

***Smart Electricity Distribution Networks 1st edition  
Wang Solutions Manual***

SKU: 9781482230550-SOLUTIONS

## Chapter 2

### *Fundamentals of Distributed Energy Resources*

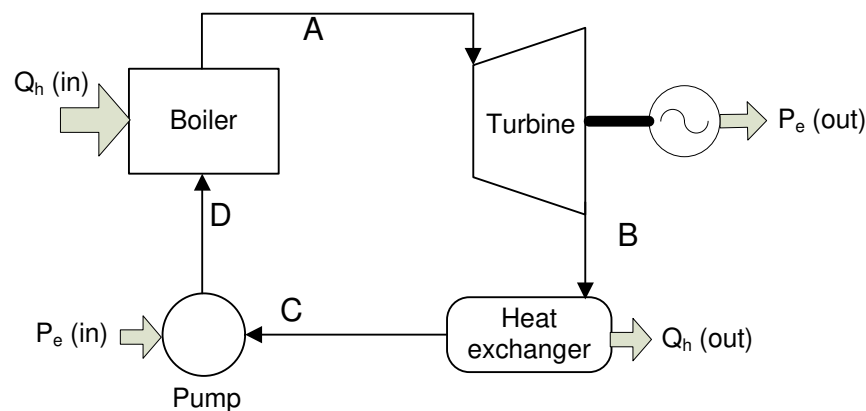
**Question 2.1.** List and explain the advantages and disadvantages of variable speed operation of large wind generators both for the wind turbine and the power system.

**Solution:**

- For maximum power extraction, the turbine should operate at a particular value of  $\lambda$ . In order to achieve this the generator speed should change with the wind speed.
- Under variable speed operation, the loading on the wind turbine is reduced.
- As variable speed wind turbine often has a power electronic interface, turbines will be able to meet the grid code requirements with less additional equipment.

**Question 2.2.** Draw the elements of a back-pressure steam turbine CHP generator. If the enthalpy of the steam just before the turbine is 3500 kJ/kg, just after the turbine is 2750 kJ/kg and mass flow rate is 10 kg/s, calculate the gross electrical power output of the CHP generator. Assume that the thermal efficiency of the turbine is 80% and the efficiency of the electrical generator is 95%. If the pump and other auxiliaries consume 5% of the gross output, what is the net electrical power output of the CHP generator?

**Solution:**



**Elements of back-pressure steam turbine cycle**

Gross power output

$$P_e(\text{out}) = \eta_t \eta_G \eta_{\text{eff}} [h_A - h_B] = 0.8 \times 0.95 \times 10 \times [3500 - 2750] = 5.7 \text{ MW}$$

$$\text{Net power output} = 5.7(1 - 0.05) = 5.42 \text{ MW}$$

**Question 2.3.** A crystalline silicon PV module has 36 cells connected in series. Each cell is square with sides 150 mm. Assume  $ISC = 300 \text{ A/m}^2$  at standard conditions and the cells have a rectangular V-I characteristic (i.e. 100% fill factor)

- Estimate the open-circuit voltage, the short circuit current and the power output of the module at an irradiance of  $800 \text{ W/m}^2$ .
- A solar array is formed by six modules, three in series and two strings in parallel. What is the open-circuit voltage, the short circuit current and the power output of the array at an irradiance of  $500 \text{ W/m}^2$ ?

**Solution:**

- a) Each cell has an open circuit voltage of 0.6V. Therefore 36 cells in series gives a module open circuit of 21.6 volts.

Each cell has an area of  $0.15 \times 0.15 \text{ m}^2$ . With a short circuit current of  $300 \text{ A/m}^2$  at an irradiance of  $1000 \text{ W/m}^2$ , this gives a current of 6.75A. However the irradiance is  $800 \text{ W/m}^2$  and so this reduces to  $0.8 \times 6.75 = 5.4 \text{ A}$ .

Hence the power output is the  $V \times I$  or 116 W

- b) Three modules in series gives an open circuit voltage of  $21.6 \times 3 = 64.8 \text{ V}$

As there are two strings of modules in parallel the total short circuit current at the irradiance of  $500 \text{ W/m}^2 = 6.75 \times 0.5 \times 2 = 6.75 \text{ A}$

Hence the power output is  $V \times I$  or 437.4 W

**Question 2.4.** The nameplate on a 400V, 600 kW, 50 Hz, 4 pole induction generator indicates that its speed at rated load is 1510 rev/min. Assume the generator to be operating at rated load. What is the

- slip of the rotor?
- frequency of the rotor current?
- angular velocity of the stator field with respect to the rotor and stator?

**Solutions:**

a)  $\omega_s = 120f/p = 120 \times 50/4 = 1500 \text{ rev/min}$

$$\text{Slip} = (1500 - 1510)/1500 = -0.67\%$$

b) Frequency of the rotor current =  $sf = 0.0067 \times 50 = 0.33 \text{ Hz}$

c) With respect to the rotor, the angular velocity =  $s\omega_s = -0.0067 \times 1500 = -10 \text{ rev/min}$  (negative sign indicates in the reverse direction to  $\omega_s$ )

With respect to the stator =  $1510 - 10 = 1500 \text{ rev/min} = 157.08 \text{ rad/s}$

**Question 2.5.** A country needs a total generation of 12,000 GWh per annum. It was decided to meet 25% of this demand from renewable energy sources. This will be met by  $P_1$  (MW) capacity of wind generation and  $P_2$  (MW) capacity of solar PV with the ratio  $P_1:P_2$  of 5:1.

a) Assuming that the average capacity factors of the wind generation is 35% and the solar generation is 20%, calculate  $P_1$  and  $P_2$ .

b) If 2 MW wind turbines are used to obtain capacity  $P_1$ , how many wind turbines are required? If the rotor radius of each wind turbine is 100 m and the coefficient of performance of each wind turbine is 0.4, calculate the average wind speed required to obtain 2 MW. Assume an air density of  $1.25 \text{ kg/m}^3$ .

