14. $PV$ Systems

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SOLAR ENERGY TECHNOLOGY

- Solar technology collects solar energy to convert into electricity.
- Solar energy can be converted directly into electricity using photovoltaic (PV) technology, or indirectly using concentrated solar power (CSP) plant technology, which uses mirrors to focus the solar energy to generate thermal energy, which is used to produce electrical energy.
OUTLINE

- Review some basic semiconductor and diode notions
- Describe the PV cell and its $i - v$ curve
- The path from the PV cell to a module and an array
- Maximum power point tracking
- A grid–connected PV system and the analysis of its performance
CONDUCTOR AND INSULATOR

- In physics and electrical engineering, a conductor, e.g., a metal, is an object or a type of material which permits electric charge to flow freely in it.

- In contrast, an insulator, e.g., glass, is a material whose internal electric charges do not flow freely, and therefore cannot generate a current even under the influence of an electric field.
A semiconductor is a material, which has electrical conductivity at some level between a conductor and an insulator.

Semiconductors are the basis of today’s modern electronics – the diodes, transistors, digital and analog integrated circuits that are widely used.
REVIEW OF DIODES

- The *diode* was one of the first semiconductor electronic devices

- The *diode* is a two–terminal electronic component, composed of two semiconductor materials

- When a voltage is applied across the diode terminals, the electric field formed in the diode
REVIEW OF DIODES

excites the electrons to generate an electric current

- The salient characteristic of a diode is that it allows the current to pass in only one direction and blocks the current flowing in the opposite direction
A DIODE $i - v$ CURVE
Semiconductor materials form also the basis of PV technology.

Certain semiconductor materials are capable to convert the solar energy of the sun rays – all the three insolation components – into DC electric current; we refer to such semiconductor types by the generic PV materials term.
Silicon is the most commonly used element in PV materials.

However, there is emerging competition from the thin films made of compounds of two or more elements, including gallium arsenide (GaAs), cadmium telluride (CdTe) and copper, indium and selenium (CIS).
The basic building block for PV systems is called the PV cell, which is constructed with PV materials with attached contact grid on the surface of these materials.
When the sun rays strike the PV cell, the cell produces a current and a voltage combination, that can supply electricity to a connected load.
To help analyze the performance of an individual PV cell, we, typically, deploy some equivalent circuit models to represent the cell behavior. These are idealized representations in terms of discrete idealized components, as there exist no such elements inside a PV cell. The $i - v$ curves of these equivalent circuit models are used to graphically describe/quantitatively assess the $i - v$ behavior of the PV cell.
AN IDEALIZED EQUIVALENT CIRCUIT MODEL OF A $PV$ CELL
THE $i - v$ CURVE OF THIS IDEAL EQUIVALENT CIRCUIT OF A $PV$ CELL

**short-circuit current:** $i_{sc}$

**open-circuit voltage:** $v_{oc}$

![Graph of the $i - v$ curve of an ideal equivalent circuit of a PV cell. The graph shows the relationship between current ($i$) and voltage ($v$). The short-circuit current ($i_{sc}$) is noted where the curve intersects the current axis, and the open-circuit voltage ($v_{oc}$) is noted where the curve intersects the voltage axis.]
A MORE DETAILED EQUIVALENT CIRCUIT OF A \textit{PV} CELL
THE $i - v$ CURVES OF A MORE DETAILED CIRCUIT OF A $PV$ CELL

- $R_s = 0$, $R_p = \infty$
- $R_s = 0.02 \Omega$, $R_p = \infty$
THE $i-v$ CURVES OF A MORE DETAILED CIRCUIT OF A $PV$ CELL

$R_s = 0 \quad R_p = \infty$

$R_s = 0 \quad R_p = 3 \, \Omega$
THE $i - v$ CURVES OF A MORE DETAILED CIRCUIT OF A $PV$ CELL

$R_s = 0 \quad R_p = \infty$

$R_s = 0.02 \, \Omega \quad R_p = 3 \, \Omega$
The performance of PV cells is a function of the insolation and the cell temperature. Manufacturers often provide the PV cell $i - v$ curve that indicates its behavior as a function of the insolation and the cell temperature.
IMPACTS OF INSOLATION ON $PV \ i - v$ CURVES

