ECE 333

GREEN ELECTRIC ENERGY

14. *PV* Systems

George Gross
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

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 plant (*CSP*) technology, which normally focuses the solar energy to generate thermal energy used to produce electrical energy

OBJECTIVE

- ☐ Review of some basic semiconductor and diode concepts
- ☐ The *PV* cell and its $i - v$ curve
- ☐ 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 that lies 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 in wide use

REVIEW OF DIODES

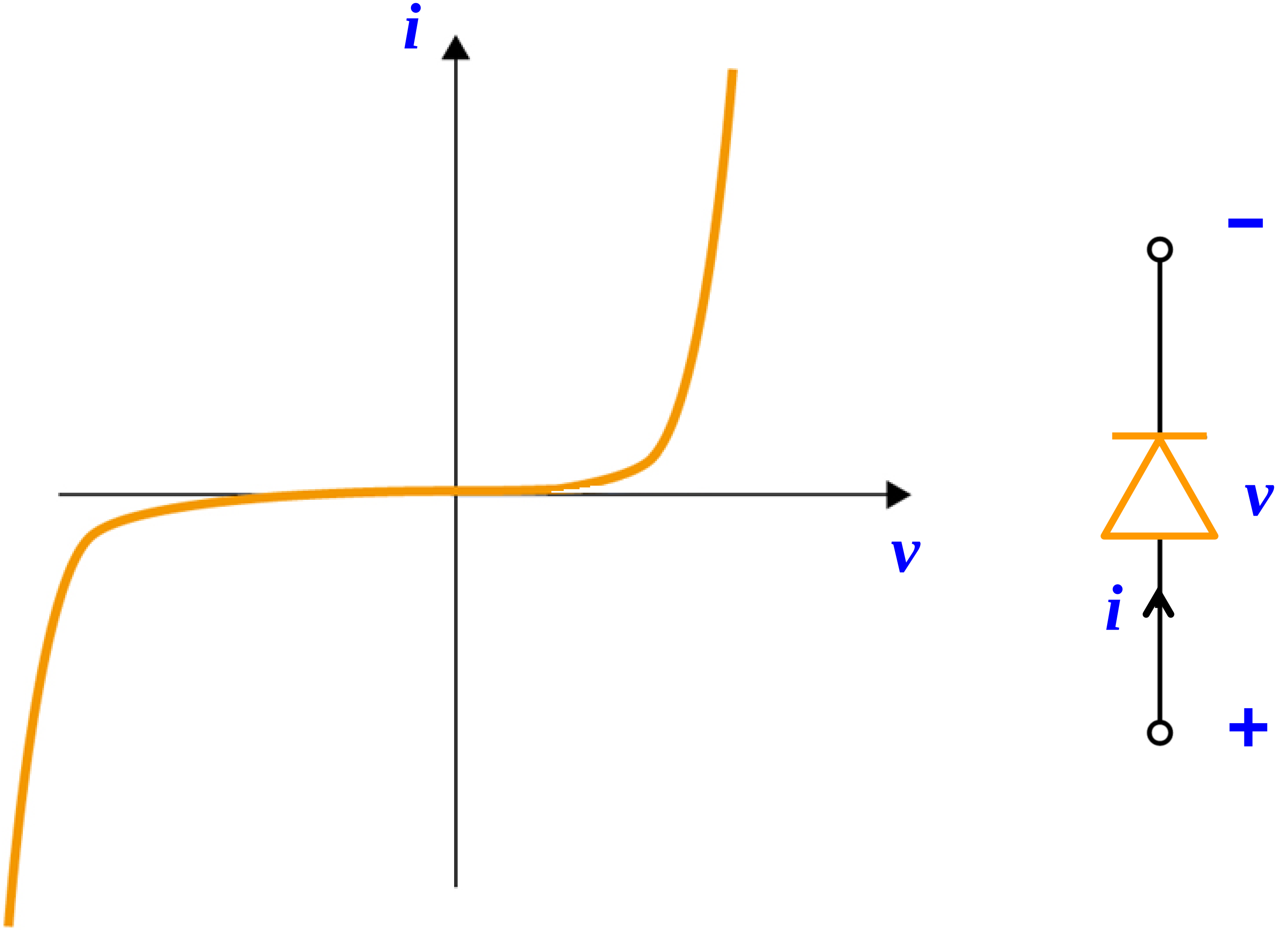
- ☐ **The *diode* was one of the first semiconductor electronic devices**
- ☐ **The *diode* is a two-terminal electronic component, composed of two semiconductor materials**
- ☐ **When a voltage is applied across the diode terminals, the electric field formed in the diode**

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



PV MATERIAL

- ☐ 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 term *PV* materials

PV MATERIALS

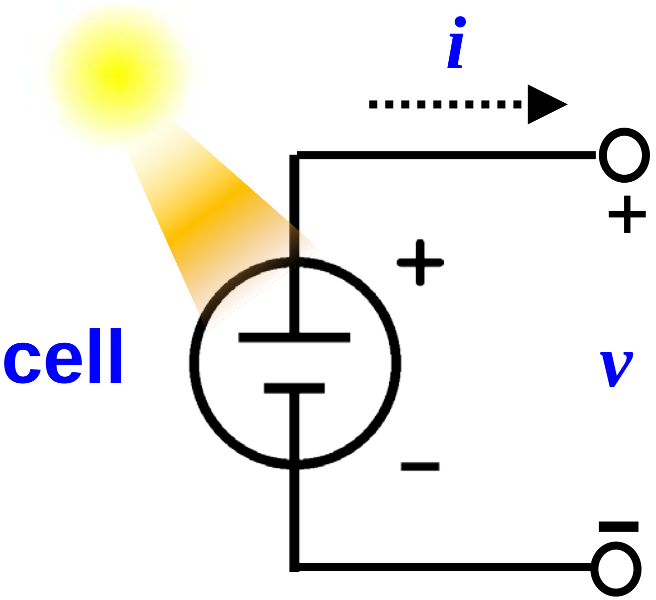
- **Silicon is the most commonly used element in *PV* materials**
- **However, there is emerging competition from the thin films made of compounds of two or more elements, including *gallium arsenide* (*GaAs*), *cadmium telluride* (*CdTe*) and *copper, indium* and *selenium* (*CIS*)**

THE *PV* CELL

- ☐ 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

THE *PV* CELL

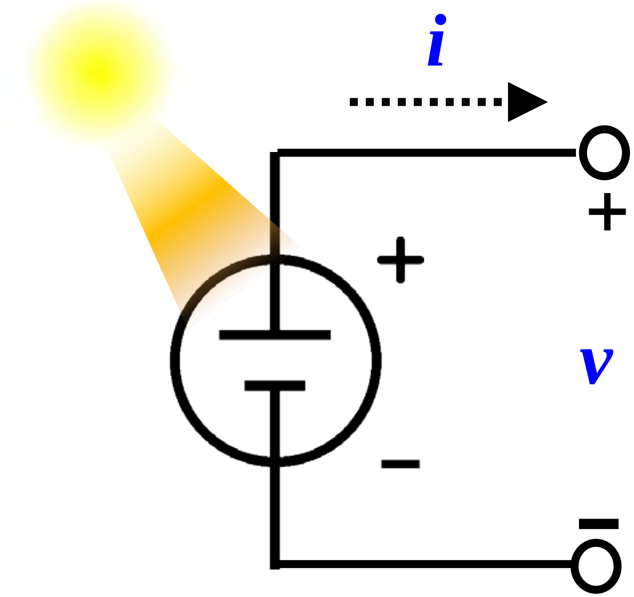
- ❑ When the sun rays strike the *PV* cell, the cell produces a current and a voltage combination, that can supply electricity to a connected load

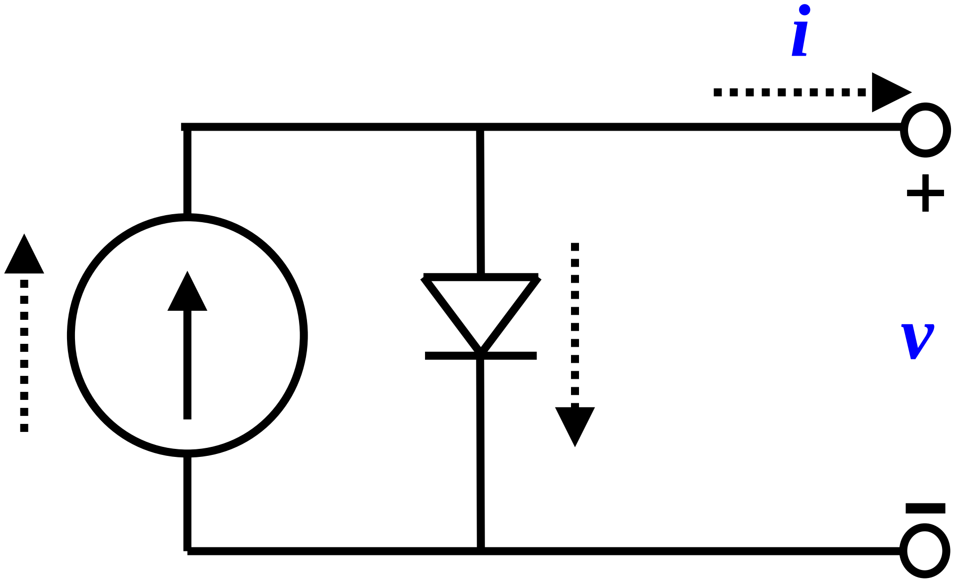


THE *PV* CELL

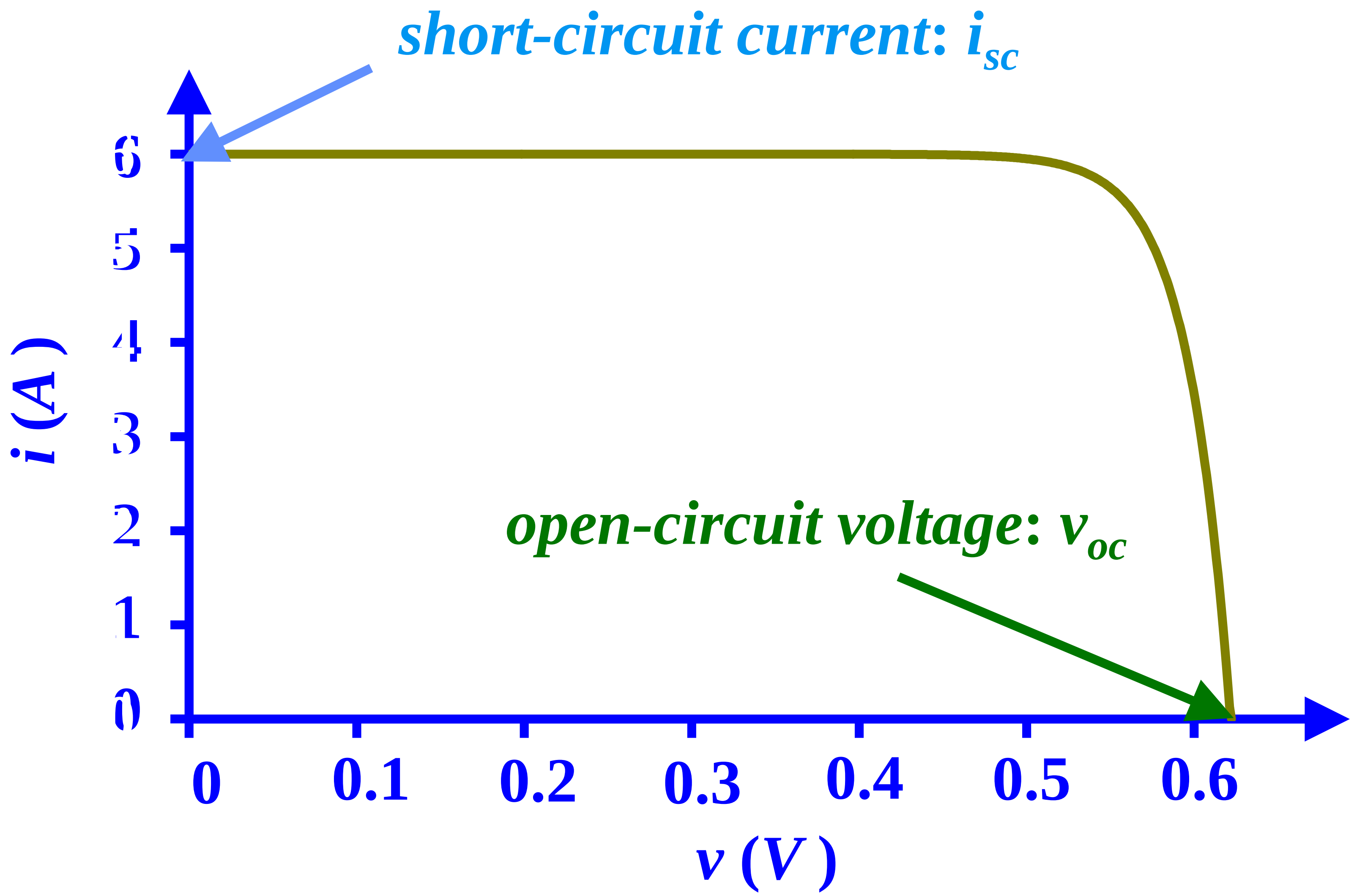
- To help analyze the performance of an individual *PV* cell, we typically deploy some equivalent circuit models to represent the cell behavior
- These are idealized representations in terms of discrete idealized components, as there are no such elements inside a *PV* cell
- The corresponding *i* - *v* curves of those equivalent circuit models are used to graphically describe the *i* - *v* behavior of the *PV* cell

