ECE 333 – GREEN ELECTRIC ENERGY

14. *PV* Systems

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SOLAR ENERGY TECHNOLOGY

- **The underlying concept of solar technology is to collect solar energy to convert it 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 produce thermal energy, which is then used to produce electricity**

OUTLINE

- ☐ Review of basic *semiconductor* and *diode* notions
- ☐ Description of the *PV* cell and its $i - v$ curve
- ☐ From the *PV cell* to a *module* and then to 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 of an insulator**

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

REVIEW OF DIODES

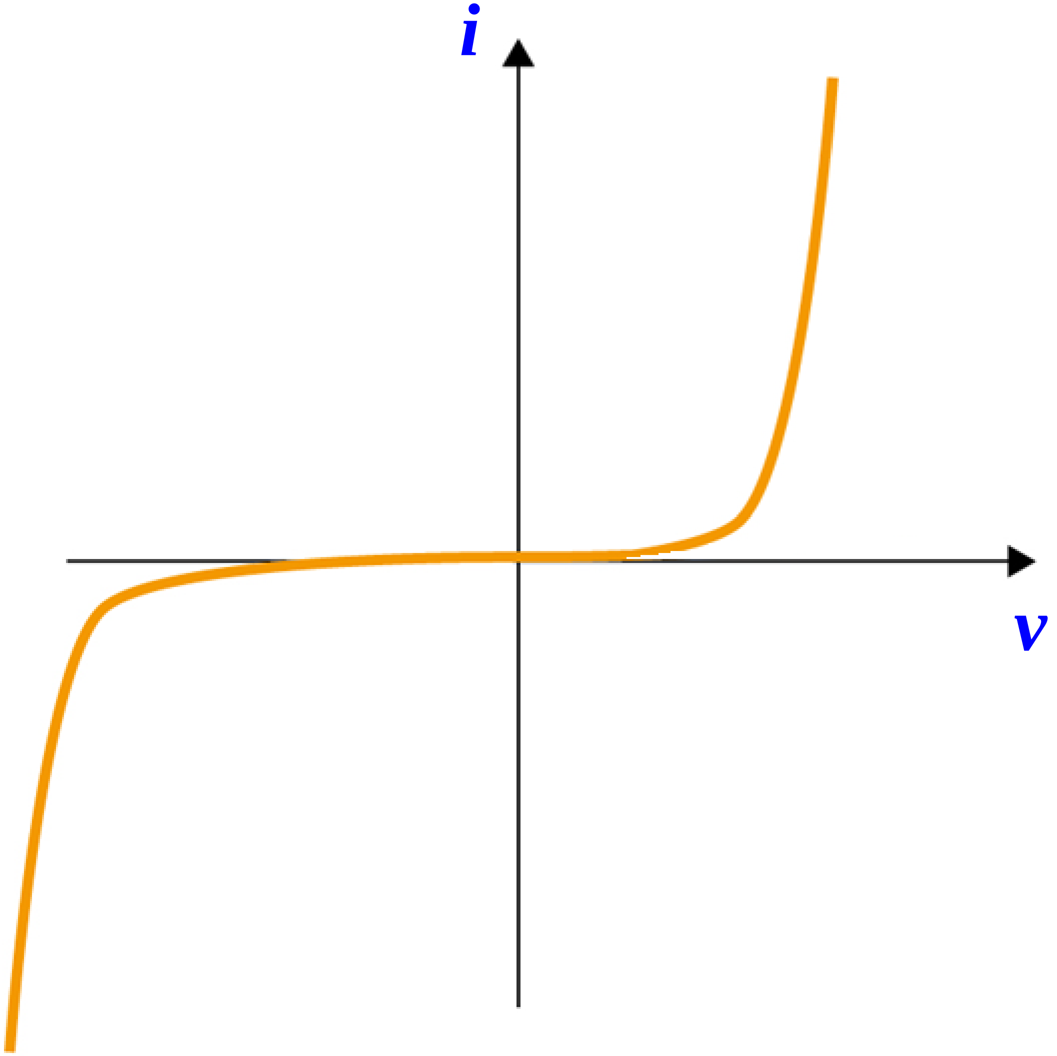
- The *diode* was one of the first semiconductor electronic devices that was invented
- The *diode* is a two–terminal electronic component, composed of two semiconductor materials
- When a voltage is applied across the diode terminals, the electric field formed in the diode

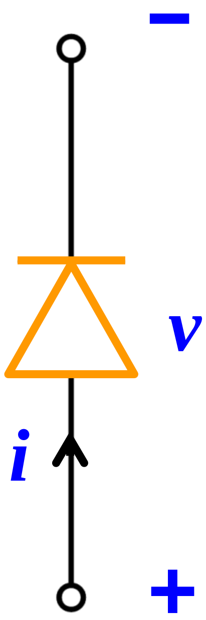
REVIEW OF DIODES

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; such a *switching mode* is of great utility in the construction of various devices and systems

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 – in 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 widely used element in ***PV*** **materials**

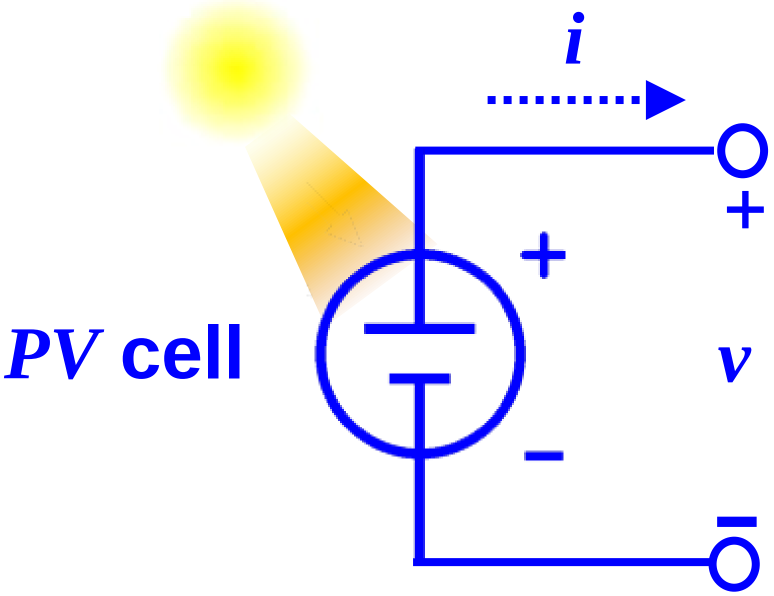
- ❑ However, there is emerging competition from the **thin films** made of compounds of two or more elements, such as ***gallium arsenide (GaAs), copper, indium and selenium (CIS)*** and ***cadmium telluride (CdTe)***

THE *PV* CELL

- **The basic building block for *PV* systems is the so–called *PV* cell, whose construction uses *PV* mate–rials, with the contact grid attached on the surface of these materials**

THE *PV* CELL

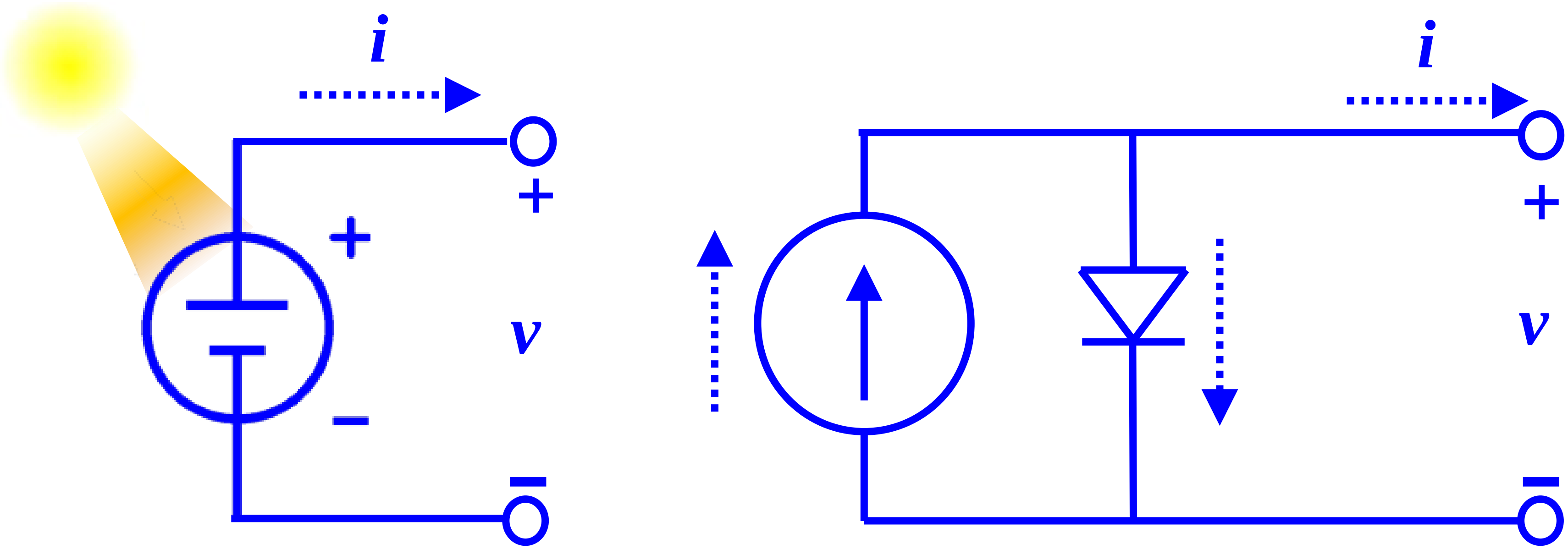
- **When the sun rays strike the *PV* cell, the cell produces a current and a voltage combination, that can supply electricity to a connected load**



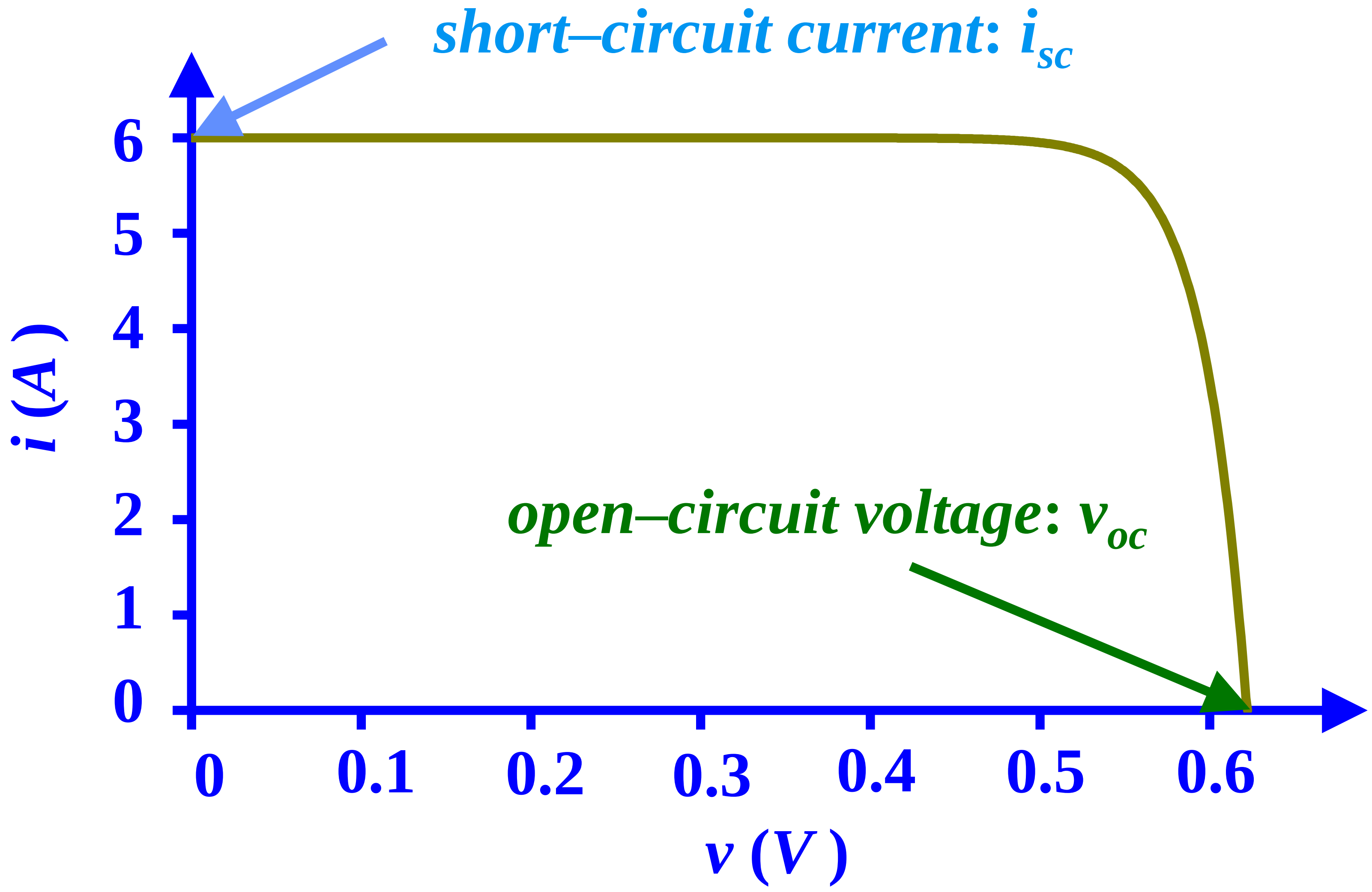
THE *PV* CELL

- To help analyze the performance of an individual *PV* cell, we, typically, deploy an equivalent circuit model to represent the cell behavior
- This idealized representation is in terms of discrete idealized components; such elements do not, however, exist inside a *PV* cell
- The *i* - *v* curves of these equivalent circuit models describe graphically and assess quantitatively the *i* - *v* behavior of the *PV* cell