$1 \ kW/m^2$

$0.67 \ kW/m^2$

$0.33 \ kW/m^2$

decreasing insolation
IMPACTS OF CELL TEMPERATURE ON $PV\ i-v$ CURVES

decreasing cell temperature

$0 \rightarrow 0.4 \rightarrow 0.2 \rightarrow v (V)$

$i (A)$

$0 \rightarrow 6$
LIMITATION OF A SINGLE \textit{PV} CELL

- The $i - \nu$ behavior of a single cell results in too small of a current and a voltage to be effectively harnessed for large-scale energy production.
- However, when \textit{PV} cells are connected in \textit{series} (\textit{parallel}), each cell has the same \textit{current} (\textit{voltage}), at which its corresponding \textit{voltage} (\textit{current}) is additive and the sum gives the \textit{total voltage} (\textit{current}).
- In this way, we aggregate multiple \textit{PV} cells to construct larger \textit{PV} modules for deployment in energy production.
FROM CELLS TO MODULES TO ARRAYS

cell
↓
basic
building
block

module
↓
structural
configuration

array
↓
solar PV element

The underlying concept is to connect multiple PV cells in series to increase voltage output or in parallel to increase current output using the PV cells that are aggregated to construct a PV module.

Typical module sizes consist of 36, 72, 96 or 128 cells with the continuing trend toward increasingly larger systems.
FROM MODULES TO ARRAYS

- Several modules, in turn, are connected in series or in parallel to construct the PV arrays; the collection of the arrays forms the PV installation.

- We make use of circuit analytic concepts to build the $i - v$ curves of a PV module and those of a PV array from the individual PV cell $i - v$ curves.
\( i - v \) CURVE FOR CELLS IN SERIES

\[ v = v_1 + v_2 + \cdots + v_n \]
$i - \nu$ CURVE FOR CELLS IN PARALLEL

\[ i = i_1 + i_2 + \ldots + i_n \]

- 1 cell
- 2 cells
- $n$ cells
The $i-v$ curve of the $PV$ array describes the relationship between the current and the voltage of the $PV$ array and provides the basis for the performance assessment.

A key element of interest is the amount of power delivered to the grid by the $PV$s – a significant metric that measures $PV$ array energy production.
POWER OUTPUT FOR A PV ARRAY

**Open circuit conditions**

- $i = 0$
- $v = v_{oc}$

**Power**

$\text{power} = i \times v = 0$

**Short circuit conditions**

- $i = i_{sc}$
- $v = 0$
The connection of a load across the PV array terminals results in a *non-zero current* and a *non-zero voltage*; their values determine the PV array instantaneous power output.

In general, our aim is to get the PVs to deliver the *maximum power* with the current/voltage set to attain the *maximum power operating point (MPP)*.
MAXIMUM POWER POINT FOR A PV ARRAY

maximum power

power = $i \times v$

MPP
EXAMPLE: A PIECE–WISE LINEAR $i – V$ CURVE

\[
i = \begin{cases} 
12 & 0 \leq V \leq 30 \\
27 - 0.5V & 30 < V \leq 36 \\
63 - 1.5V & 36 < V \leq 42 \\
0 & \text{otherwise}
\end{cases}
\]
EXAMPLE: THE PIECEWISE LINEAR \( i - v \) CURVE POWER OUTPUT

\[
p = i \times v = \begin{cases} 
12v & 0 \leq v \leq 30 \\
-0.5(v - 27)^2 + 0.5(27)^2 & 30 < v \leq 36 \\
-1.5(v - 21)^2 + 1.5(21)^2 & 36 < v \leq 42 \\
0 & \text{otherwise}
\end{cases}
\]

\[
p^M = 360 \text{ W at } v_{MPP} = 30 \text{ V, } i_{MPP} = 12 \text{ A}
\]
In general, to operate at MPP, a *maximum power point tracker* (MPPT) is used to adjust the current/voltage of the PV array.

A simple implementation of MPPT includes a DC–DC converter and a control mechanism.
MPPT

DC current

DC–DC converter

control mechanism

load
Given a fixed load voltage, the control mechanism senses the $PV$ array current/voltage and adjusts the $DC-DC$ converter parameters to change the voltage across the $PV$ array so as to shift the $PV$ operating point $(i,v)$ to the $MPP$ values.