AN IDEALIZED EQUIVALENT CIRCUIT MODEL OF A *PV* CELL

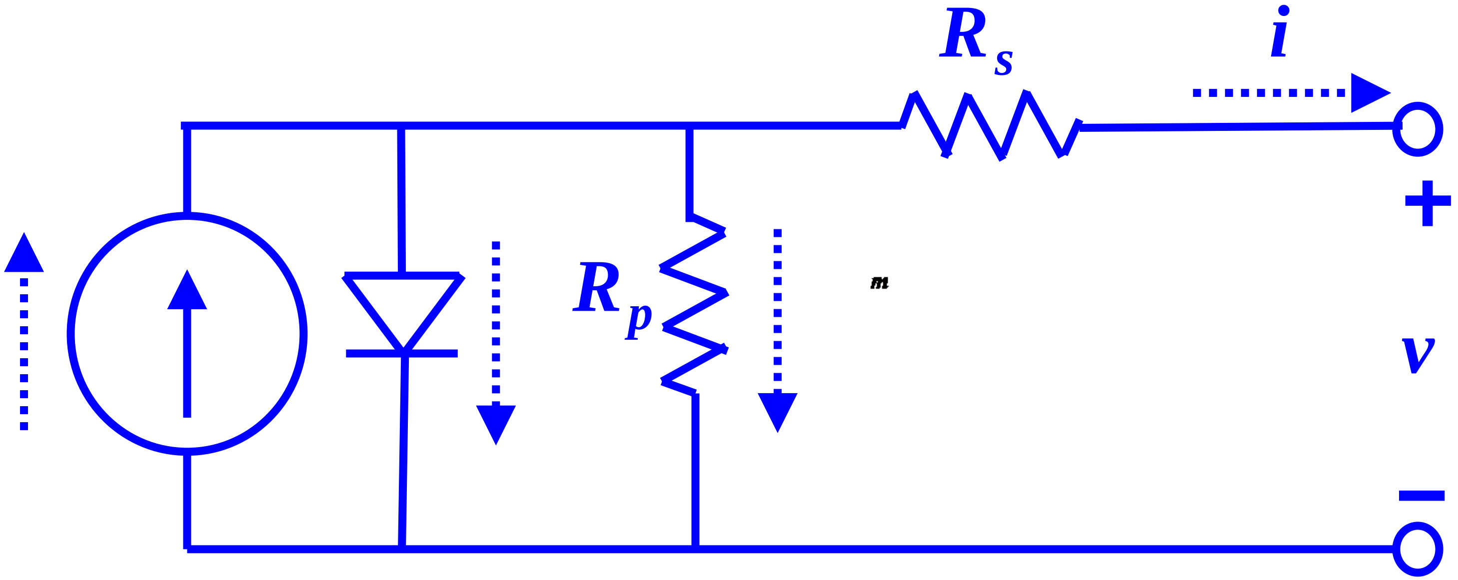




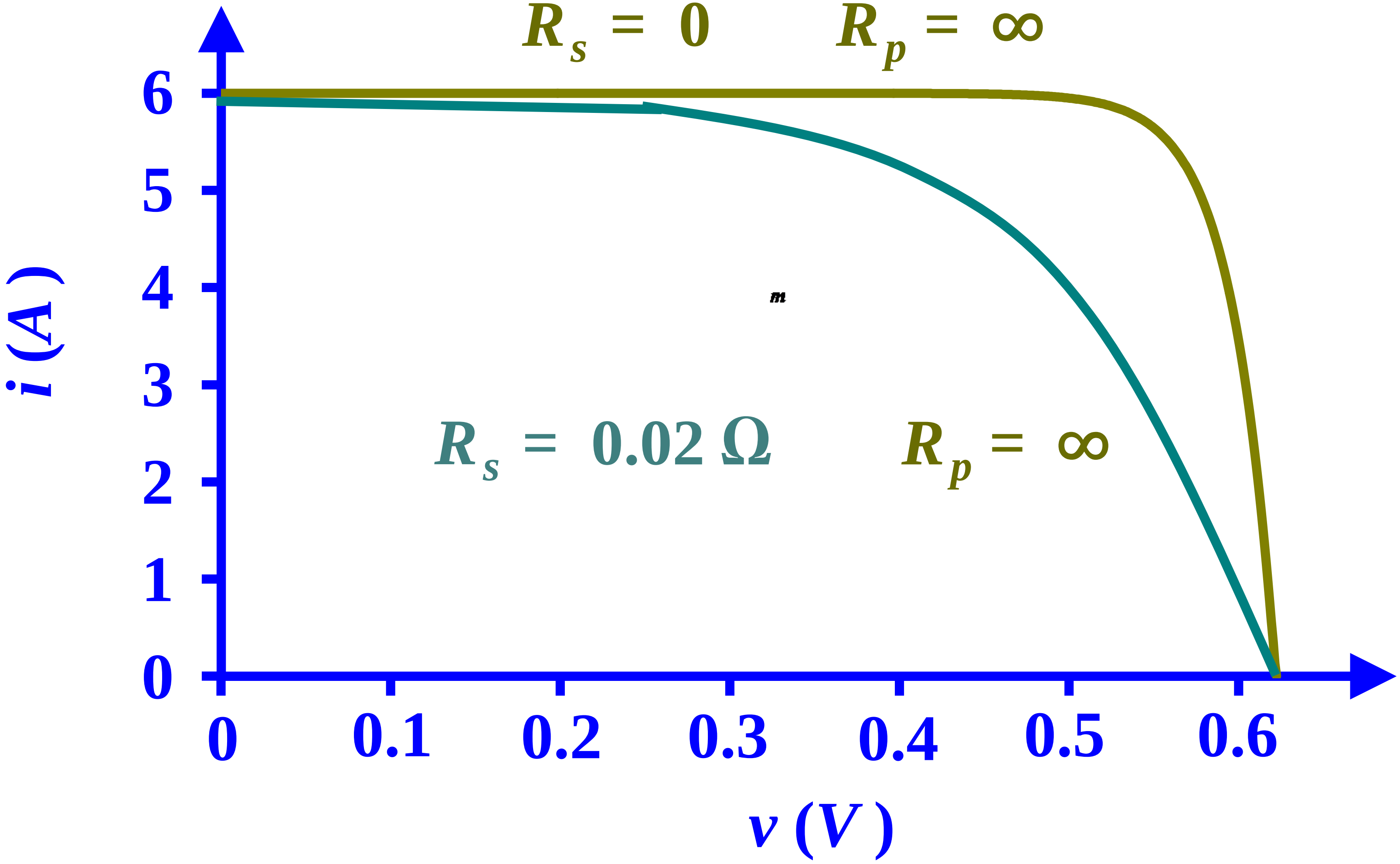
THE *i* - *v* CURVE OF THIS IDEAL EQUIVALENT CIRCUIT OF A *PV* CELL



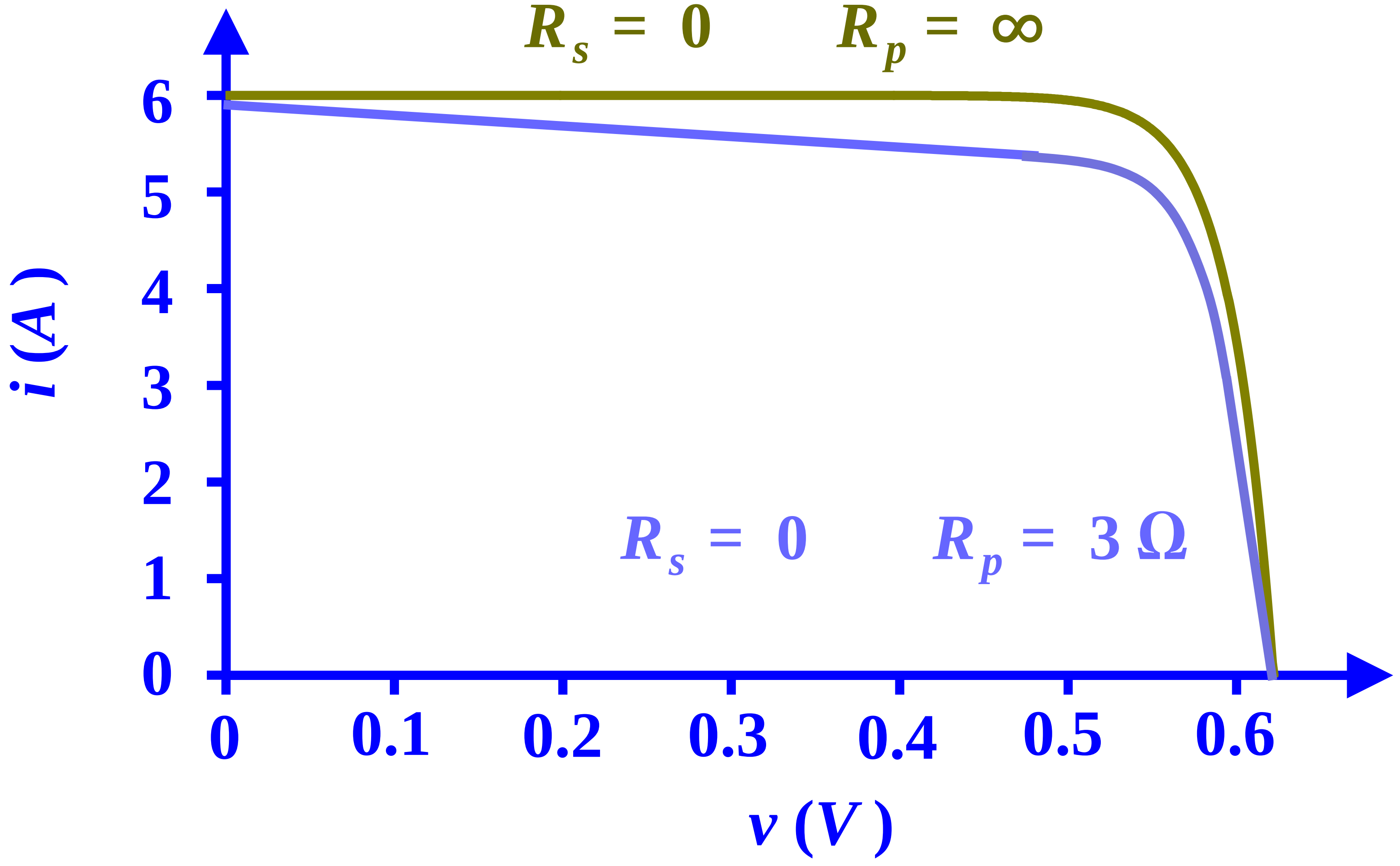
A MORE DETAILED EQUIVALENT CIRCUIT OF A *PV* CELL



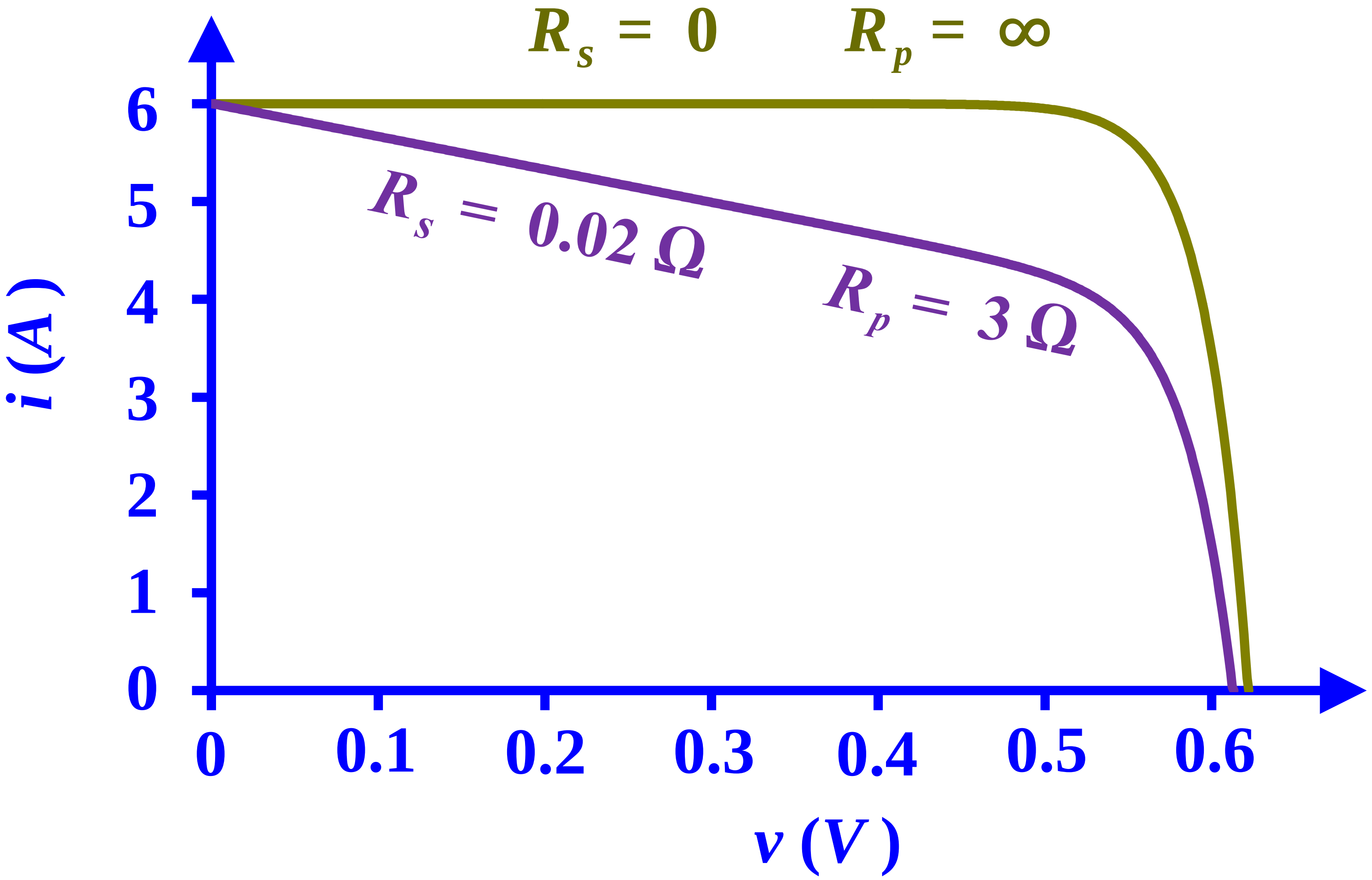
THE *i - v* CURVES OF A MORE DETAILED CIRCUIT OF A *PV* CELL



