SOLAR ENERGY TECHNOLOGY

- Solar technology collects solar energy for its conversion 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 then 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
SEMICONDUCTOR

- A semiconductor is a material, which has electrical conductivity at some level between that of a conductor and an insulator.

- Semiconductors form the basis of today’s modern electronics: diodes, transistors, digital/analog integrated circuits are representative examples.

REVIEW OF DIODES

- The diode was one of the first semiconductor electronic devices that was invented.

- 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 any current flowing in the opposite direction; this switching mode is of great utility.

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 – in 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), copper, indium and selenium (CIS) and cadmium telluride (CdTe).
THE $PV$ CELL

- The basic building block for $PV$ systems is the so-called $PV$ cell, whose construction uses $PV$ 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 \textit{PV} cell, we, typically, deploy an equivalent circuit model to represent the cell behavior.

This idealized representation is in terms of discrete idealized components, as such elements do not exist inside a \textit{PV} cell.

The $i - v$ curves of these equivalent circuit models are used to describe graphically and assess quantitatively the $i - v$ behavior of the \textit{PV} cell.
THE \( i - v \) CURVE OF THIS IDEAL EQUVALENT CIRCUIT OF A \( PV \) CELL

A MORE DETAILED EQUIVALENT CIRCUIT OF A \( PV \) CELL
THE $i-v$ CURVES OF A MORE DETAILED CIRCUIT OF A $PV$ CELL

$R_s = 0 \quad R_p = \infty$

$R_s = 0.02 \, \Omega \quad R_p = \infty$

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

$R_s = 0 \quad R_p = \infty$

$R_s = 0.02 \, \Omega \quad R_p = 3 \, \Omega$

IMPACTS OF INSOLATION AND CELL TEMPERATURE

- 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 describes its behavior as a function of the cell temperature and the insolation.
IMPACTS OF INSOLATION ON $PV \ i - v$ CURVES

- $1 \text{ kW/m}^2$
- $0.67 \text{ kW/m}^2$
- $0.33 \text{ kW/m}^2$

decreasing insolation

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

decreasing cell temperature
LIMITATION OF A SINGLE $PV$ CELL

- The $i - v$ 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 $PV$ cells are connected in series (parallel), each cell has the same current (voltage), at which its corresponding voltage (current) is additive and the sum gives the total voltage (current).

- In this way, we aggregate multiple $PV$ cells to construct larger $PV$ modules that we deploy in electricity production.

FROM CELLS TO MODULES TO ARRAYS

FROM CELLS TO MODULES

- 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 configurations.

FROM MODULES TO ARRAYS

- Several modules, in turn, are connected in series or in parallel to construct the PV arrays; the set of these 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.
CURVE FOR CELLS IN SERIES

\[ v = v_1 + v_2 + \cdots + v_n \]

CURVE FOR CELLS IN PARALLEL

\[ i = i_1 + i_2 + \cdots + i_n \]
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 its performance assessment.

A key element of interest is the amount of power delivered to the grid by the $PV$s – an important metric that is used to determine the total $PV$ array energy production.

**POWER OUTPUT FOR A $PV$ ARRAY**

- For **open circuit conditions**:
  - $v = v_{oc}$
  - $i = 0$

- For **short circuit conditions**:
  - $i = i_{sc}$
  - $v = 0$

**Power** under either condition:

\[ \text{power} = i \times v = 0 \]
POWER OUTPUT FOR A $PV$ ARRAY

- The connection of a load across the $PV$ array terminals results in a non-zero current and a non-zero voltage; their values thus determine the $PV$ array instantaneous power output.

- In general, the goal is to use the maximum power with the current/voltage set from the $PV$ array to attain the maximum power operating point (MPP).

MAXIMUM POWER POINT FOR A $PV$ ARRAY

$power = i \times v$

$maximum power$
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 PIECE–WISE LINEAR $i - v$ CURVE POWER OUTPUT

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

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

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

- Given a fixed load voltage, the control mechanism senses the PV array current/voltage values 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

- 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.

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**Diagram:**

- Power ($W$) vs. Voltage ($V$)
- Maximum power indicated
- $\Delta p > 0$ and $\Delta v > 0$ for hill climbing
- Continue hill climbing direction

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**MPPT METHODS**

- The two presented *MPPT* schemes are, in concept, rather simple, but have only limited usefulness.
- 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 or other complications.
**PV SYSTEMS**

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

- However, MPPT is unable 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
- ground
- aggregation box
- array disconnect switches
- grid interconnection node
- PCU
- breaker
- AC
- grid
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:
  - to set the PV array MPP operating point; and
  - to convert DC into AC.
- The system also includes additional protection devices, such as breakers, and leads to meters.
THE PCU ELEMENT

- 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 $i – v$ values can be easily accommodated over a wide range of conditions.
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 are asked to design a *PV* array structure that delivers the maximum power to the *PCU*, without any violations of the specifications of the *PCU* parameter values.