**Solutions:**

a) Generation from renewables =  $12000 \times 0.25 = 3000 \text{ GWh}$

$$0.35 \times P_1 \times 8760 + 0.2 \times P_2 \times 8760 = 3000 \text{ GWh}$$

$$0.35P_1 + 0.2P_2 = 342.47 \text{ MW}$$

Since  $P_1/P_2 = 5$

$$P_1 = 878.1 \text{ MW and } P_2 = 175.62 \text{ MW}$$

b) No of wind turbines required =  $878.1/2 = 440$

$$P_{out} = 0.5 \times C_p \rho A U^3$$

$$2 \times 10^6 = 0.5 \times 0.4 \times 1.225 \times \pi \times 100^2 \times U^3$$

$$U = 6.38 \text{ m/s}$$

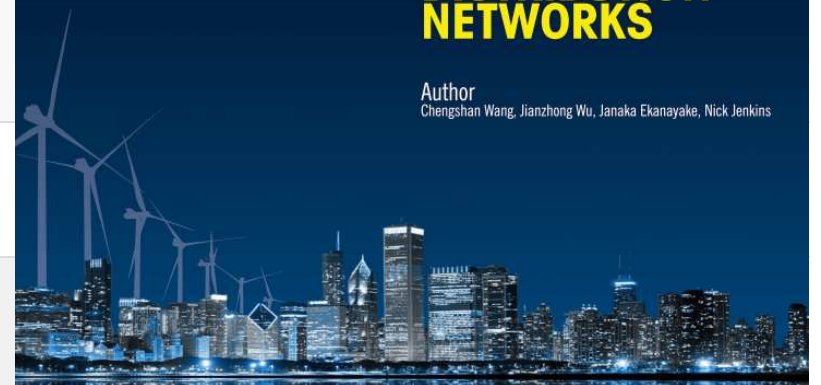


# Chapter 2

Smart Electricity Distribution Networks

## SMART ELECTRICITY DISTRIBUTION NETWORKS

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# Fundamentals of Distributed Energy Resources