THE *i - v* CURVES OF A MORE DETAILED CIRCUIT OF A *PV* CELL



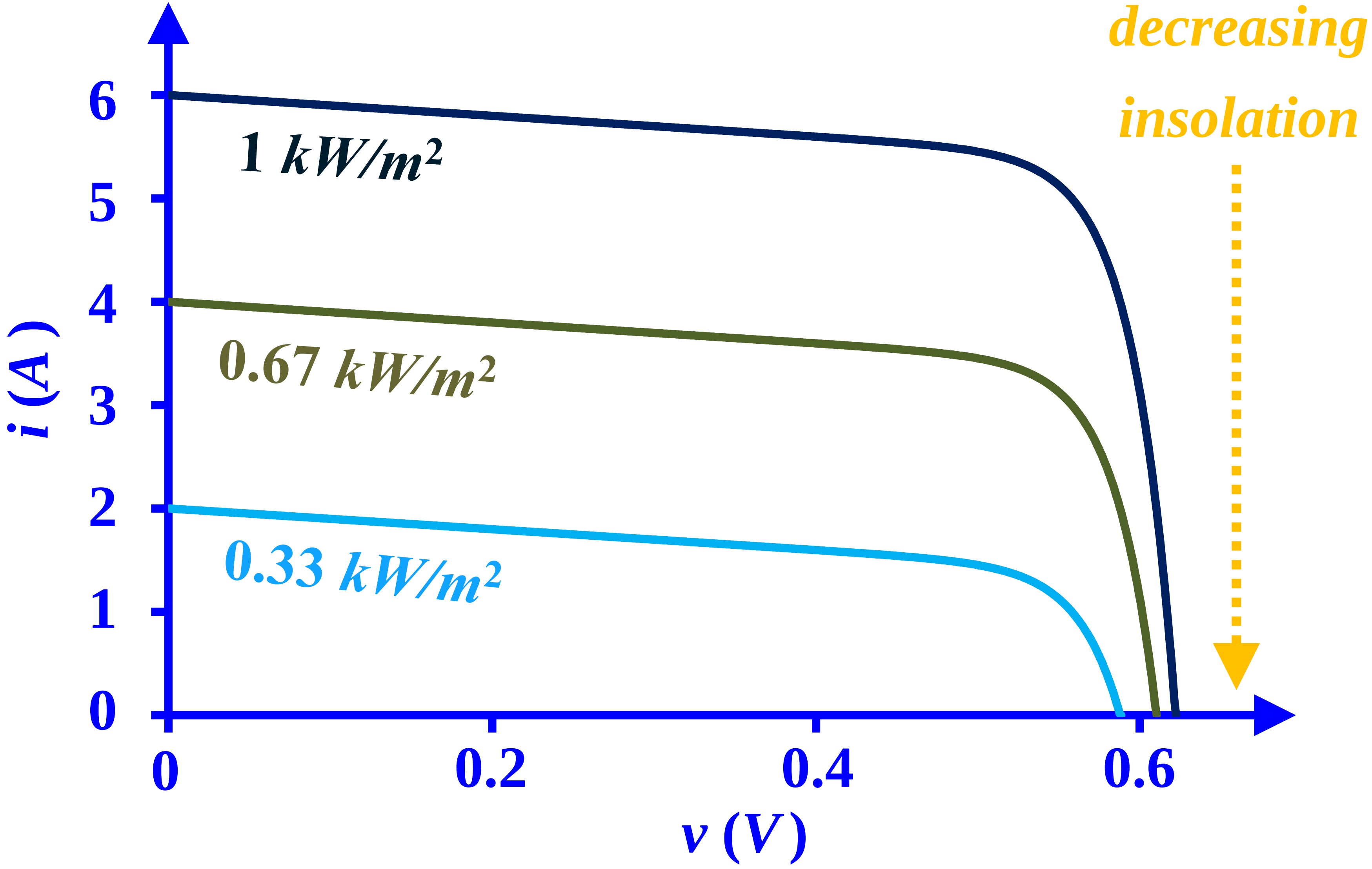
THE i - v CURVES OF A MORE DETAILED CIRCUIT OF A *PV* CELL



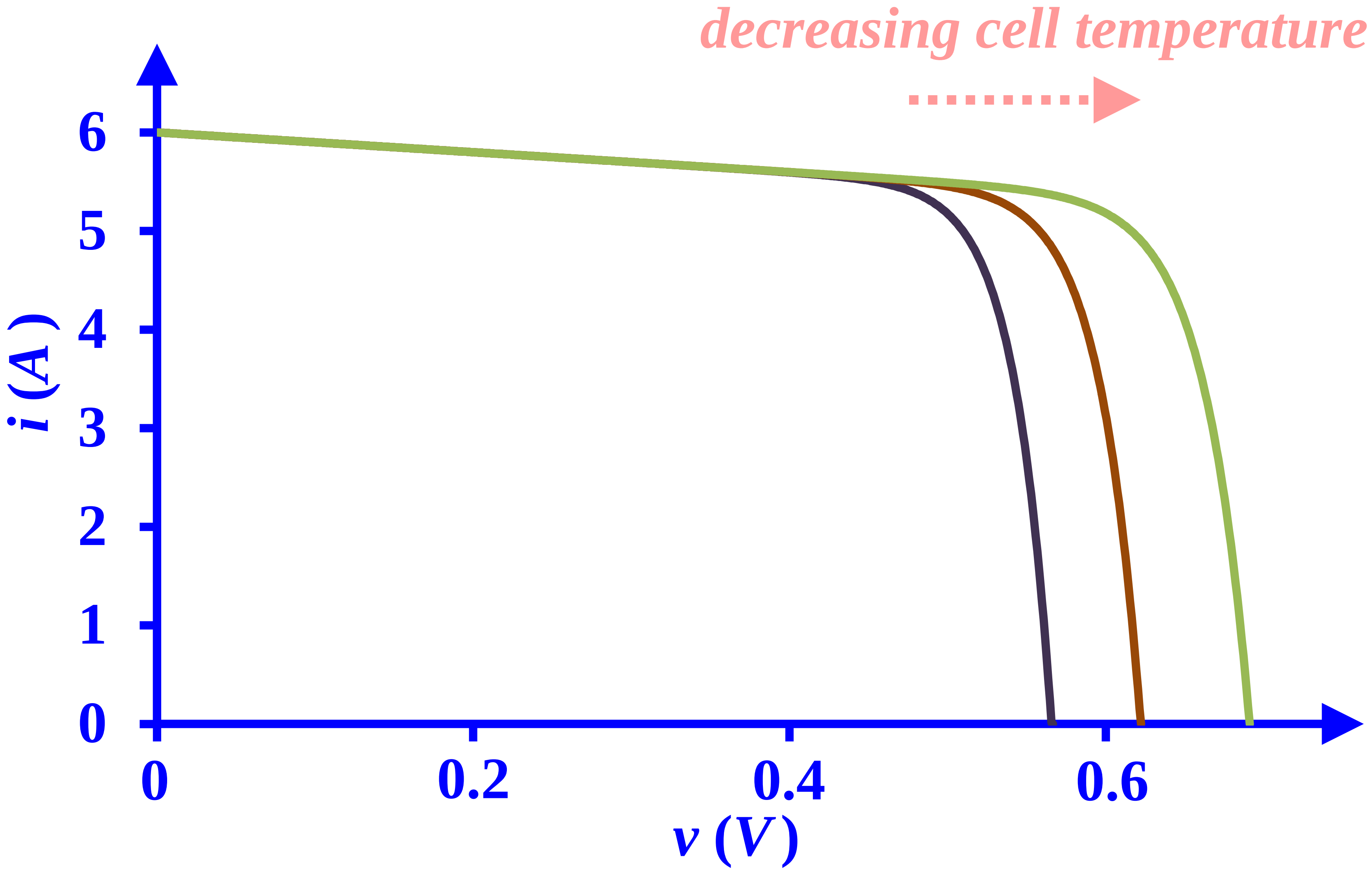
IMPACTS OF INSOLATION AND CELL TEMPERATURE

- ☐ The performance of *PV* cells is a function of the insolation and the cell temperature
- ☐ Manufacturers often provide the *PV* cell i - v curves that indicate its behavior as a function of the insolation and the cell temperature cell

IMPACTS OF INSOLATION ON PV $i-v$ CURVES



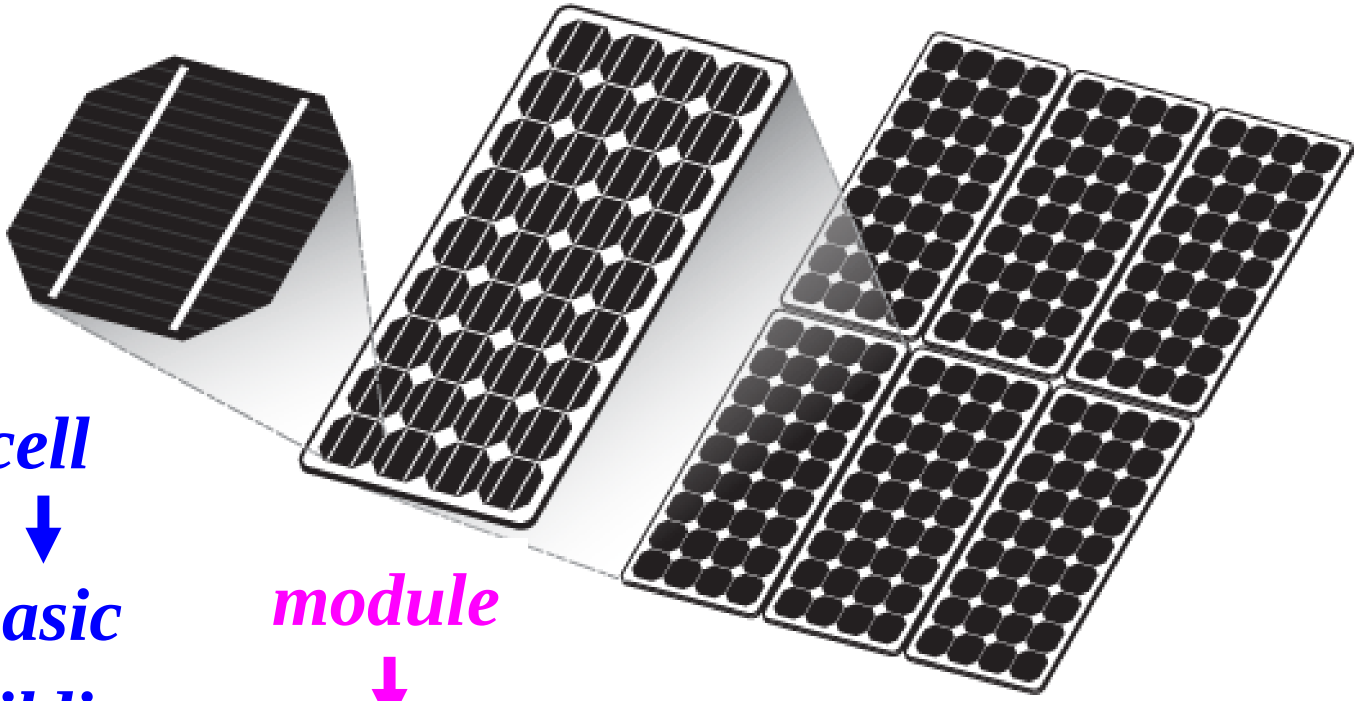
IMPACTS OF CELL TEMPERATURE ON PV $i - v$ CURVES



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 for deployment in energy production**

FROM CELLS TO MODULES TO ARRAYS



cell
↓
basic building block

module
↓
structural configuration

array
↓
solar PV element

Source: http://www.samlexsolar.com/images/learning-center/Solar_Illustration_6.gif

