Levelized Cost Of Electricity
Sensitivity Assessment

PV Systems Integrator Workshop
Clarion Hotel, San Jose

Wednesday, March 31 – Thursday, April 1, 2010

Christopher P. Cameron
Sandia National Laboratories
Levelized Cost of Energy

• A Convenient Metric for Comparing Energy Costs Across Energy Sources
  – Captures Installed, Financing, and O&M Costs, and Reduction in Future Energy Output (Degradation)
  – Used by DOE to Evaluate Competitiveness of Solar Relative to Conventional Energy Sources

• Other Metrics May Be More Important to Customer or Investor Decisions, e.g.
  – First Cost – a barrier to purchase
  – Return on Investment – 3rd Party-Owned Systems
Levelized Cost of Energy

- Numerator includes all costs, $C_n$, by year
  - Includes first cost, financing, incentives, O&M
- Denominator includes energy production, $Q_n$, by year
  - Includes reduced energy production due to degradation
- $d$ is discount rate
  - Future year costs and energy production have lower value/impact
- LCOE is calculated in real dollars

$$LCOE = \frac{\sum_{n=0}^{N} \frac{C_n}{(1 + d)^n}}{\sum_{n=1}^{N} \frac{Q_n}{(1 + d)^n}}$$
$/W is not a reliable indicator of LCOE

Levelized Cost of Energy

Installed Cost

Outages

O&M Costs

Degradation Rate

Component and System Lifetime

LCOE MODEL

Weather Data

Efficiency vs. POA, Ta, WS...

Inverter

System Losses

PERFORMANCE

RELIABILITY
# Financial Assumptions

<table>
<thead>
<tr>
<th>Type of Financing</th>
<th>Residential Mortgage</th>
<th>Commercial Loan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflation Rate (%)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Analysis Period (yrs)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Real Discount Rate (%)</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Loan Term (yrs)</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Loan Rate (%)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Loan (Debt) Fraction (%)</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Federal Tax (%)</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>State Tax (%)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Property Tax (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Insurance (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sales Tax (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Federal Depreciation Type</td>
<td>n/a</td>
<td>MACRS-Mid-Q</td>
</tr>
<tr>
<td>State Depreciation Type</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Incentives</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Federal Tax Credit (%)</td>
<td>30%</td>
<td>30%</td>
</tr>
</tbody>
</table>
## Reference Systems - Phoenix

<table>
<thead>
<tr>
<th>Rack Mount</th>
<th>Res</th>
<th>Com</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Power (Wdc)</td>
<td>3,200</td>
<td>500,000</td>
</tr>
<tr>
<td>System Derate Factor</td>
<td>90.0%</td>
<td>90.0%</td>
</tr>
<tr>
<td>System Degradation</td>
<td>0.50%</td>
<td>0.50%</td>
</tr>
<tr>
<td>Tilt</td>
<td>20.00</td>
<td>33.40</td>
</tr>
<tr>
<td>Inverter Efficiency</td>
<td>94.2%</td>
<td>94.8%</td>
</tr>
<tr>
<td><strong>Yield kWh/kW- yr 1</strong></td>
<td>1782</td>
<td>1816</td>
</tr>
<tr>
<td>System Perf Factor</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td><strong>COSTS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module $/Wdc</td>
<td>$4.84</td>
<td>$4.35</td>
</tr>
<tr>
<td>Inverter $/Wac</td>
<td>$0.71</td>
<td>$0.64</td>
</tr>
<tr>
<td>Total Installed Cost $/Wdc</td>
<td>$7.96</td>
<td>$6.59</td>
</tr>
<tr>
<td>Inverter Replace/Rebuild (%)</td>
<td>100%</td>
<td>50%</td>
</tr>
<tr>
<td>Inverter Life (Yrs)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Routine O&amp;M ($/yr)</td>
<td>$127</td>
<td>$8,237</td>
</tr>
<tr>
<td>Routine O&amp;M (% of 1st cost)</td>
<td>0.50%</td>
<td>0.25%</td>
</tr>
</tbody>
</table>
Analysis Performed with Solar Advisor Model
A Decision Support Tool

Free: www.nrel.gov/analysis/sam/
# O&M Inputs in SAM

![Image of SAM software interface showing O&M inputs]

## Operation and Maintenance Costs

<table>
<thead>
<tr>
<th>First Year Cost</th>
<th>Escalation Rate (above inflation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Annual Cost</td>
<td>$/yr</td>
</tr>
<tr>
<td>Fixed Cost by Capacity</td>
<td>$/kW-yr</td>
</tr>
<tr>
<td>40.00</td>
<td>0 %</td>
</tr>
</tbody>
</table>