## 2.1 Introduction



## 2.2 Combined Heat and Power plants



## 2.3 Photovoltaic Energy Systems



## 2.4 Wind Energy Systems



## 2.5 Electrical Energy Storage



## 2.6 Flexible demand



## 2.1 Introduction

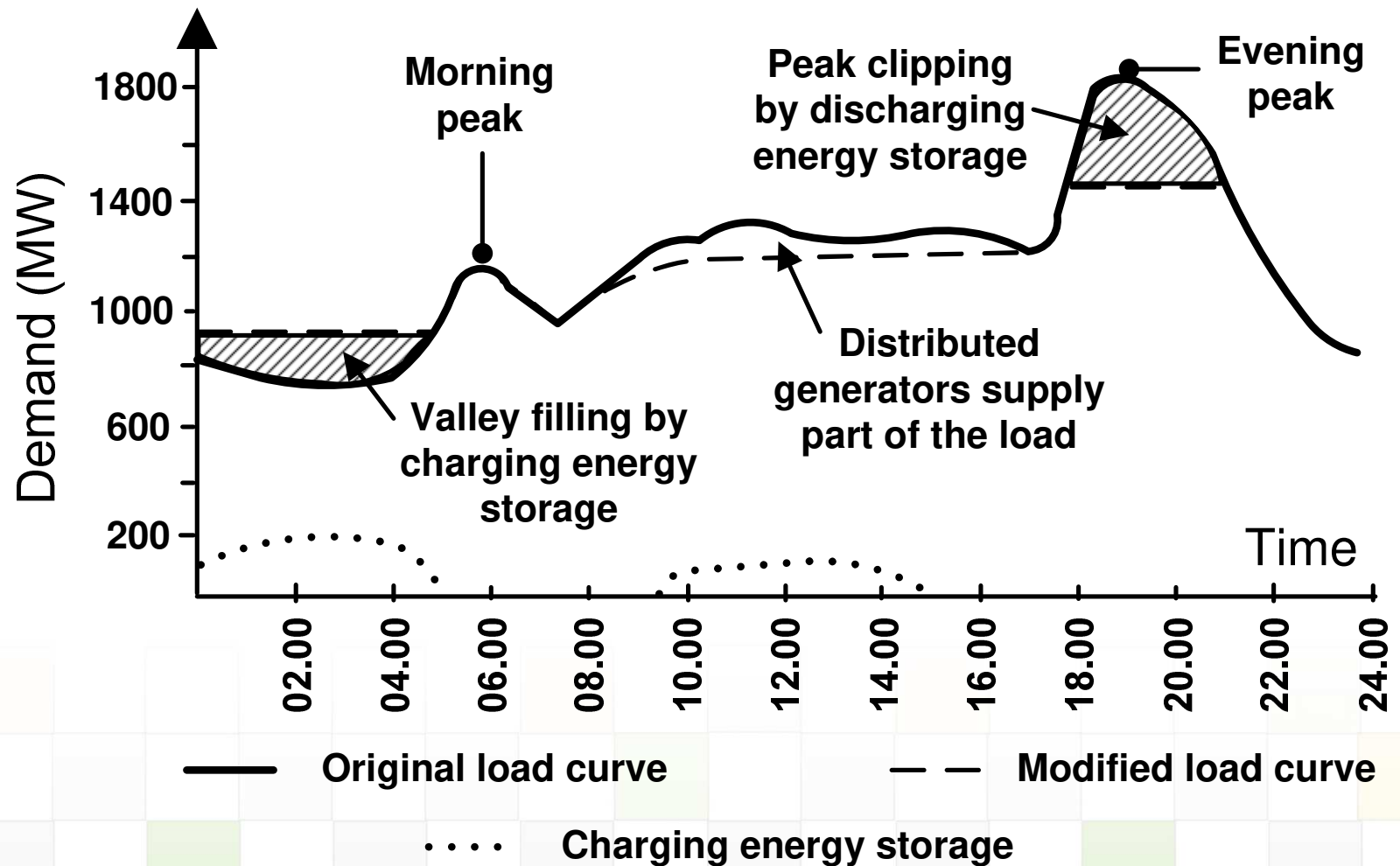


Figure 2.1 Benefits of DER