Two widely used methods to obtain the $MPP$ are:

- fractional open-circuit voltage method
- perturb and observe technique
FRACTIONAL OPEN-CIRCUIT VOLTAGE METHOD

- *Fractional open–circuit voltage* method sets the voltage value at the *MPP* equal to some *fixed* fraction of the *measured* open–circuit voltage.

- As the *PV* cells continue to operate over longer periods, their open–circuit voltages become reduced and so do the values of their *MPPs*.
Perturb and observe technique is, essentially, an application of the hill–climbing method.

- If an adjustment that increases the voltage raises the PV power output, then the voltage needs to be increased until the voltage increment no longer raises the power output.
- If the voltage increment lowers the PV power output, then in the next voltage adjustment we reverse the sign of the perturbation.
PERTURB AND OBSERVE

Maximum power

Continue hill climbing

\[ \Delta p > 0 \]

\[ \Delta v > 0 \]
PERTURB AND OBSERVE

maximum power

Δp' < 0

Δv' > 0

reverse the direction
The two presented MPPT schemes are, conceptually quite simple, but have only limited applicability.

To handle more general/realistic situations, some necessary modifications of the MPPT algorithms need to be made to solve actual MPPT problems such as the case of more complex $i - v$ curves due to the presence of partial shadow on the PV cells.
MAXIMUM POWER POINT TRACKER METHODS

Global maximum point

Local maximum point
PV SYSTEMS

- PV arrays, equipped with MPPT control, may also be used to charge batteries for energy storage.

- However, a MPPT is inadequate to connect the PV to the grid since the output is DC power.

- Indeed, for a grid–connected PV system, the PV arrays and the MPPT require also a DC–AC converter to inject AC power into the grid.
GRID – CONNECTED PV SYSTEMS
INTERCONNECTION OF A GRID–CONNECTED PV SYSTEM

- DC current
- Lightning surge arrestor
- PV arrays
- Aggregation box
- Array disconnect switches
- Grid interconnection node
- Power conversion unit (PCU)
- AC
- Breaker
- Ground
PRINCIPAL ELEMENTS OF A GRID–CONNECTED PV SYSTEM

- **PV arrays**, which consist of multiple **PV** modules, absorb solar energy, which they convert into **DC** electricity.

- An **aggregation box** includes individual fuses for each string of modules in the array and blocking diodes; its key functions include the aggregation of the currents from each string of **PV** modules and the delivery of **DC** power to a **fused array disconnect switch**.
PRINCIPAL COMPONENTS OF A GRID–CONNECTED $PV$ SYSTEM

- The array *disconnect switches* are used to isolate the $PV$ array in cases of need.

- The *power conditioning unit (PCU)* serves to:
  - set the $PV$ array *MPP* operating point; and
  - convert $DC$ into $AC$.

- The system also includes additional protection devices, such as breakers, and leads to meters.
In some PCU installations, the DC–DC converter of the MPPT is not needed since the DC–AC converter is used instead to set the PV array voltage and to convert the DC current into AC current.

The PCU automatically senses the PV array currents/voltages as well as the grid voltage at the interconnection node and subsequently sets the PV array variables to their MPP values.
THE PCU ELEMENT

- The limiting values of the parameters of the PCU for a specific PV array are selected so as to ensure the PV MPP values can be accommodated.

for a specific $PV$ array are selected so as to ensure the $PV$ MPP $i - v$ values can be accommodated.
EXAMPLE: PV ARRAY DESIGN

- A grid–connected PV system consists of 36 PV modules that can be arranged in series or in parallel to produce DC power.

- We need to design a PV array structure that delivers the maximum power to the PCU, in accordance with the specifications of the PCU parameter values.
EXAMPLE: $PV$ MODULE SPECIFICATIONS

<table>
<thead>
<tr>
<th>parameter/variable</th>
<th>symbol</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum power</td>
<td>$p^M$</td>
<td>200</td>
<td>$W (DC)$</td>
</tr>
<tr>
<td>$MPP$ voltage</td>
<td>$v_{MPP}$</td>
<td>50</td>
<td>$V (DC)$</td>
</tr>
<tr>
<td>$MPP$ current</td>
<td>$i_{MPP}$</td>
<td>4</td>
<td>$A (DC)$</td>
</tr>
<tr>
<td>open-circuit voltage</td>
<td>$v_{oc}$</td>
<td>60</td>
<td>$V (DC)$</td>
</tr>
<tr>
<td>short-circuit current</td>
<td>$i_{sc}$</td>
<td>5</td>
<td>$A (DC)$</td>
</tr>
</tbody>
</table>
EXAMPLE: *PCU* SPECIFICATIONS