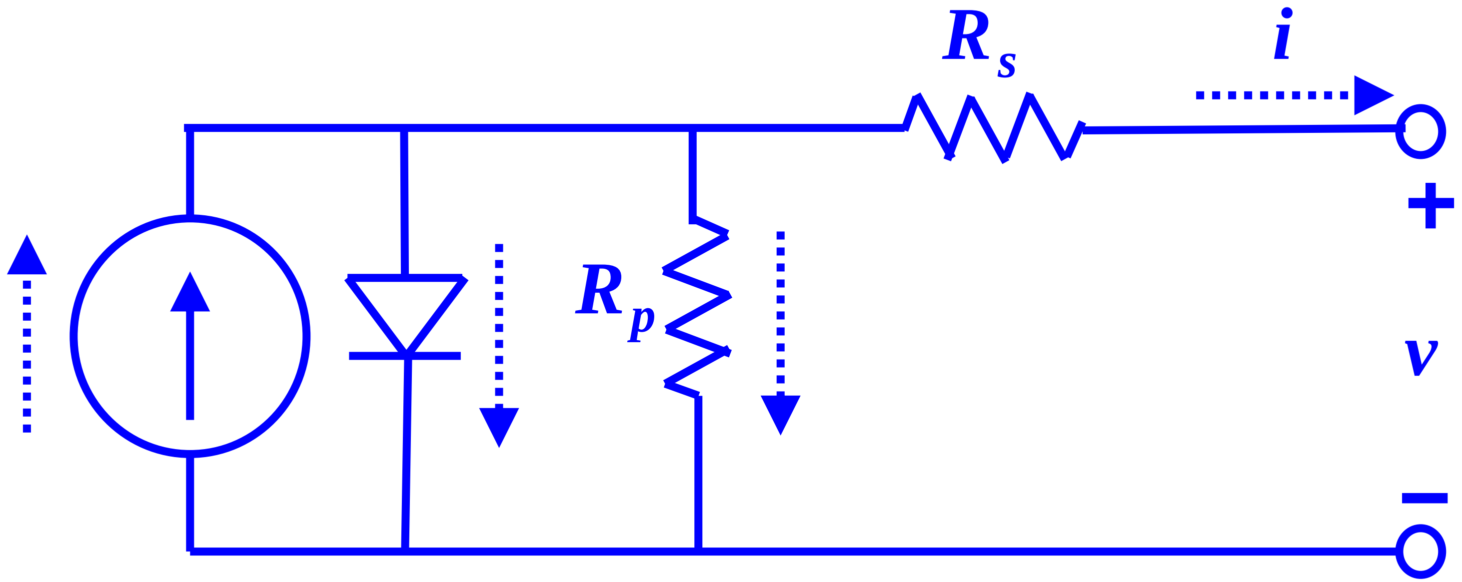
AN IDEALIZED EQUIVALENT CIRCUIT MODEL OF A *PV* CELL



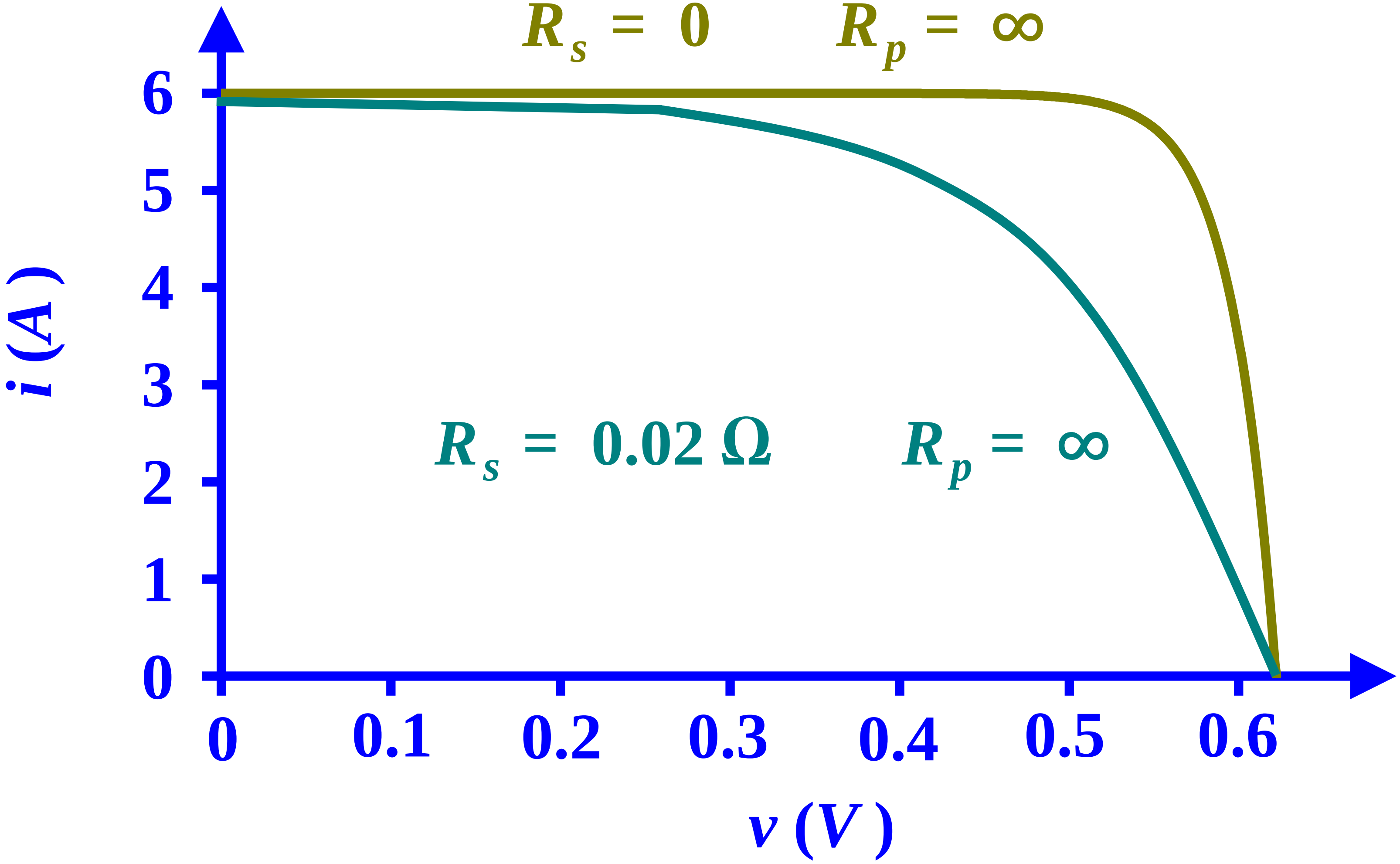
THE $i-v$ CURVE OF THIS IDEAL EQUIVALENT CIRCUIT OF A *PV* CELL



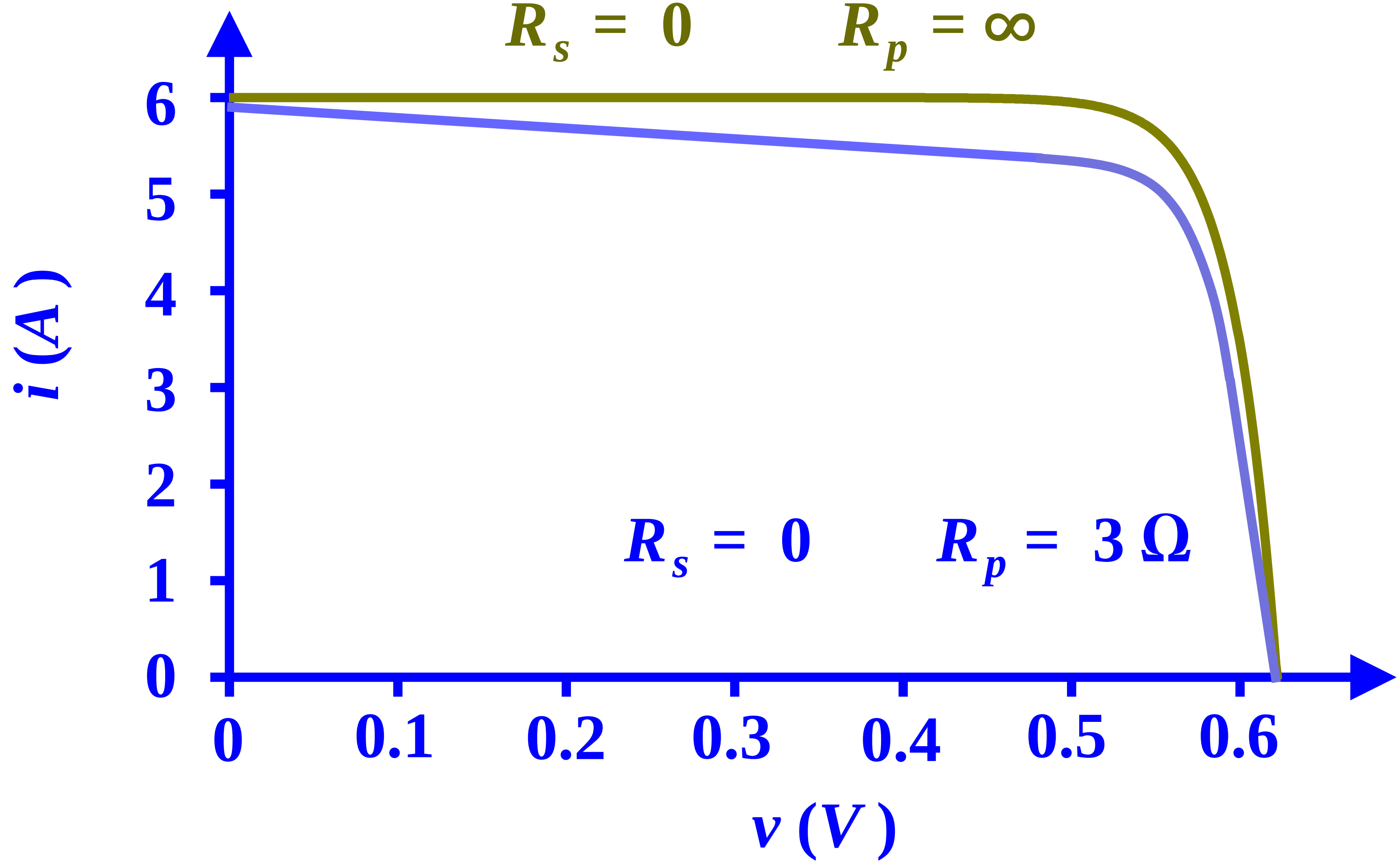
A MORE DETAILED EQUIVALENT CIRCUIT OF A *PV* CELL



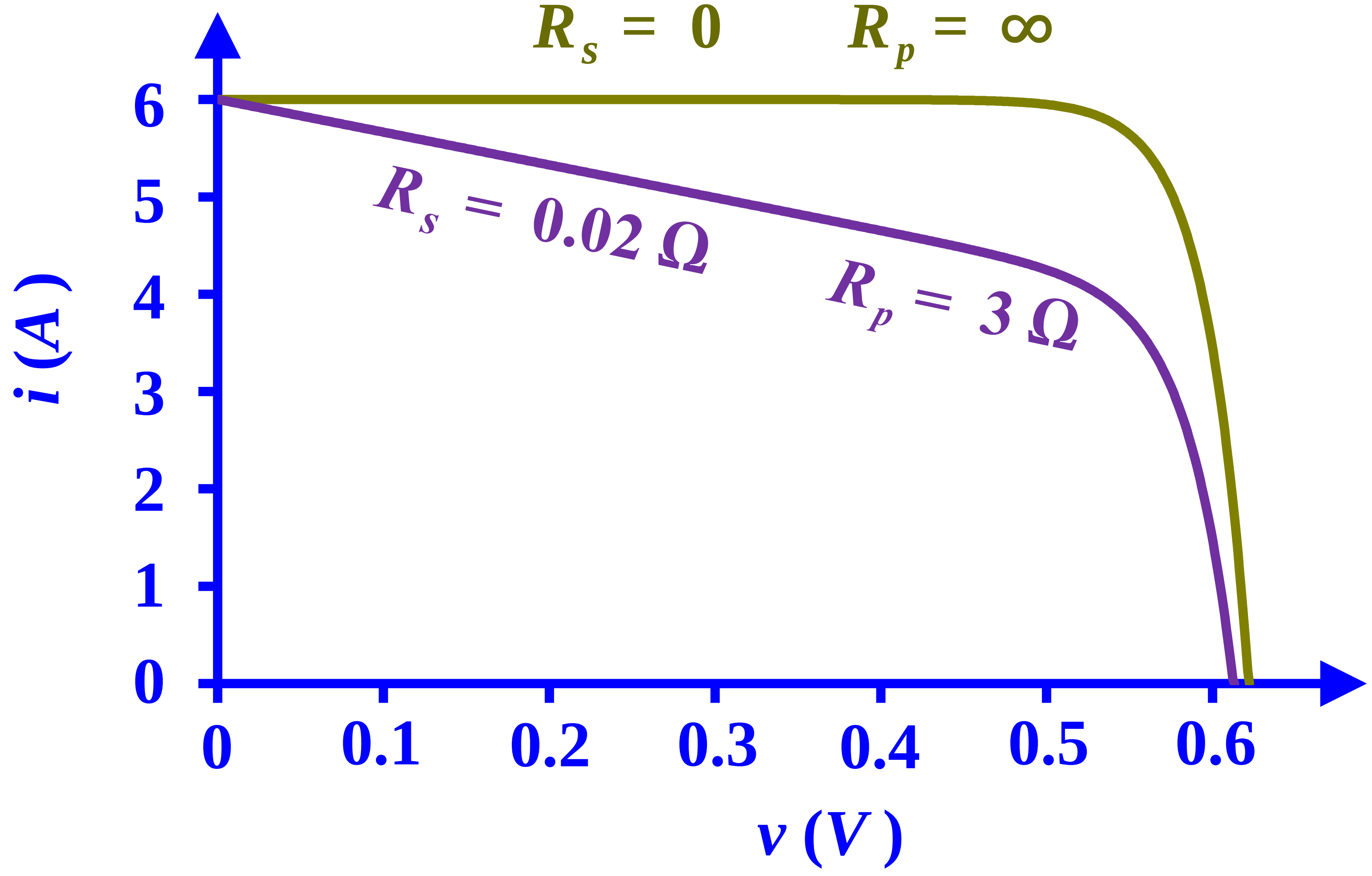
THE $i - v$ CURVES OF A MORE DETAILED CIRCUIT OF A *PV* CELL