## 2.2 Combined Heat and Power plants

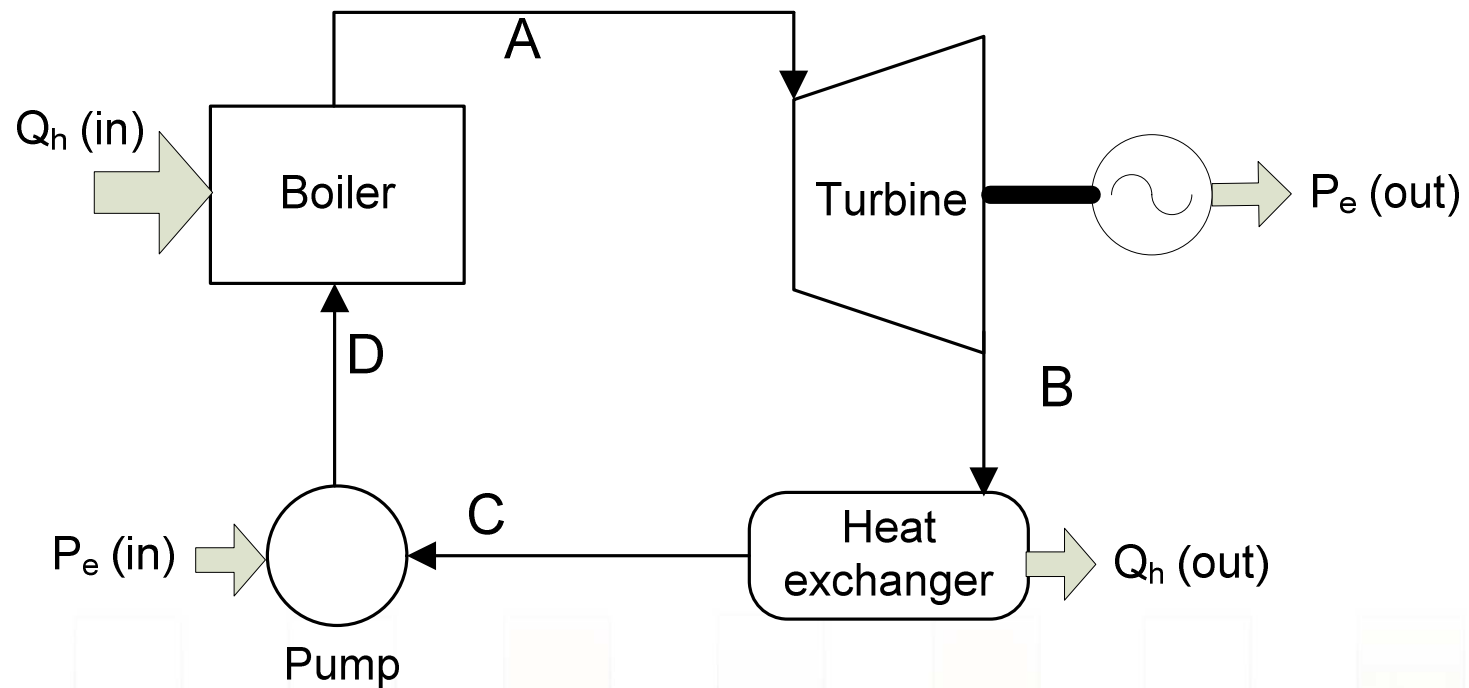


Figure 2.2 Elements of back-pressure steam turbine cycle



## 2.2 Combined Heat and Power plants

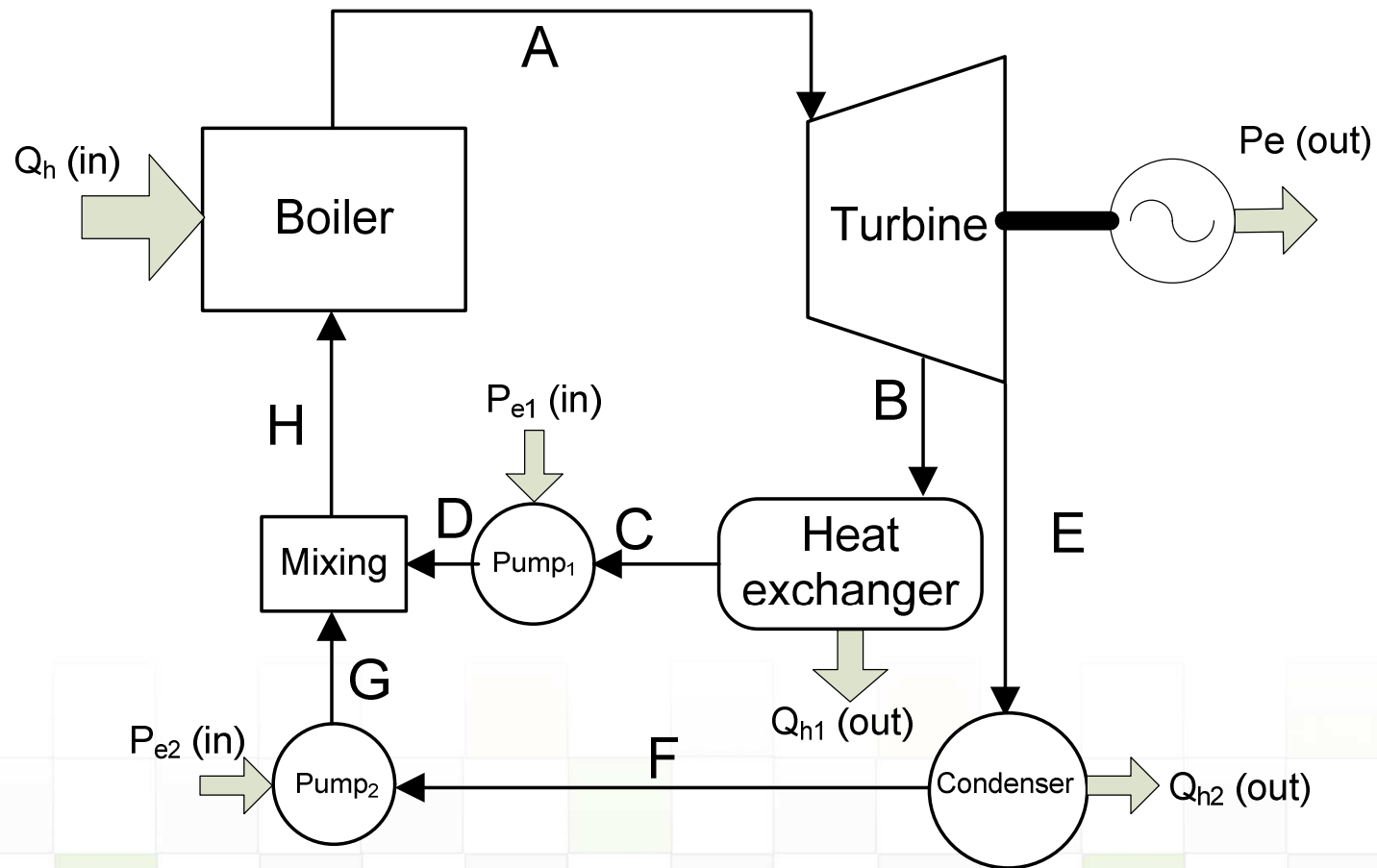


Figure 2.3 Elements of pass out condensing steam turbine cycle