<table>
<thead>
<tr>
<th>parameter/variable</th>
<th>symbol</th>
<th>value</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>maximum voltage input</strong></td>
<td>$v_{PCU}^M$</td>
<td>730</td>
<td>$V \ (DC)$</td>
</tr>
<tr>
<td><strong>maximum current input</strong></td>
<td>$i_{PCU}^M$</td>
<td>23</td>
<td>$A \ (DC)$</td>
</tr>
<tr>
<td><strong>maximum MPPT voltage input</strong></td>
<td>$v_{MPPT}^M$</td>
<td>620</td>
<td>$V \ (DC)$</td>
</tr>
<tr>
<td><strong>minimum MPPT voltage input</strong></td>
<td>$v_{MPPT}^m$</td>
<td>330</td>
<td>$V \ (DC)$</td>
</tr>
</tbody>
</table>
Our goal is to configure the 36 PV modules such that every module operates at its MPP value.
EXAMPLE: \( PV \) ARRAY DESIGN

- As some modules are connected in series to form a string with a higher voltage output, we compute the value of the number \( N_s \) of modules in a string that satisfies

\[
N_s \leq \min \left\{ \frac{v_{PCU}^M}{v_{MPP}^M}, \frac{v_{MPPT}^M}{v_{MPP}^M} \right\} = \min \left\{ \frac{730}{50}, \frac{620}{50} \right\} = 12.4
\]

\[
N_s \geq \frac{v_{MPPT}^m}{v_{MPP}^M} = \frac{330}{50} = 6.6
\]
EXAMPLE: *PV* ARRAY DESIGN

- For the $N_p$ modules connected in parallel to raise the current output, we determine the $N_p$ value that satisfies:

$$N_p \leq \frac{i^M_{PCU}}{i^M_{MPP}} = \frac{23}{4} = 5.75$$

- Thus, a possible design to meet requirements is an array with 4 parallel strings of 9 *PV* modules in series.
An alternative approach removes the single PCU and installs a dedicated micro–inverter and a dedicated MPPT for each PV module.

Diagram:
- DC
- MPPT micro-inverter
- DC
- 240-V AC
There are certain advantages in the use of micro-inverters, such as the ability to wire together the modules using AC components, which cost less and are safer than DC components and the measurable improvement of reliability.

However, the overall costs increase because a single PCU is cheaper than a large number of micro-inverters/MPPTs in large array systems.
THE TWO GRID–CONNECTED PV SYSTEM CATEGORIES

Based on which side of the electric meter the PVs are located, the grid–connected PV systems are classified as either

- **behind–the–meter systems**: usually installed on rooftops to feed their power outputs directly to the loads on the same side of the meter;

or,
GRID–CONNECTED $PV$ SYSTEM

**CATEGORY**

- systems on the utility side of the meter: generally larger farms with power outputs sold by their owners into the wholesale electricity markets

- Unlike the systems on the utility side of the meter, behind–the–meter systems avoid land issues and compete simply against the retail electricity price; indeed, under net metering, these customers are paid *retail* not wholesale rates
BEHIND–THE–METER
GRID–CONNECTED $PV$ SYSTEM

$PV$  $DC$  $PCU$  $AC$  $sell \ kWh$  $AC$  $buy \ kWh$

$ground$
BEHIND–THE–METER GRID–CONNECTED $PV$ SYSTEM

- In the case that the loads exceed the power output of the $PV$ system, the $PV$ system owner buys the energy from the grid; otherwise, the $PV$ system owner sells the excess energy to the grid.