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



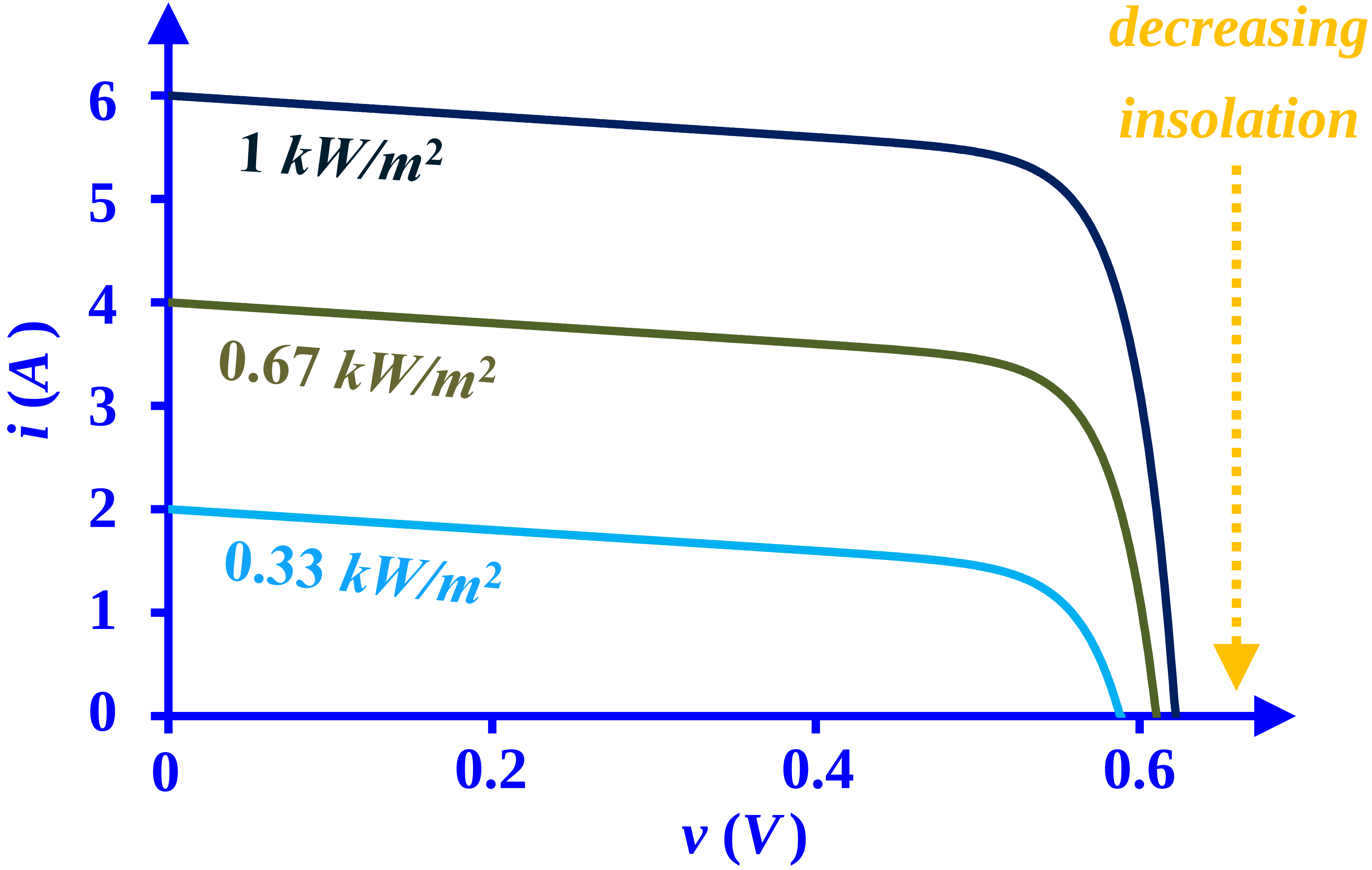
THE $i-v$ CURVES OF A MORE DETAILED CIRCUIT OF A *PV* CELL



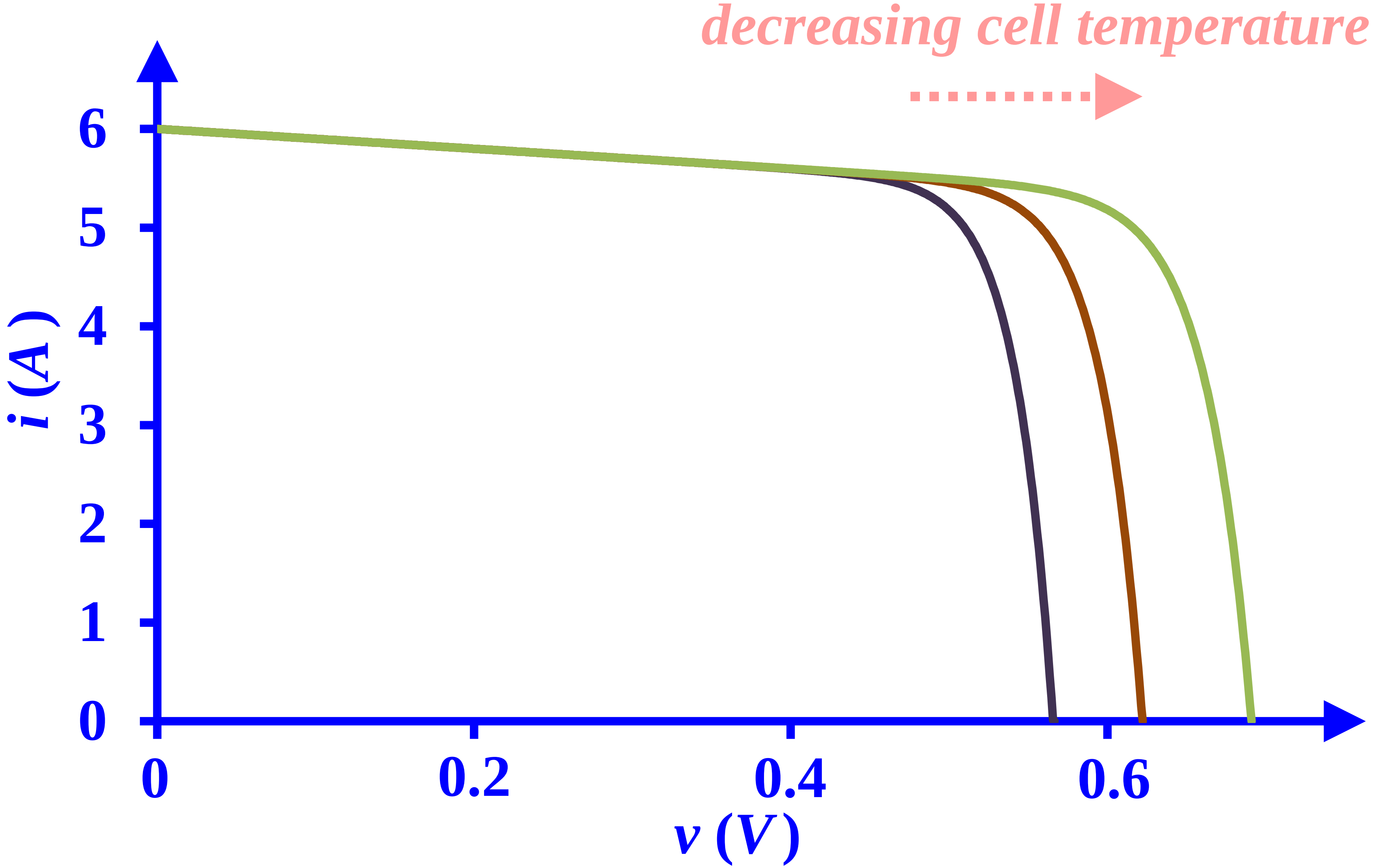
IMPACTS OF INSOLATION AND CELL TEMPERATURE

- ☐ The performance of *PV* cells is a function of the solar 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 AND CELL TEMPERATURE