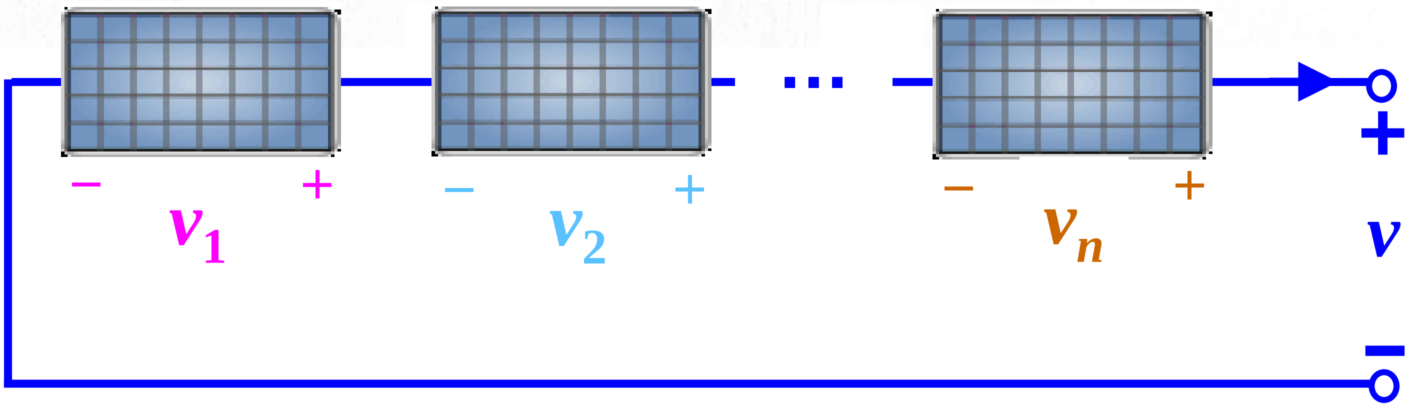
FROM CELLS TO MODULES

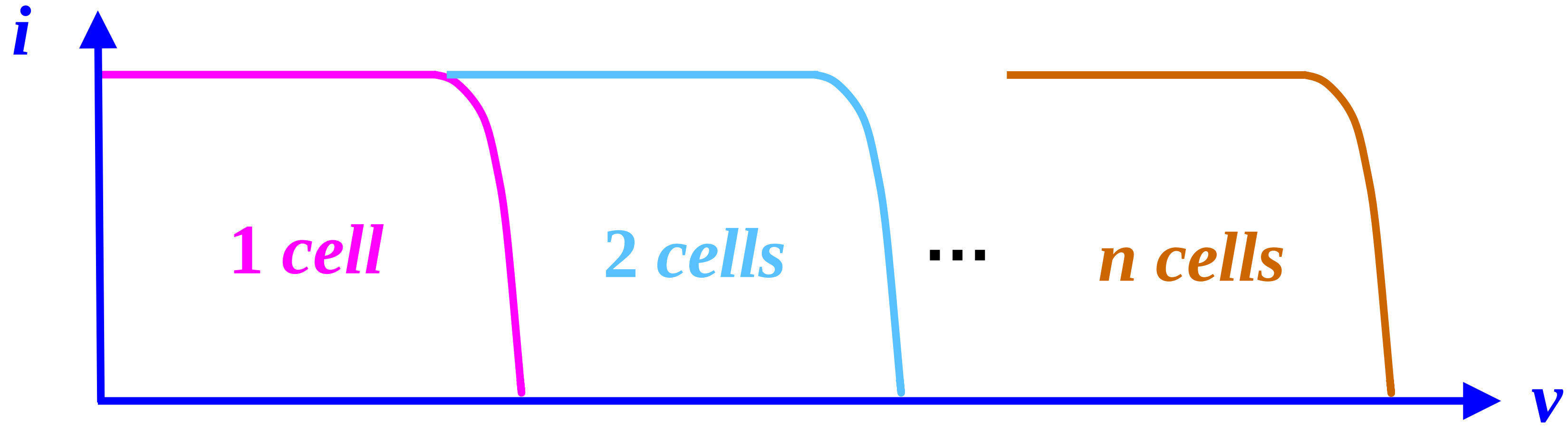
- ❑ **The underlying concept is to connect multiple *PV* cells *in series to increase voltage output* or *in parallel to increase current output* using the *PV* cells that are aggregated to construct a *PV* module**
- ❑ **Typical module sizes consist of 36, 72, 96 or 128 cells with the continuing trend toward increasingly larger systems**

FROM MODULES TO ARRAYS

- **Several modules, in turn, are connected *in series* or *in parallel* to construct the *PV* arrays that form the installation**
- **We make use of circuit analytic concepts to construct the i - v curves of a *PV* module and that of a *PV* array from the individual *PV* cell i - v curves**

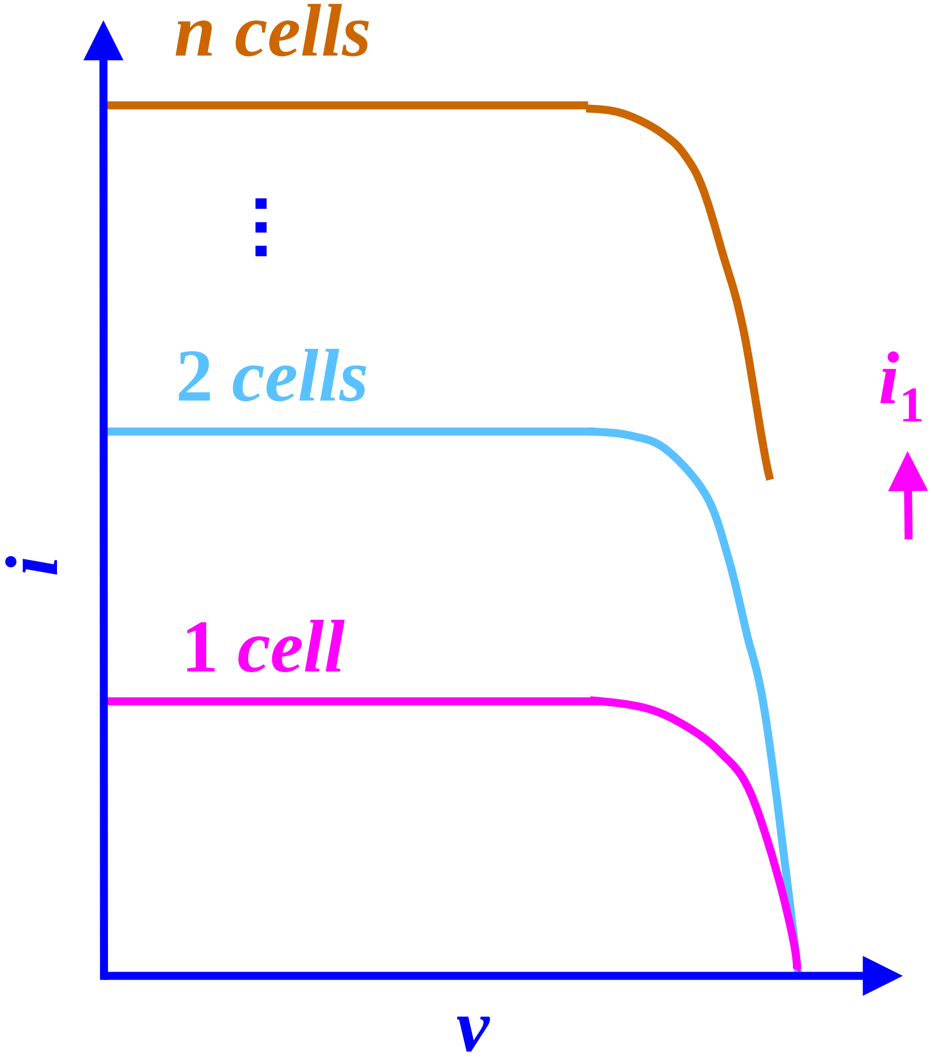
i - *v* CURVE FOR CELLS IN SERIES



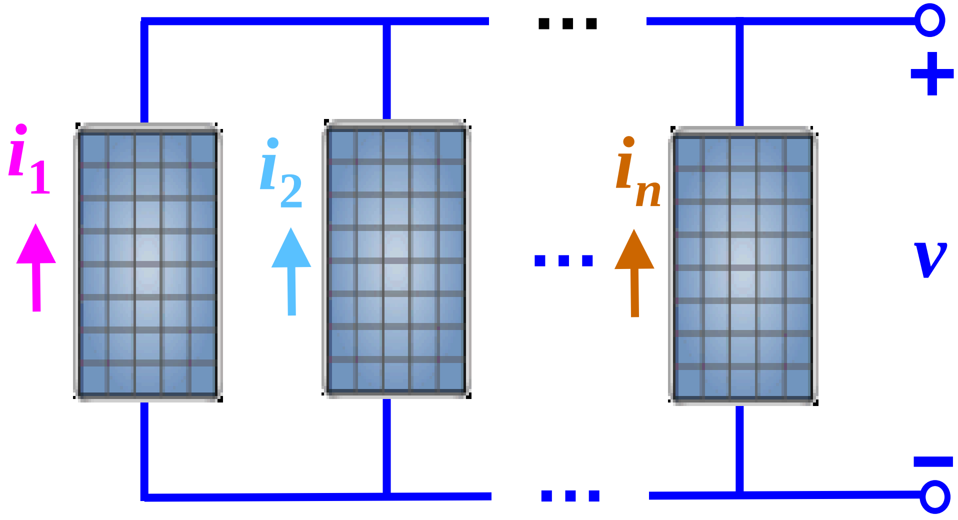


$$v = v_1 + v_2 + \cdots + v_n$$

i - *v* CURVE FOR CELLS IN PARALLEL



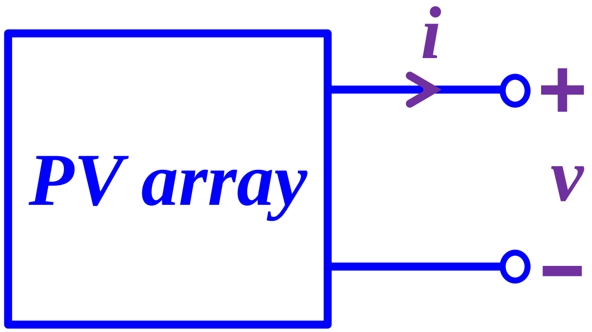
$$i = i_1 + i_2 + \cdots + i_n$$



POWER OUTPUT FOR A *PV* ARRAY

- 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 – an important metric used in *PV* array energy production

