ECE 333 – GREEN ELECTRIC ENERGY

15. PV ECONOMICS

George Gross
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
PV SYSTEM ECONOMICS
Now that we know how to approximate the power and the energy delivered by a grid-connected PV system, the next step is to explore its economics.

The key inputs into an economic analysis of a PV system are the investment costs and the expected annual energy production under a set of reasonable and justifiable assumptions.
Key considerations in the performance of a detailed economic analysis include:

- Electricity prices
- Debt terms and discount rates
- Incentives, such as ITC and rebates
- Tax benefits
- Costs or residual values at system retirement
- The O&M costs
Total $PV$ system cost estimation

$LCOE$ determination of a $PV$ system

The $PV$ system tax incentive impacts on the $LCOE$

The $PV$ system tax benefits and rebate program impacts

Power purchase agreement issues
The PV system for a Boulder house is designed to generate roughly 4,000 kWh annually.

The key cost components are:

<table>
<thead>
<tr>
<th>component</th>
<th>costs ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVs</td>
<td>4.20/W (DC)</td>
</tr>
<tr>
<td>inverter</td>
<td>1.20/W (DC)</td>
</tr>
<tr>
<td>tracker</td>
<td>400 + 100/m²</td>
</tr>
<tr>
<td>installation</td>
<td>3,800</td>
</tr>
</tbody>
</table>
EXAMPLE: BOULDER HOUSE $PV$ SYSTEM

- Assume the $PV$s have a 12% efficiency and the inverter efficiency is 75%.

- We use the solar insolation tables in Appendix G to obtain the average daily insolation for a fixed array.

- We compare the costs of a fixed array with a $-15^\circ$ tilt angle and those with a single-axis tracker.
The solar insolation tables in Appendix G indicate the average daily insolation for a fixed array to be 5.4 kWh/m$^2$ - d.

We interpret the insolation as 5.4 h/d of 1 sun.

We compute

$$P_{DC, stc} = \frac{4,000}{(0.75)(5.4)(365)} = 2.71 \text{ kW}_p$$
The costs of the PVs and the inverters are

\[ \text{costs of PVs} = 4.20 \times 2,710 = \$11,365 \]

\[ \text{costs of inverters} = 1.20 \times 2,710 = \$3,247 \]

Given the 12% efficiency of the PVs, the array area required is

\[ \text{area} = \frac{P_{DC, stc}}{(1 \text{ kW/m}^2)\eta} = \frac{2.71}{1 \times 0.12} = 22.6 \text{ m}^2 \]
We next consider the average daily insolation

with a single-axis tracker of $7.2 \text{ kWh/m}^2 - d$ – i.e.,

$7.2 \text{ h/d of full sun} – \text{as given in Appendix G}$

We compute

$$P_{DC, stc} = \frac{4,000}{(0.75)(7.2)(365)} = 2.03 \text{ kW}_p$$

The costs of the $PV$s and the inverters are
Thus the area for the system is

\[
\text{area} = \frac{P_{DC, stc}}{\left(1 \text{ kW} / \text{m}^2\right) \eta} = \frac{2.03}{1 \times 0.12} = 16.9 \text{ m}^2
\]

The tracker costs are

\[
\text{costs of trackers} = 400 + 16.9 \times 100 = 2,090
\]
### EXAMPLE: BOULDER HOUSE PV SYSTEM

<table>
<thead>
<tr>
<th>element</th>
<th>fixed tilt array</th>
<th>single-axis tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PVs</strong></td>
<td>$11,365</td>
<td>$8,524</td>
</tr>
<tr>
<td><strong>inverter</strong></td>
<td>$3,247</td>
<td>$2,436</td>
</tr>
<tr>
<td><strong>tracker</strong></td>
<td>–</td>
<td>$2,090</td>
</tr>
<tr>
<td><strong>installation</strong></td>
<td>$3,800</td>
<td>$3,800</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>$18,412</td>
<td>$16,850</td>
</tr>
</tbody>
</table>
EXAMPLE: BOULDER HOUSE $PV$ SYSTEM

- The installation of the trackers increases the average daily insolation received at the $PV$ panels and decreases the area required for the system.

- While the trackers add $2,090 to the fixed costs of the $PV$ system, the $PV$ system investment costs with the trackers are nevertheless markedly below those of the fixed panels.
The capital recovery factor is the principal mechanism we use to determine the financing costs of a $PV$ project.