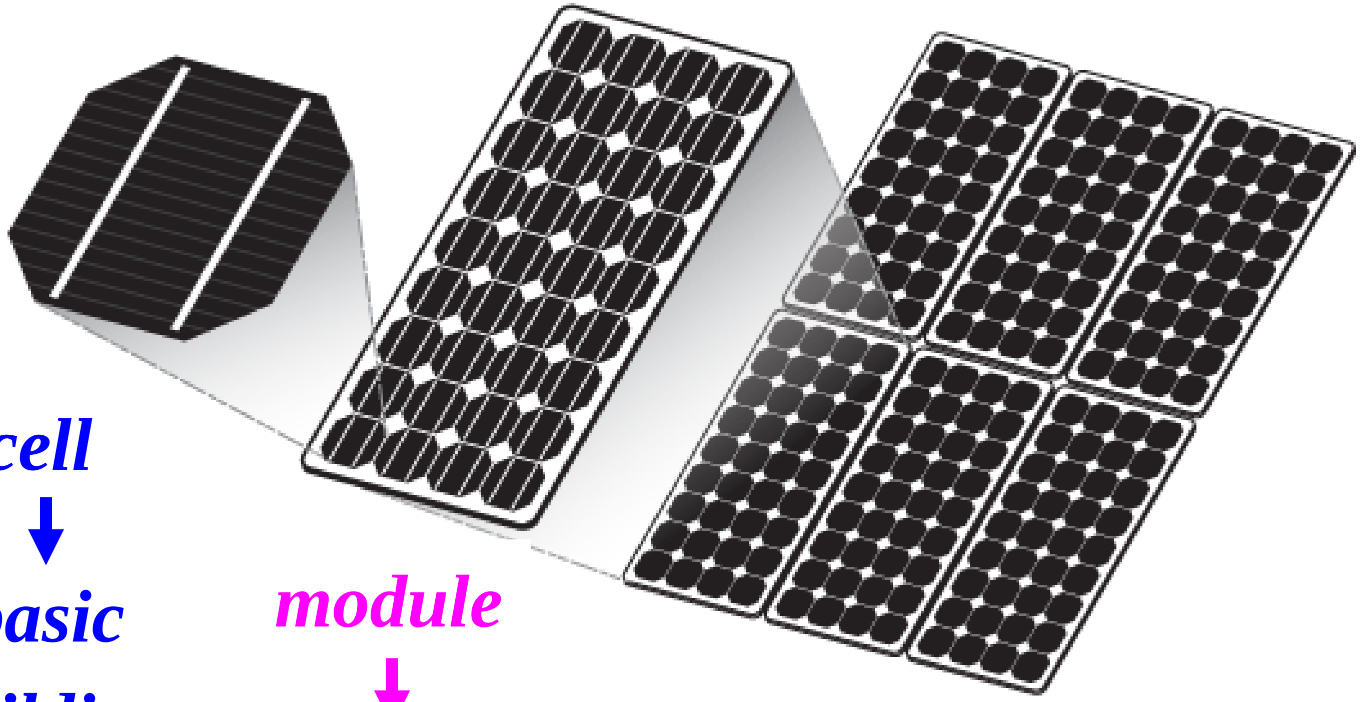
IMPACTS OF CELL TEMPERATURE ON *PV* $i - v$ CURVES



LIMITATION OF A SINGLE *PV* CELL

- ❑ The *i – v* behavior of a single cell results in too small 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



cell
↓
basic building block

module
↓
structural configuration

array
↓
solar PV element

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

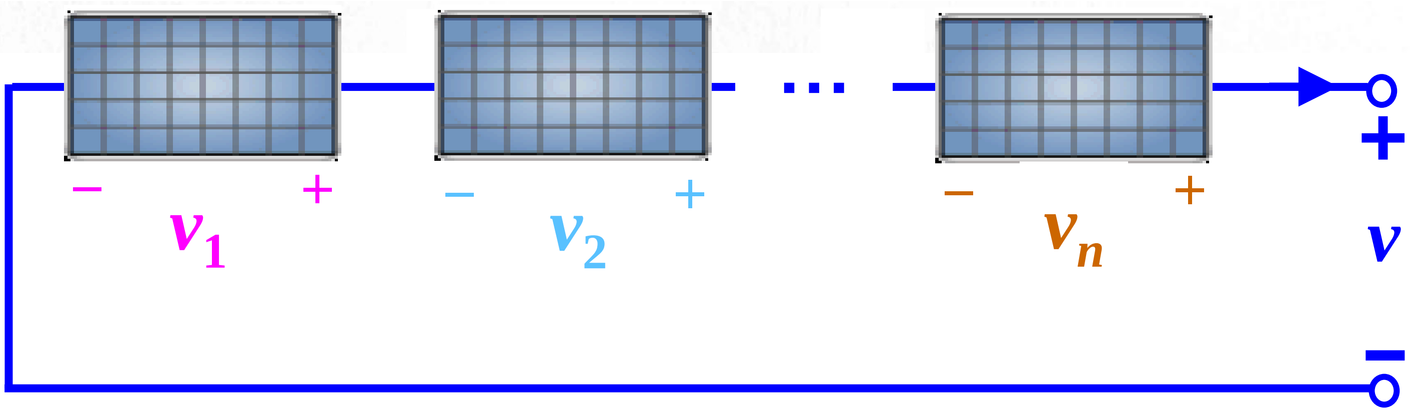
FROM CELLS TO MODULES

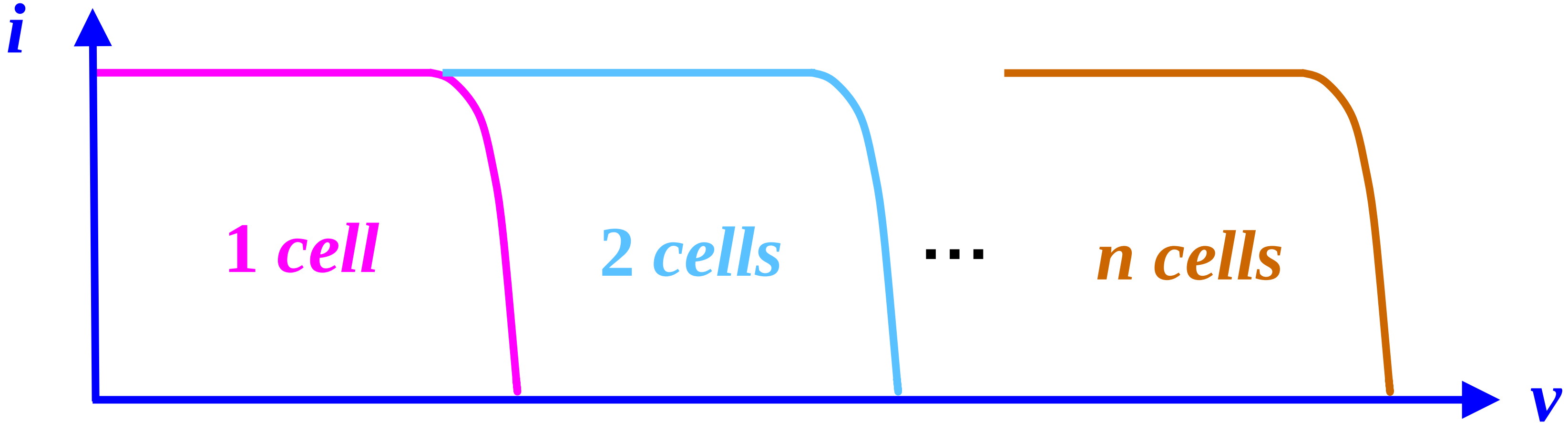
- **The underlying concept is to connect multiple *PV* cells *in series to increase voltage output* or *in parallel to increase current output* using the *PV* cells that are aggregated to construct a *PV* module**
- **Typical module sizes consist of 36, 72, 96 or 128 cells with the continuing trend toward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

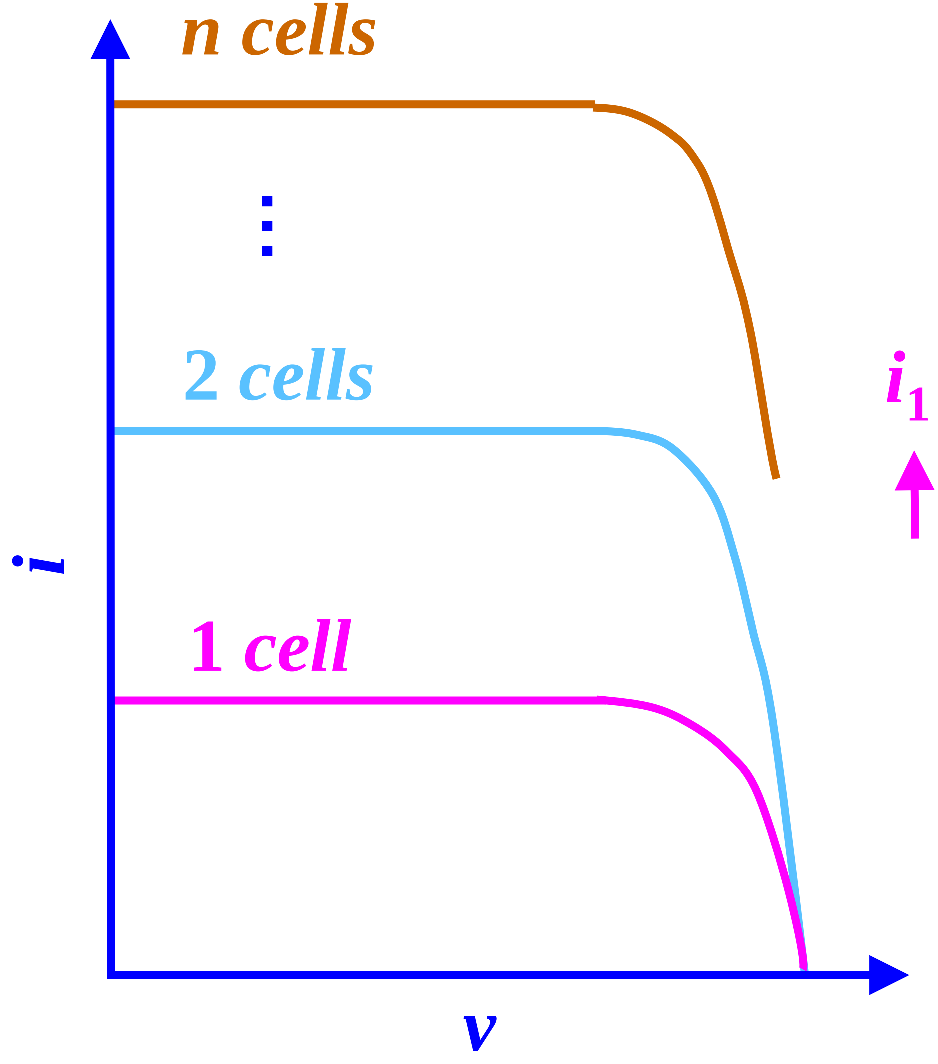
$i - v$ CURVE FOR CELLS IN SERIES



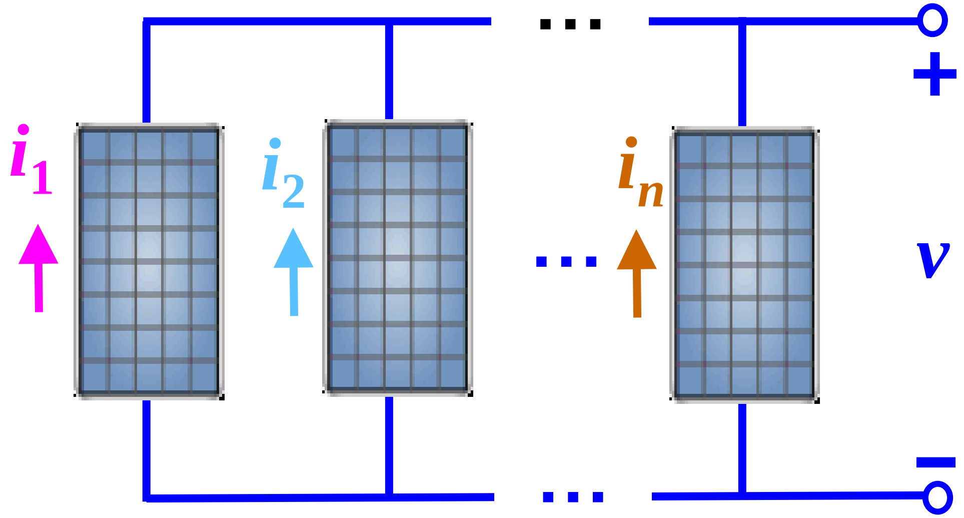


$$v = v_1 + v_2 + \cdots + v_n$$

$i - v$ CURVE FOR CELLS IN PARALLEL



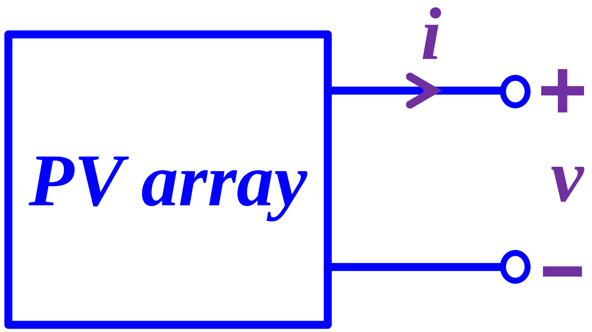
$$i = i_1 + i_2 + \ldots + i_n$$



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 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

