ECE 333 – GREEN ELECTRIC ENERGY

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

SEMICONDUCTOR

- ☐ 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

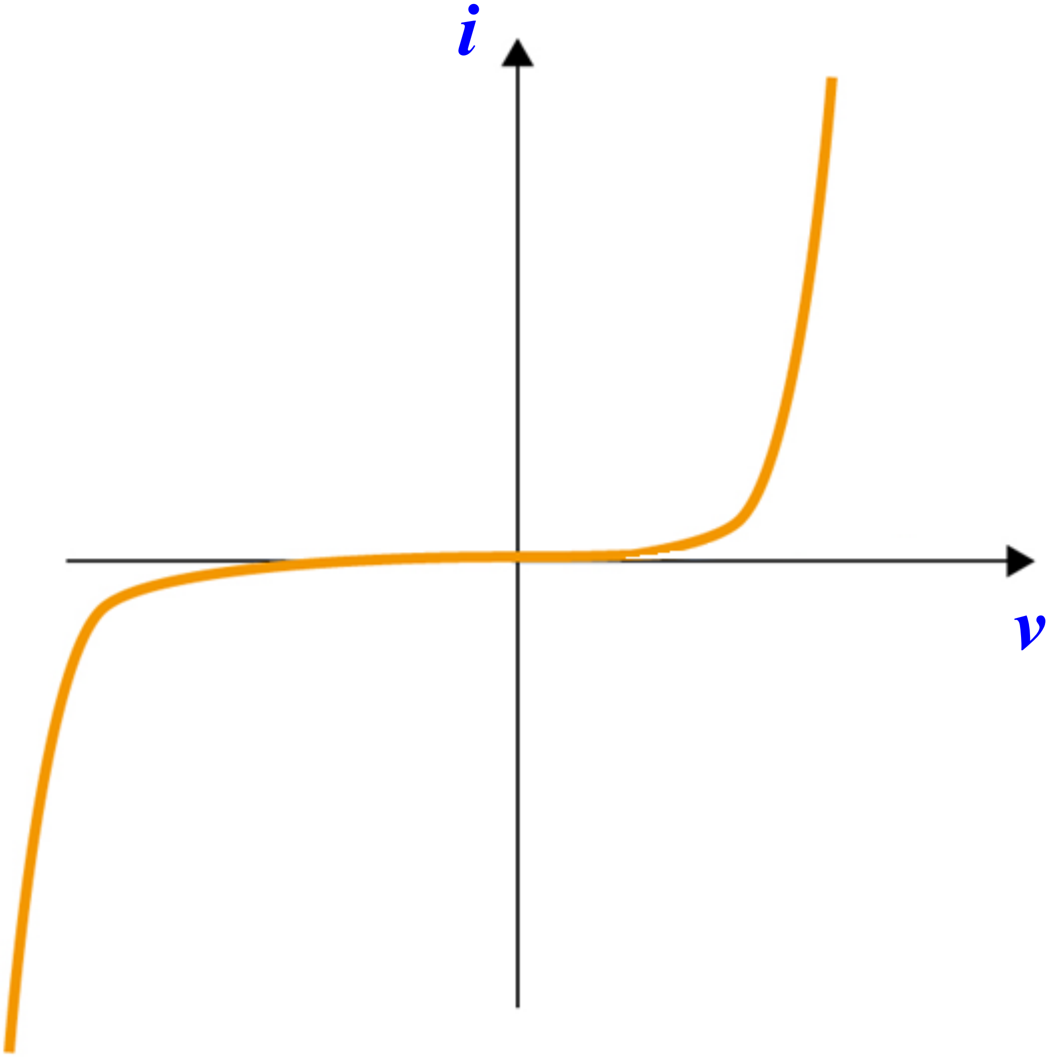
- ☐ The *diode* was one of the first semiconductor electronic devices
- ☐ The *diode* is a two–terminal electronic component, composed of two semiconductor materials
- ☐ When a voltage is applied across the diode terminals, the electric field formed in the diode

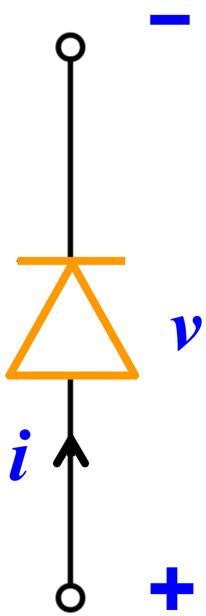
REVIEW OF DIODES

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





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 generic *PV* materials term

PV MATERIALS

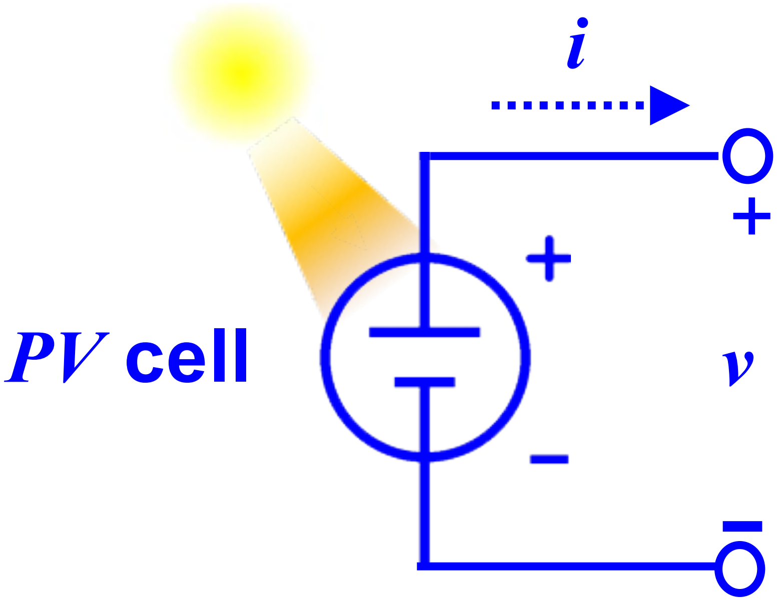
- Silicon is the most commonly used element in *PV* materials
- However, there is emerging competition from the thin films made of compounds of two or more elements, including *gallium arsenide* (*GaAs*), *cadmium telluride* (*CdTe*) and *copper, indium and selenium* (*CIS*)

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

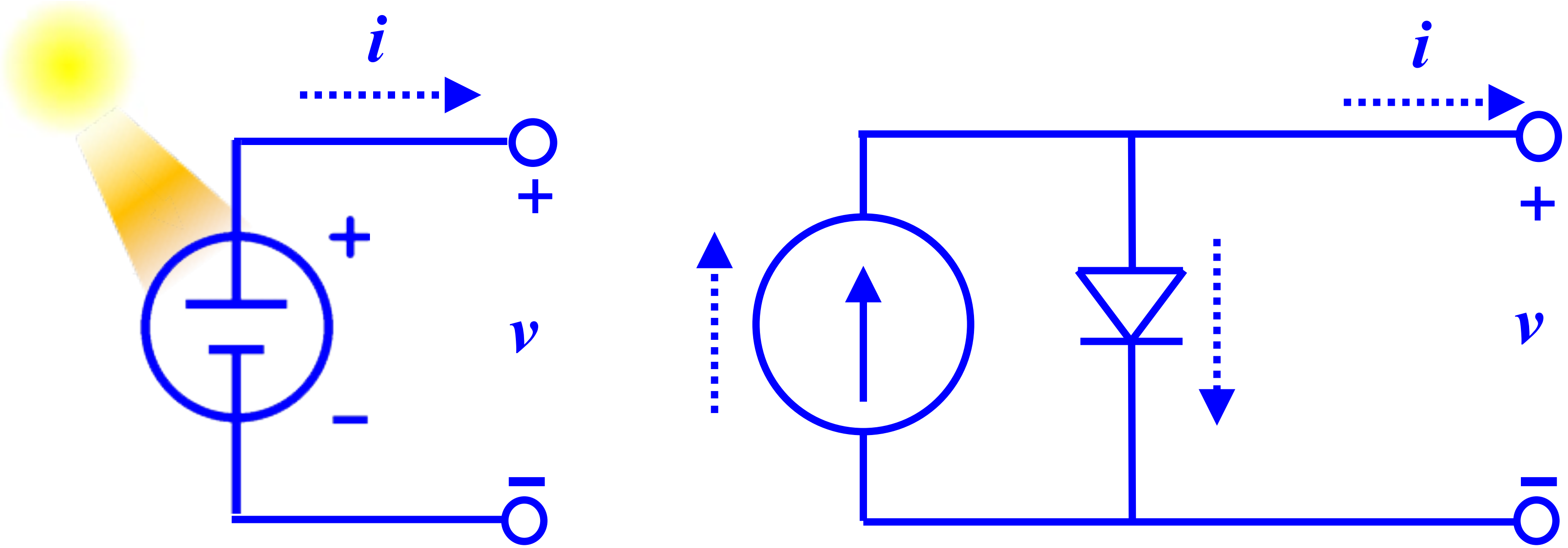
- When the sun rays strike the *PV* cell, the cell produces a current and a voltage combination, that can supply electricity to a connected load



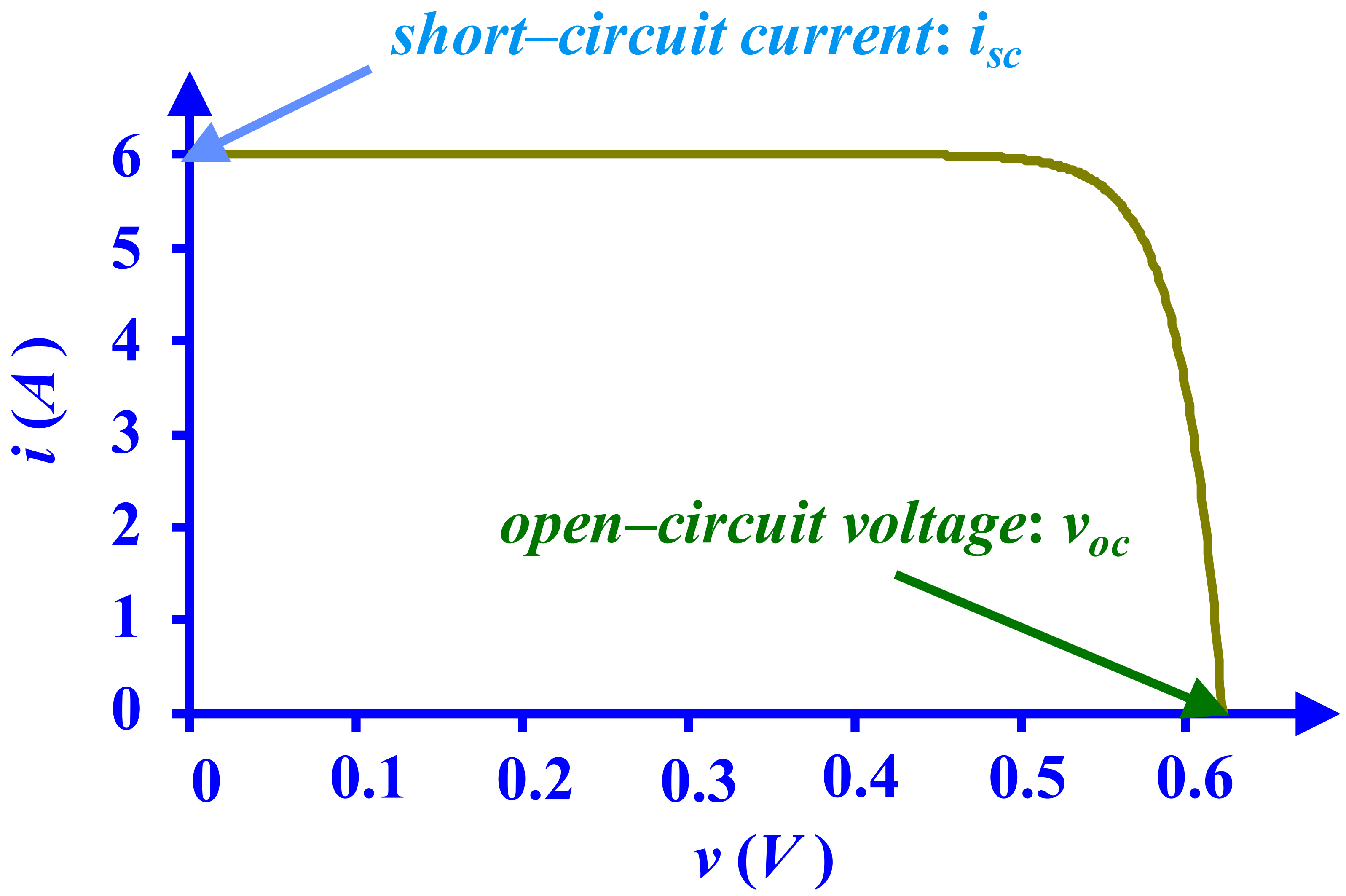
THE *PV* CELL

- 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 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