A loan of $P$ at interest rate $i$ may be recovered over $n$ years through fixed annual payments of $A$.

$$A = P \frac{i}{1 - (\frac{1}{1+i})^n}$$

$\beta \triangleq \frac{1}{1+i}$

**R.I.V.E.W. O.F. T.H.E. c.r.f.**
EXAMPLE: \textit{LCOE} FOR THE \textit{PV} SYSTEMS

We illustrate the determination of the \textit{LCOE} with a \textit{PV} system example with the following features:

- installation costs: \$7 million
- annual \textit{O&M} costs: \$35,000
- annual land lease fee: \$40,000
- annual energy production: 4 \textit{GWh}
- 9 \%, 20 – year loan

The \textit{c.r.f.} is computed to be...
EXAMPLE: \( \text{LCOE FOR THE PV SYSTEMS} \)

\[
c.r.f. (9 \%, 20\text{ y}) = \frac{(0.09)(1 + 0.09)^{20}}{(1 + 0.09)^{20} - 1} = 0.1095 \text{ y}^{-1}
\]

- The \( c.r.f. \) results in the annual amortized fixed costs of

\[
7,000,000 \times 0.1095 = \$ 766,500
\]

- Then we can evaluate the \( \text{LCOE} \) using

\[
\frac{766,500 + 35,000 + 40,000}{4,000,000} = 0.21 \frac{\$}{kWh}
\]
A significant factor that was ignored in the cost calculation in the previous example is the impacts of the financial and tax incentives.

Many solar installations are eligible for federal and state tax incentives for the purchase and implementation of PV systems.
## Federal Business Energy Investment Tax Credit (ITC)

<table>
<thead>
<tr>
<th>State:</th>
<th>Federal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incentive Type:</td>
<td>Corporate Tax Credit</td>
</tr>
<tr>
<td>Administrator:</td>
<td>U.S. Internal Revenue Service</td>
</tr>
<tr>
<td>Expiration Date:</td>
<td>Varies by technology, see below</td>
</tr>
<tr>
<td>Applicable Sectors:</td>
<td>Commercial, Industrial, Investor-Owned Utility, Cooperative Utilities, Agricultural</td>
</tr>
</tbody>
</table>
| Incentive Amount: | 30% for solar, fuel cells, small wind*  
10% for geothermal, microturbines and CHP |
| Maximum Incentive: | Fuel cells: $1,500 per 0.5 kW  
Microturbines: $200 per kW  
Small wind turbines placed in service 10/4/08 - 12/31/08: $4,000  
Small wind turbines placed in service after 12/31/08: no limit  
All other eligible technologies: no limit |

Source: [http://programs.dsireusa.org/system/program/detail/658](http://programs.dsireusa.org/system/program/detail/658)
TAX INCENTIVES FOR SOLAR

- The *ITC* originally enacted in the *Energy Policy Act* of 2005 for solar has been renewed numerous times and is currently set at 30% of the initial investment.

- The *ITC* supports electricity generated by solar systems on residential and commercial properties.
EXAMPLE: TAX INCENTIVES FOR SOLAR

- We illustrate the ITC impacts on the LCOE in the previous PV system example.
- With the ITC, the initial investment tax savings amount to
  \[0.3 \times 7,000,000 = \$2,100,000\]
- The resulting annual amortized fixed costs are
  \[(1 - 0.3) \times 7,000,000 \times 0.1095 = \$536,550\]
EXAMPLE: TAX INCENTIVES FOR SOLAR

- Then we can evaluate the \( LCOE \) using

\[
\frac{536,550 + 35,000 + 40,000}{4,000,000} = 0.15 \frac{\$}{kWh}
\]

- We observe that the \( ITC \) introduction results in a 6 \( \frac{\cent}{kWh} \) reduction in the \( LCOE \)

- This corresponds to a 27 % reduction in the \( LCOE \)
The use of a home loan to finance the installation of a $PV$ system has an important impact on the $PV$ electricity price in light of the income tax benefits, which depend on the homeowner marginal tax bracket (MTB).
For a loan over several years, almost all of the first year payments constitute the interest due, with a very small contribution to the reduction of the loan principal, while the opposite allocation occurs towards the end of the loan life.