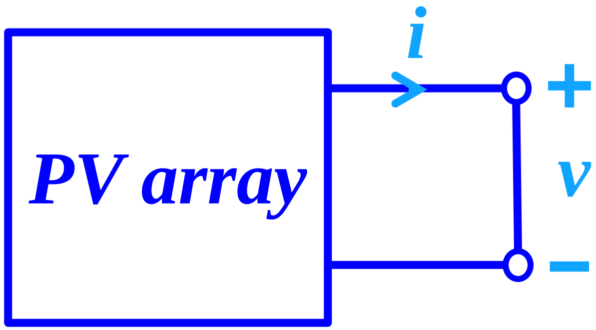
POWER OUTPUT FOR A *PV* ARRAY



$i = 0$

$v = v_{oc}$

open circuit conditions



$i = i_{sc}$

$v = 0$

short circuit conditions

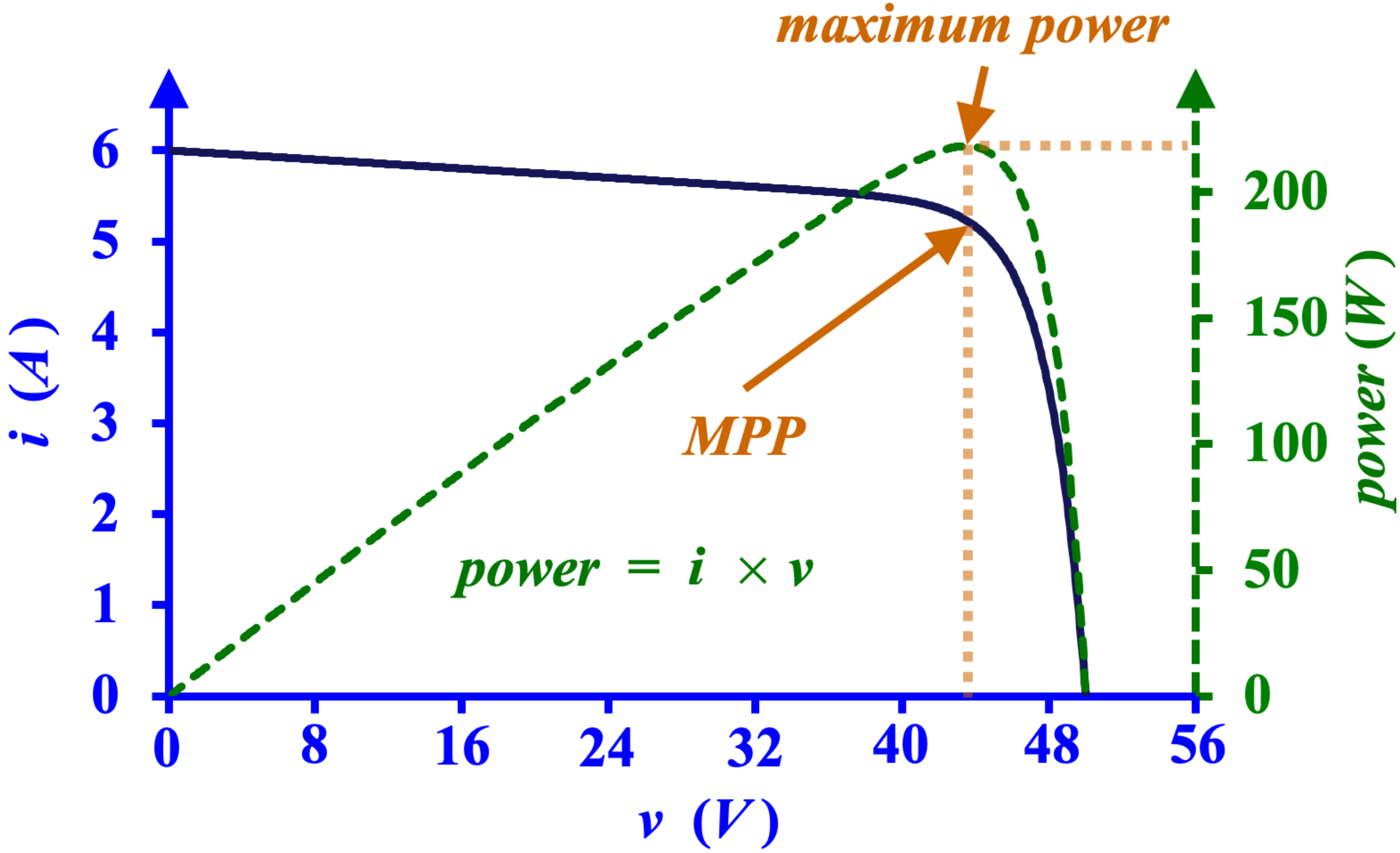
$power = i \times v = 0$

for both conditions

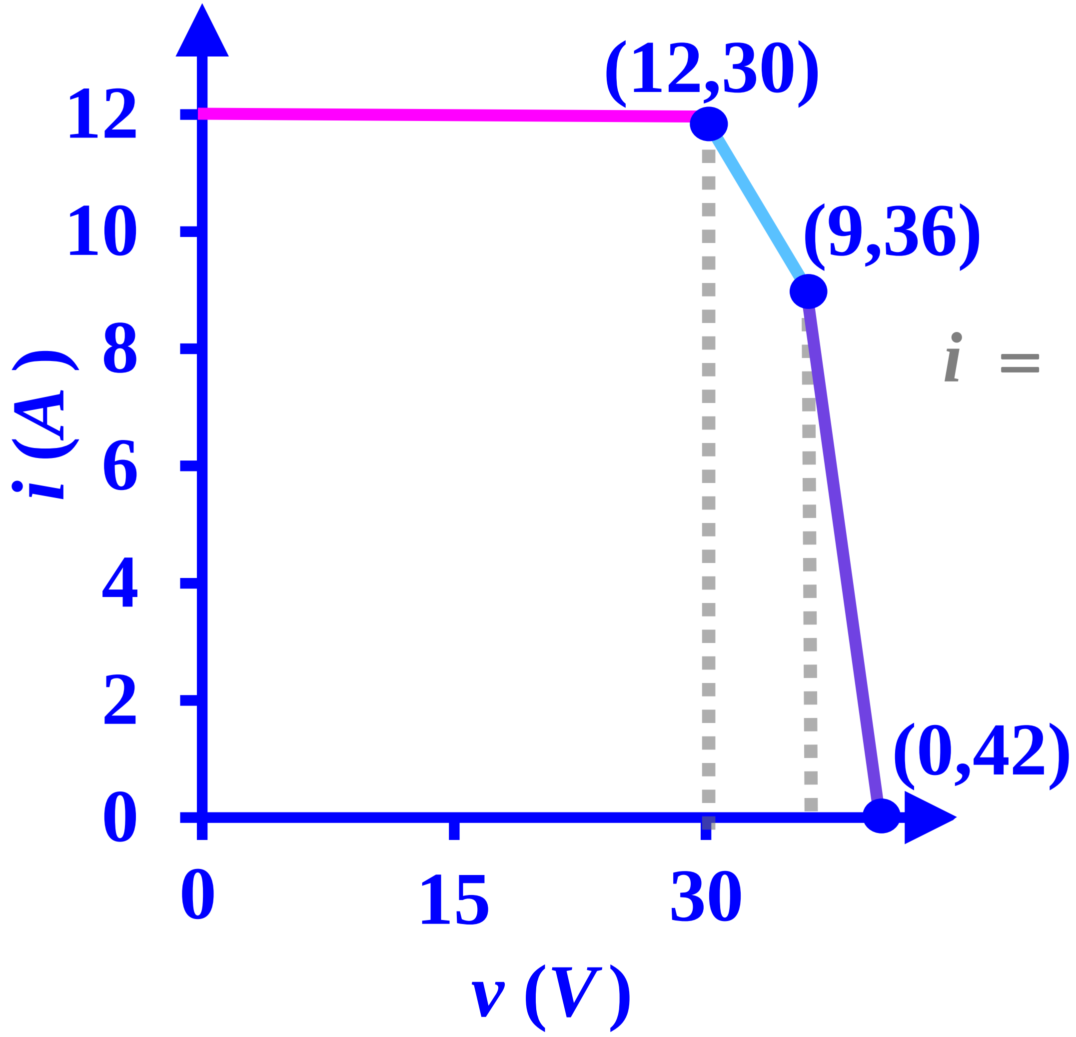
POWER OUTPUT FOR A *PV* ARRAY

- ☐ **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



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



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

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

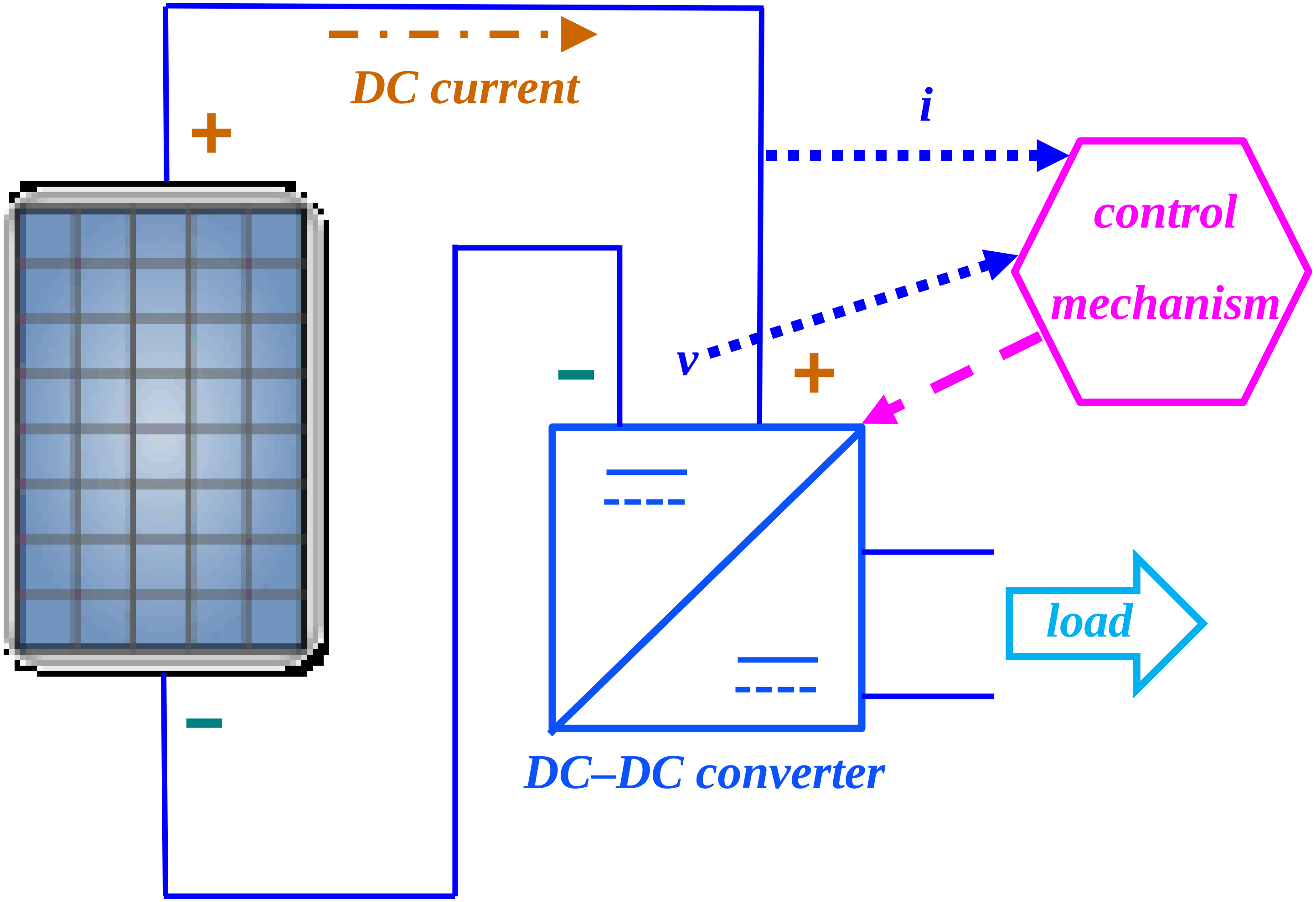
$$p = i \times v = \begin{cases} 12\,v & 0 \leq v \leq 30 \\ -0.5\,(v - 27)^2 + 0.5\,(27)^2 & 30 < v \leq 36 \\ -1.5\,(v - 21)^2 + 1.5\,(21)^2 & 36 < v \leq 42 \\ 0 & \textit{otherwise} \end{cases}$$