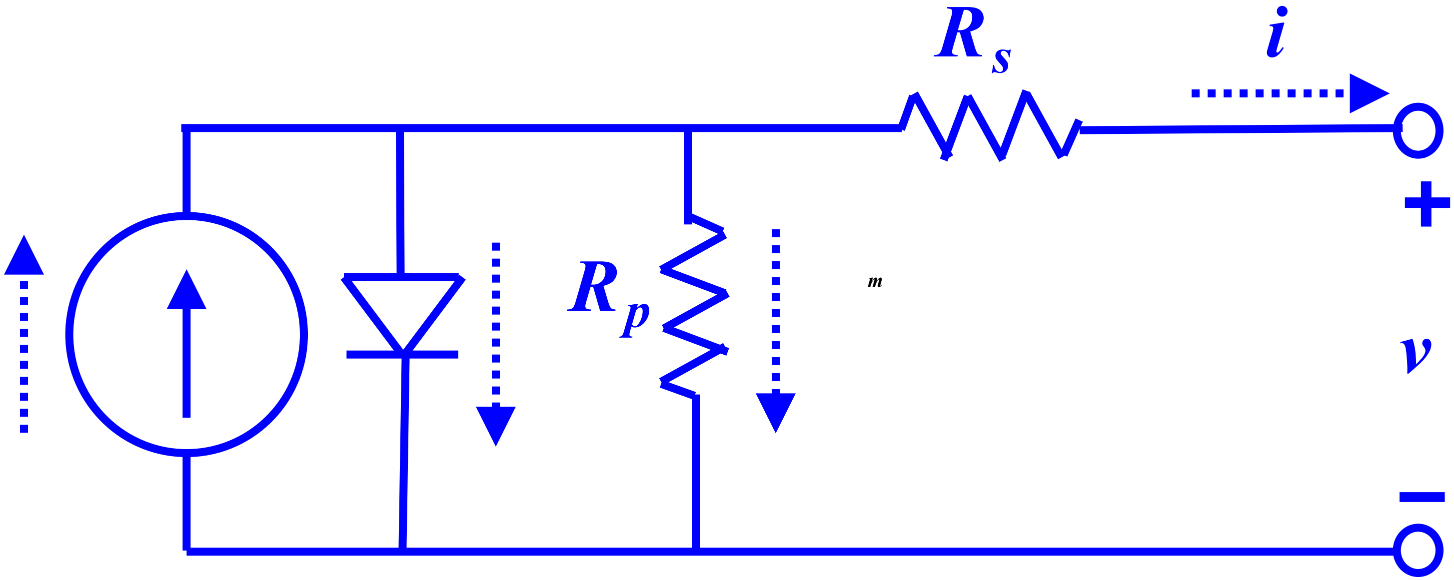
AN IDEALIZED EQUIVALENT CIRCUIT MODEL OF A *PV* CELL



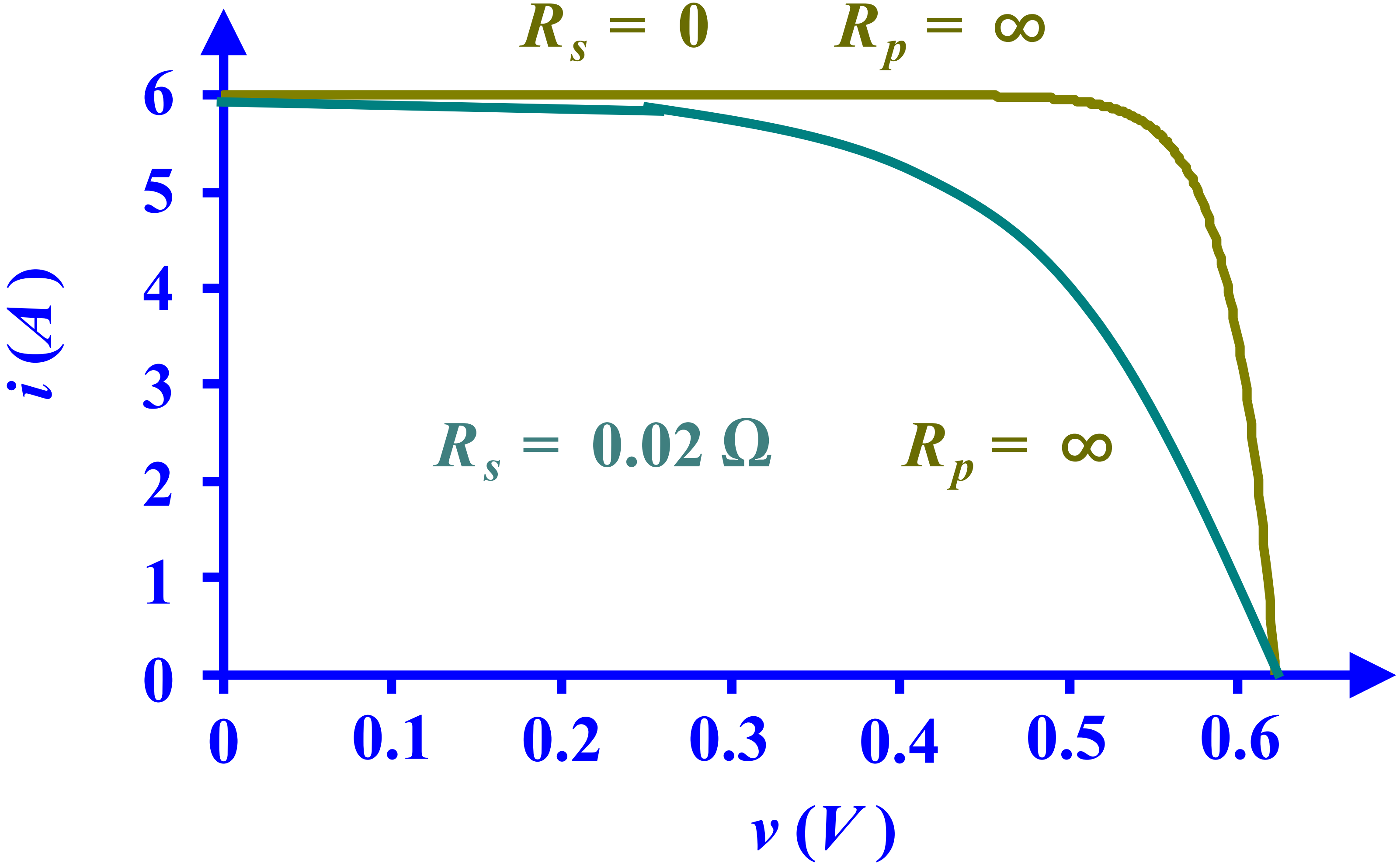
THE $i-v$ CURVE OF THIS IDEAL EQUIVALENT CIRCUIT OF A *PV* CELL



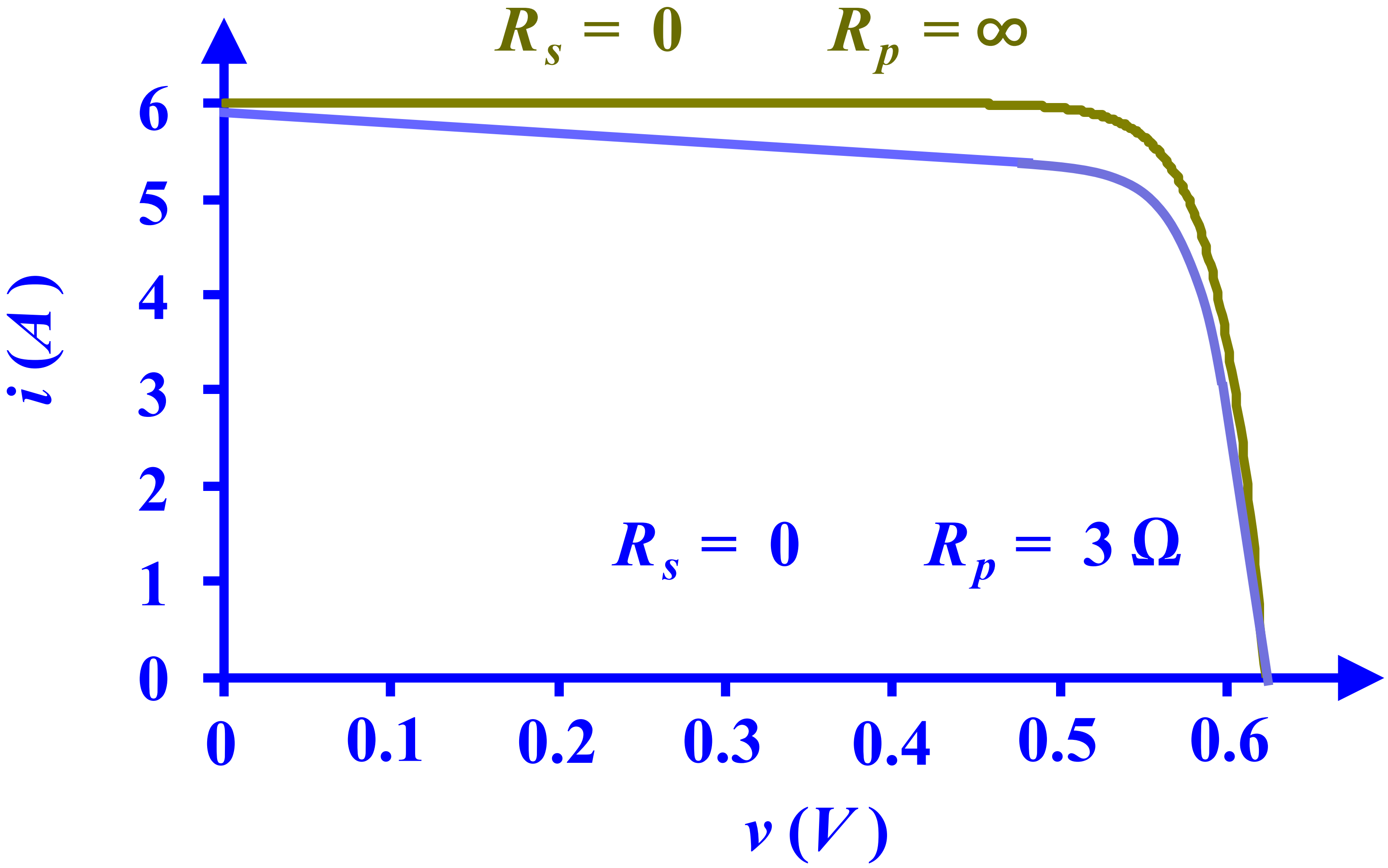
A MORE DETAILED EQUIVALENT CIRCUIT OF A *PV* CELL



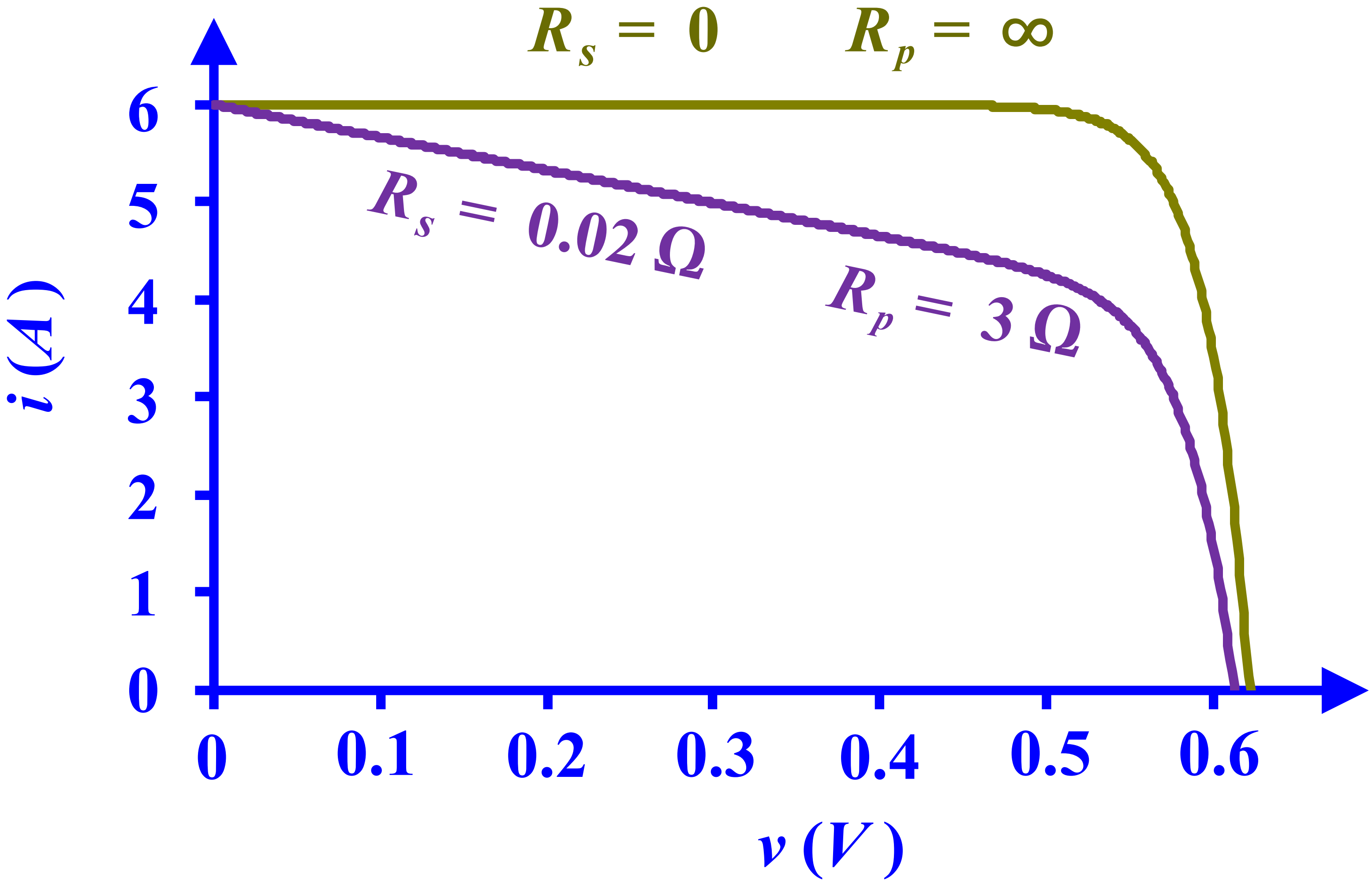
THE $i - v$ CURVES OF A MORE DETAILED CIRCUIT OF A *PV* CELL



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



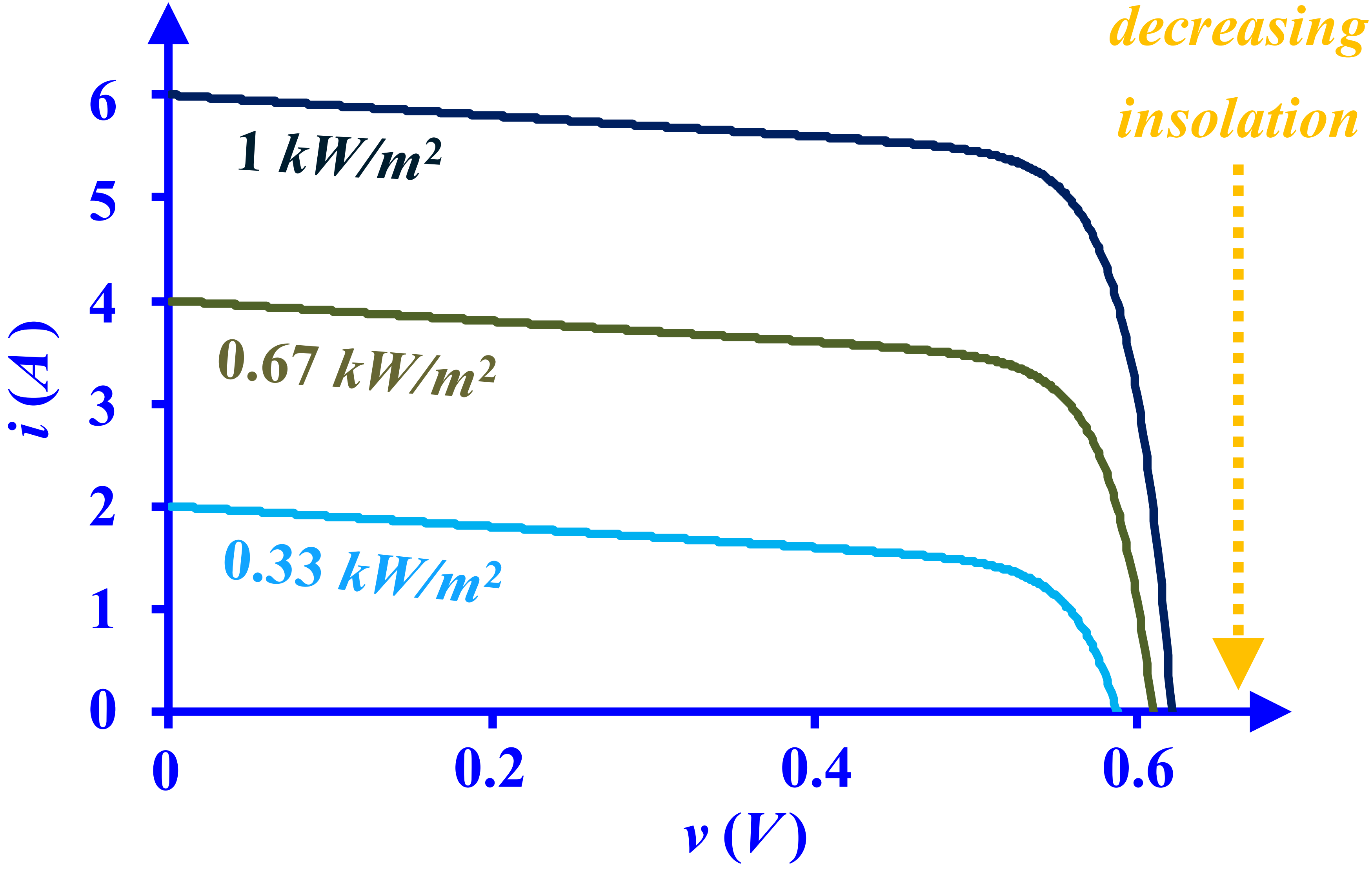
THE $i-v$ CURVES OF A MORE DETAILED CIRCUIT OF A PV CELL