- As such, the customer’s bill is only for the net energy that the $PV$ system is unable to supply to meet its loads.
NET METERING

Net energy consumption = $\mathcal{E}_2 + \mathcal{E}_3 - \mathcal{E}_1$

PV power output

Excess energy sold to the grid

Energy bought from the grid

Midnight
EXAMPLE: NET METERING OVER A DAY

<table>
<thead>
<tr>
<th>time</th>
<th>PV power output (kW)</th>
<th>load (kW)</th>
<th>net load (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00 – 6:00</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6:00 – 9:00</td>
<td>9</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>9:00 – 12:00</td>
<td>45</td>
<td>20</td>
<td>–25</td>
</tr>
<tr>
<td>12:00 – 15:00</td>
<td>45</td>
<td>25</td>
<td>–20</td>
</tr>
<tr>
<td>15:00 – 18:00</td>
<td>9</td>
<td>30</td>
<td>21</td>
</tr>
<tr>
<td>18:00 – 24:00</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
EXAMPLE: NET METERING OVER A DAY

The net energy the customer needs to buy from the grid is:

\[
(5 \times 6 + 15 \times 3 + 20 \times 3 + 25 \times 3 + 30 \times 3 + 20 \times 6)
- (0 \times 6 + 9 \times 3 + 45 \times 3 + 45 \times 3 + 9 \times 3 + 0 \times 6)
\]

\[= 96 \text{ kWh/d}\]

Suppose the electricity price is fixed at 0.20 $/kWh, the bill for this day is

\[0.2 \times 96 = \$19.2\]
TIME–OF–USE RATES

☐ For most grid systems, the peak loads occur during the hot summer afternoons due to the heavy air conditioner loads, requiring the utilization of less–efficient plants to meet the loads.

☐ During the peak load times, the market prices are considerably higher than in the periods with low demands; some utilities use time–differentiated tariffs for certain customer classes.
The time–of–use (TOU) rates provide customers an opportunity to save through their electricity consumption reductions at times of peak demand and encourage consumption during low-load hours.

TOU rates, consequently, further stimulate the installation of residential/commercial PV systems.
### EXAMPLE: TIME–OF–USE RATES OVER A DAY

<table>
<thead>
<tr>
<th>period</th>
<th>hours</th>
<th>PV output (kW)</th>
<th>load (kW)</th>
<th>rate ($/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>off-peak</td>
<td>0:00 – 6:00</td>
<td>0</td>
<td>5</td>
<td>0.10</td>
</tr>
<tr>
<td>off-peak</td>
<td>6:00 – 9:00</td>
<td>9</td>
<td>15</td>
<td>0.10</td>
</tr>
<tr>
<td>partial-peak</td>
<td>9:00 – 12:00</td>
<td>45</td>
<td>20</td>
<td>0.17</td>
</tr>
<tr>
<td>peak</td>
<td>12:00 – 15:00</td>
<td>45</td>
<td>25</td>
<td>0.27</td>
</tr>
<tr>
<td>peak</td>
<td>15:00 – 18:00</td>
<td>9</td>
<td>30</td>
<td>0.27</td>
</tr>
<tr>
<td>partial-peak</td>
<td>18:00 – 24:00</td>
<td>0</td>
<td>20</td>
<td>0.17</td>
</tr>
</tbody>
</table>
EXAMPLE: TIME–OF–USE RATES OVER A DAY

The daily bill for this customer is

\[
(5 - 0) \times 6 \times 0.10 + (15 - 9) \times 3 \times 0.10 +
\]

\[
(20 - 45) \times 3 \times 0.17 + (25 - 45) \times 3 \times 0.27 +
\]

\[
(30 - 9) \times 3 \times 0.27 + (20 - 0) \times 6 \times 0.17
\]

\[
= 13.26 \frac{\$}{d}
\]
For the grid customers with bi–directional meters that measure the energy consumed and the energy produced by the $PV$, they pay or get paid at time–differentiated rates as specified by the policy in the particular jurisdiction.

This policy on the so–called *feed–in tariffs* aims to accelerate investment in behind–the–meter $PV$ systems but may cause the *death spiral* of the electricity distribution companies – a major issue.
The uncertainty of climatic conditions makes the accurate prediction of insolation a highly challenging task and thus the evaluation of the PV system power outputs is fraught with complications.