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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><em>MPP voltage</em></td>
<td>$v_{MPP}$</td>
<td>50</td>
<td>V (DC)</td>
</tr>
<tr>
<td><em>MPP current</em></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>Maximum voltage input</td>
<td>$V_{PCU}^M$</td>
<td>730</td>
<td>$V (DC)$</td>
</tr>
<tr>
<td>Maximum current input</td>
<td>$I_{PCU}^M$</td>
<td>23</td>
<td>$A (DC)$</td>
</tr>
<tr>
<td>Maximum MPPT voltage input</td>
<td>$V_{MPPT}^M$</td>
<td>620</td>
<td>$V (DC)$</td>
</tr>
<tr>
<td>Minimum MPPT voltage input</td>
<td>$V_{MPPT}^m$</td>
<td>330</td>
<td>$V (DC)$</td>
</tr>
</tbody>
</table>

**EXAMPLE: PV ARRAY DESIGN**

- Our goal is to configure the 36 PV modules such that every module operates at its MPP value.

Diagram showing PV modules connected in series and parallel.
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:

\[
N_p \leq \frac{i_{PCU}^M}{i_{MPP}^M} = \frac{23}{4} = 5.75
\]

- Thus, a feasible design to meet requirements is an array with 4 parallel strings of 9 PV modules in series.
MICROINVERTERS

An alternative approach removes the single PCU and installs a dedicated micro-inverter and a dedicated MPPT for each PV module.

MICRO–INVERTERS

- 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 bring a 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,

THE TWO GRID–CONNECTED PV SYSTEM CATEGORIES

- *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 certain *net metering* schemes, these customers are paid *retail* not wholesale rates
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 = $\varepsilon_2 + \varepsilon_3 - \varepsilon_1$

- **PV power output**
- **Excess energy sold to the grid**
- **Energy bought from the grid**
- **Loads**

**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 many US grids, 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.
TIME–OF–USE RATES

- The time–of–use (TOU) rates provide customers an opportunity to save from their electricity usage reductions at times of peak demand and engender 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

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

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

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

\[= 13.26 \frac{\$}{d}\]

FEED–IN TARIFFS

A grid customer, with installed bi–directional meter to measure the consumed energy and the energy produced by the PV, pay or get paid at time–
differentiated rates as specified by the net metering 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 result in the death spiral of the electricity distribution companies – a key concern
PREDICTION OF THE PERFORMANCE OF A GRID–CONNECTED $PV$ SYSTEM

- 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, specific 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 kW/m$^2$ or 1 sun
  - cell temperature of 25$^\circ$ C
  - air mass ratio of 1.5 (AM 1.5)

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

- We observe that *actual operational conditions* may vary significantly from those under *stc* and, thus, so do the actual outputs since:
  - solar irradiation is not exactly 1 *sun*
  - the cell temperature is, typically, $20^\circ - 40^\circ C$
    higher than the ambient temperature
  - modules tend to get soiled over time

NON–TEMPERATURE–RELATED \( PV \) POWER DERATING

- A simple way to convert the *stc* rated power output into the *stc* \( AC \) power of a \( PV \) system is to introduce a *derate factor* \( \chi \)

\[
 p_{AC, stc} = p_{DC, stc} \times \chi \quad PV \text{ system}
\]

\[
 W_p \quad \text{or} \quad W_{stc}
\]

\( stc \) \( AC \) power

output of the \( PV \) system in \( W \)
The derate factor $\chi$ varies significantly because:

- not all 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 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
The Solar Advisor Model called *PVWATTS* developed by Sandia National Laboratory to measure solar plant performance is the basis for this widely-used online *PV* performance calculator.

*PVWATTS* provides appropriate estimates of each factor that contributes to the *derate factor value*.

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### *PVWATTS* DERATE FACTOR VALUES

<table>
<thead>
<tr>
<th>factor</th>
<th>default</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>PV module DC nameplate rating</em></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><em>DC wiring</em></td>
<td>0.98</td>
<td>0.97 – 0.99</td>
</tr>
<tr>
<td><em>AC wiring</em></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**

- We consider a 72–module series–connected PV system with specified 100 $W_p$ nameplate capacity.

- We adopt the default derate factor in PVWATTS; the $PVAC$ system power output under stc is

\[
p_{AC, stc} = 72 \times 100 \times 0.77 = 5.544 \text{ kW}
\]
TEMPERATURE–RELATED PV POWER DERATE FACTORS

- We 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 actual cell temperature may differ considerably from that in the stc value.