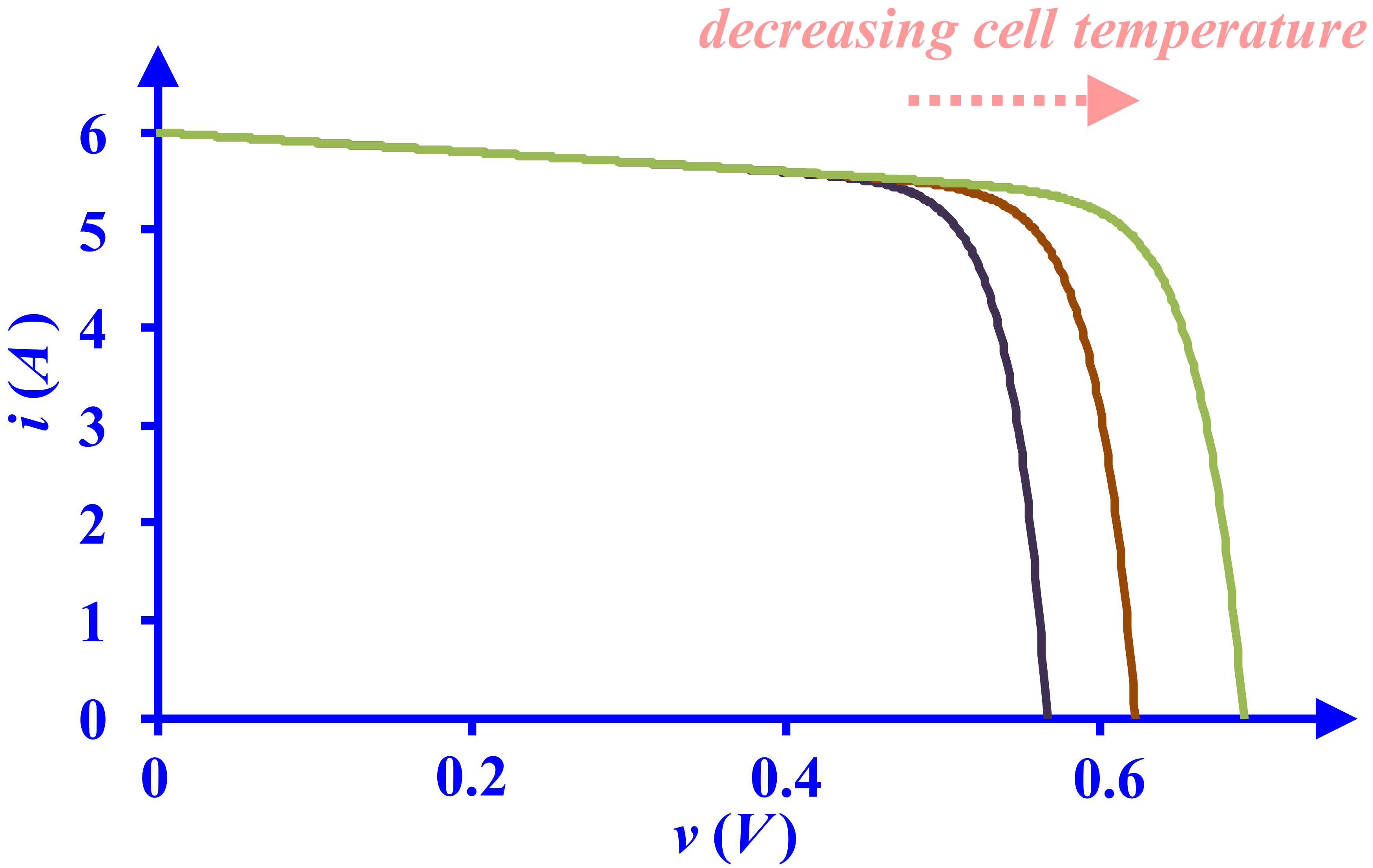
IMPACTS OF INSOLATION AND CELL TEMPERATURE

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

IMPACTS OF INSOLATION ON PV $i - v$ CURVES



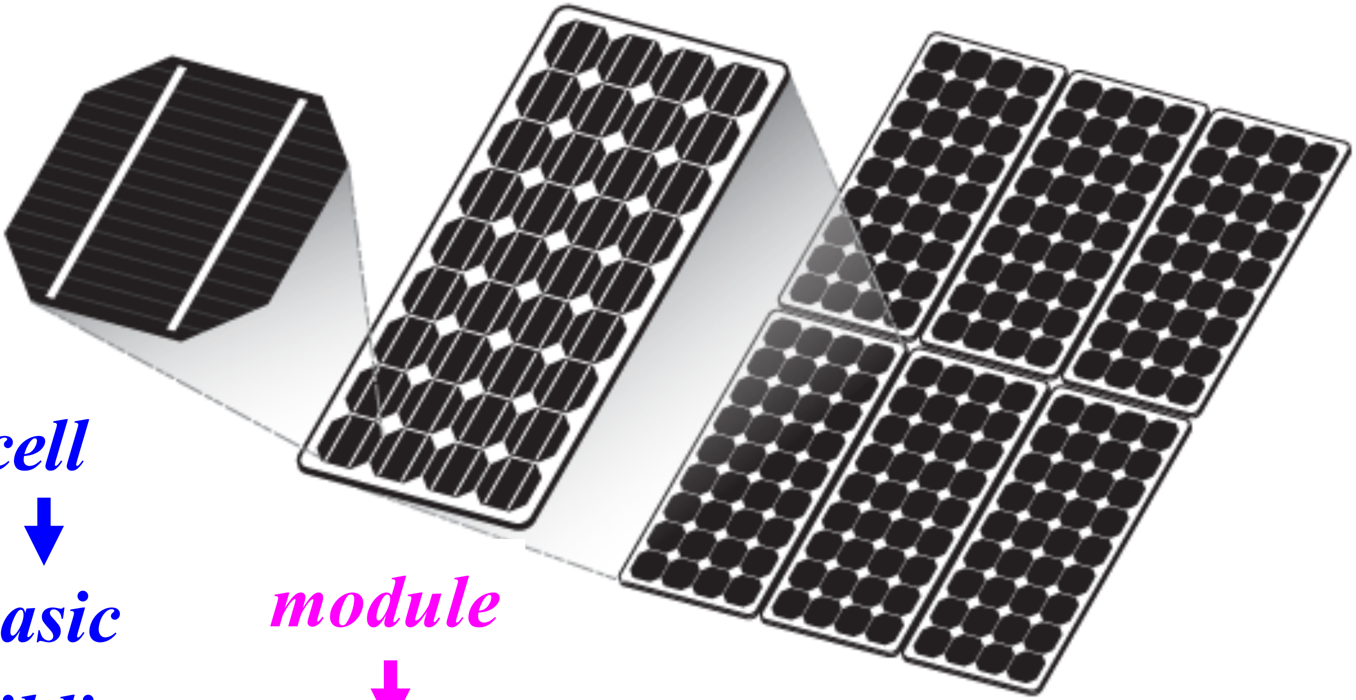
IMPACTS OF CELL TEMPERATURE ON $PV\ i-v$ CURVES



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

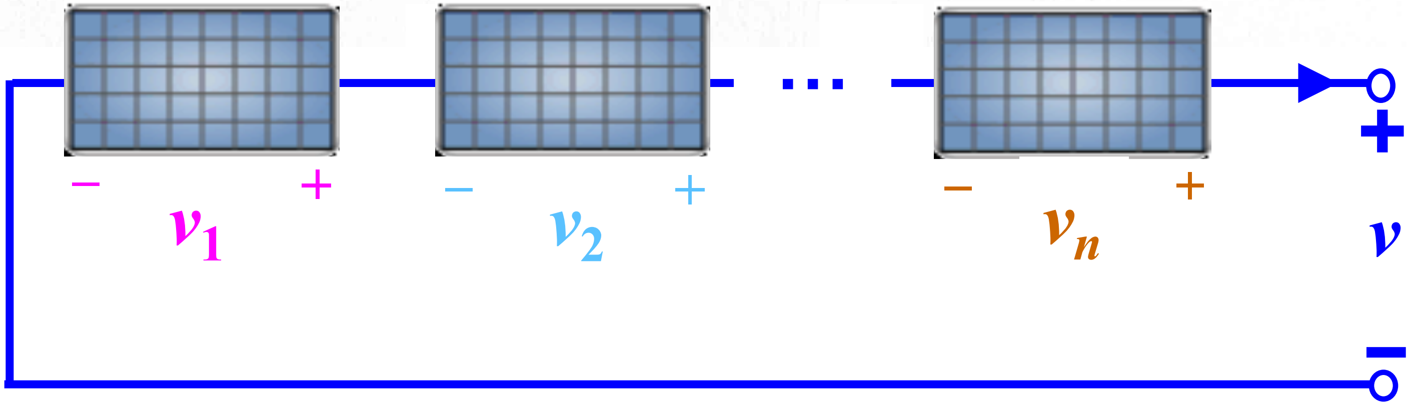
- ☐ The underlying concept is to connect multiple *PV* cells *in series to increase voltage output* or *in parallel to increase current output* using the *PV* cells that are aggregated to construct a *PV* module
- ☐ Typical module sizes consist of 36, 72, 96 or 128 cells with the continuing trend toward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

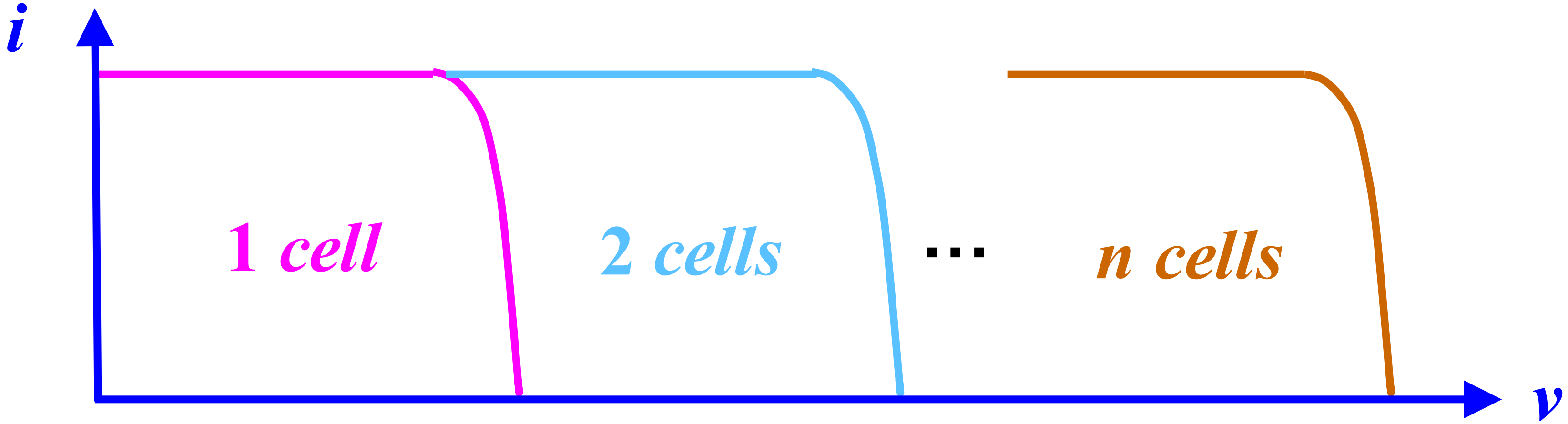
FROM MODULES TO ARRAYS

- Several modules, in turn, are connected *in series* or *in parallel* to construct the *PV* arrays; 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

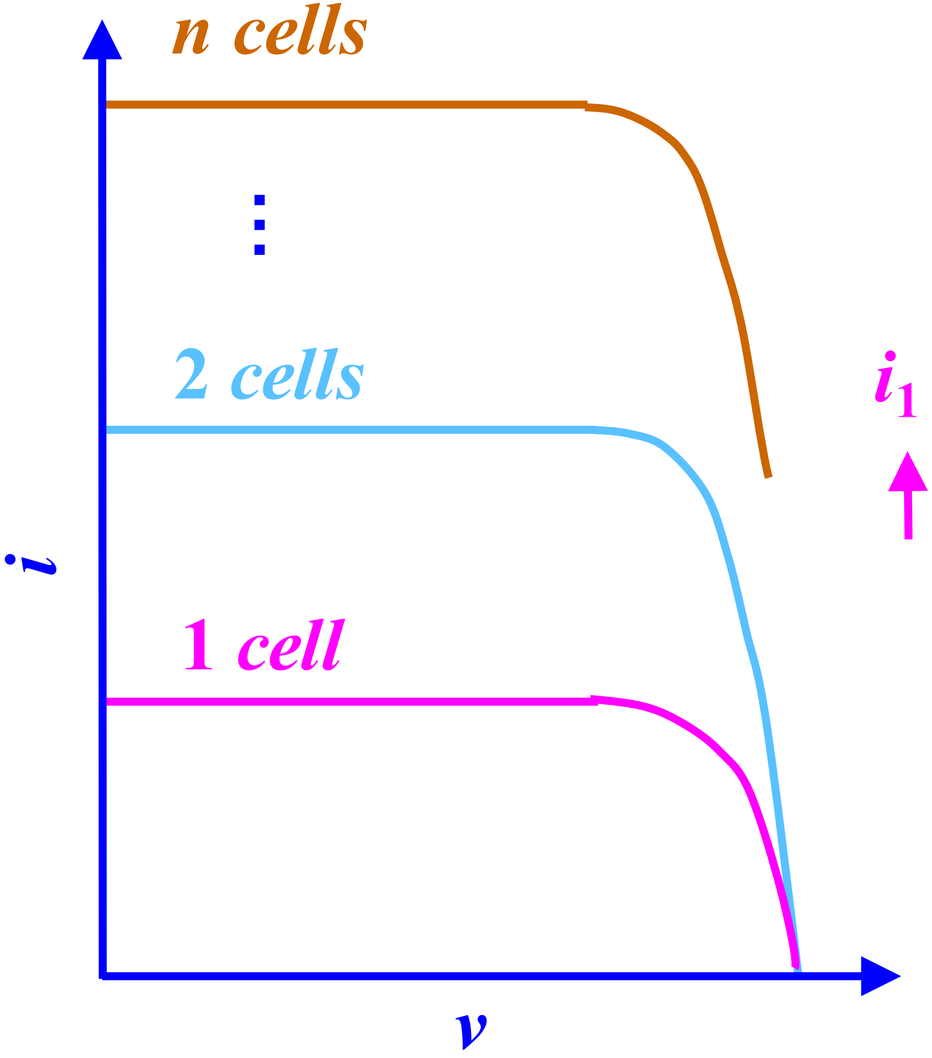
$i - v$ CURVE FOR CELLS IN SERIES



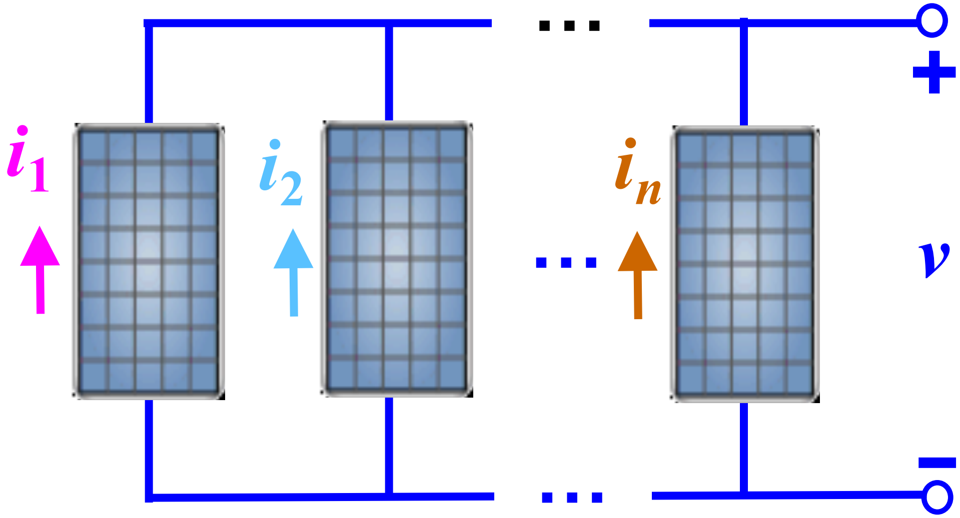


$$v = v_1 + v_2 + \cdots + v_n$$

$i - v$ CURVE FOR CELLS IN PARALLEL



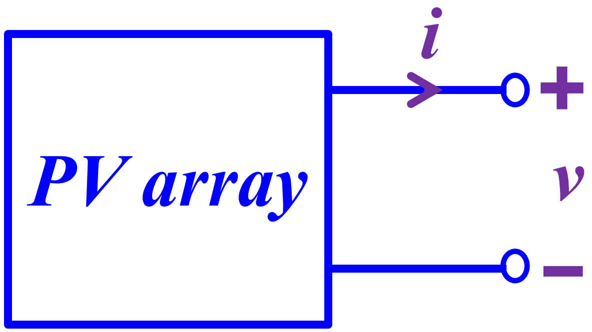
$$i = i_1 + i_2 + \ldots + i_n$$



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 – a significant metric that measures *PV* array energy production