In general, some approximation methods are used to predict the performance of the grid–connected PV systems.
STANDARD TEST CONDITION

- PV modules are rated under the so-called standard test conditions (stc) specified by
  - insolation of $1 \text{ kW/m}^2$ or 1-sun
  - cell temperature of $25^\circ C$
  - air mass ratio of 1.5 (AM 1.5)

- Under the stc, we use “watts stc” – $W_{stc}$ – units for the PV DC power output or “peak watts” – $W_p$
ACTUAL OPERATIONAL CONDITIONS

- We observe that actual operational conditions vary significantly from those under \( stc \) and, as such, so do the actual outputs since:
  - solar irradiation is not exactly \( 1\text{-sun} \)
  - the cell temperature is, typically, \( 20^\circ - 40^\circ C \) higher than the ambient temperature
  - modules tend to get \textit{dirty} over time
A simple way to convert the \( stc \) rated power output into the \( stc \ AC \) power of the \( PV \) systems is to introduce a derate factor

\[
p_{AC, stc} = p_{DC, stc} \times \chi
\]

\( stc \ AC \) power

output of the PV system in \( W \)

\( stc \) rated DC

\( PV \) system

power output

\( W_p \) or \( W_{stc} \)
The derate factor $\chi$ varies significantly because

- not all of the modules produce under the stc as much power as the nameplate rating stated in the manufacturer specifications
- the converter efficiency varies under different load conditions
- an isolation transformer may be integrated, for safety, into the PV system and contributes
NONTEMPERATURE – RELATED $PV$
POWER DERATING

to an increase in the power losses

- the soiling factor is highly variable as it depends on the washing frequency and may result in mismatches among the modules
- operations over longer periods lead to decreases in the overall module efficiency
- nearby obstructions or nearby $PV$ modules may cast shadows on some of the modules
DERATE FACTOR

- The *Solar Advisor Model* developed by Sandia National Laboratory for solar plant performance evaluation is the basis for the widely-used online *PV performance calculator called PVWATTS*.

- *PVWATTS* provides appropriate estimates of each factor that contributes to the *derate factor*.
# PVWATTS Derate Factors

<table>
<thead>
<tr>
<th>factor</th>
<th>default</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV module DC nameplate rating</td>
<td>0.95</td>
<td>0.80 – 1.05</td>
</tr>
<tr>
<td>converter and transformer</td>
<td>0.92</td>
<td>0.88 – 0.98</td>
</tr>
<tr>
<td>module mismatch</td>
<td>0.98</td>
<td>0.97 – 0.995</td>
</tr>
<tr>
<td>diodes and connections</td>
<td>1.00</td>
<td>0.99 – 1.00</td>
</tr>
<tr>
<td>DC wiring</td>
<td>0.98</td>
<td>0.97 – 0.99</td>
</tr>
<tr>
<td>AC wiring</td>
<td>0.99</td>
<td>0.98 – 0.993</td>
</tr>
</tbody>
</table>
**PVWATTS DERATE FACTORS**

<table>
<thead>
<tr>
<th>factor</th>
<th>default</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>soiling</td>
<td>0.95</td>
<td>0.30-0.995</td>
</tr>
<tr>
<td>system availability</td>
<td>0.98</td>
<td>0.00-0.995</td>
</tr>
<tr>
<td>shading</td>
<td>1.00</td>
<td>0.00-1.00</td>
</tr>
<tr>
<td>sun tracking</td>
<td>1.00</td>
<td>0.95-1.00</td>
</tr>
<tr>
<td>age</td>
<td>1.00</td>
<td>0.70-1.00</td>
</tr>
<tr>
<td>total non-temperature-related derate factor</td>
<td>0.77</td>
<td>0.00-1.01</td>
</tr>
</tbody>
</table>
EXAMPLE: \( PV \) SYSTEM POWER OUTPUT

- Consider a 72–module series connected \( PV \) system with specified 100 \( W_p \) nameplate capacity

- We adopt the default derate factor in \( PVWATTS \); the \( PV \) system power output under the \( stc \) is

\[
p_{AC, stc} = 72 \times 100 \times 0.77 = 5.544 \, kW
\]
Note that the *PVWATTS* derate factor does not take into account the significant impacts caused by the varying cell temperatures.

In light of the variations in the insolation and the ambient temperature, the cell temperature may differ considerably from that specified in the *STC*.
The approximation of cell temperature is given by

\[ \tau_{\text{cell}} = \tau_a + \left( \frac{\tau_n - 20}{0.8} \right) \cdot \text{insolation} \]

- **cell temperature** when the cell operates under a 0.8–sun and ambient temperature of 20° C, the so–called normal operating cell temperature (NOCT) given in °C
- **cell temperature**
- **ambient temperature**
Then, we introduce a temperature coefficient to account for the impacts of cell temperature.

\[
\chi' = \chi \cdot \left[ 1 + \frac{z (\tau_{cell} - 25)}{\text{temperature coefficient} / ^\circ C} \right]
\]
TEMPERATURE–RELATED PV POWER DERATE FACTOR

AC power output of the PV system in W

\[ p_{AC} = p_{DC, stc} \times \chi' \]

\[ = p_{AC, stc} \times \left[ 1 + z (\tau_{cell} - 25) \right] \]
EXAMPLE: TEMPERATURE–RELATED PV POWER DERATE FACTOR

- Consider a site in Chicago with a 0.7–sun and 35°C ambient temperature.