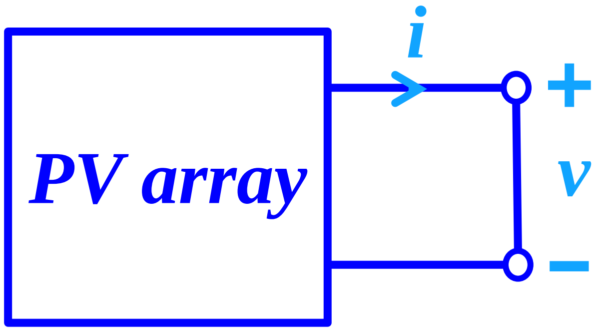
POWER OUTPUT FOR A *PV* ARRAY



$i = 0$

$v = v_{oc}$

open circuit conditions



$i = i_{sc}$

$v = 0$

short circuit conditions

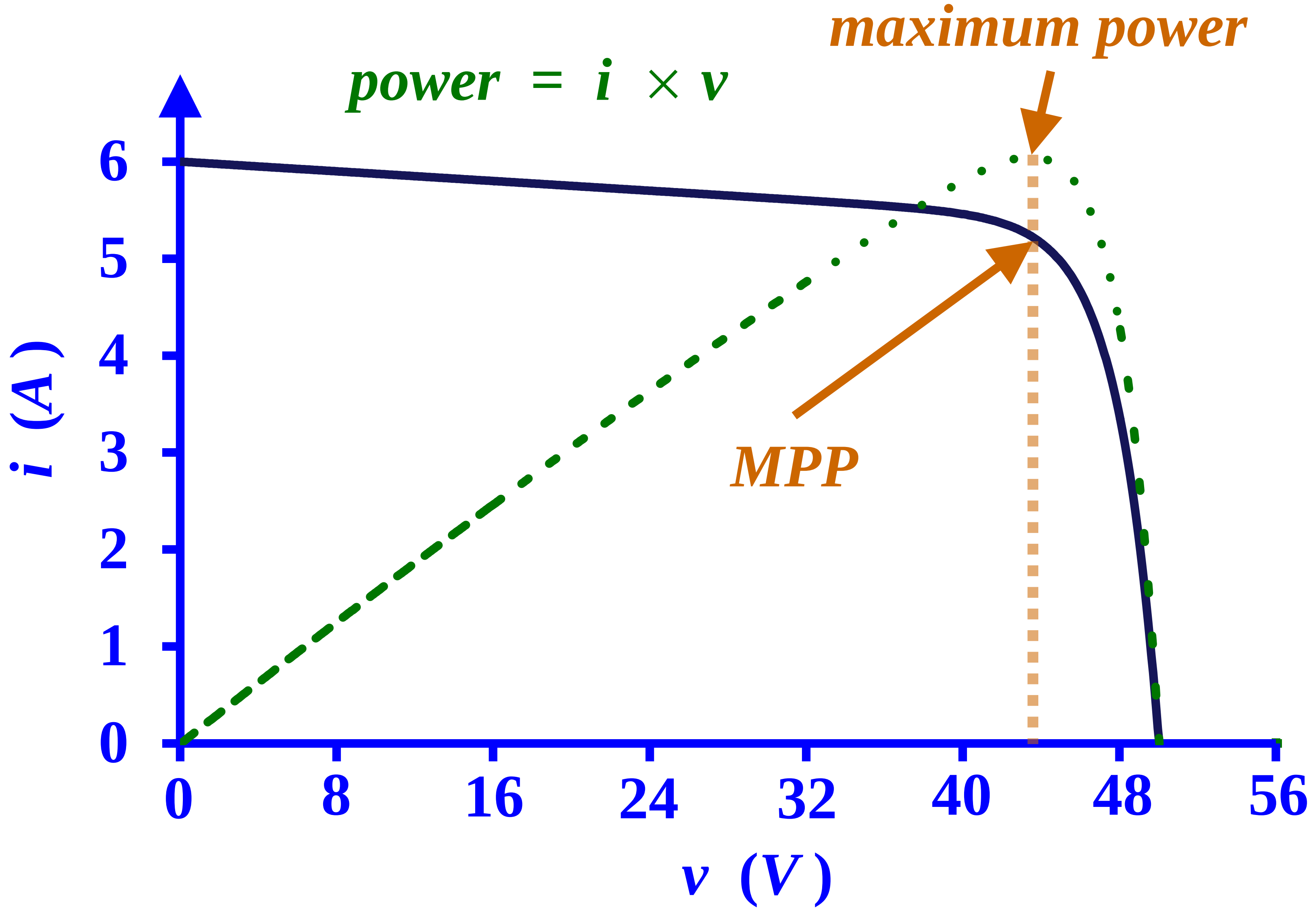
$$power = i \times v = 0$$

under either condition

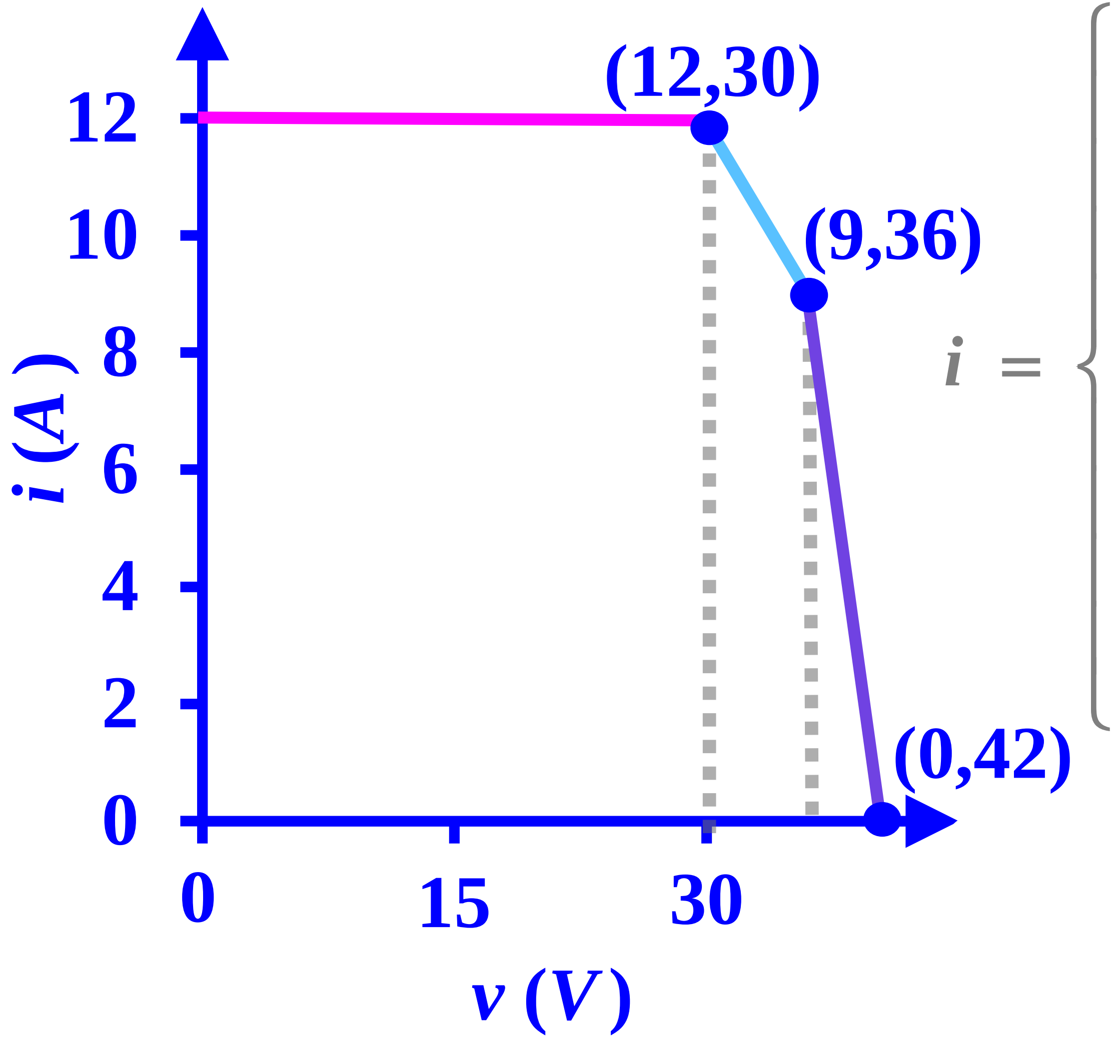
POWER OUTPUT FOR A *PV* ARRAY

- ❑ **The connection of a load across the *PV* array terminals results in a *non-zero current* and a *non-zero voltage* combination, which determines the instantaneous power output of the *PV* array**
- ❑ **In general, we aim to get the *PV*s to deliver the *maximum power* by setting the current/voltage to attain the *maximum power operating point* (*MPP*)**

MAXIMUM POWER POINT FOR A *PV* ARRAY



EXAMPLE: A PIECE-WISE LINEAR $i - v$ CURVE



$$i = \begin{cases} 12 & 0 \leq v \leq 30 \\ 27 - 0.5\,v & 30 < v \leq 36 \\ 63 - 1.5\,v & 36 < v \leq 42 \\ 0 & \textit{otherwise} \end{cases}$$

EXAMPLE: THE PIECE-WISE LINEAR *i* - *v* CURVE POWER OUTPUT

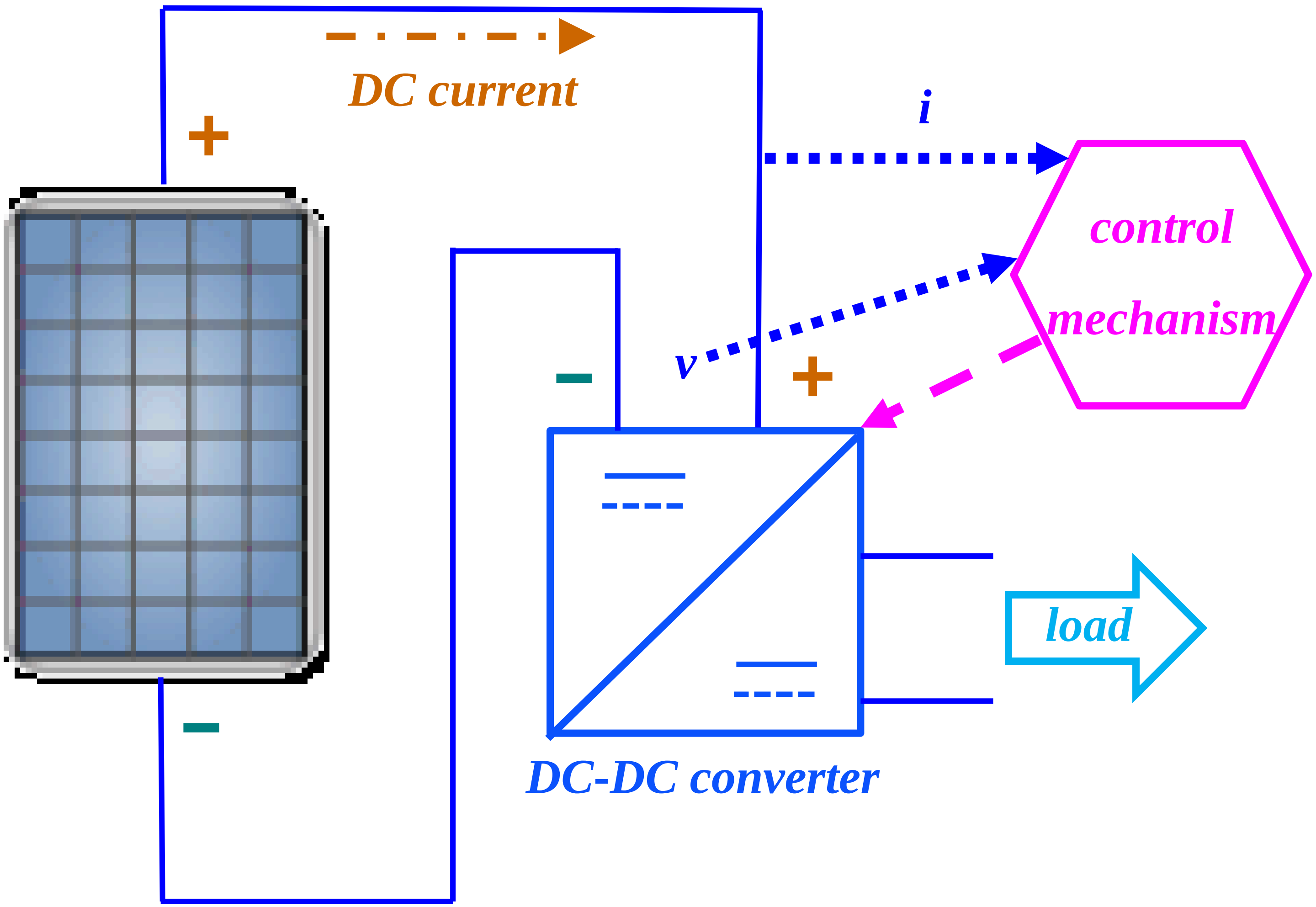
$$p = i \times v = \begin{cases} 12\,v & 0 \leq v \leq 30 \\ -0.5\,(v - 27)^2 + 0.5 \cdot 27^2 & 30 < v \leq 36 \\ -1.5\,(v - 21)^2 + 1.5 \cdot 21^2 & 36 < v \leq 42 \\ 0 & otherwise \end{cases}$$

$p^M = 360\,W$ at $v_{MPP} = 30\,V,\ i_{MPP} = 12\,A$

MAXIMUM POWER POINT TRACKER

- ❑ 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



MPPT

- 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 *MPP* are
  - *fractional open-circuit voltage* method
  - *perturb and observe* technique

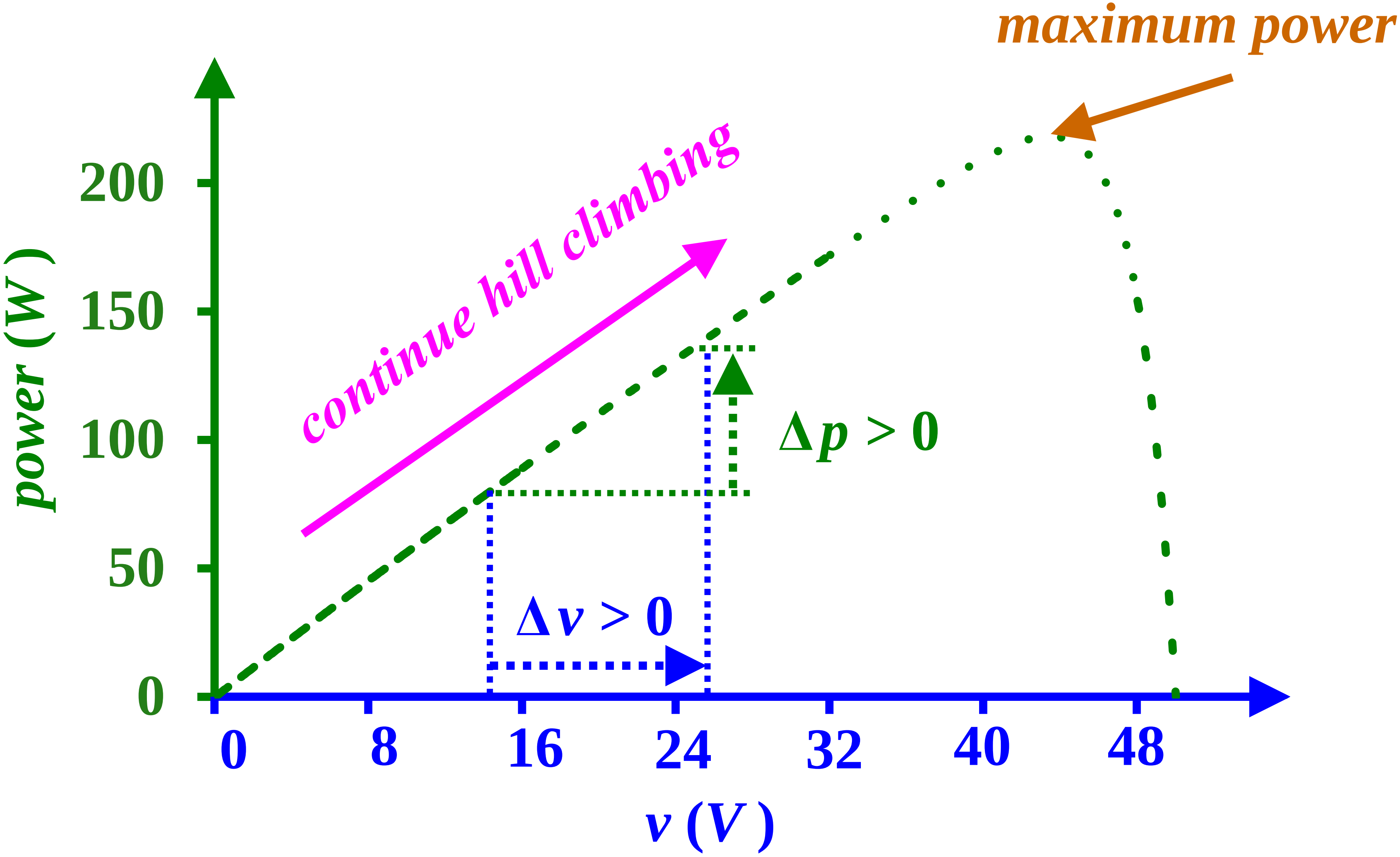
FRACTIONAL OPEN-CIRCUIT VOLTAGE METHOD

- *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 keep operating over longer periods, their open-circuit voltages are reduced and so are the values used for *MPPT*