The approximation of cell temperature is given by

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

\[\text{cell temperature when the cell operates under a 0.8–sun ambient temperature of } 20^\circ C \text{ and } 1 \text{ m/s wind speed is the so–called normal operating cell temperature (NOCT) given in } ^\circ C\]
Then, we introduce a temperature coefficient to account for the impacts of actual cell temperature.

\[
\chi' = \chi \cdot \left[ 1 + \frac{z}{\tau_{cell} - 25} \right]
\]

Temperature-related PV power derate factor

\[
p_{AC} = p_{DC, stc} \times \chi'
= p_{AC, stc} \times \left[ 1 + \frac{z}{\tau_{cell} - 25} \right]
\]
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
  \[ 0.7 \text{ sun} \times \frac{1 \text{ kW} / \text{m}^2}{1 \text{ sun}} = 0.7 \text{ kW} / \text{m}^2 \]
- Given a PV cell with \( \tau_n = 45^\circ C \), the actual cell temperature is computed to be
  \[ \tau_{cell} = 35 + \left( \frac{45 - 20}{0.8} \right) \times 0.7 = 42.3^\circ C \]

- The installation of this PV system in Chicago with a specified – 0.5 %/° C temperature coefficient, the AC power delivered by the system is
  \[ 2.31 \times \left[ 1 + (-0.005)(42.3 - 25) \right] = 2.16 \text{ kW} \]
### THE PEAK–HOURS APPROACH TO ESTIMATE \( PV \) PERFORMANCE

- The methods in use explicitly deploy *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 and the cell temperature.

### INSOLATION TERMINOLOGY

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

  \[
  1 \text{ h/d of 1 sun insolation} \iff 1 \text{ h peak sun} \iff 1 \text{ kWh} / \text{m}^2 \text{ – d}
  \]

- For example, an average daily insolation of \( 5.5 \text{ kWh} / \text{m}^2 \text{ – d} \) is equivalent to 1 *sun* or \( 1 \text{ kW} / \text{m}^2 \) for 5.5 *hours* or to 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

\[
\text{daily energy} = \text{daily insolation} \times \text{area} \times \bar{\eta}
\]

\[
kWh / d \quad PV \text{ array area } m^2
\]

\[
kWh / m^2 - d \quad \text{average system efficiency}
\]

THE PEAK–HOURS APPROACH TO ESTIMATE PV PERFORMANCE

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

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

- Thus for arbitrary insolation

\[
daily \text{ energy} = P_{AC} \times \left(\frac{\text{daily insolation}}{1 \frac{kW}{m^2}}\right) \times \frac{\bar{\eta}}{\eta_{1\text{sun}}}
\]
THE PEAK–HOURS APPROACH TO ESTIMATE PV PERFORMANCE

- Under the assumption 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

- Coupled with the temperature–related derate factor, the peak–hours approach can also be used to estimate the annual energy production

\[
\text{annual\ energy} = P_{DC, stc} \times \chi' \times \left(\frac{\text{daily\ insolation}}{1\ kW/ m^2}\right) \times 365
\]

THE PEAK–HOURS APPROACH TO ESTIMATE PV PERFORMANCE

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\]
A 82,961–m² 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 $5.1 \text{ kWh/m}^2 \cdot \text{d}$.

Assume the capacity of the arrays under stc is $6 \text{ MW}_p$ and $\chi'$ equals to 0.7, the annual energy is

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

We can estimate the overall PV system efficiency by

$$\bar{\eta} = \frac{7,820,000}{5.1 \times 82,961 \times 365} \approx 5\%$$
CAPACITY FACTORS FOR GRID-CONNECTED PV SYSTEMS

- 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 $c.f_{DC}$ is given by:

$$\text{annual energy} = p_{DC, stc} \times c.f_{DC} \times 8,760$$

CAPACITY FACTORS FOR GRID-CONNECTED PV SYSTEMS

- Substitute the peak-hours approach equations into the capacity equation:

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

- For example, for the solar farm in Champaign:

$$c.f_{DC} = 0.7 \times \left( \frac{5.1}{1} \right) \times \frac{1}{24 h/d} = 0.149$$
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 Chicago average daily insolation is 4.86 kWh/m²/day and \( \chi' = 0.7 \).

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

- We select the SunPower 240–W PV module and the SunPower 5000 PCU with the following parameters:

---

### SunPower 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>240</td>
<td>W (DC)</td>
</tr>
<tr>
<td>MPP voltage</td>
<td>( v_{MPP} )</td>
<td>40</td>
<td>V (DC)</td>
</tr>
<tr>
<td>MPP current</td>
<td>( i_{MPP} )</td>
<td>6</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>
### SunPower PCU SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter/Variable</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum voltage input</td>
<td>$V_{PCU}^M$</td>
<td>730</td>
<td>V (DC)</td>
</tr>
<tr>
<td>Maximum current input</td>
<td>$i_{PCU}^M$</td>
<td>36</td>
<td>A (DC)</td>
</tr>
<tr>
<td>Maximum MPPT voltage input</td>
<td>$V_{MPPT}^M$</td>
<td>500</td>
<td>V (DC)</td>
</tr>
<tr>
<td>Minimum MPPT voltage input</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 MPPT 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

$$N_p \leq \frac{i_{PCU}^M}{i_{MPP}} = \frac{36}{6} = 6$$

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

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