- The insolation is computed to be

\[
0.7 \text{ sun} \times \frac{1 \text{ kW/m}^2}{1 \text{ sun}} = 0.7 \text{ kW/m}^2
\]

- Given a PV cell with \( \tau_n = 45^\circ C \), the actual cell temperature is computed to be
EXAMPLE: TEMPERATURE–RELATED PV POWER DERATE FACTOR

\[ \tau_{cell} = 35 + \left( \frac{45 - 20}{0.8} \right) \times 0.7 = 42.3^\circ C \]

- The installation of this PV system in Chicago with a\[-0.5\%/^\circ C\] temperature coefficient, the AC power delivered by the system is

\[ 2.31 \times [1 + (-0.005)(42.3 - 25)] = 2.16 kW \]
THE PEAK–HOURS APPROACH TO ESTIMATE PV PERFORMANCE

- The methods we discuss introduce the *derate factors* to estimate the AC power outputs of the system.

- The *peak–hours approach* provides a very convenient way to estimate the average energy produced by the PV system based on daily, monthly or annual average insolation, as well as the cell temperature.
INSOLATION TERMINOLOGY

- For the peak-hours approach, we first introduce the appropriate insolation terminology:

  1 h/d of 1-sun

  1–h peak sun  ⇔ 1 kW/h/m² – d

- For example, an average daily insolation of 5.5 kW/h/m² – d is equivalent to 1-sun (1 kW/m²) for 5.5 hours and the same as 5.5-hours of peak-sun.
THE PEAK–HOURS APPROACH TO ESTIMATE $PV$ PERFORMANCE

We assume that the system efficiency remains constant over time.

Therefore, we may write the daily $PV$ system delivered energy as

\[
\text{daily energy} = \frac{\text{kWh}}{\text{d}} = \frac{\text{kWh}}{\text{m}^2 - \text{d}}
\]

\[
P_V\text{ array area } \times \frac{\text{kWh}}{\text{d}} \times \text{area} \times \bar{\eta}
\]

average system efficiency

$PV$ array area $m^2$
THE PEAK–HOURS APPROACH TO ESTIMATE PV PERFORMANCE

When arrays are exposed to 1–sun of insolation, we can write for AC power delivered from the PV system as

\[
p_{AC} = \left( 1 \text{ kW/m}^2 \right) \times \text{area} \times \eta_{1\text{-sun}}
\]

the system efficiency under 1-sun

Thus for arbitrary insolation

\[
\text{daily energy} = p_{AC} \times \left( \frac{\text{daily insolation}}{1 \text{ kW/m}^2} \right) \times \frac{\bar{\eta}}{\eta_{1\text{-sun}}}
\]
If we assume that the average system efficiency is equal to the efficiency under 1-sun

\[
daily\ energy = p_{AC} \times \left( \frac{\text{daily insolation}}{1\ kW / m^2} \right)
\]

number of hours of peak sun per day
THE PEAK–HOURS APPROACH TO ESTIMATE PV PERFORMANCE

Coupled with the temperature–related derate factor,

the peak–hours approach can also be used to estimate the annual energy production

\[
\text{annual energy} = p_{DC, stc} \times \chi' \times \left(\frac{\text{daily insolation}}{1 \text{ kW} / \text{m}^2}\right) \times 365
\]
EXAMPLE: ANNUAL ENERGY OF A SOLAR FARM AT CHAMPAIGN

- A 82,961–$m^2$ solar farm on the south campus is considered as a key element of the University of Illinois’ Climate Change Program.