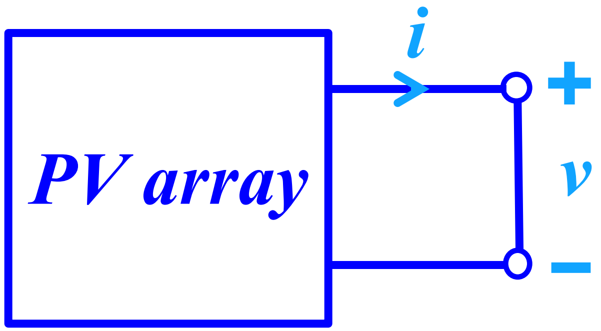
POWER OUTPUT FOR A *PV* ARRAY



$i = 0$

$v = v_{oc}$

open circuit conditions



$i = i_{sc}$

$v = 0$

short circuit conditions

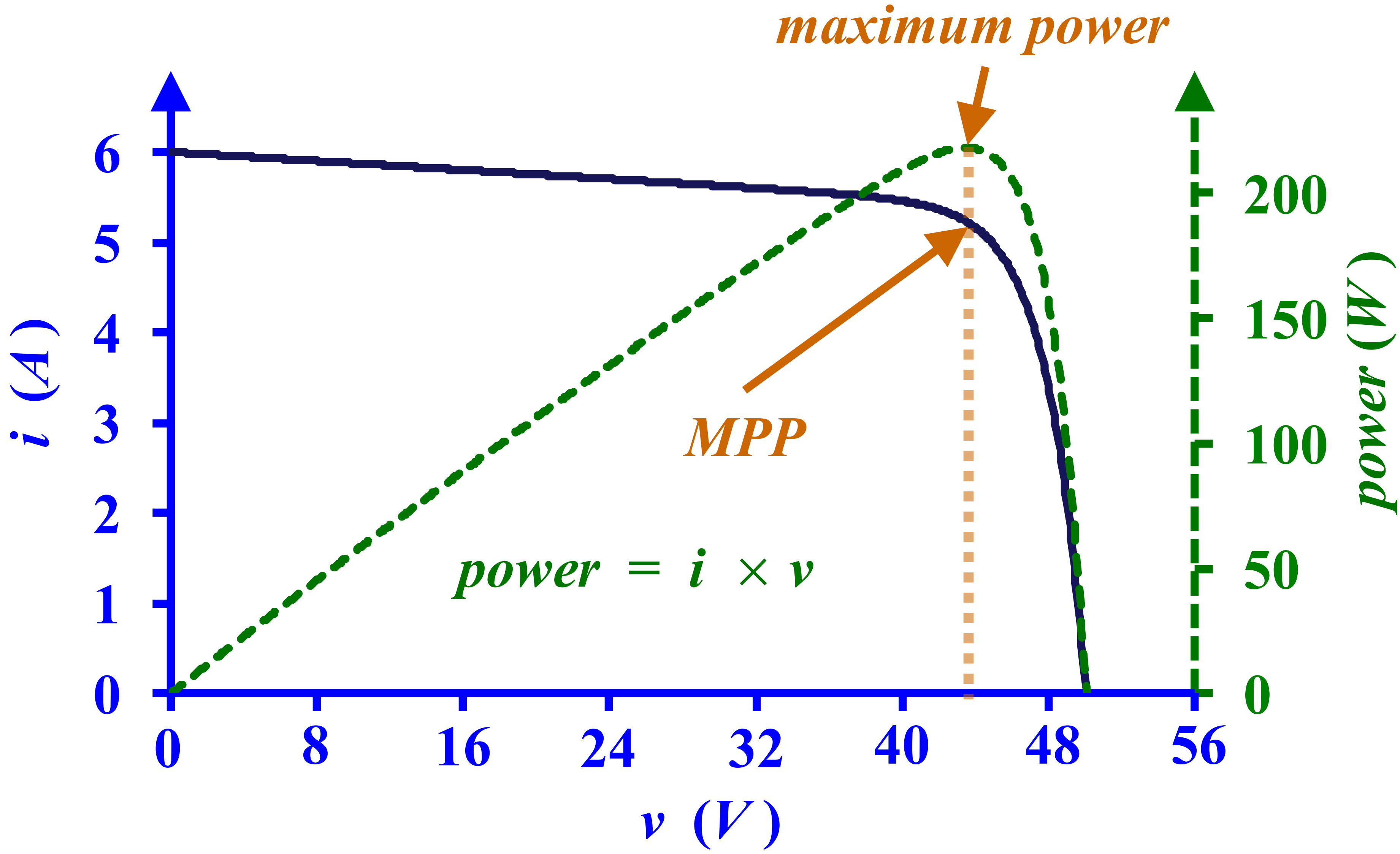
$power = i \times v = 0$

under either condition

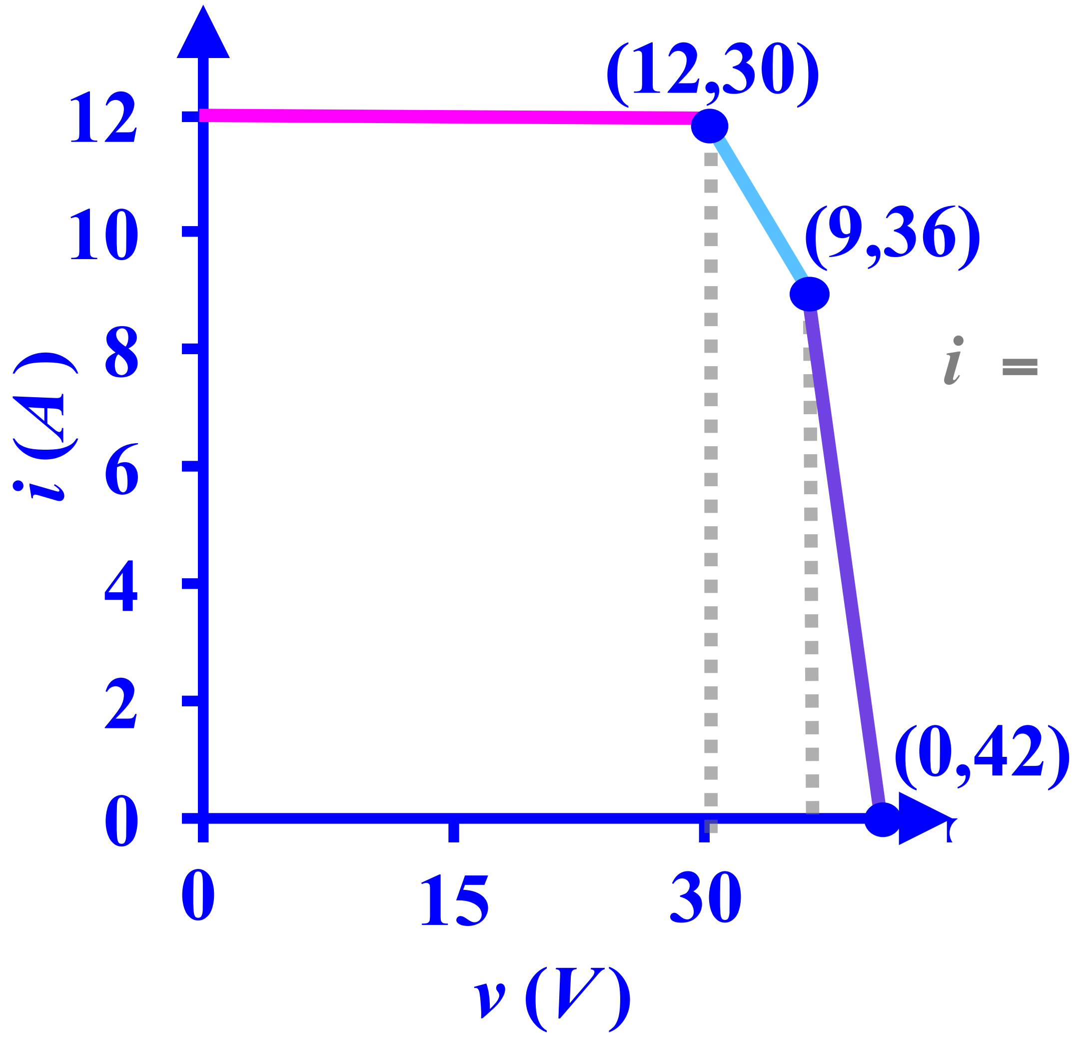
POWER OUTPUT FOR A *PV* ARRAY

- ☐ The connection of a load across the *PV* array terminals results in a ***non-zero current*** and a ***non-zero voltage***; their values determine the *PV* array instantaneous power output
- ☐ In general, our aim is to get the *PV*s 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



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

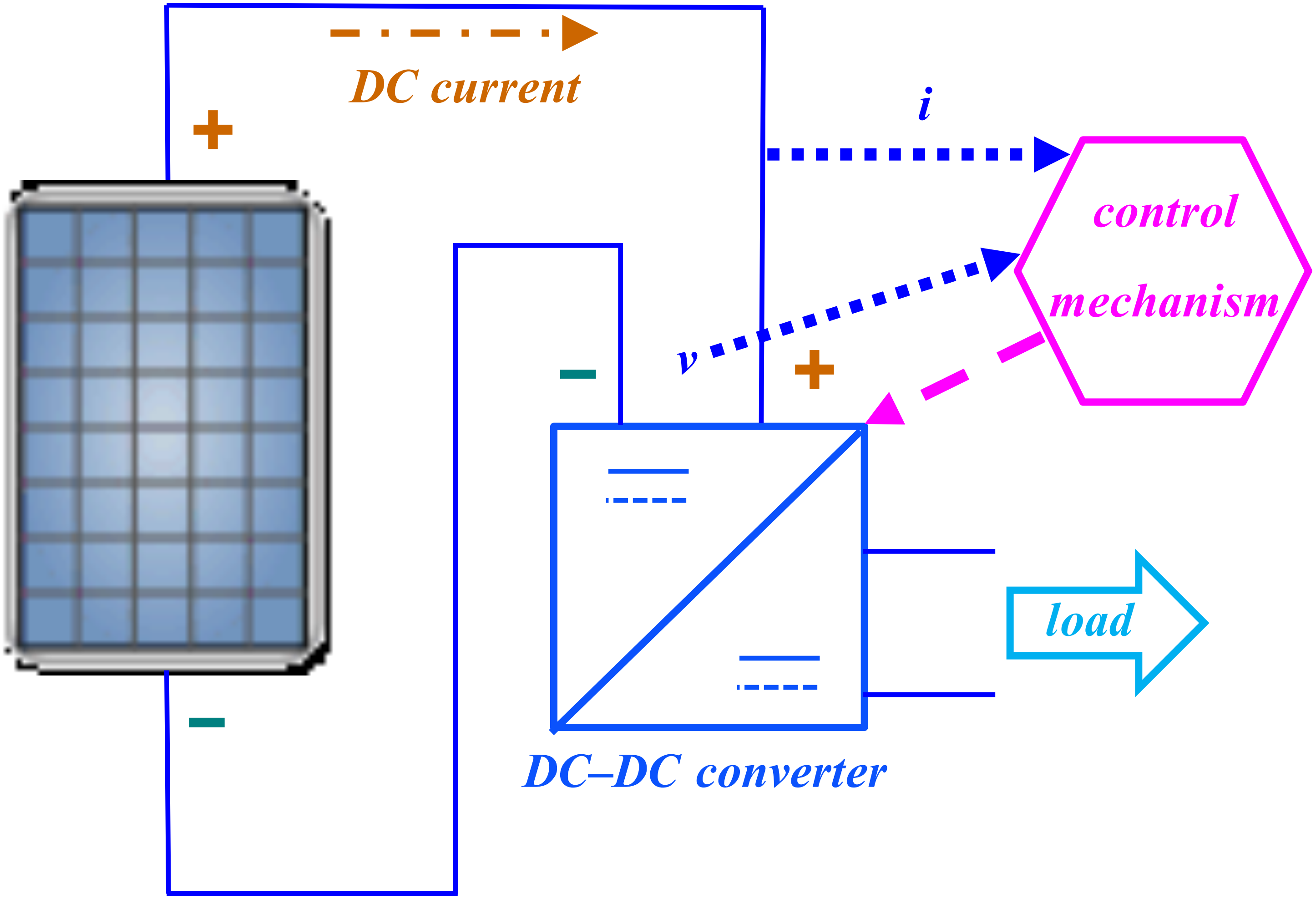
$$p = i \times v = \begin{cases} 12\,v & 0 \le v \le 30 \\ -0.5\,(v - 27)^2 + 0.5\,(27)^2 & 30 < v \le 36 \\ -1.5\,(v - 21)^2 + 1.5\,(21)^2 & 36 < v \le 42 \\ 0 & \textit{otherwise} \end{cases}$$