In the first year, interest is owed on the entire amount of the loan and the tax benefits are:

\[ i \times \text{loan} \times MTB \]
EXAMPLE: TAX BENEFIT FOR SOLAR

Consider a 30 – year 4.5% loan to install a residential 3.36 – kW<sub>p</sub> PV system in Chicago, with the annual energy of 4,942 kWh.

The c.r.f. for the loan is

\[
\frac{\left( 0.045 \right) \left( 1 + 0.045 \right)^{30}}{\left( 1 + 0.045 \right)^{30} - 1} = 0.06139 \text{ y}^{-1}
\]
EXAMPLE: TAX BENEFIT FOR SOLAR

- The residential PV system costs $19,186 and the annual loan payment is

\[ 19,186 \times 0.06139 = \$1,178 \]

- Thus the cost of PV electricity in the first year is

\[ \frac{1,178}{4,932} = 0.239 \frac{\$}{kWh} \]

- During the first year, the owner pays the annual interest on the $19,186 loan in the amount of
EXAMPLE: TAX BENEFIT FOR SOLAR

first year interest = 19,186 \times 0.045 = $863

We assume the homeowner is in the 25\% \textit{MTB}

and determine the first year tax savings to be

863 \times 0.25 = $216

which reduce the cost of \textit{PV} electricity to

\[
\frac{1,178 - 216}{4,932} = 0.192 \frac{\$}{\text{kWh}}
\]
Many states and certain jurisdictions have introduced rebate programs to promote investments in solar systems.

A rebate reduces the total investment required by, in effect, returning some of the costs of the PV system installation to the investor:

\[
\text{reduced costs} = \text{original costs} - \text{rebate}
\]
### Illinois Solar and Wind Energy Rebate Program

<table>
<thead>
<tr>
<th><strong>Budget:</strong></th>
<th>$2.5 million</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Start Date:</strong></td>
<td>12/16/1997</td>
</tr>
<tr>
<td><strong>Expiration Date:</strong></td>
<td>10/10/2014 (current applications)</td>
</tr>
<tr>
<td><strong>Eligible Renewable/Other Technologies:</strong></td>
<td>Solar Water Heat, Solar Photovoltaics, Wind (All), Solar Pool Heating, Wind (Small)</td>
</tr>
<tr>
<td><strong>Applicable Sectors:</strong></td>
<td>Commercial, Industrial, Local Government, Nonprofit, Residential, Schools, State Government, Federal Government</td>
</tr>
<tr>
<td><strong>Incentive Amount:</strong></td>
<td>Residential PV: $1.50/watt or 25% of project costs&lt;br&gt;Commercial PV: $1.25/watt or 25% of project costs&lt;br&gt;Nonprofits and Public Sector PV: $2.50/watt or 40% of project costs&lt;br&gt;Residential and Commercial Wind (SWCC certified): $1.75/watt or 30% of project costs&lt;br&gt;Nonprofits and Public Sector Wind (SWCC certified): $2.60/watt or 40% of project costs&lt;br&gt;Wind energy systems that are not SWCC certified: $1.00/watt&lt;br&gt;Residential and Commercial Solar Thermal: 30% of eligible project costs&lt;br&gt;Nonprofits and Public Sector Solar Thermal: 40% of eligible project costs</td>
</tr>
<tr>
<td><strong>Maximum Incentive:</strong></td>
<td>Residential: $10,000&lt;br&gt;Commercial: $20,000&lt;br&gt;Nonprofits and Public Sector: $30,000</td>
</tr>
<tr>
<td><strong>Eligible System Size:</strong></td>
<td>PV systems: Rated design capacity of at least 1 kW;&lt;br&gt;Solar thermal systems: Designed to produce at least 0.5 therms or 50,000 Btus per day or contain at least 60 sq. ft. of collectors&lt;br&gt;Wind: Name-plate capacity 1-100 kW</td>
</tr>
</tbody>
</table>

Source: [http://programs.dsireusa.org/system/program/detail/585](http://programs.dsireusa.org/system/program/detail/585)
EXAMPLE: REBATES

For instance, if the total investment costs in the previous example are reduced by the 25% rebate under the Illinois solar and wind energy program, we can determine the reduced annual payment

$$19,186 \times (1 - 0.25) \times 0.06139 = \$883$$

Then the first year interest reduces to
EXAMPLE: REBATES

\[ 19,186 \times (1 - 0.25) \times 0.045 = \$648 \]

Therefore the first year tax savings are given by

\[ 648 \times 0.25 = \$162 \]

Consequently the cost of \( PV \) electricity in the first year reduces to

\[ \frac{648 - 162}{4,932} = 0.146 \frac{\$}{kWh} \]
In the broadest terms, a *power purchase agreement* (PPA) is a contract between two parties – a *seller* who generates electricity and a *buyer* who purchases the electricity.