$p^M = 360\,W$ **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 tune the current/ voltage combination of the *PV* array**
- **A simple implementation of *MPPT* includes a *DC* – *DC* converter with a control mechanism**

MPPT



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**

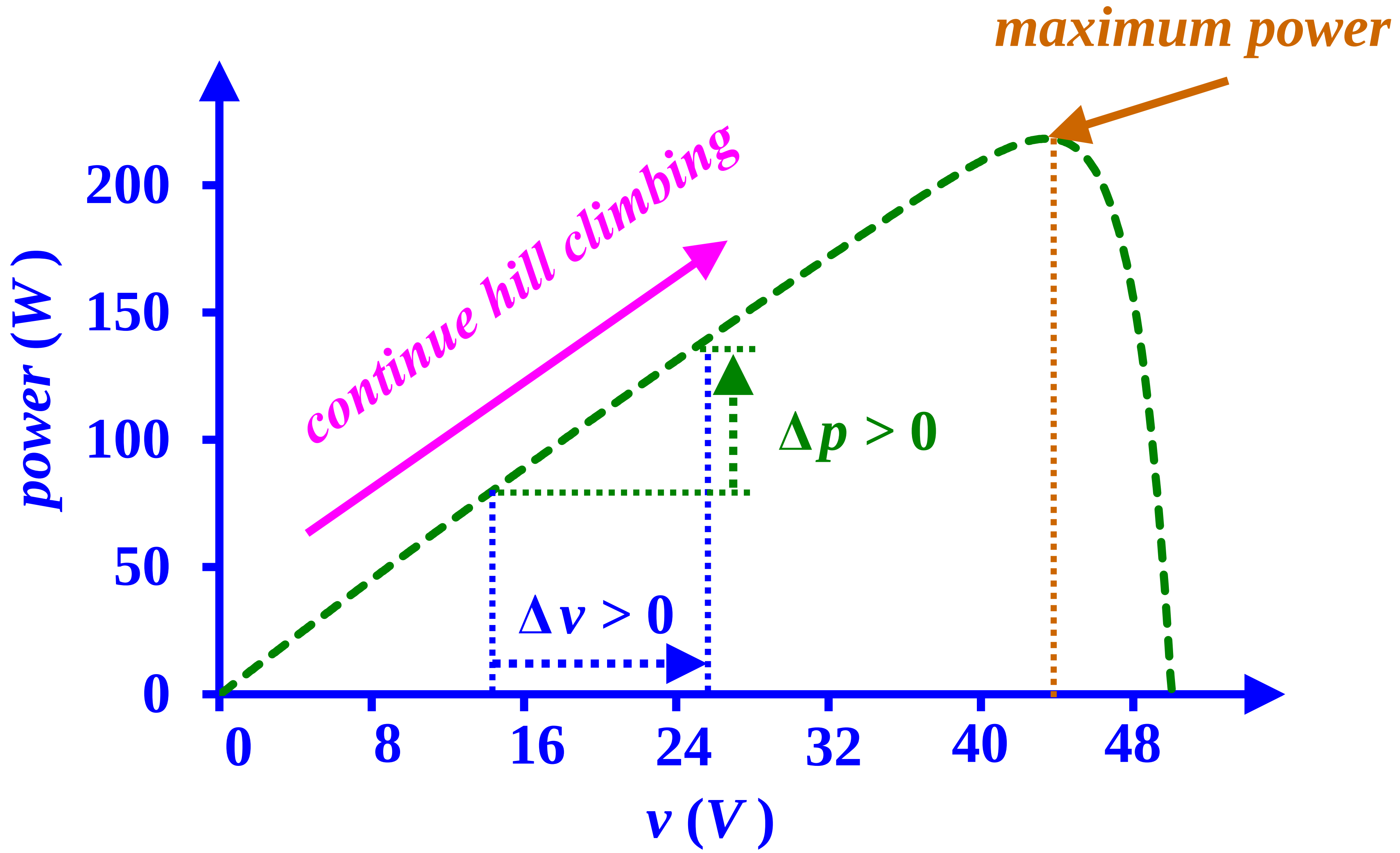
FRACTIONAL OPEN-CIRCUIT VOLTAGE METHOD

- *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 *MPP*s

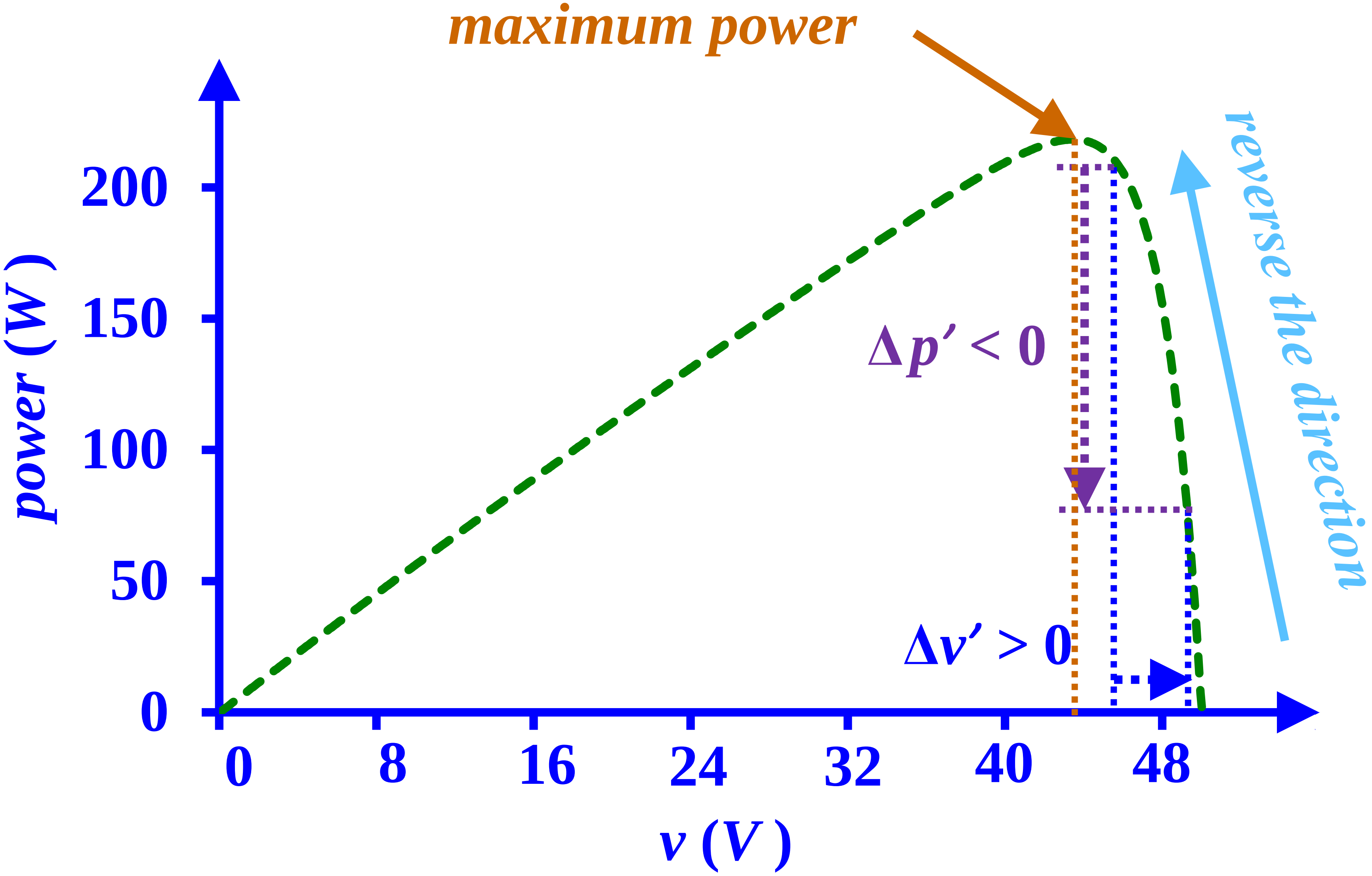
PERTURB AND OBSERVE

- *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



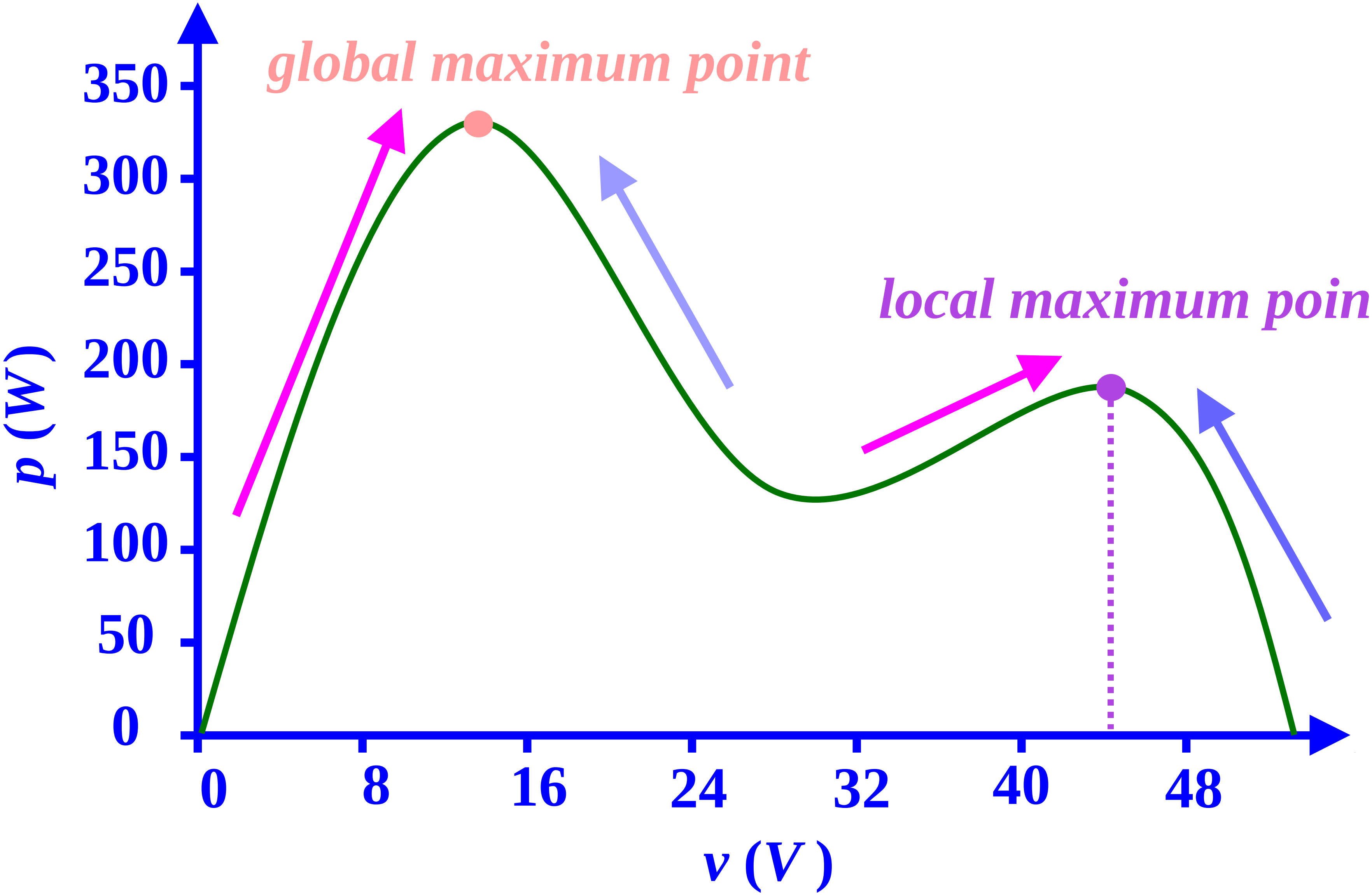
PERTURB AND OBSERVE



MPPT METHODS

- The two presented *MPPT* schemes are, in concept, rather simple and have only limited usefulness
- To handle more general/realistic situations, some necessary modifications of the *MPPT* algorithms need to be introduced to solve the actual *MPPT* problems in cases of more complex $i - v$ curves due to the presence of partial shadow on the *PV* cells or other complications that may arise