$p^M = 360\,W$ 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 the *MPP* are
  - ○ *fractional open–circuit voltage* method
  - ○ *perturb and observe* technique

FRACTIONAL OPEN-CIRCUIT VOLTAGE METHOD

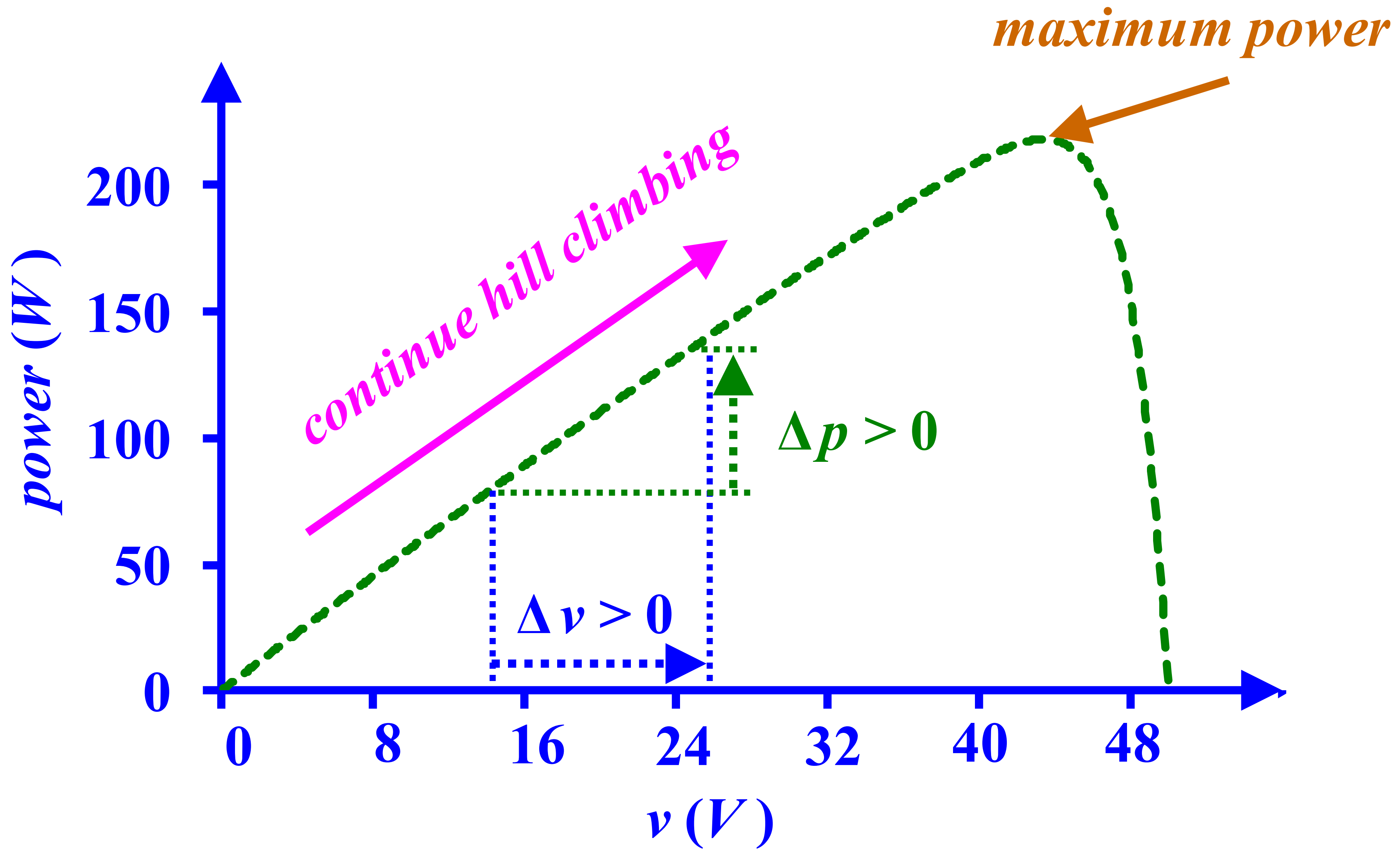
☐ *Fractional open–circuit voltage* method sets the voltage value at the *MPP* equal to some *fixed* fraction of the *measured* open–circuit voltage

☐ As the *PV* cells continue to operate over longer periods, their open–circuit voltages become reduced and so do the values of their *MPP*s