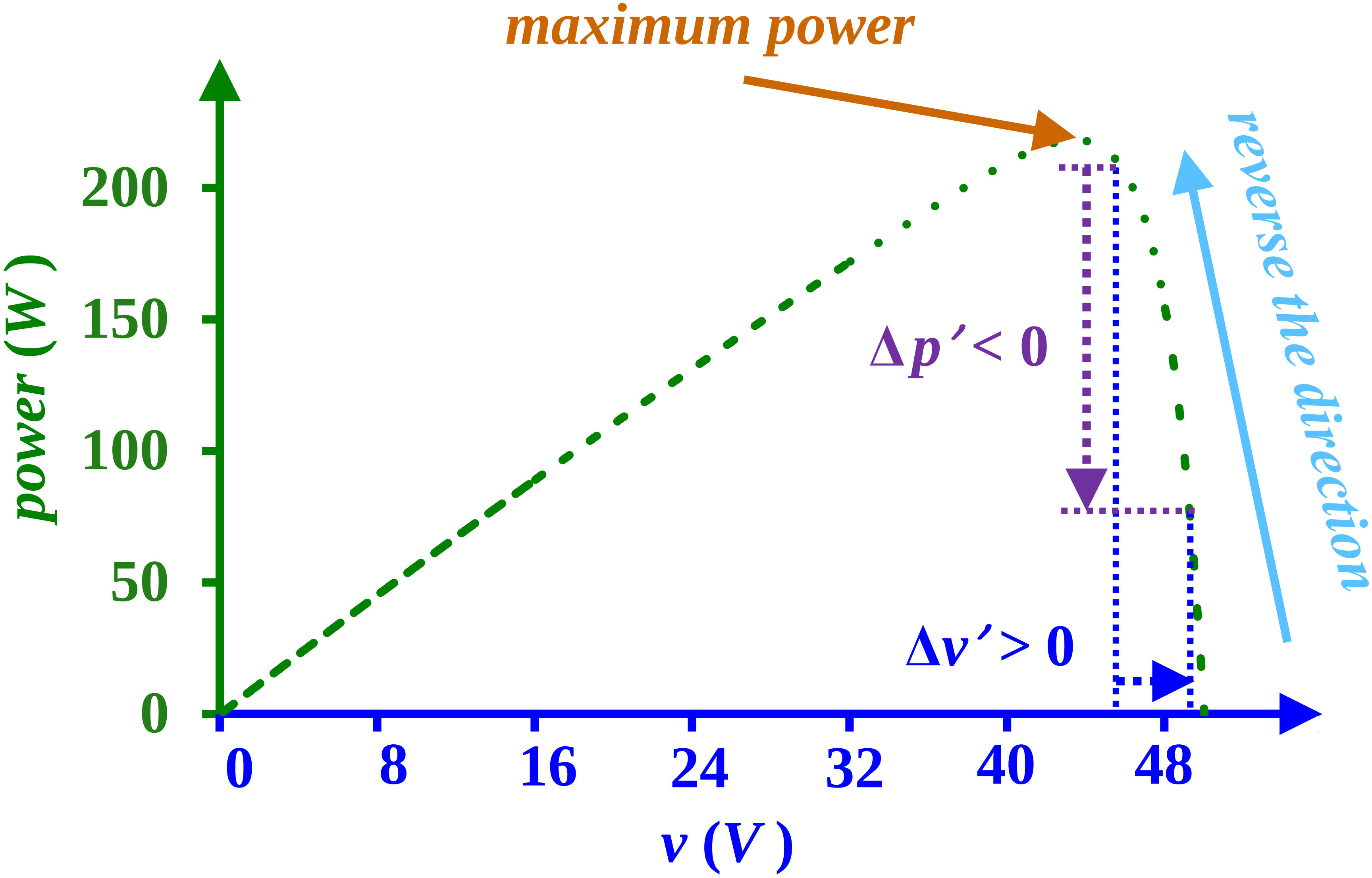
PERTURB AND OBSERVE

- *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 disturbance**

PERTURB AND OBSERVE



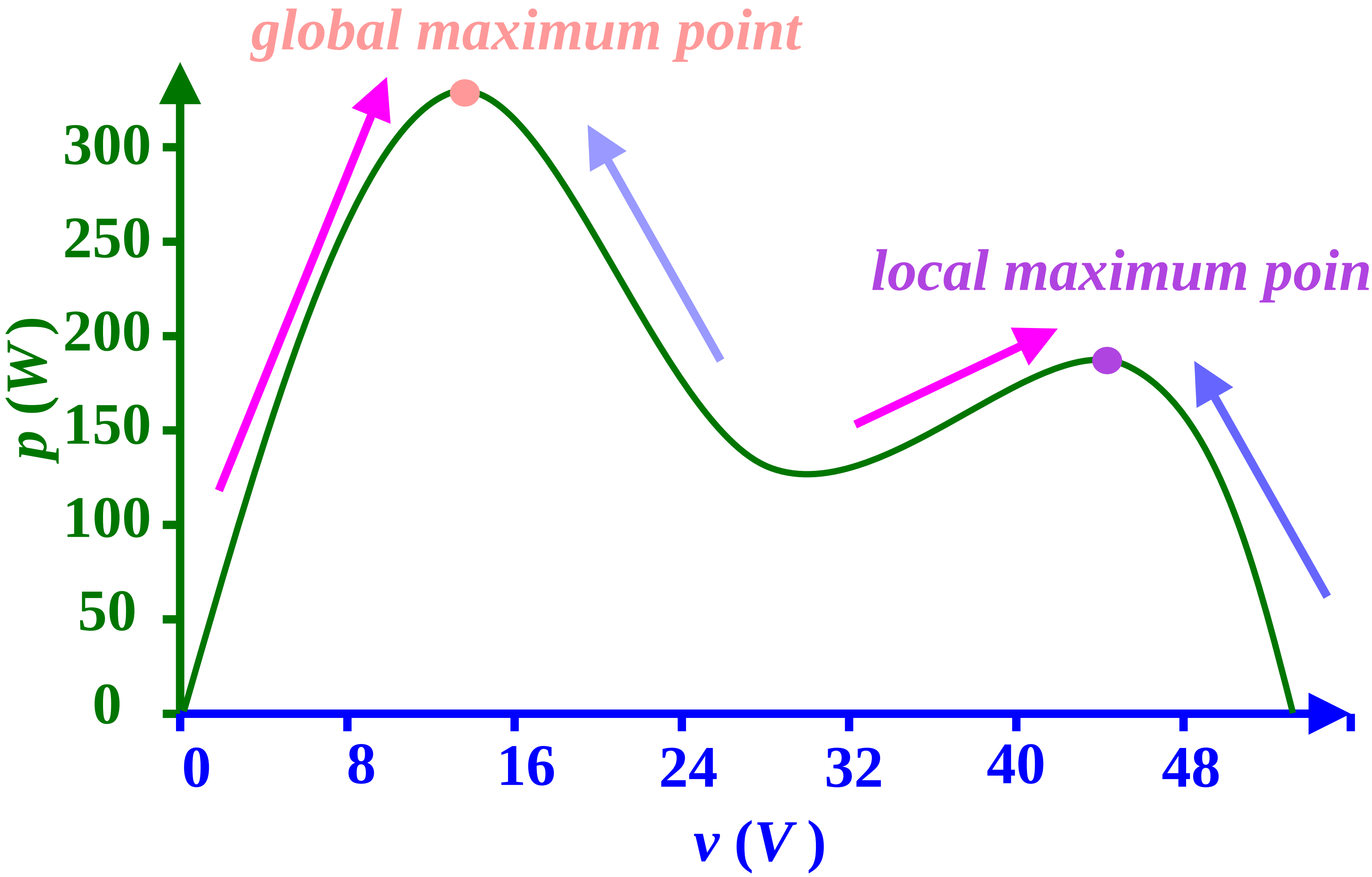
PERTURB AND OBSERVE



MPPT METHODS

- ❑ The two presented *MPPT* schemes are conceptually quite simple and have only limited application
- ❑ To handle more general/realistic situations, some necessary modifications of the *MPPT* algorithms need to be made to solve actual *MPPT* problems such as for more complex $i - v$ curves that result from the presence of partial shadow on the *PV*

MAXIMUM POWER POINT TRACKER METHODS

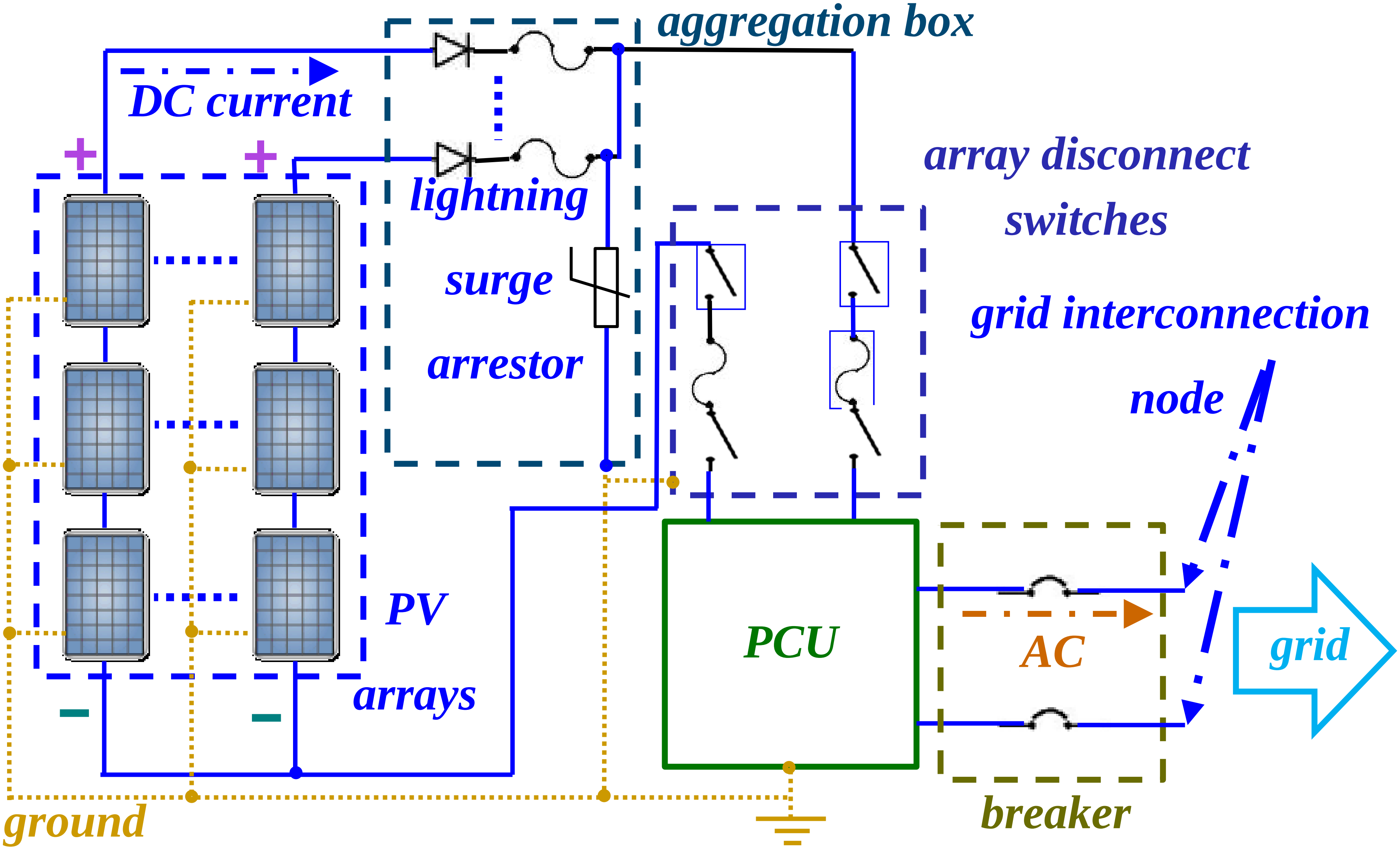


PV SYSTEMS

- *PV* arrays, equipped with *MPPT*s, may be used to charge batteries for energy storage purposes
- However, a *MPPT* is not sufficient 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



PRINICPAL 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; important functions are the aggregation of the currents from all the strings of *PV* modules and the delivery of *DC* power to a fused array disconnect switch**

PRINICPAL COMPONENTS OF A GRID-CONNECTED *PV* SYSTEM

- ☐ The array *disconnect switches* are used to isolate the *PV* array in case 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

THE *PCU* ELEMENT

- ☐ In some *PCU* installations, the *DC-DC* converter of the *MPPT* is not needed because the *DC -AC* converter is instead used to set the *PV* array voltage and to convert the *DC* 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 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 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**