MAXIMUM POWER POINT TRACKER METHODS

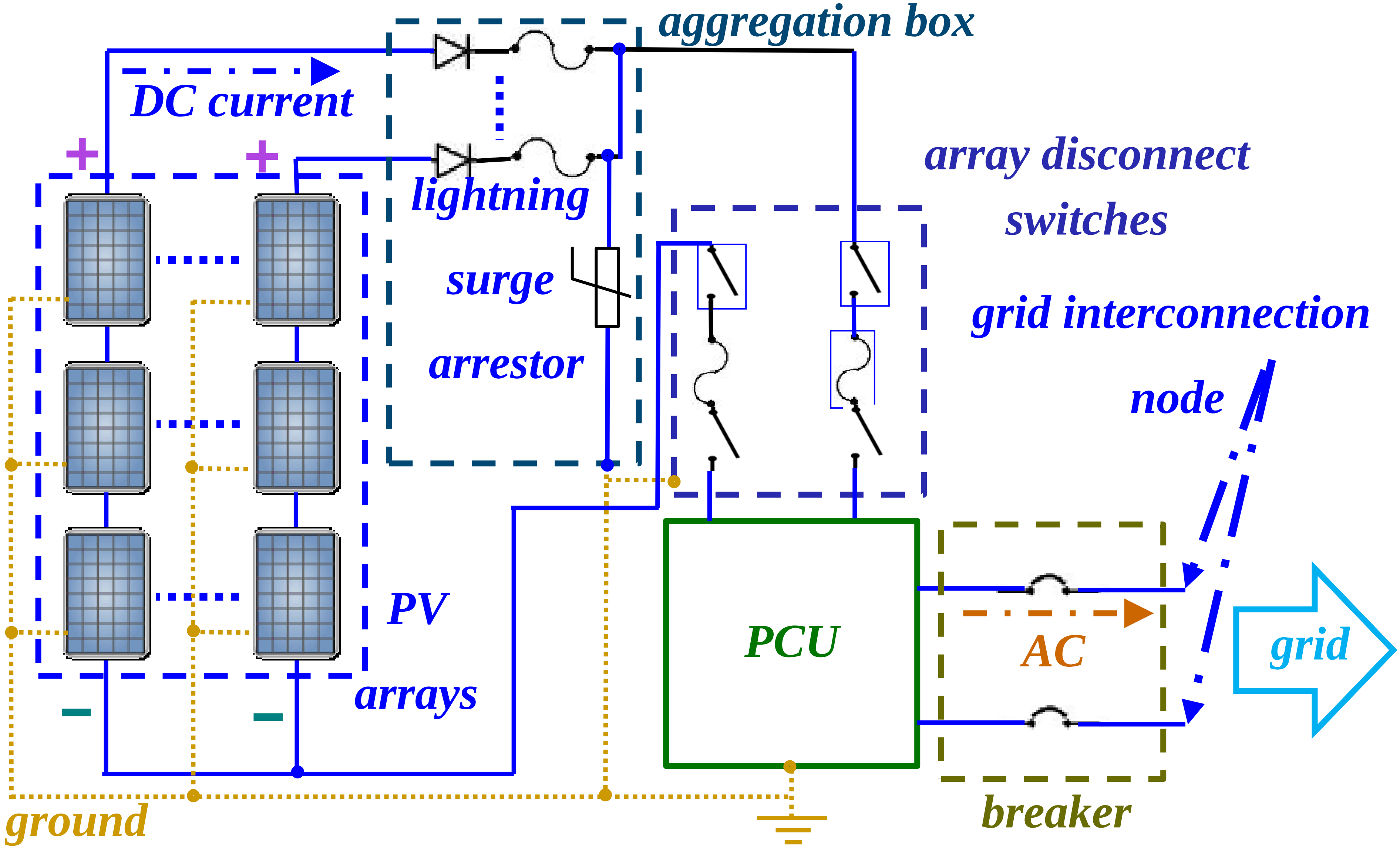


PV SYSTEMS

- ☐ ***PV*** **arrays, equipped with *MPPT* control, may also be used to charge batteries for energy storage**
- ☐ **However, *MPPT*, by itself, is unable to connect the *PV* to the grid since the solar output is *DC* power**
- ☐ **Indeed, for a *grid–connected PV system*, the *PV arrays* and the *MPPT* require also a *DC–AC* converter to allow injection of *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
  - 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 *MPPT DC–DC converter* becomes unnecessary as 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**

EXAMPLE: *PV* MODULE SPECIFICATIONS

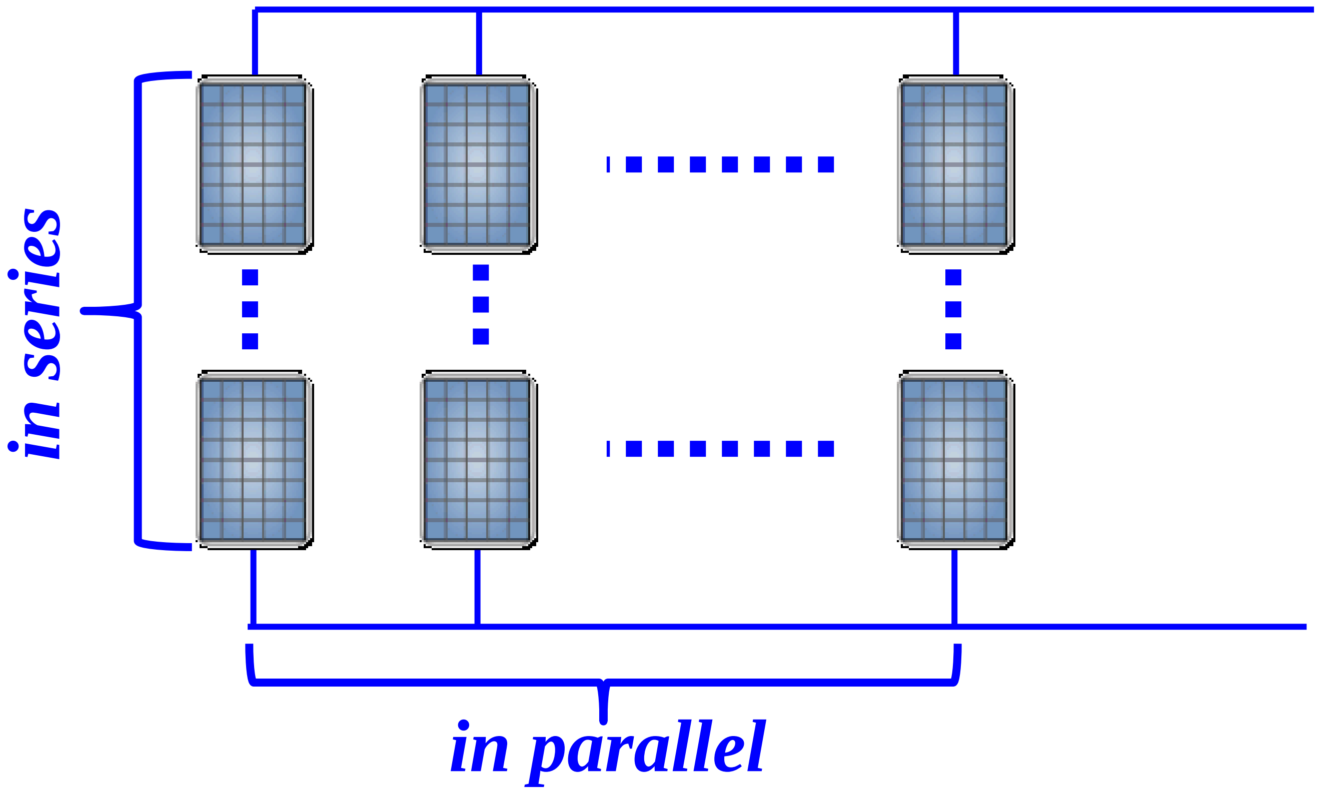
variable/parameter	*symbol*	*DC value*	*units*
maximum power	p^M	200	*W*
MPP voltage	v_{MPP}	50	*V*
MPP current	i_{MPP}	4	*A*
open-circuit voltage	v_{oc}	60	*V*
short-circuit current	i_{sc}	5	*A*

EXAMPLE: *PCU* SPECIFICATIONS

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

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

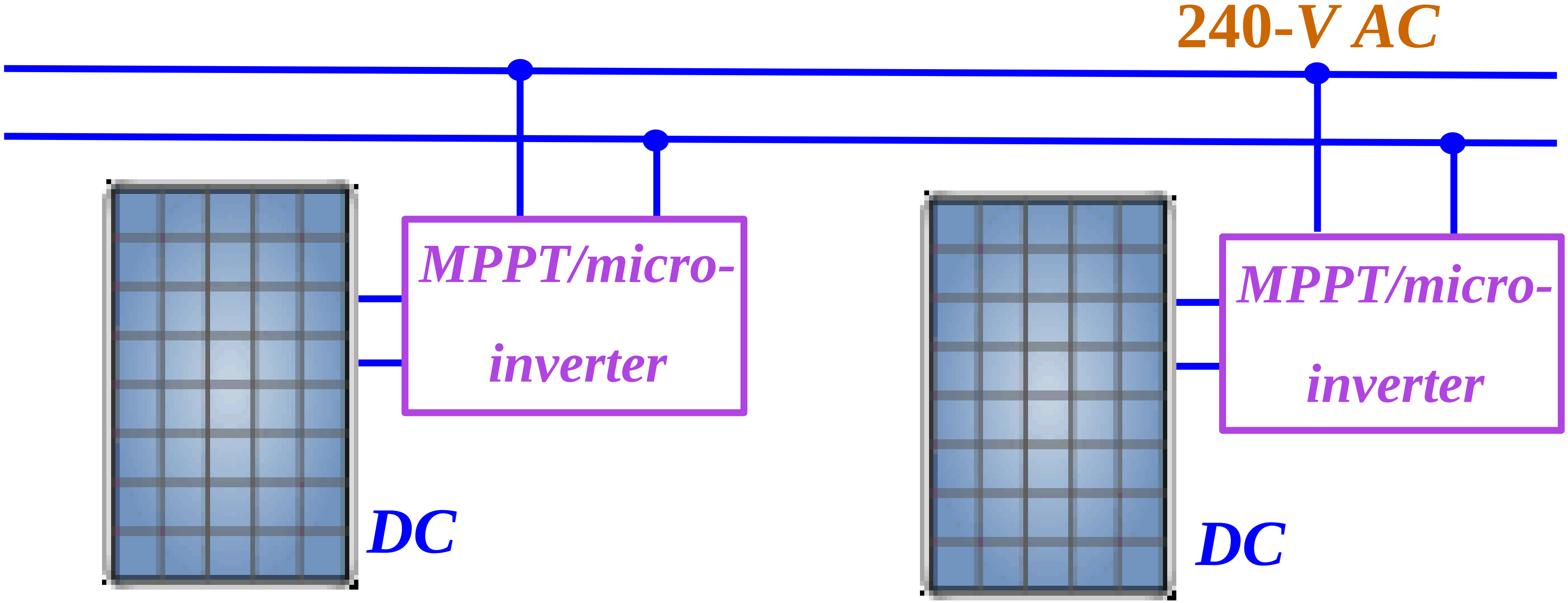
- ☐ **For the N_p modules connected in parallel to raise the current output, we determine the N_p value that satisfies:**

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

- ☐ **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 so as to result in a 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