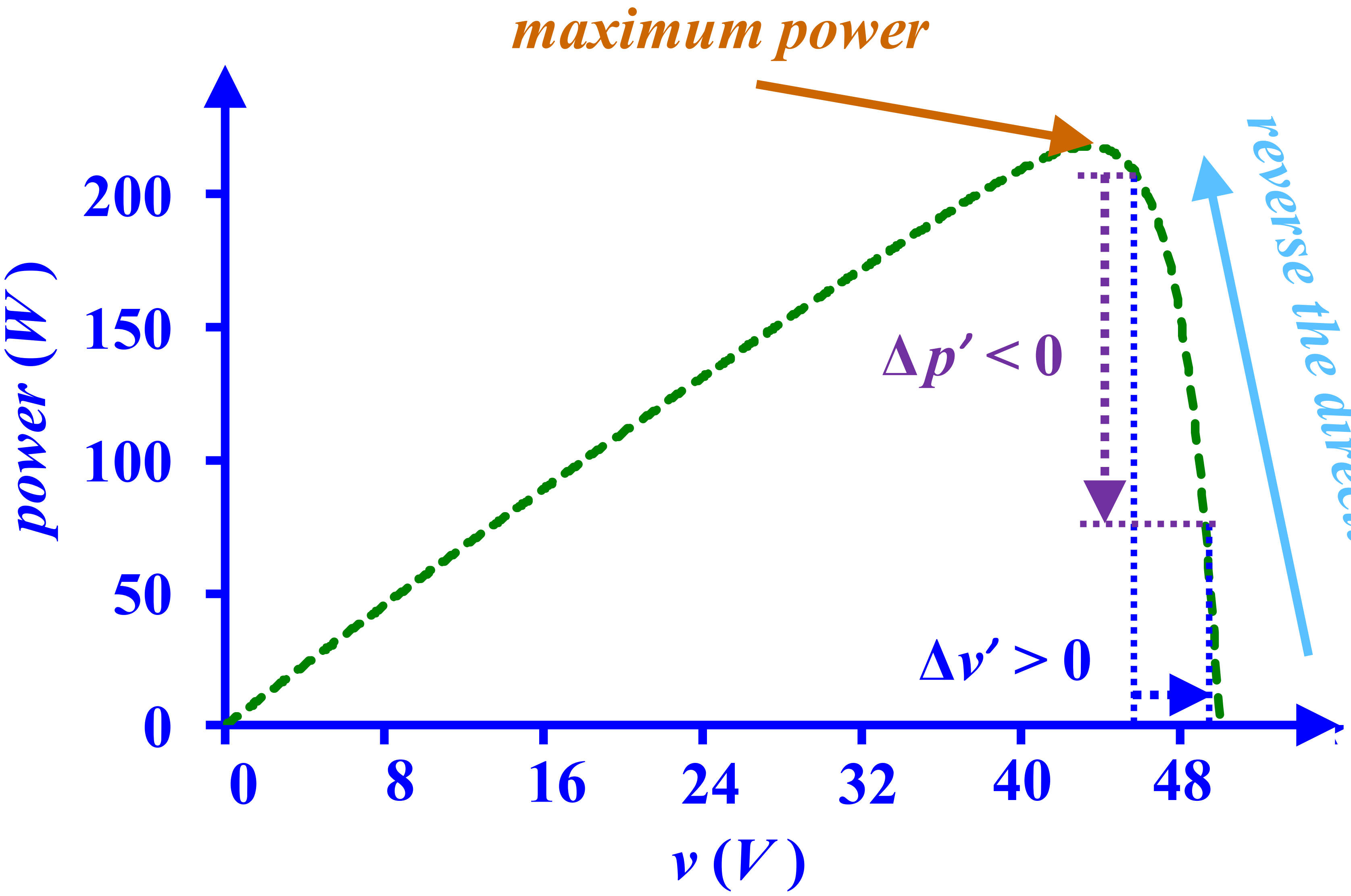
PERTURB AND OBSERVE

- *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

PERTURB AND OBSERVE



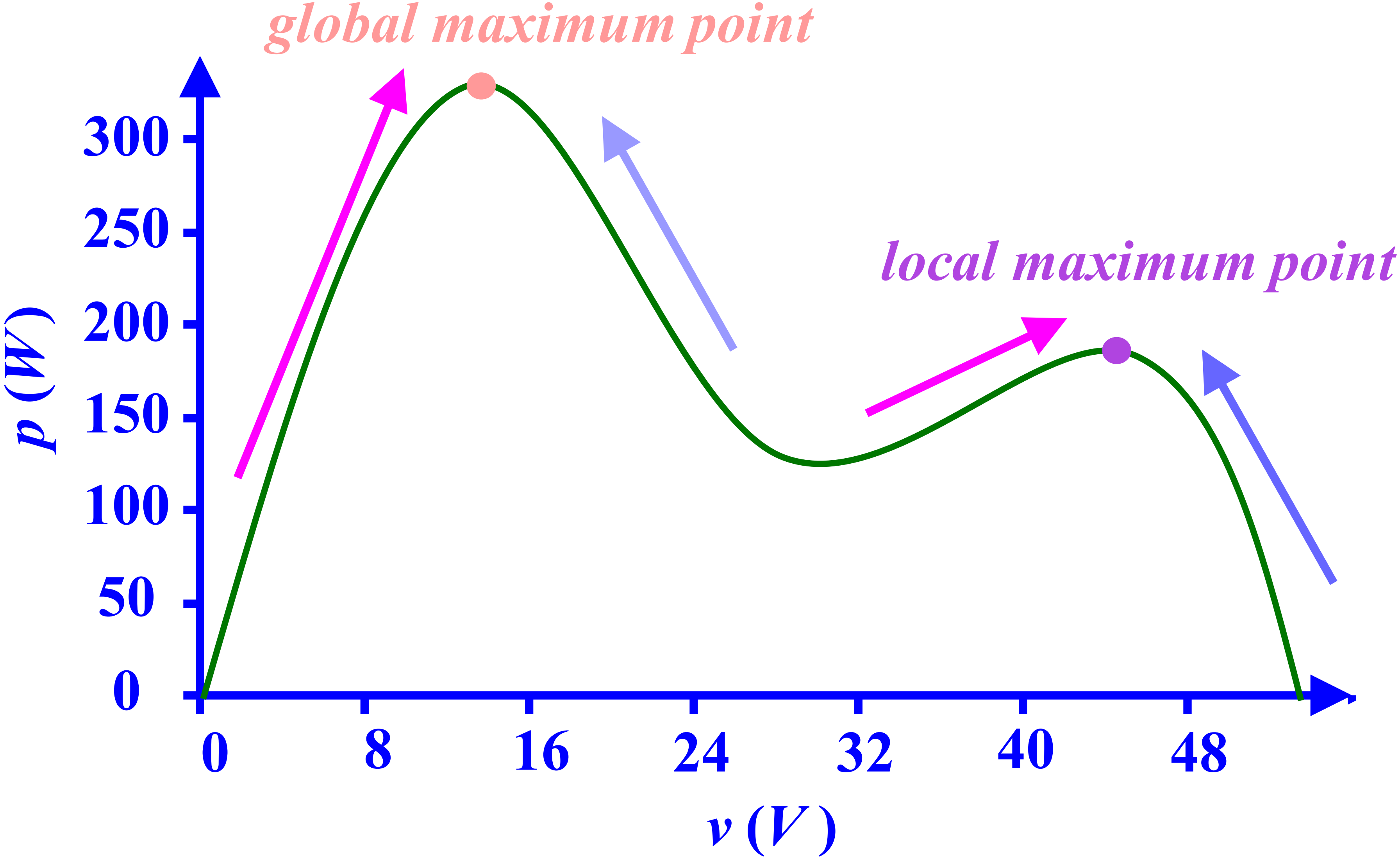
PERTURB AND OBSERVE



MPPT METHODS

- 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

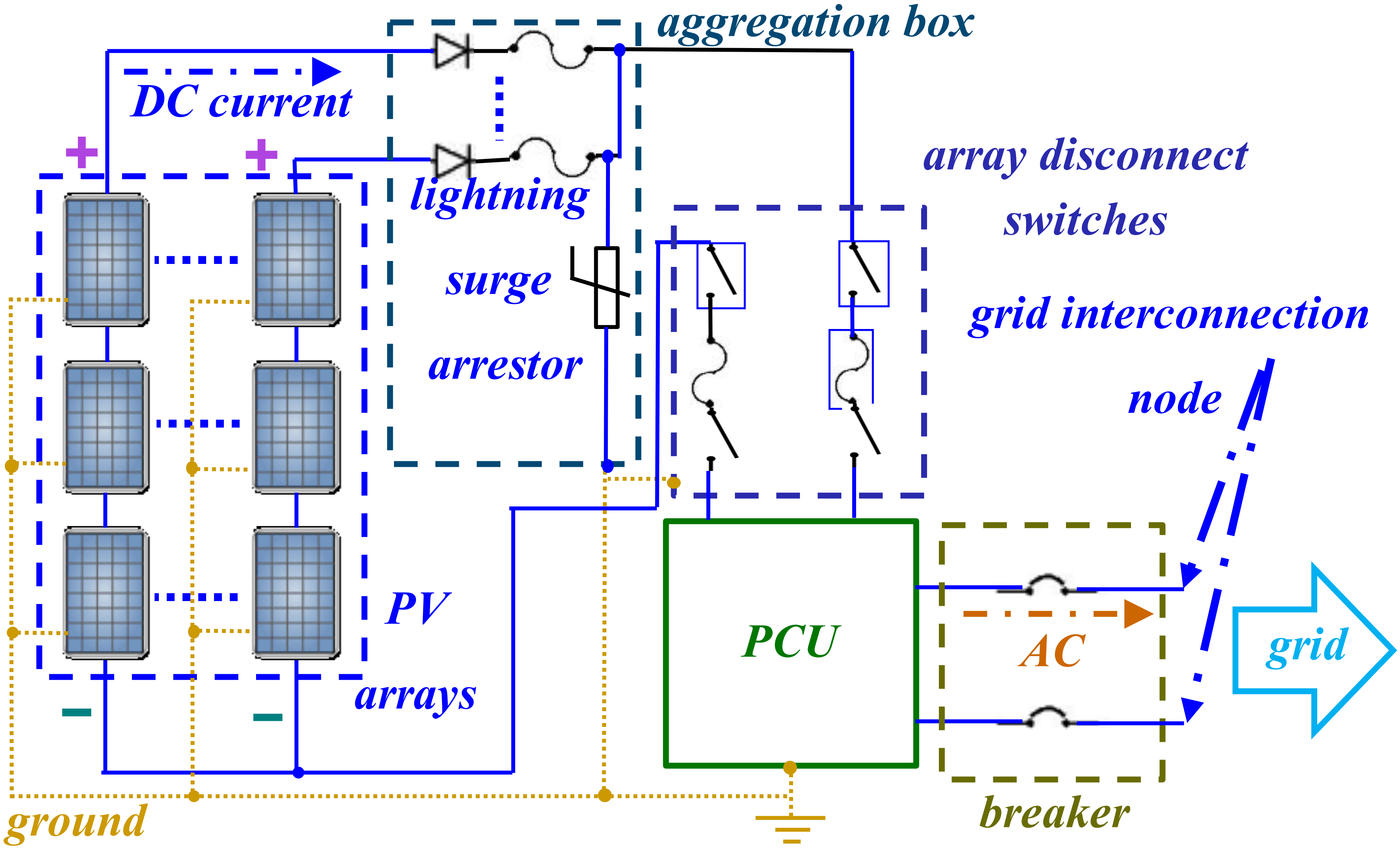


PV SYSTEMS

- ☐ *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



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; 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

PRINICPAL 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

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 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