- The average daily insolation received by the panels in the solar farm project is 5.1 $kWh / m^2 - d$.
EXAMPLE: ANNUAL ENERGY OF A SOLAR FARM AT CHAMPAIGN

Assume the capacity of the arrays under stc is

\[ 6 \text{ MW}_p \text{ and } \chi' \text{ equals to } 0.7, \text{ the annual energy is} \]

\[ 6 \times 0.7 \times \left( \frac{5.1}{1} \right) \times 365 = 7,820,000 \text{ kWh/yr} \]

We can estimate the overall PV system efficiency by

\[ \bar{\eta} = \frac{7,820,000}{5.1 \times 82,961 \times 365} \approx 5\% \]
We can also use the peak–hours approach to approximate the capacity factor of a grid–connected PV system.

The commonly used equation to approximate the PV capacity factor is given by:

\[
\text{annual energy} = p_{DC, stc} \times c.f._{DC} \times 8,760
\]
Substitute the peak-hours approach equations into the capacity equation

\[ c.f._{DC} = \chi' \times \left( \frac{\text{daily insolation}}{1 \text{ kW} / \text{m}^2} \right) \times \frac{1}{24 \text{ h} / \text{d}} \]

For example, for the solar farm in Champaign

\[ c.f._{DC} = 0.7 \times \left( \frac{5.1}{1} \right) \times \frac{1}{24 \text{ h} / \text{d}} = 0.149 \]
EXAMPLE: \( PV \) SYSTEM SIZING IN CHICAGO

- We are asked to size a \( PV \) system to supply 11,000 kWh/y to a home in Chicago.
- Assume the average daily insolation in Chicago is 4.86 kWh/m\(^2\) – \( d \) and \( \chi' = 0.7 \).
- We select the \textit{SunPower 240–W PV} module and the \textit{SunPower 5000 PCU} with the following parameters:

\[
p_{DC, stc} = \frac{11,000}{0.7 \times \left( \frac{4.86}{1} \right) \times 365} = 8.84 \text{ kW}_p
\]
### SunPower PV MODULE SPECIFICATIONS

<table>
<thead>
<tr>
<th>parameter/variable</th>
<th>symbol</th>
<th>value</th>
<th>units</th>
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</thead>
<tbody>
<tr>
<td>maximum power</td>
<td>$P_m$</td>
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<td>$W (DC)$</td>
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<td>MPP voltage</td>
<td>$v_{MPP}$</td>
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<td>$V (DC)$</td>
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<td>MPP current</td>
<td>$i_{MPP}$</td>
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<td>$A (DC)$</td>
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<tr>
<td>open-circuit voltage</td>
<td>$v_{oc}$</td>
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<td>$V (DC)$</td>
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<tr>
<td>short-circuit current</td>
<td>$i_{sc}$</td>
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<td>$A (DC)$</td>
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</tbody>
</table>
### SunPower PCU Specifications

<table>
<thead>
<tr>
<th>Parameter/Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maximum Voltage Input</strong></td>
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<td>( V \ (DC) )</td>
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<tr>
<td><strong>Maximum Current Input</strong></td>
<td>( i_{PCU}^M )</td>
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<td>( A \ (DC) )</td>
</tr>
<tr>
<td><strong>Maximum MPPT Voltage Input</strong></td>
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<td>( V \ (DC) )</td>
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<tr>
<td><strong>Minimum MPPT Voltage Input</strong></td>
<td>( v_{MPPT}^m )</td>
<td>160</td>
<td>( V \ (DC) )</td>
</tr>
</tbody>
</table>
EXAMPLE: PV SYSTEM SIZING IN CHICAGO

- The total number of PV modules is estimated by
  \[
  \frac{8,840}{240} = 36.8
  \]

- The next step is to determine the number of the PV modules and to configure them in such a way that every module operates at its MPP value.

- Since modules connected in series form a string with increased voltage output, we determine the number \( N_s \) of modules in a string from
For modules connected in parallel, the number of modules $N_p$ must satisfy

$$N_p \leq \frac{i_{PCU}^M}{i_{MPP}^M} = \frac{36}{6} = 6$$
A possible design that meets the requirements is an array with 4 parallel strings of 9 PV modules in series; its annual energy is approximated by

$$36 \times 0.24 \times 0.7 \times \left( \frac{4.86}{1} \right) \times 365 = 10,728 \text{ kWh/y}$$

The capacity factor of the configuration is

$$c.f_{DC} = \frac{10,728}{36 \times 0.24 \times 8,760} = 0.14$$