The *PPA* defines all the terms for the purchase/sale of electricity between these parties, such as:

- the start date of the project commercial operation;
- the schedule for delivery of electricity;
POWER PURCHASE AGREEMENT

- penalties for under delivery;
- payment terms; and
- termination

A PPA defines the revenue and credit quality of a generation project and constitutes thus a key instrument of project finance.

There are many forms of PPA in use today and they vary according to the needs of the buyer, the seller, and the financing counterparties.
While the PPA's signed with utilities serve to finance utility-scale renewable energy resource installations under, typically, long-term, fixed-price energy, the use of the PPA vehicle to implement distributed generation projects to supply residential, commercial and municipal and state governments is a more recent application.

Under the PPA structure, project developers find a way to use federal tax credits to supply renewable...
POWER PURCHASE AGREEMENT

energy without involving any up-front investment on the part of the buyer

- The owner provides the space to the seller to install the system and purchases energy from the system at a negotiated price for the contract term

- Typically, the ownership of the project passes to the customer at the end of the tax credit payments

- More recently, research centers and campuses make use of PPAs to install larger PV systems
http://www.fs.illinois.edu/services/utilities-energy/production/solar-farm
The University of Illinois modified the goal in the 2015 Climate Action Plan to specify that 12.5 GWh of electricity is to be provided by solar installations on campus property by 2020. Unfortunately, there is no budget for any additional investment in solar projects and so the realism of the higher goal is unclear.
In order to take advantage of the tax incentives, the University of Illinois signed a 10–year PPA with the developer Phoenix Solar Inc. to design, build, operate and maintain the solar farm for the first 10 years of its life, at which point the solar farm becomes the property of the University.
The solar farm is connected directly to the University’s electrical distribution system. The annual energy production from the solar farm is estimated at 7.86 GWh, roughly 2% of the 2012 electricity consumption of 432.45 GWh for the campus. University of Illinois has agreed to buy all the net energy from the solar farm during the first 10 years at 0.19 $/kWh.
We provide an approximation of this solar farm based on the data that is representative for today’s PV systems.

We do not have information on the company’s tax situation and therefore we use a reasonable debt financing situation of a 5–%, 10–year loan for the solar farm.
Phoenix Solar Inc. design is for the $PV$ system to generate roughly $7.86\; GWh$ annually.

The average daily insolation received by a fixed panel is $5.2\; kWh/m^2\cdot d$ – i.e., $5.2\; h/d$ of $1$–sun.

We assume a value of $\chi' = 0.7$, so that

$$P_{DC,\text{stc}} = \frac{7,860,000}{(0.7)(5.2)(365)} = 5,916\; kW_p$$
EXAMPLE: THE UNIVERSITY OF ILLINOIS PV PROJECT

- The key cost components are

<table>
<thead>
<tr>
<th>component</th>
<th>costs ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module</td>
<td>1.20/W (DC)</td>
</tr>
<tr>
<td>PCU</td>
<td>0.30/W (DC)</td>
</tr>
<tr>
<td>other equipment</td>
<td>0.60/W (DC)</td>
</tr>
</tbody>
</table>

- The total fixed costs of the solar farm are

$$(1.20 + 0.30 + 0.60)(5,916,000) = \$12.4 \text{ million}$$
Phoenix Solar Inc. leases the land at 1 $/m^2 – y with annual costs of

\[ \text{costs}_{\text{land}} = 1 \times 82,961 = \$ 82,961 \]

We assume the annual O&M costs of the solar farm is 37 $/MWh so the total annual O&M costs are

\[ \text{costs}_{\text{O&M}} = 0.037 \times 7,860,000 = \$ 290,820 \]
If the developer of the solar project uses a debt instrument with a 5–% interest 10–year term

c.r.f. (5%, 10 y) = \frac{(0.05)(1 + 0.05)^{10}}{(1 + 0.05)^{10} - 1} = 0.129 \text{ y}^{-1}