## Annual System Performance

<table>
<thead>
<tr>
<th>System Degradation</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 %</td>
<td>99 %</td>
</tr>
</tbody>
</table>
Solar Advisor Model Includes
PVWatts, CEC-5 Parameter Model,
Sandia PV Array Performance Model

TMY Data

Radiation Model
  Incident
  DNI and Diffuse

Module Model

Array

DC Derate

Inverter Model

AC Derate

PV Model

Calculate $T_c$ from $E$, $T_a$, WS, and mounting type

Sandia or CEC Module Measurements
  Regression Analysis

Module Database

CEC/SNL Inverter Data
  Regression Analysis

Inverter Database

Temperature Correction Using Manufacturer’s Power Coefficient

Using Manufacturer’s Power Coefficient
## Levelized Cost of Energy for Reference Systems

<table>
<thead>
<tr>
<th>LCOE (¢/kWh)</th>
<th>Res</th>
<th>Comm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td>15.6</td>
<td>7.9</td>
</tr>
<tr>
<td><strong>First Cost Contribution</strong></td>
<td>11.4</td>
<td>6.9</td>
</tr>
<tr>
<td><strong>Total O&amp;M Contribution</strong></td>
<td>4.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Routine O&amp;M Contribution</td>
<td>2.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Inverter O&amp;M Contribution</td>
<td>1.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Scales with First-Cost and Energy Yield

Scales with O&M Cost and Energy Yield
Cash Flow with 12¢/kWh Utility Rate with 2% Escalation (above inflation)
Effect of System Lifetime on LCOE

- Residential Rack
- Commercial Rack

Graph showing the relationship between system lifetime (years) and LCOE (cents/kWh). The LCOE decreases as the system lifetime increases.
Effect of Inverter Lifetime on LCOE

Excludes any other inverter O&M

- Residential Rack
- Commercial Rack

Replacement at 100% of 1st Cost in Nominal $’s

71¢/W Res. inverter contributes 1 ¢/kWh due to first cost
- 10 year replacement interval adds 1.9 ¢/kWh

Refurbishment at 50% of 1st Cost in Nominal $’s

LCOE (cents/kWh)

Inverter Lifetime (Years)
Effect of Routine* O&M on LCOE
*Other Than Inverter Replacement/Refurbishment

- Residential O&M ($'s/yr)
- Routine O&M (% of Installed Cost)
- LCOE (cents/kWh)

Graph showing the relationship between Residential O&M ($'s/yr) and LCOE (cents/kWh) for residential and commercial racks.
Effect of System Degradation Rate

1% Degradation Rate Increases LCOE by 10%
Mounting Configuration Affects Cell Temperature and Performance

- STC Rating

Annual Yield (%)

Pmp Temperature Coefficient

Rack (71°C max)
Close Roof (91°C max)
BIPV (100°C max)
What Values Should We Be Using for Model Inputs
Low, High, Most Likely?

<table>
<thead>
<tr>
<th>Residential (~ 4 kW)</th>
<th>Commercial (500 kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• System</td>
<td>• System</td>
</tr>
<tr>
<td>– Installed Cost ($/W)</td>
<td>– Installed Cost ($/W)</td>
</tr>
<tr>
<td>– O&amp;M ($/yr)</td>
<td>– O&amp;M ($/yr)</td>
</tr>
<tr>
<td>– Derate Factor</td>
<td>– Derate Factor</td>
</tr>
<tr>
<td>• Modules ($/Wp)</td>
<td>• Modules ($/Wp)</td>
</tr>
<tr>
<td>• Inverter</td>
<td>• Inverter</td>
</tr>
<tr>
<td>– First Cost ($/Wp)</td>
<td>– First Cost ($/Wp)</td>
</tr>
<tr>
<td>– Lifetime (Yrs)</td>
<td>– Lifetime (Yrs)</td>
</tr>
<tr>
<td>– Replacement Cost</td>
<td>– Replacement Cost</td>
</tr>
<tr>
<td>• % of First Cost for Inverter</td>
<td>• % of First Cost for Inverter</td>
</tr>
<tr>
<td>• $’s for Labor…</td>
<td>• $’s for Labor…</td>
</tr>
</tbody>
</table>

What, If Any, Routine Maintenance Do You Perform? Inspection? Cleaning? Other?