## 2.2 Combined Heat and Power plants

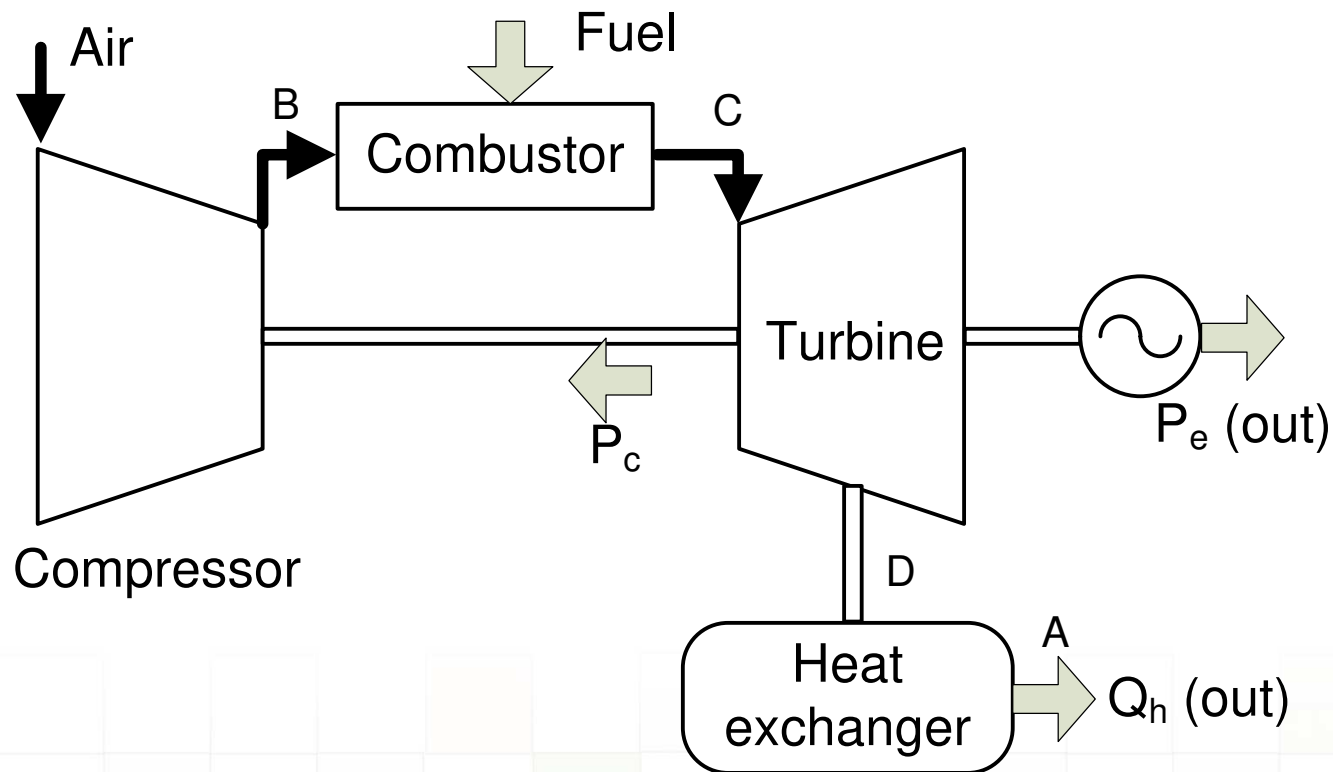


Figure 2.4 Simple cycle, single shaft gas turbine



## 2.2 Combined Heat and Power plants

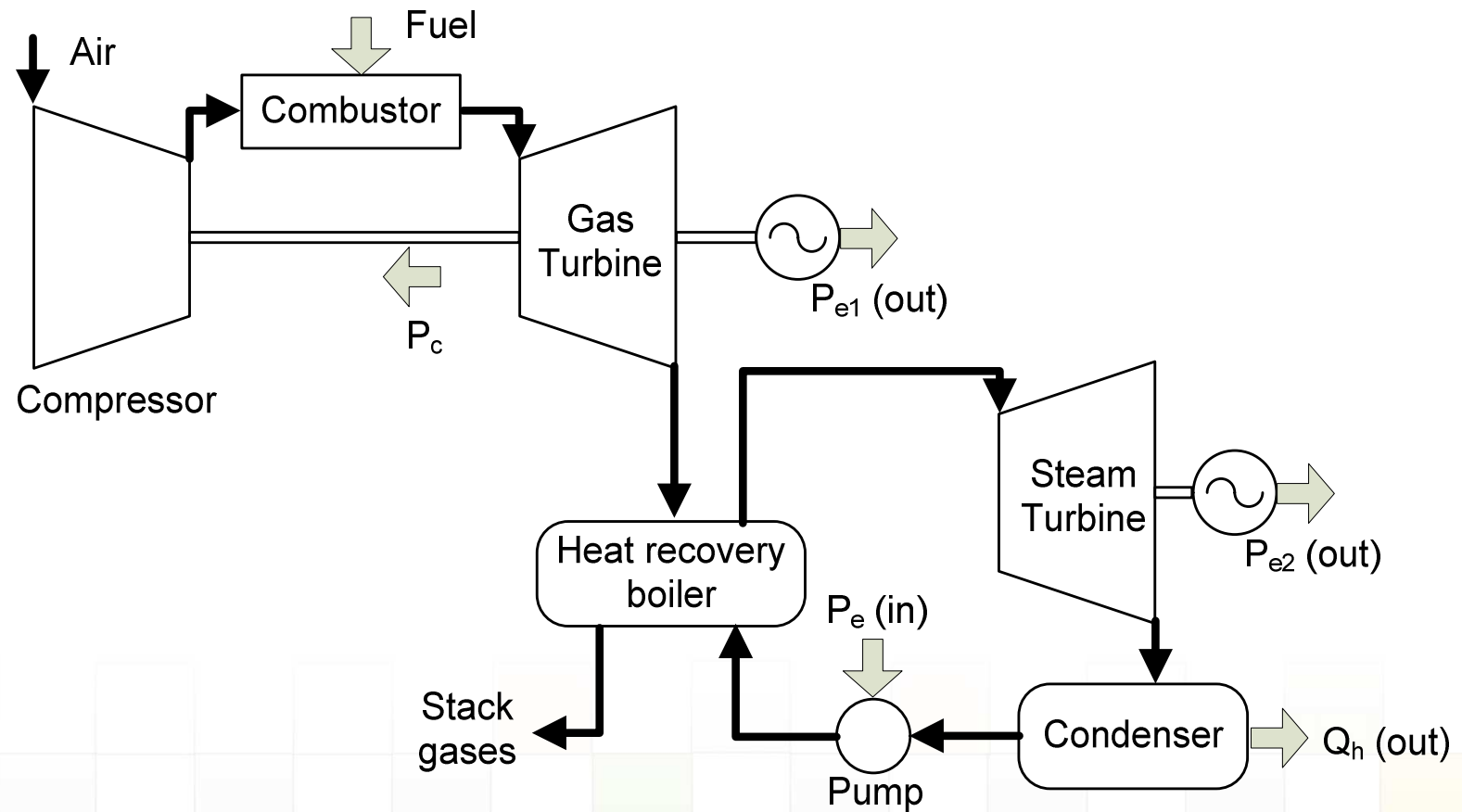


Figure 2.5 Combined cycle gas turbine



## 2.2 Combined Heat and Power plants

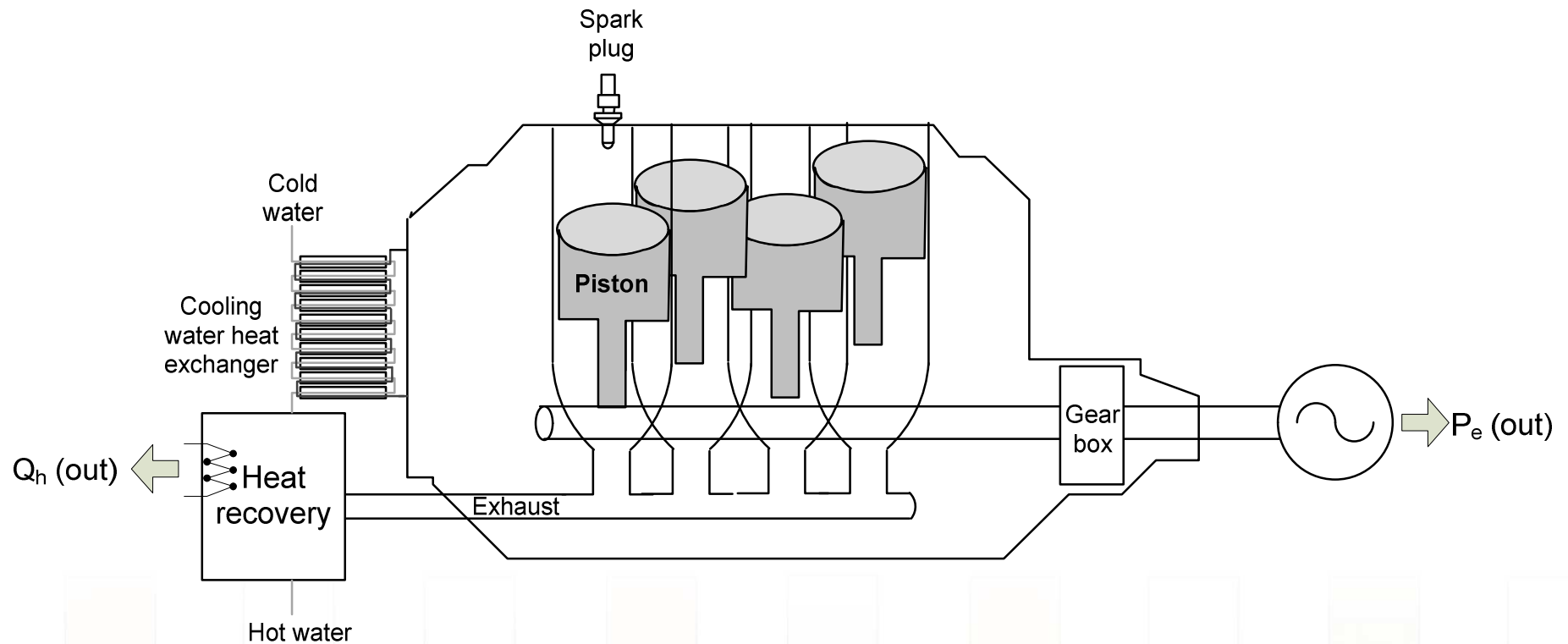


