5% increase), while none of the other input values are changed, the worksheet computes that the

Levelized Cost is increased from US 28.78¢ to 38.05¢/kWh (32.3% increase).

If the Interest Rate (Line 6) is reduced from 10% to 7% (30% reduction) while none of the other input values are changed, the worksheet computes that the Levelized Cost is reduced from US 28.78¢ to 23.44¢/kWh (18.55% reduction).

If the Physical Life (Line 5) is reduced from 25 years to 20 years (20% reduction) while none of the other input values are changed, the worksheet computes that the Levelized Cost is increased from US 28.78¢ to 30.38¢/kWh (5.56% increase).

If Chicago had Rio's Full Sun Hours, Line 8 would increase from 5 hours to 6.5 hours (30% increase). If none of the other input values are changed, the worksheet computes that the Levelized Cost is decreased from US 28.78¢ to 22.20¢/kWh (22.87% decrease).

5. DISCLAIMER

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6. REFERENCES

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