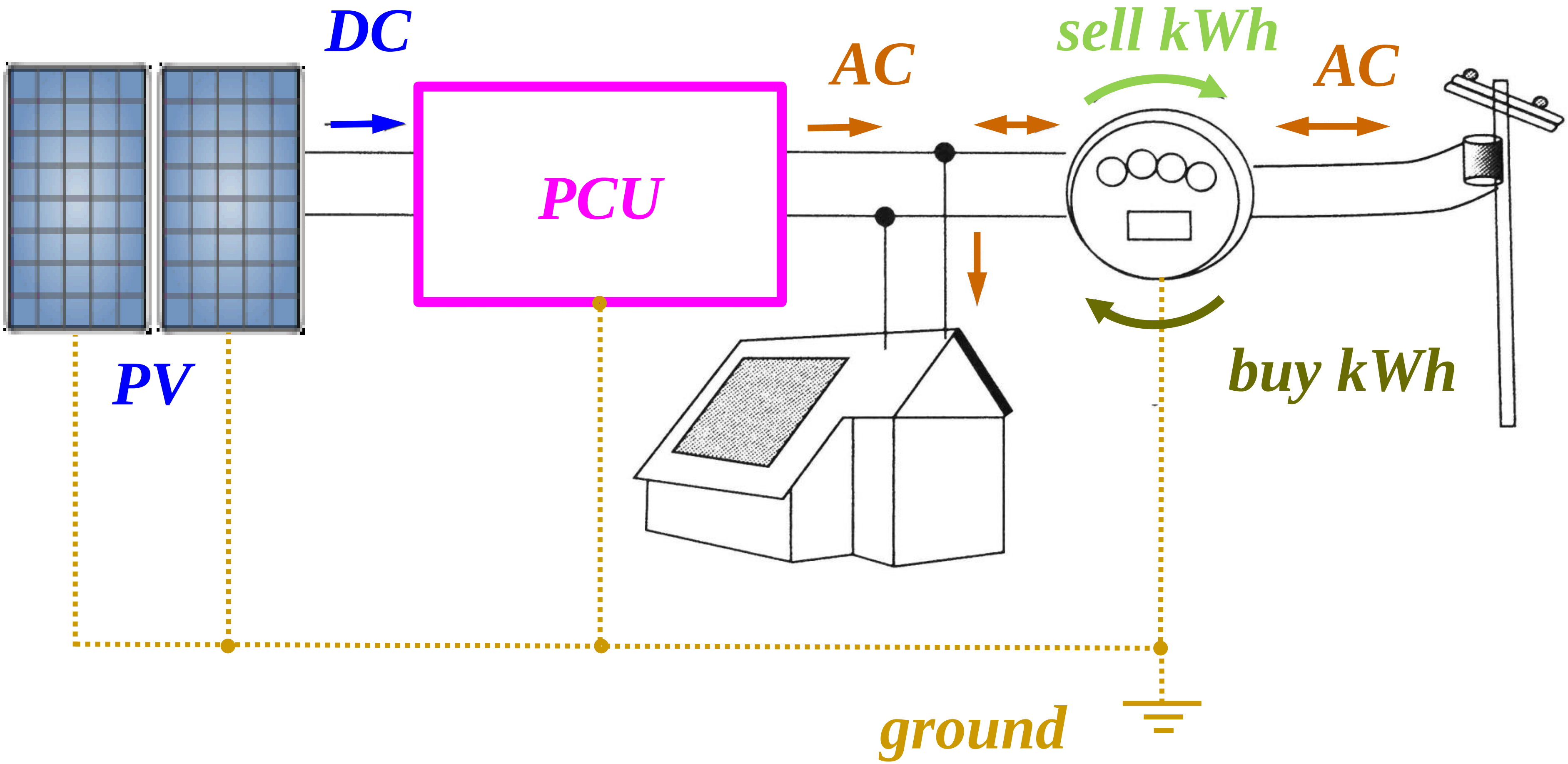
- Based on which side of the electric meter the *PV*s are located, the grid–connected *PV* systems are classified as either
  - *behind–the–meter systems*: usually installed on rooftops to feed their power outputs directly to the loads on the same side of the meter; or,

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 use 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

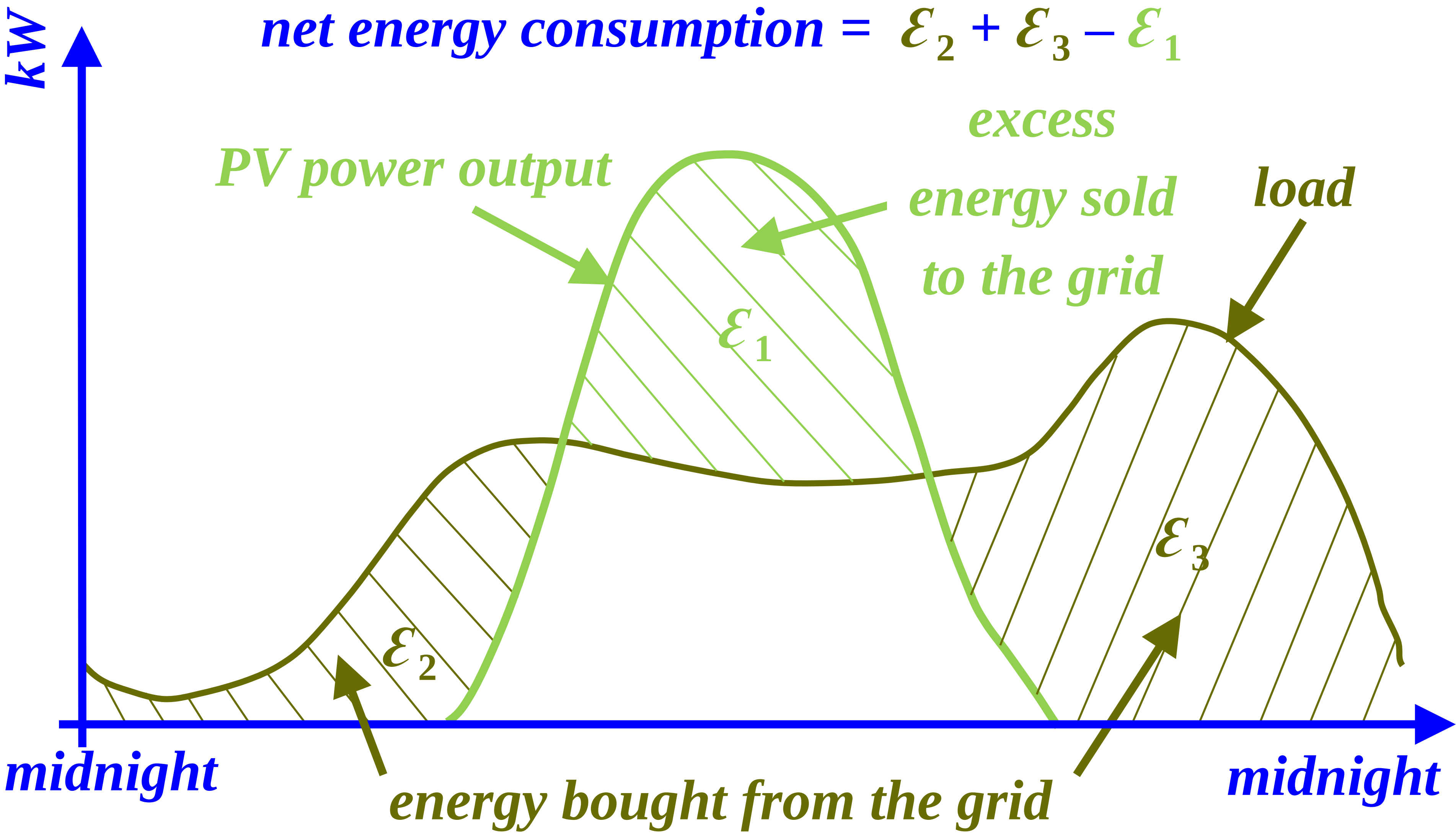


BEHIND–THE–METER GRID–CONNECTED *PV* SYSTEM

- ❑ **In the case that the loads exceed the power output of the *PV* system, the *PV* system owner buys the energy from the grid; otherwise, the *PV* system owner sells the excess energy to the grid**
- ❑ **As such, the customer's bill is only for the *net energy* that the *PV* system is unable to supply to meet its loads**

NET METERING

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



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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 time-independent electricity price is fixed at $0.20\ \$/kWh$, the bill for this day is

$$0.2\ \times\ 96 = \ \$\,19.2$$

TIME–OF–USE RATES

- **In many *US* grids, the peak loads occur in the hot summer afternoons to run the heavy *a.c.* loads that require the use of less–efficient, typically polluting plants to meet the loads**
- **During peak load times, the market prices are considerably higher than in the periods with low demands; some utilities use time–differentiated rates 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 peak demand times and transfer of their consumption to the *low–load hours*
- *TOU* rates, consequently, can further stimulate the installation of residential/commercial *PV* systems

EXAMPLE: *TOU* 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

- ☐ A grid customer, with a *bi–directional meter* to measure the consumed energy and the energy produced by the *PV*, pays or gets 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 schemes 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 $25^{o}\,C$
  - ○ 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, $20^{o} - 40^{o}\,C$ 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* 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 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**

NON–TEMPERATURE–RELATED *PV* POWER DERATING

to increased 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

PVWATTS

- ☐ The *Solar Advisor Model* called *PVWATTS* developed by *Sandia National Laboratory* to *quantify* 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

PVWATTS DERATE FACTOR VALUES AND RANGES

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 FACTOR VALUES AND RANGES

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

- ❑ **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 *PV AC* system power output under *stc* is**

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

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**

TEMPERATURE–RELATED *PV POWER DERATE* FACTORS

The approximation of cell temperature is given by

cell temperature $^{\circ}C$

cell temperature when the cell operates under a 0.8–sun ambient temperature of 20° C and 1 m/s wind speed is 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* FACTORS

- ❑ **Then, we introduce a temperature coefficient to account for the impacts of actual cell temperature**

temperature–related

temperature coefficient/ ^{o}C

derate factor

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

TEMPERATURE–RELATED *PV POWER DERATE* FACTORS

AC power output of the PV system in W

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

$$= p_{AC,\,stc} \times \left[1 + z \left(\tau_{cell} - 25 \right) \right]$$

EXAMPLE: TEMPERATURE–RELATED *PV* POWER DERATE FACTOR

- ☐ Consider a site in Chicago with a $0.7 - sun$ 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

$$\tau_{cell} = 35 + \left(\frac{45 - 20}{0.8} \right) \times 0.7 = 56.9^{o} C$$

- ☐ The installation of this *PV* system in Chicago with a specified $-0.5\,\%/^{o}\,C$ temperature coefficient and with $p_{AC,\,stc} = 2.31\,kW$, we compute the *AC* power delivered by the system to be

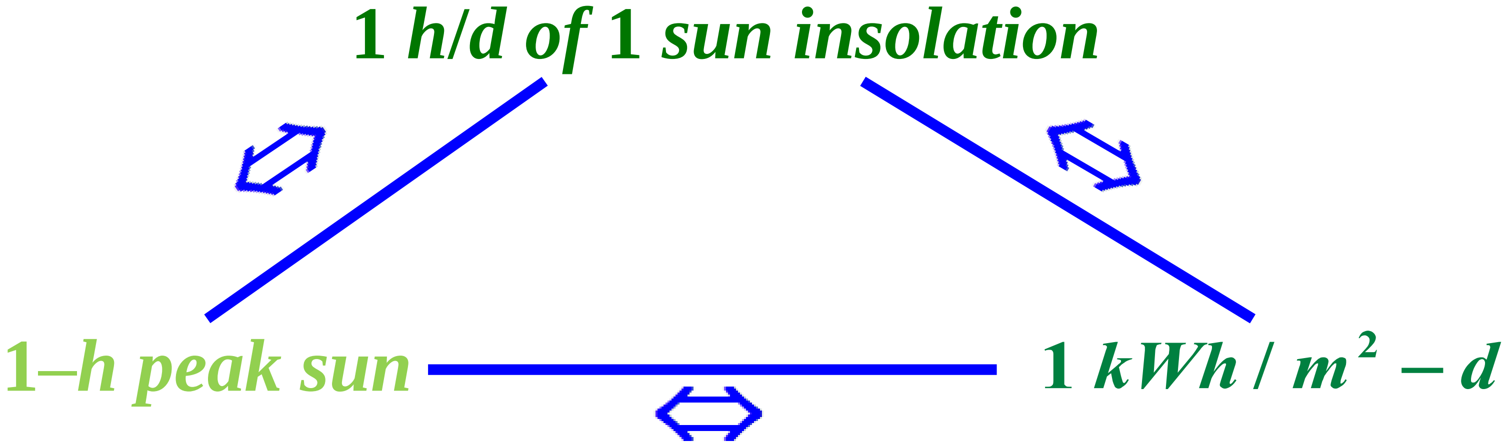
$$2.31 \times \left[1 + \left(-0.005 \right) \left(56.9 - 25 \right) \right] = 1.94\ kW$$

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 h/d of 1 sun insolation

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* or $1\ kW/m^2$ 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 the time of the study**
- ☐ **Therefore, we may write the daily *PV* system delivered energy as**

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

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

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

the system efficiency under 1 sun

- Then, for an 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

- ☐ **Under the assumption that the average system efficiency equals the efficiency under 1 *sun***

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

THE PEAK–HOURS APPROACH TO ESTIMATE *PV* PERFORMANCE

- ☐ **Coupled with the temperature–related *derate factor*, the peak–hours approach may 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: *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 $4.86 \ kWh / m^2 - d$ 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

variable/parameter	*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

variable/parameter	*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 *series-connected* modules form a string with additive voltage output, we determine the number N_s of modules in a string to satisfy the parameters:

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**

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