PV MODULE SPECIFICATIONS

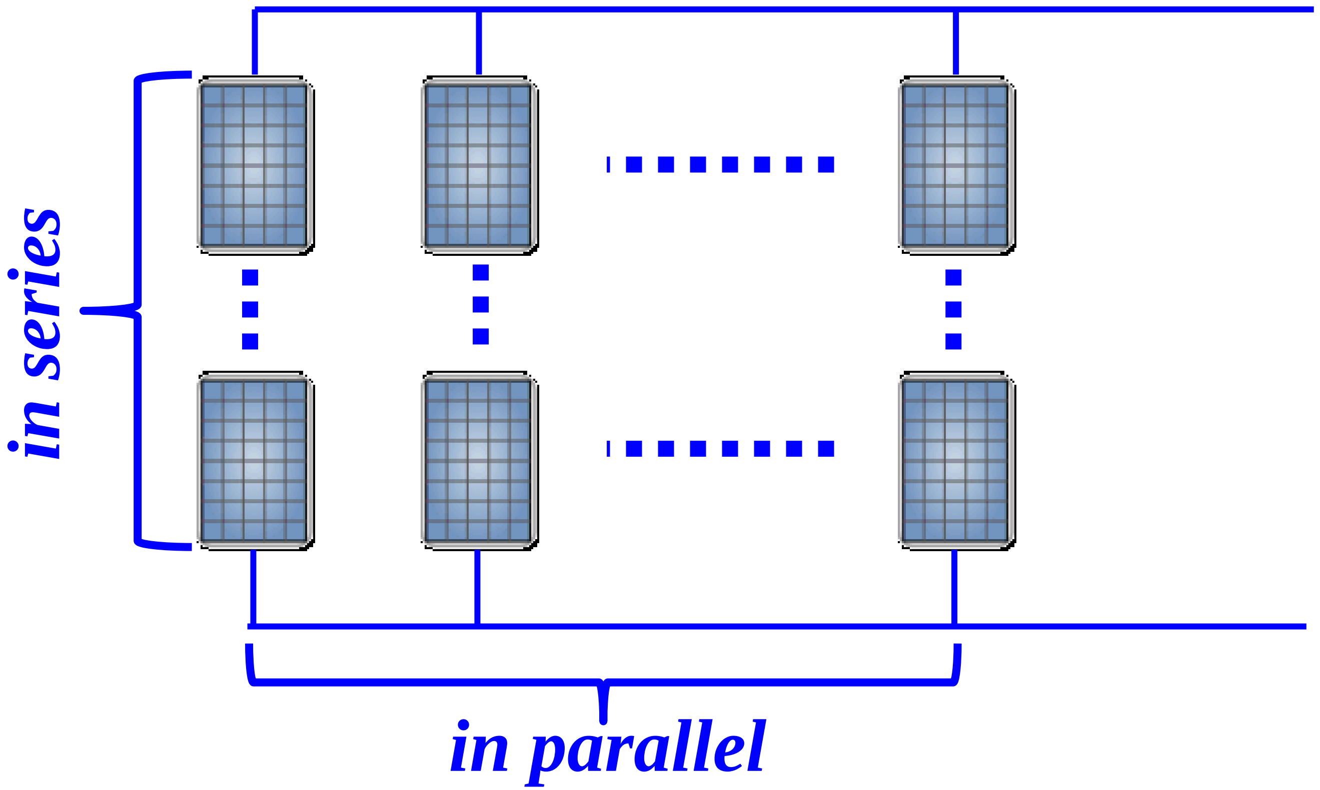
parameter/variable	*symbol*	*value*	*units*
maximum power	p^{M}	**200**	*W* (*DC*)
MPP voltage	v_{MPP}	**50**	*V* (*DC*)
MPP current	i_{MPP}	**4**	*A* (*DC*)
open-circuit voltage	v_{oc}	**60**	*V* (*DC*)
short-circuit current	i_{sc}	**5**	*A* (*DC*)

PCU SPECIFICATIONS

parameter/variable	*symbol*	*value*	*units*
maximum voltage input	v^{M}_{PCU}	730	*V (DC)*
maximum current input	i^{M}_{PCU}	23	*A (DC)*
maximum MPPT voltage input	v^{M}_{MPPT}	620	*V (DC)*
minimum MPPT voltage input	v^{m}_{MPPT}	330	*V (DC)*

EXAMPLE: *PV* ARRAY DESIGN

- ☐ Our goal is to configure the 36 *PV* modules such that every module operates at the *MPP* values



EXAMPLE: *PV* ARRAY DESIGN

- Since some modules are connected in series to form a string with increased voltage output, we determine the value of the number N_s of modules in a string so as to satisfy

$$N_s \leq \min \left\{ \frac{v^M_{PCU}}{v_{MPP}}, \frac{v^M_{MPPT}}{v_{MPP}} \right\} = \min \left\{ \frac{730}{50}, \frac{620}{50} \right\} = 12.4$$

$$N_s \geq \frac{v^m_{MPPT}}{v_{MPP}} = \frac{330}{50} = 6.6$$

EXAMPLE: *PV* ARRAY DESIGN

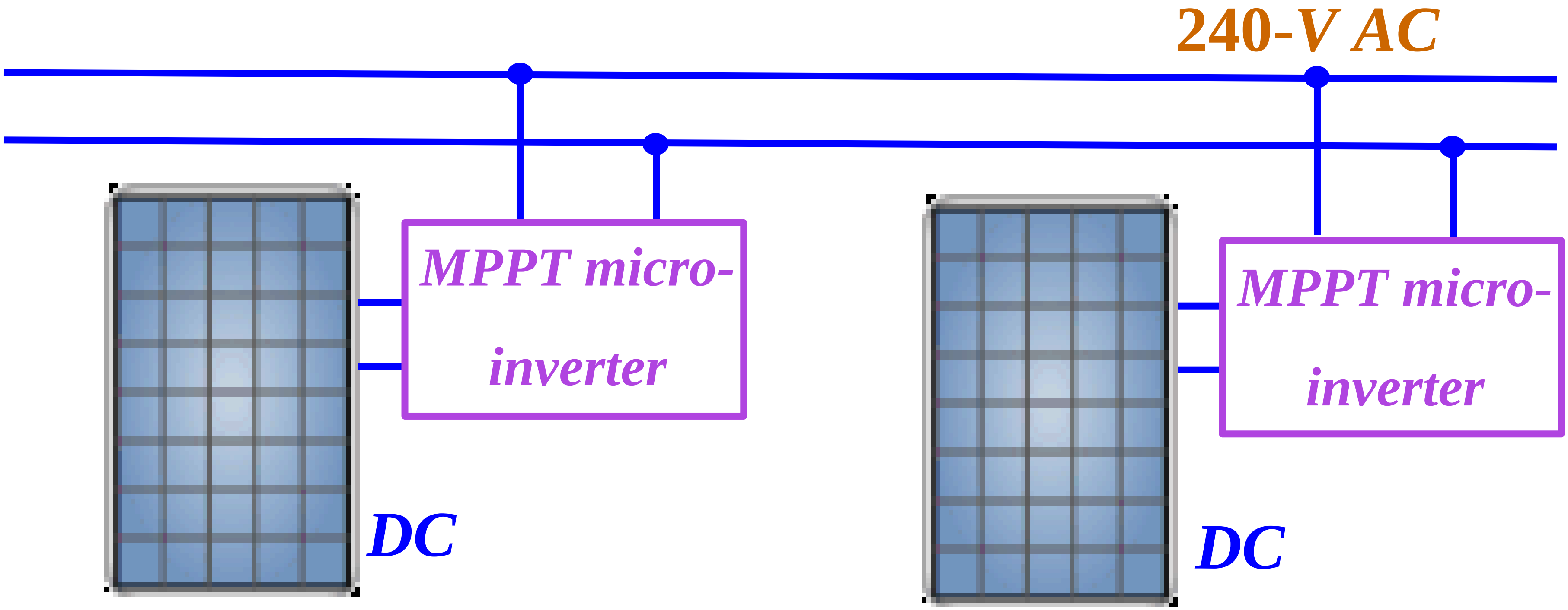
- ❑ **For the modules N_p connected in parallel so as to increase the current output, we determine N_p that satisfies:**

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

- ❑ **Thus, a possible design to meet requirements is an array with 4 parallel strings of 9 *PV* modules in series**

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 the measurable improvement of reliability**
- ☐ **However, the overall costs go up because a single *PCU* is cheaper than a large number of micro-inverters/*MPPT*s for large array systems**

THE TWO GRID-CONNECTED *PV* SYSTEM CATEGORIES

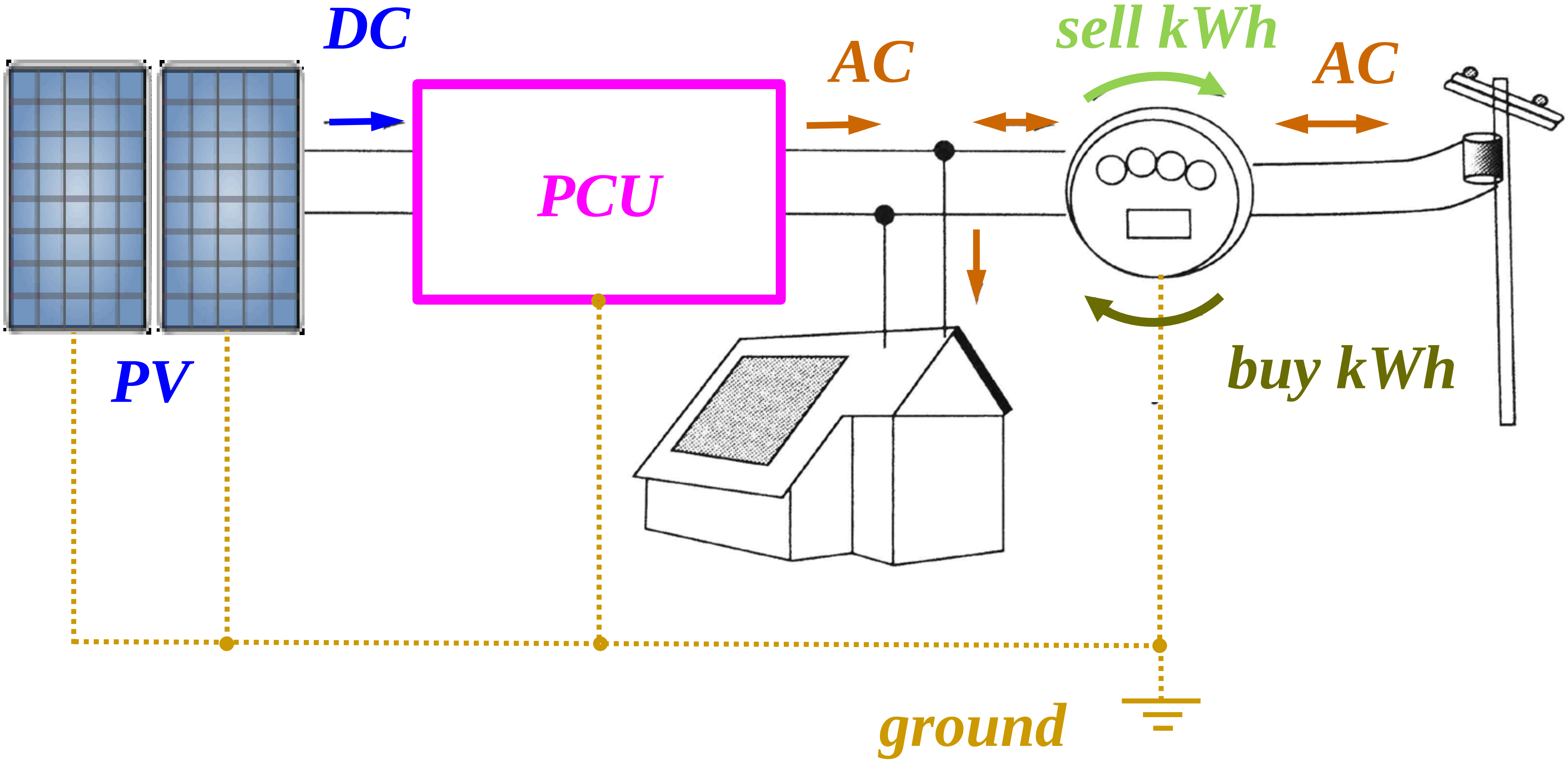
- **Based on which side of the electric meter the *PV*s are located, the grid-connected *PV* systems are classified as either**
  - ***behind-the-meter systems*: are usually installed on rooftops and feed their power outputs directly to the loads on the same side of the meter; or,**

GRID-CONNECTED *PV* SYSTEM CATEGORY

- *systems on the utility side of the meter*: are, generally, larger and whose power outputs are 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