The use of the ITC, results in savings that reduce the investment costs by

12,400,000 \times 0.3 = \$ 3,720,000
The annual amortized fixed costs are then

\[
12,400,000 \times (1 - 0.3) \times 0.129 = 1,119,720
\]

Consequently, the \( LCOE \) is determined to be

\[
\frac{1,119,720 + 82,961 + 290,820}{7,860,000} = 0.19 \frac{\$}{kWh}
\]
Indeed, the University of Illinois pays about $15 million to Phoenix Solar Inc. for the first 10 years of operation and receives ownership thereafter.

Once the University of Illinois becomes the owner and operator of the solar farm, all the variable costs are born by the University.
IMPLICATIONS OF THE *ITC*

- The residential and commercial solar *ITC* has helped annual solar installation grow by over 1,600% since 2006.

- In 2015 the *ITC* was extended for another eight years, providing market certainty for the solar industry.
A residential PV system is designed to generate roughly 4,000 kWh annually.

The total costs of 2.93 $/W (DC) include modules, inverters and installation.

We assume a derate factor of 75% and an average daily insolation of 6.5 kWh/m² - d.
EXAMPLE: RESIDENTIAL PV PROJECT

- We compute

\[ P_{DC, \text{stc}} = \frac{4,000}{(0.75)(6.5)(365)} = 2.25 \text{kW}_p \]

- Thus, the total investment is given by

\[ 2.25 \text{kW}_p \times 1,000 \text{W}_p / \text{kW}_p \times 2.93 \$ / \text{W}_p = 6,592.5 \$

- Suppose that the electricity price is 6.5 c/kWh and

so the solar produced electricity yearly worth is

\[ 4,000 \text{kWh} \times 0.065 \$ / \text{kWh} = 260 \$ \]
EXAMPLE: RESIDENTIAL PV PROJECT

- We may now compute the expected cash flows during the first ten years of operation.

<table>
<thead>
<tr>
<th>Year</th>
<th>Cash Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-6,332.5 $</td>
</tr>
<tr>
<td>1</td>
<td>260 $</td>
</tr>
<tr>
<td>2</td>
<td>260 $</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>260 $</td>
</tr>
</tbody>
</table>

- The resultant IRR is \(-16\%\)
The negative IRR implies the net present value for this investment over the considered time period is negative.

In fact, if we assume that the yearly electricity worth remains constant, the project takes 24 years for the net present value to reach zero.
If we apply the ITC, the initial investment is reduced by 30% and becomes

\[ 6,592.5 \times 0.7 = \$ 4,614.75 \]

The resultant IRR for the first ten years of operation is – 11%
EXAMPLE: RESIDENTIAL PV PROJECT WITH ITC

<table>
<thead>
<tr>
<th>Project Lifetime (years)</th>
<th>IRR (with ITC)</th>
<th>IRR (without ITC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-0.109</td>
<td>-0.163</td>
</tr>
<tr>
<td>11</td>
<td>-0.084</td>
<td>-0.136</td>
</tr>
<tr>
<td>12</td>
<td>-0.109</td>
<td>-0.163</td>
</tr>
<tr>
<td>13</td>
<td>-0.095</td>
<td>-0.113</td>
</tr>
<tr>
<td>14</td>
<td>-0.079</td>
<td>-0.095</td>
</tr>
<tr>
<td>15</td>
<td>-0.066</td>
<td>-0.079</td>
</tr>
<tr>
<td>16</td>
<td>-0.055</td>
<td>-0.066</td>
</tr>
<tr>
<td>17</td>
<td>-0.045</td>
<td>-0.055</td>
</tr>
<tr>
<td>18</td>
<td>-0.037</td>
<td>-0.045</td>
</tr>
<tr>
<td>19</td>
<td>0.008</td>
<td>-0.037</td>
</tr>
<tr>
<td>20</td>
<td>0.013</td>
<td>-0.023</td>
</tr>
</tbody>
</table>
While the ITC considerably improves the project’s economics, the project is very far from a solid investment vehicle. Indeed, this project is financially so weak that even with the ITC there is no reason to undertake the investment.