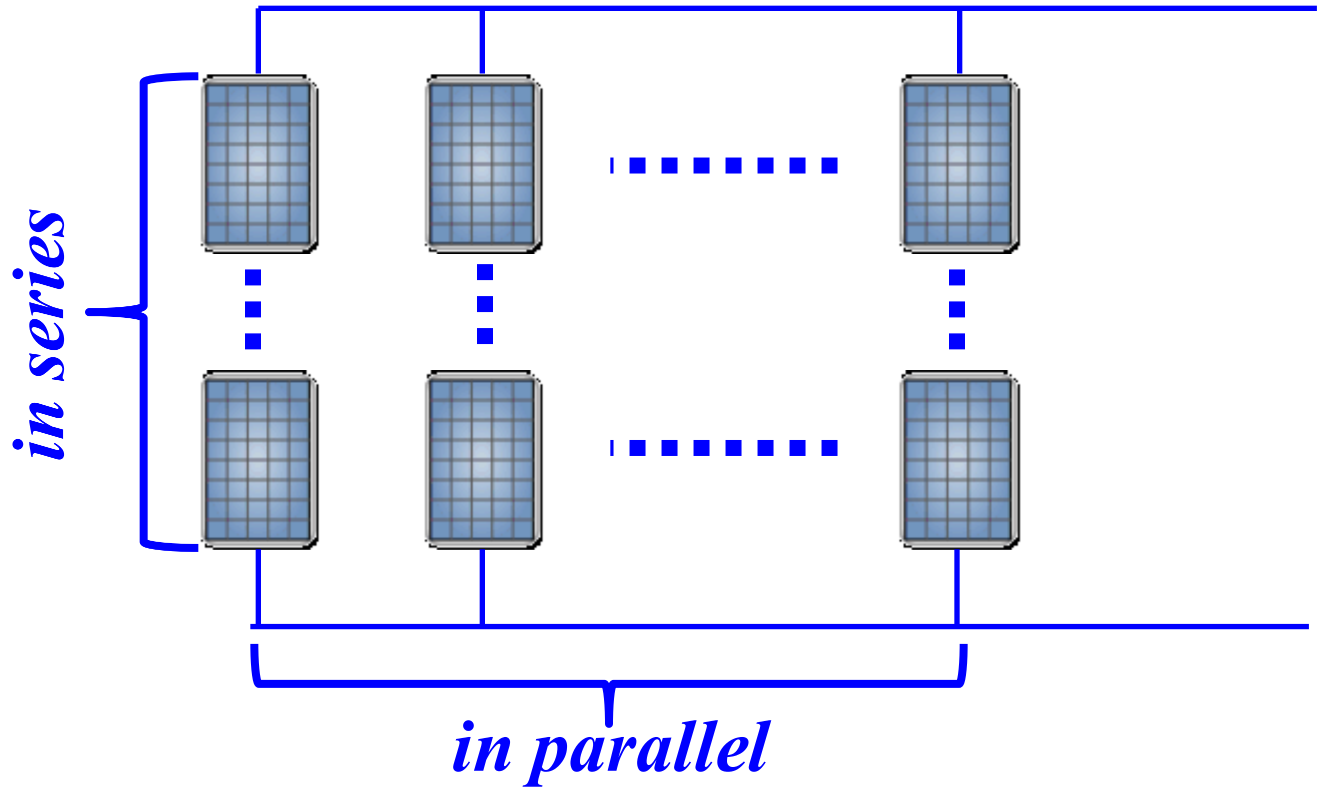
parameter/variable	*symbol*	*value*	*units*
maximum power	p^{M}	200	$W\,(DC)$
MPP voltage	v_{MPP}	50	$V\,(DC)$
MPP current	i_{MPP}	4	$A\,(DC)$
open-circuit voltage	v_{oc}	60	$V\,(DC)$
short-circuit current	i_{sc}	5	$A\,(DC)$

EXAMPLE: *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 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**

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

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

EXAMPLE: *PV* ARRAY DESIGN

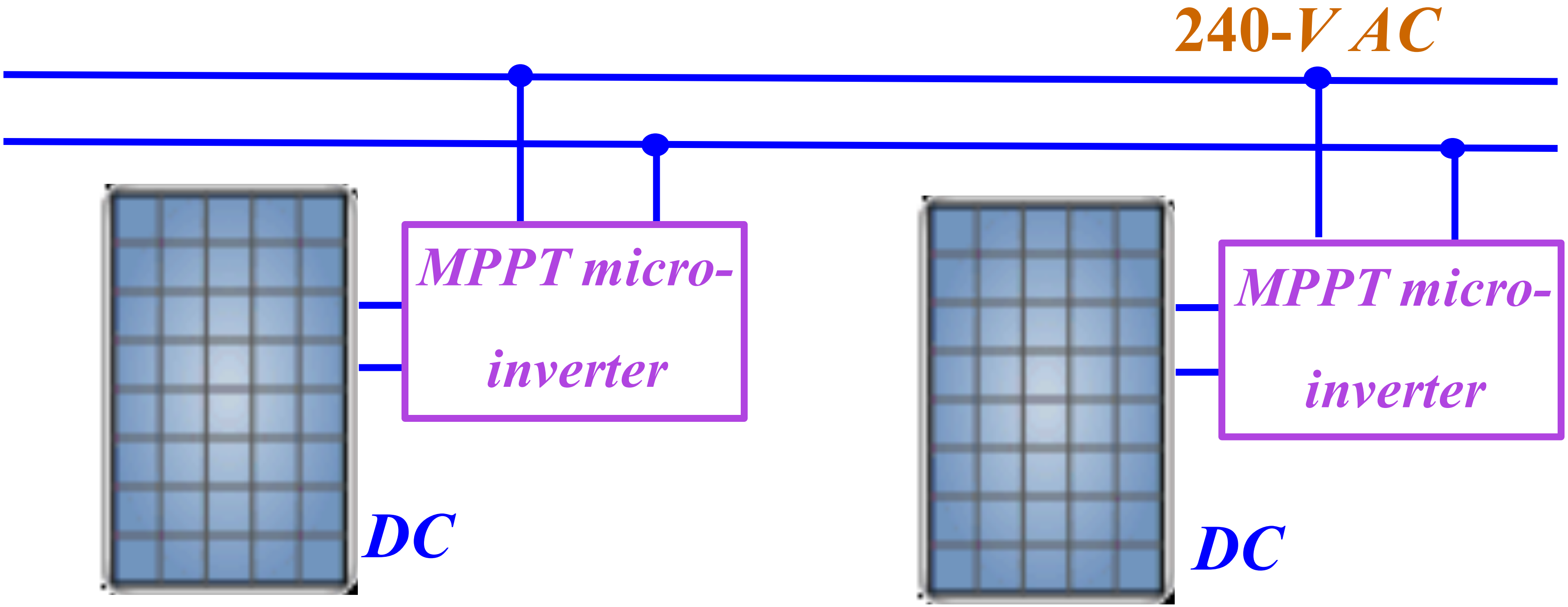
- ☐ For the N_p modules connected in parallel to raise the current output, we determine the N_p value that satisfies:

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

- ☐ 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 increase because a single *PCU* is cheaper than a large number of micro–inverters/*MPPT*s in large array systems

THE TWO GRID–CONNECTED *PV* SYSTEM CATEGORIES

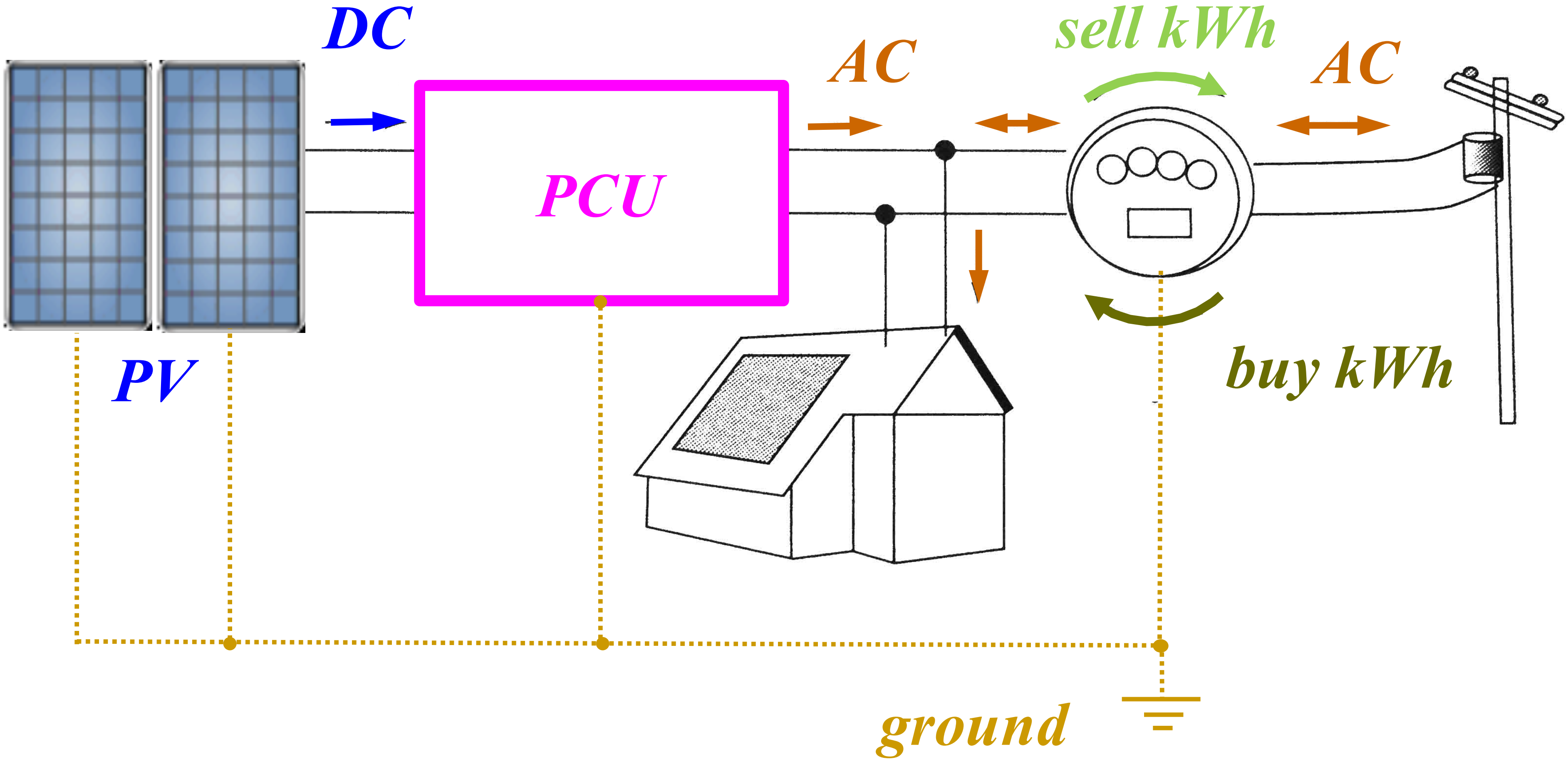
- ☐ Based on which side of the electric meter the *PV*s are located, the grid–connected *PV* systems are classified as either
  - ○ ***behind–the–meter systems***: usually installed on rooftops to feed their power outputs directly to the loads on the same side of the meter; or,

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

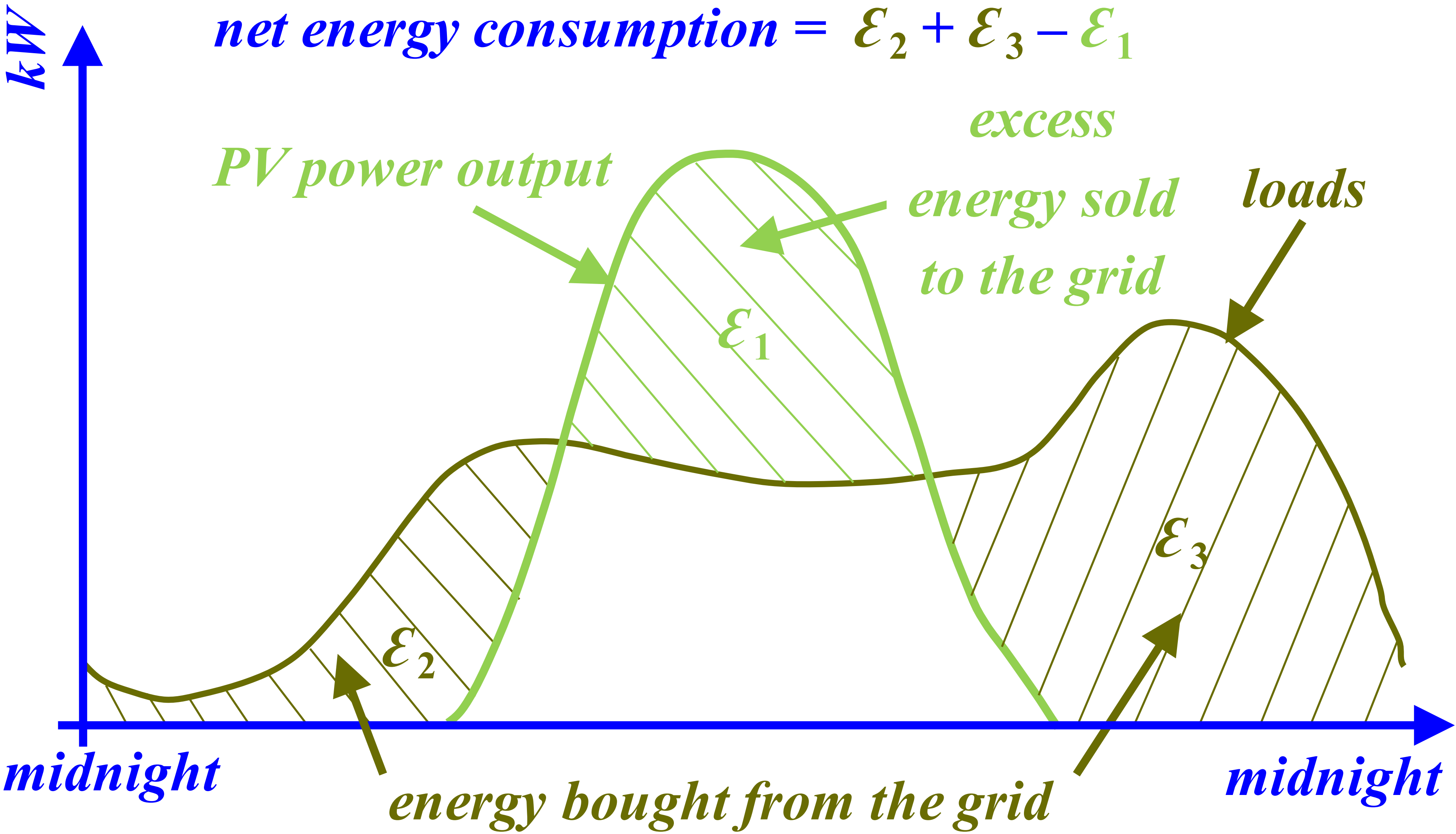
BEHIND–THE–METER GRID–CONNECTED *PV* SYSTEM



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



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 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

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 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

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 $25°\ C$
  - ○ 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-*sun*
  - the cell temperature is, typically, $20^{\circ} - 40^{\circ}\ C$ 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 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

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 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
°C

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

°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 $35^{\circ}C$ 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 $\tau_{n} = 45^{\circ}C$, the actual cell temperature is computed to be

EXAMPLE: TEMPERATURE–RELATED *PV* POWER DERATE FACTOR

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

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

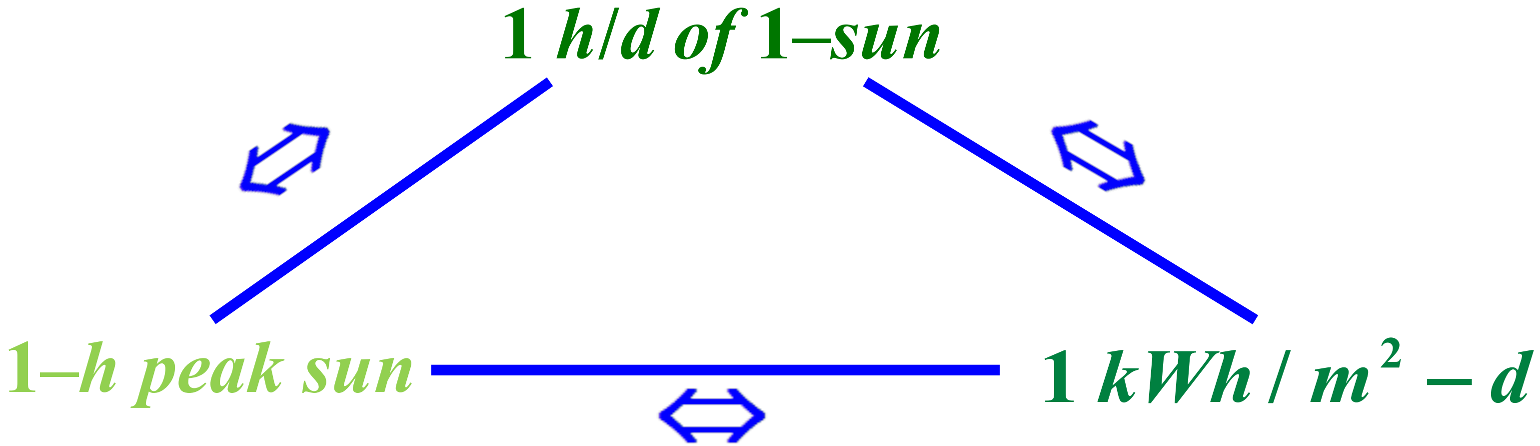
$$2.31 \times \left[1 + \left(-0.005\right)\left(42.3 - 25\right)\right] = 2.16 \; kW$$

THE PEAK–HOURS APPROACH TO ESTIMATE *PV* PERFORMANCE

- ☐ The methods 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



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

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

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*

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

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

$$\text{annual energy} \longleftarrow kWh\,/\,y$$

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

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 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 $6\ MW_p$ 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 approximate 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 $4.86\ kWh/m^2-d$ 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

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