BEHIND–THE–METER GRID–CONNECTED *PV* SYSTEM

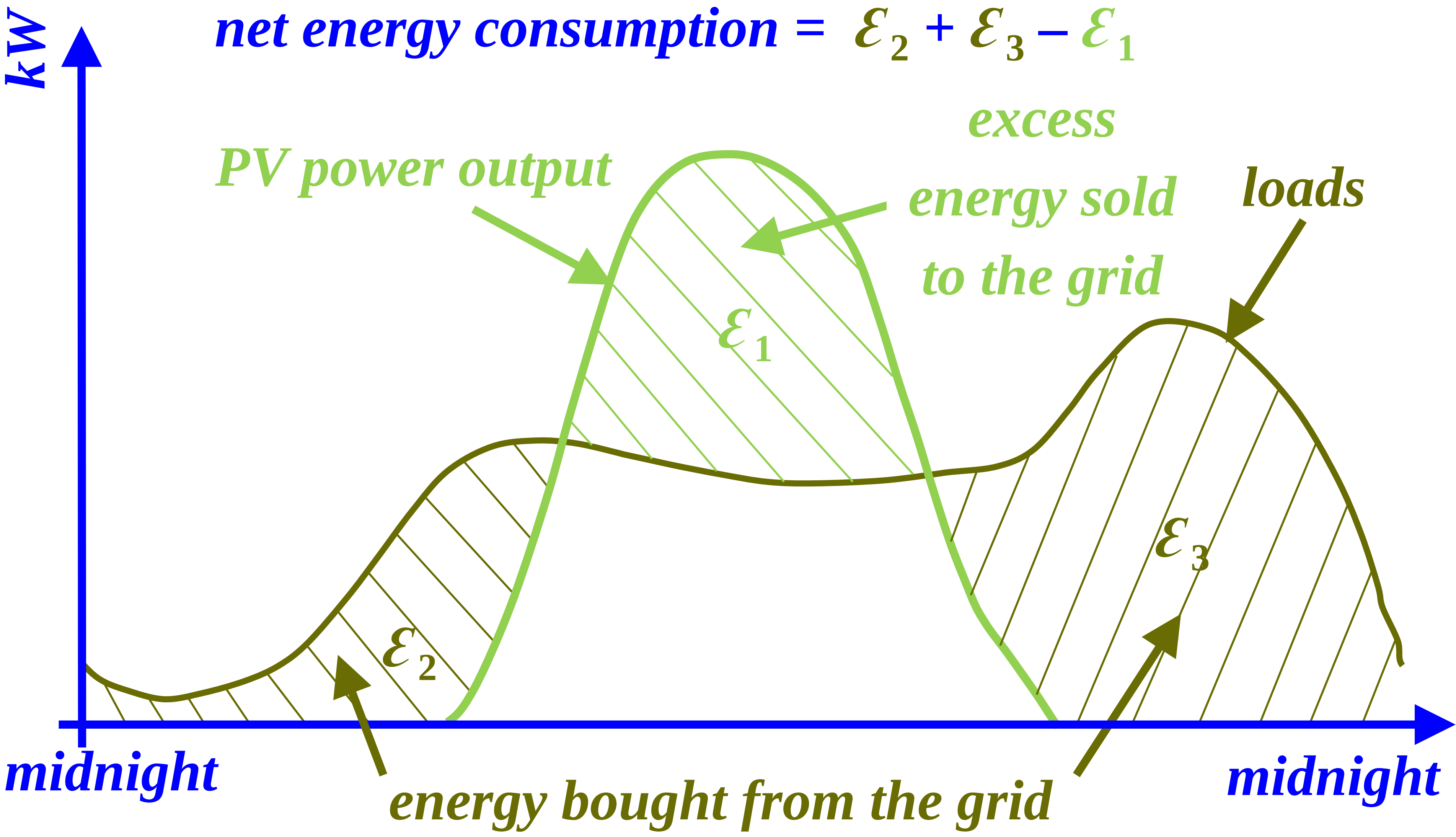


BEHIND–THE–METER GRID–CONNECTED *PV* SYSTEM

- In the case that the loads exceed the energy produced by 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 the loads

NET METERING

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



EXAMPLE: NET METERING OVER A DAY

time	*PV power output (kW)*	*load (kW)*	*net load (kW)*
0:00 – 6:00	**0**	**5**	**5**
6:00 – 9:00	**9**	**15**	**6**
9:00 – 12:00	**45**	**20**	**– 25**
12:00 – 15:00	**45**	**25**	**– 20**
15:00 – 18:00	**9**	**30**	**21**
18:00 – 24:00	**0**	**20**	**20**

EXAMPLE: NET METERING OVER A DAY

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

$$(5 \times 6 + 15 \times 3 + 20 \times 3 + 25 \times 3 + 30 \times 3 + 20 \times 6)$$

$$-(0 \times 6 + 9 \times 3 + 45 \times 3 + 45 \times 3 + 9 \times 3 + 0 \times 6)$$

$$= 96\, kWh / d$$

- ☐ 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

TIME–OF–USE RATES

- **The time–of–use (*TOU*) rates provide customers an opportunity to save by lowering electricity consumption at times of peak demand and encouraging consumption during low load times**
- ***TOU* rates, consequently, stimulate the installation of residential/commercial *PV* systems**

EXAMPLE: TIME–OF–USE RATES OVER A DAY

period	*hours*	*PV output (kW)*	*load (kW)*	*rate ($/kWh)*
off-peak	**0:00 – 6:00**	**0**	**5**	**0.10**
off-peak	**6:00 – 9:00**	**9**	**15**	**0.10**
partial-peak	**9:00 – 12:00**	**45**	**20**	**0.17**
peak	**12:00 – 15:00**	**45**	**25**	**0.27**
peak	**15:00 – 18:00**	**9**	**30**	**0.27**
partial-peak	**18:00 – 24:00**	**0**	**20**	**0.17**

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

- ☐ 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 of the 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 utmost concern to the electricity distribution companies

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, 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 $1\, kW / m^2$ 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*" or 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-*sun***
  - **the cell temperature is, typically, $20^{o} - 40^{o}\ C$ higher than the ambient temperature**
  - **modules tend to get dirty over time**

NON–TEMPERATURE–RELATED *PV* POWER DERATING

- **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* χ**

stc AC power output of the PV system in W

$$p_{AC,\,stc} = p_{DC,stc} \times \chi$$

stc rated DC PV system power output

W_p or W_{stc}

NON–TEMPERATURE–RELATED *PV* POWER DERATING

- ☐ **The *derate factor* χ varies significantly because**
  - ○ **not all of the modules produce under the *stc* as much power as the nameplate rating provided 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

factor	*default*	*range*
PV module DC nameplate rating	**0.95**	**0.80 – 1.05**
converter and transformer	**0.92**	**0.88 – 0.98**
module mismatch	**0.98**	**0.97 – 0.995**
diodes and connections	**1.00**	**0.99 – 1.00**
DC wiring	**0.98**	**0.97 – 0.99**
AC wiring	**0.99**	**0.98 – 0.993**

PVWATTS DERATE FACTORS

factor	*default*	*range*
soiling	**0.95**	**0.30-0.995**
system availability	**0.98**	**0.00-0.995**
shading	**1.00**	**0.00-1.00**
sun tracking	**1.00**	**0.95-1.00**
age	**1.00**	**0.70-1.00**
total non-temperature-related derate factor	**0.77**	**0.00-1.01**

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

$$p_{AC,\,stc} = 72 \times 100 \times 0.77 = 5.544\ kW$$

TEMPERATURE-RELATED *PV POWER DERATE* FACTORS

- ❑ 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*

TEMPERATURE–RELATED *PV* POWER DERATE FACTOR

The approximation of cell temperature is given by

cell temperature

$^{\circ}C$

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

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

$^{\circ}C$

ambient temperature

kW / m^2

TEMPERATURE-RELATED *PV* POWER DERATE FACTOR

- ☐ Then, we introduce a temperature coefficient to account for the impacts of cell temperature

temperature-related

derate factor

temperature coefficient $/\,^{o}C$

$$\chi' = \chi \cdot \left[1 + z\,(\tau_{cell} - 25) \right]$$

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 $0.7\text{-}sun$ and $35^{o}C$ ambient temperature**
- ❑ **The insolation is computed to be**

$$0.7\ sun \times \frac{1\,kW / m^{2}}{1\,sun} = 0.7\,kW / m^{2}$$

- ❑ **Given a *PV* cell with $\tau_{n} = 45^{o}C$, the actual cell temperature is computed to be**

EXAMPLE: TEMPERATURE-RELATED *PV* POWER DERATE FACTOR

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

- ☐ The installation of the *PV* system in the previous example in Chicago with a $-0.5\,\%/{}^{o}\,C$ temperature coefficient, the *AC* power delivered by the system is

$$2.31 \times \left[1 + \left(-0.005 \right) \left(42.3 - 25 \right) \right] = 2.16\ kW$$

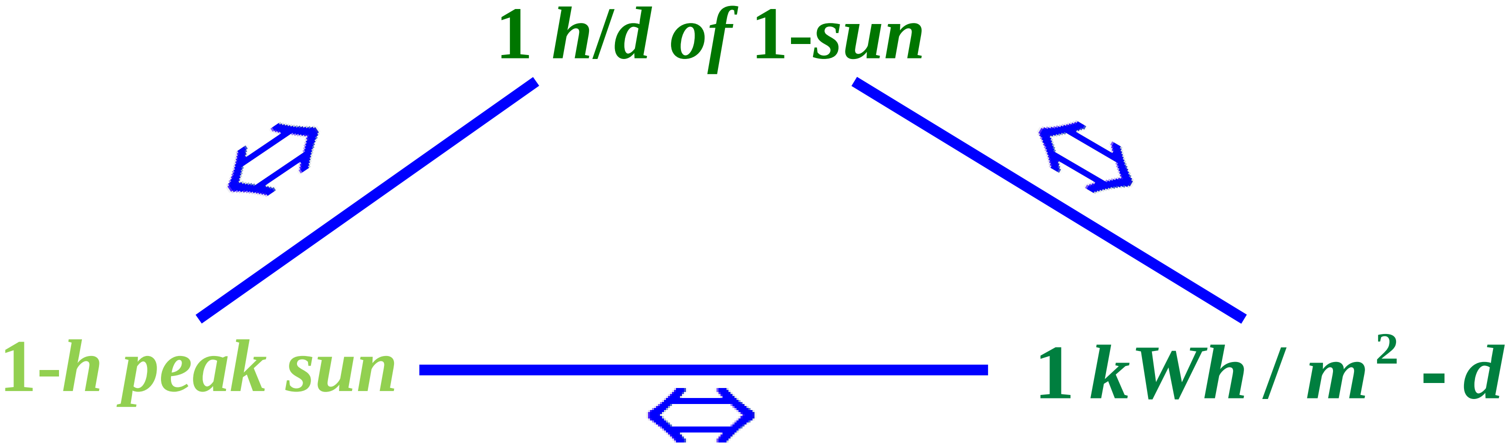
THE PEAK-HOURS APPROACH TO ESTIMATE *PV* PERFORMANCE

- ☐ **The methods discussed introduce *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*

$1\ kWh/m^2 - d$

- For example, an average daily insolation of $5.5\ kWh/m^2 - d$ is equivalent to 1-*sun* ($1\ kW/m^2$) for 5.5 *hours* and the same as 5.5-*hours* of peak-sun

THE PEAK-HOURS APPROACH TO ESTIMATE *PV* PERFORMANCE

- ❑ **Assume that the system efficiency remains constant over time**
- ❑ **Therefore, we can write the daily *PV* system delivered energy as**

$$\overset{kWh/d}{\textit{daily energy}} = \underset{kWh/m^2\text{-}d}{\textit{daily insolation}} \times \overset{PV\ array\ area\ \ m^2}{\textit{area}} \times \underset{\textit{average system efficiency}}{\bar{\eta}}$$

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

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

$$\uparrow$$

the system efficiency under 1-*sun*

- Thus for arbitrary insolation

$$daily\ energy = p_{AC} \times \left(\frac{daily\ insolation}{1\,kW / m^2} \right) \times \frac{\bar{\eta}}{\eta_{1-sun}}$$

THE PEAK-HOURS APPROACH TO ESTIMATE *PV* PERFORMANCE

- If we assume that the average system efficiency is equal to the efficiency under 1-*sun*

$$daily\ energy = p_{AC} \times \underbrace{\left(\frac{daily\ insolation}{1\,kW / m^2} \right)}_{number\ of\ hours\ of\ peak\ sun\ per\ day}$$

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**

$$\textit{annual energy} \longleftarrow kWh/y$$

$$= p_{DC,stc} \times \chi' \times \left(\frac{\textit{daily insolation}}{1\, kW/m^2} \right) \times 365$$

EXAMPLE: ANNUAL ENERGY OF A SOLAR FARM AT CHAMPAIGN

- ☐ A $82,961\text{–}m^2$ solar farm on the south campus is considered as a key part of the University of Illinois’ Climate Change Program

- ☐ The average daily insolation received by the panels in the solar farm project is 5.1 $kWh / m^2 \text{-} d$

EXAMPLE: ANNUAL ENERGY OF A SOLAR FARM AT CHAMPAIGN

- ☐ Assume the capacity of the arrays under *stc* is $6\ MW_p$ and χ' equals to 0.7, the annual energy is

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

- ☐ 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 estimate the *c. f.* of a grid-connected *PV* system**

- **The commonly used equation to approximate the *PV* capacity factor $c.f._{DC}$ is given by**

$$annual\ energy \; = \; p_{DC,stc} \times c.f._{DC} \times 8{,}760$$

CAPACITY FACTORS FOR GRID-CONNECTED *PV* SYSTEMS

- ☐ **Substitute the peak-hours approach equations into the capacity equation**

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

- ☐ **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 average daily insolation in Chicago is $4.86\ kWh/m^2\text{-}d$ and $\chi' = 0.7$

$$p_{DC,stc} = \frac{11,000}{0.7 \times \left(\frac{4.86}{1}\right) \times 365} = 8.84\ kW_p$$

- ☐ We select the *SunPower* 240-*W PV* module and the *SunPower* 5000 *PCU* with the following parameters

SunPower PV MODULE SPECIFICATIONS

parameter/variable	*symbol*	*value*	*units*
maximum power	p_m	240	*W (DC)*
MPP voltage	v_{MPP}	40	*V (DC)*
MPP current	i_{MPP}	6	*A (DC)*
open-circuit voltage	v_{oc}	60	*V (DC)*
short-circuit current	i_{sc}	5	*A (DC)*

SunPower *PCU* SPECIFICATIONS

parameter/variable	*symbol*	*value*	*units*
maximum voltage input	v_{PCU}^{M}	730	*V (DC)*
maximum current input	i_{PCU}^{M}	36	*A (DC)*
maximum MPPT voltage input	v_{MPPT}^{M}	500	*V (DC)*
minimum MPPT voltage input	v_{MPPT}^{m}	160	*V (DC)*

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

EXAMPLE: *PV* SYSTEM SIZING IN CHICAGO

$$N_s \leq \min\left\{ \frac{v^{M}_{PCU}}{v_{MPP}}, \frac{v^{M}_{MPPT}}{v_{MPP}} \right\} = \min\left\{ \frac{730}{40}, \frac{500}{40} \right\} = 12.5$$

$$N_s \geq \frac{v^{m}_{MPPT}}{v_{MPP}} = \frac{160}{40} = 4$$

- ☐ For modules connected in parallel, the number of modules N_p must satisfy

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

EXAMPLE: *PV* SYSTEM SIZING IN CHICAGO

- **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**

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

- **The capacity factor of the configuration is**

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