Figure 2.6 Components of an Otto engine based CHP unit



## 2.2 Combined Heat and Power plants

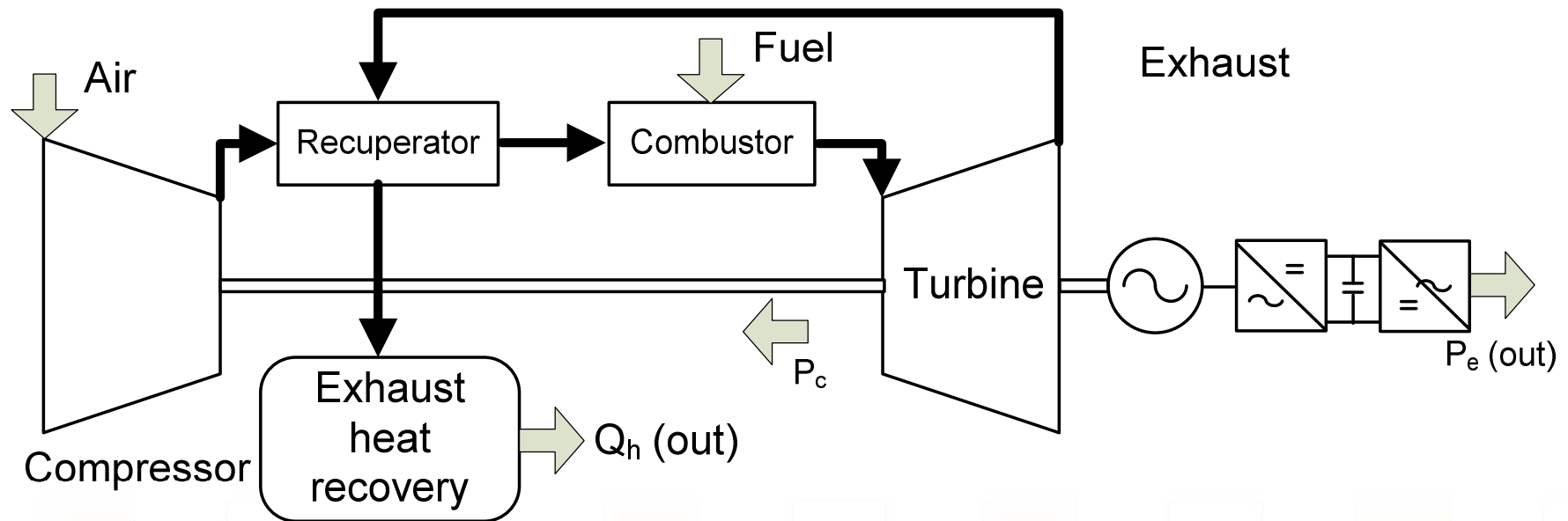


Figure 2.7 Components of an internal combustion based CHP unit



## 2.2 Combined Heat and Power plants

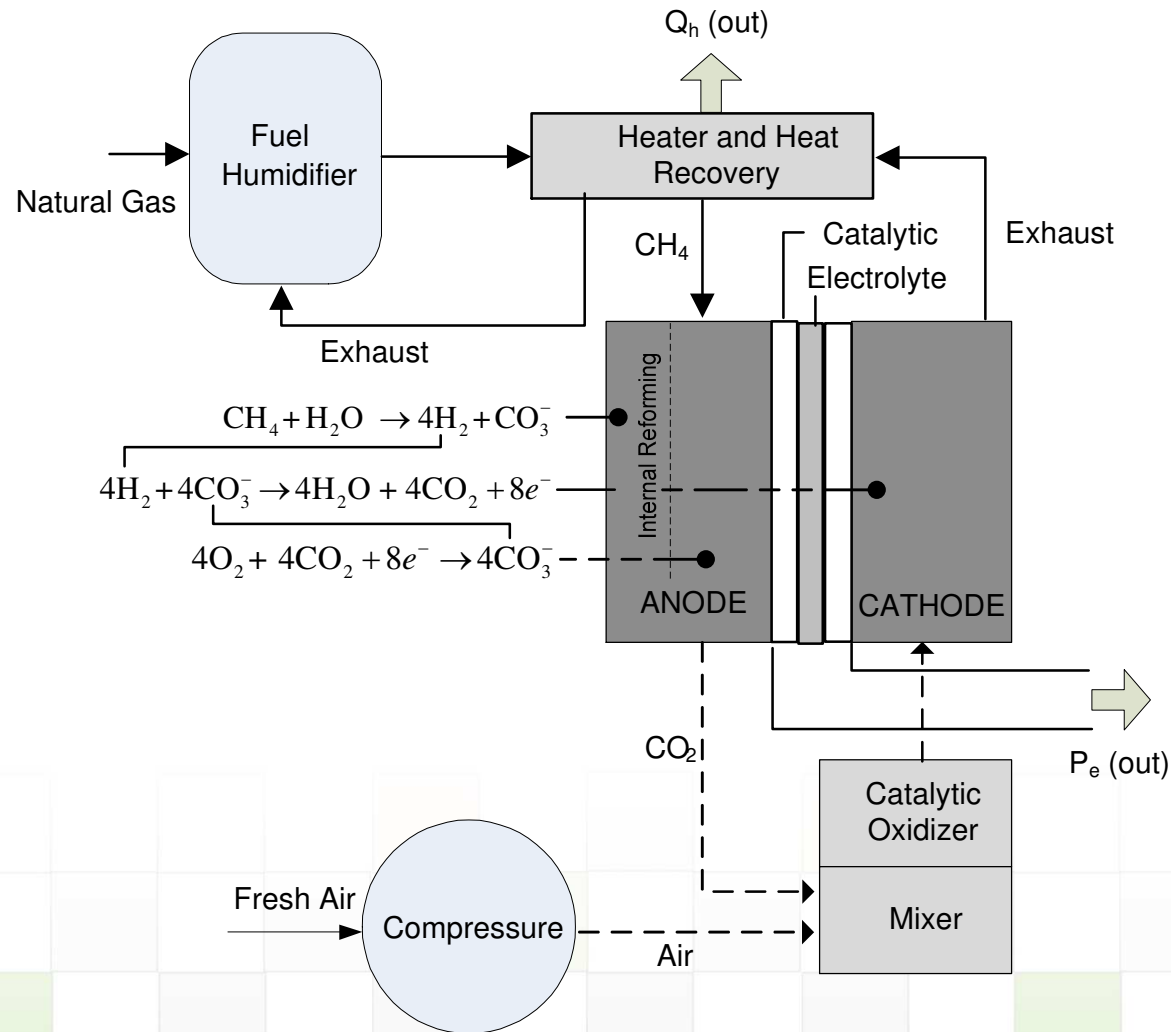


Figure 2.8 Fuel cell based CHP



## 2.3 Photovoltaic Energy Systems

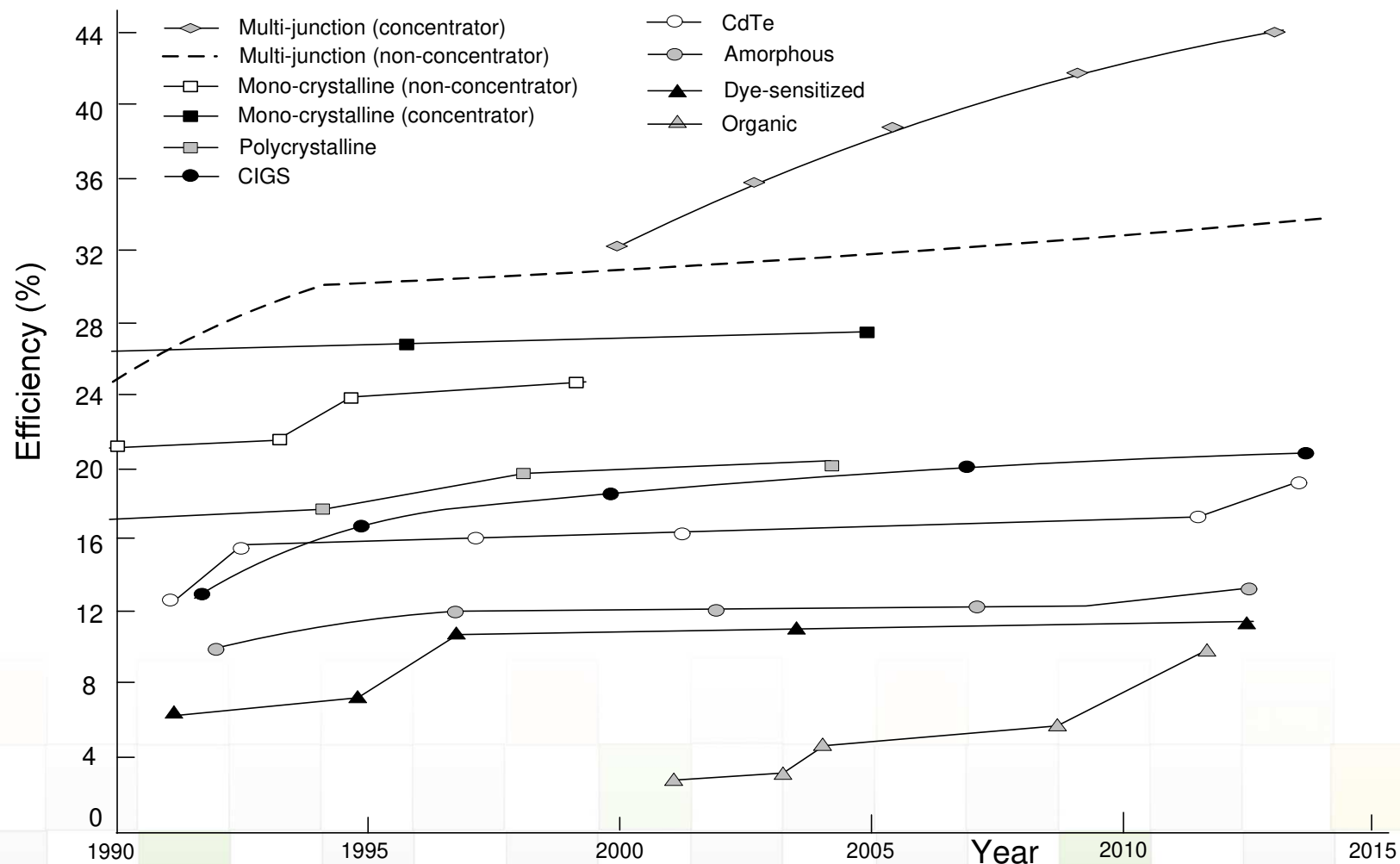
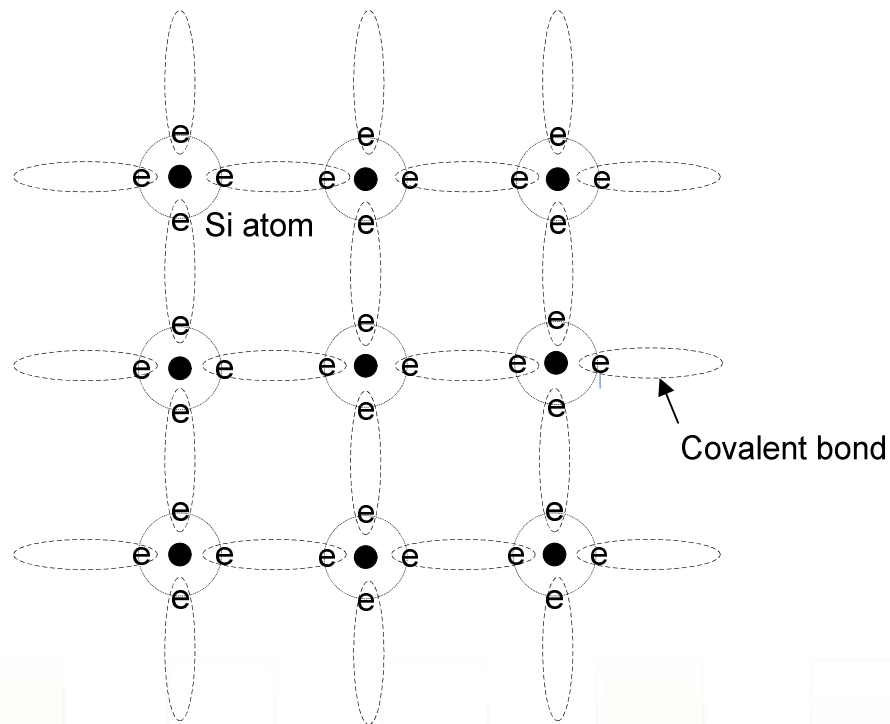


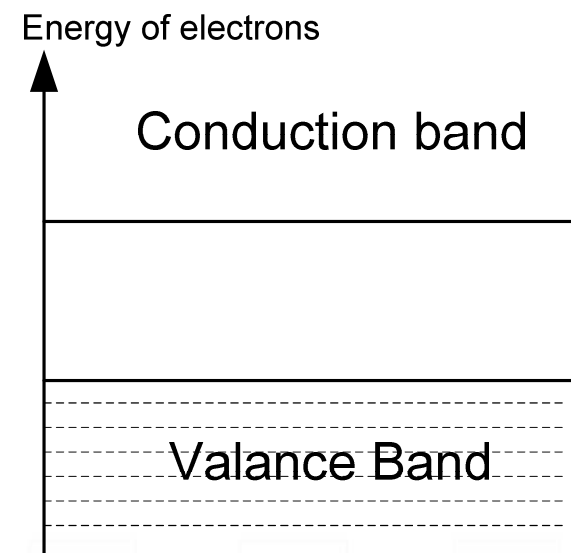
Figure 2.9 Trend lines of efficiencies of different PV technologies



## 2.3 Photovoltaic Energy Systems



(a) Crystalline Si structure

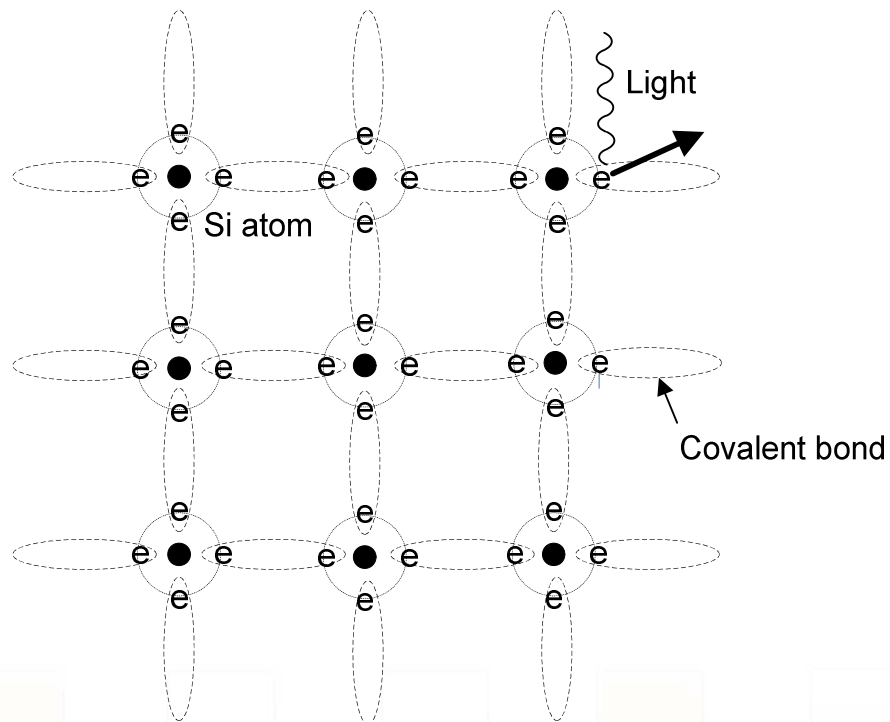


(b) Energy bands

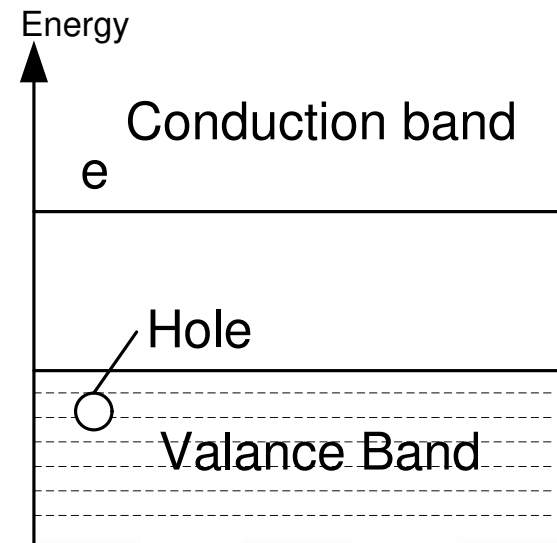
Figure 2.10 Intrinsic Si at absolute zero temperature



## 2.3 Photovoltaic Energy Systems



(a) Crystalline Si structure



(b) Energy bands

Figure 2.11 Intrinsic Si at when exposed to light



## 2.3 Photovoltaic Energy Systems

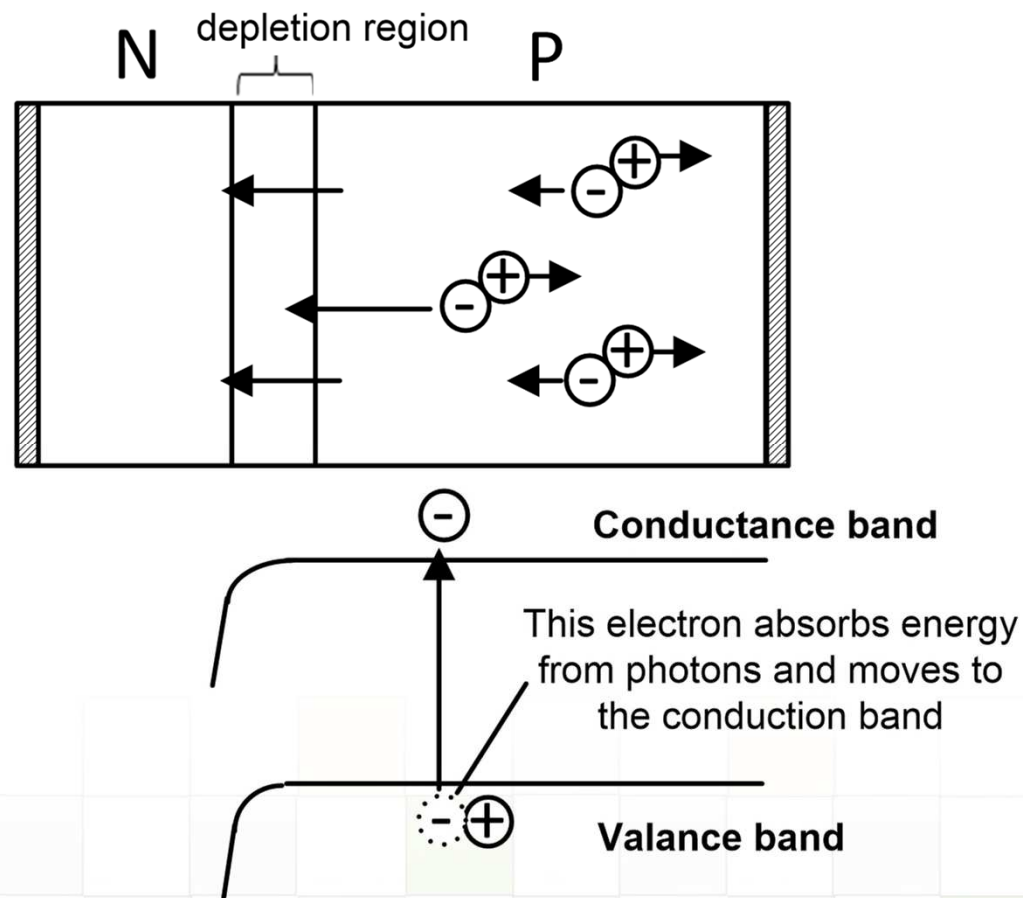


Figure 2.12 PN junction



## 2.3 Photovoltaic Energy Systems

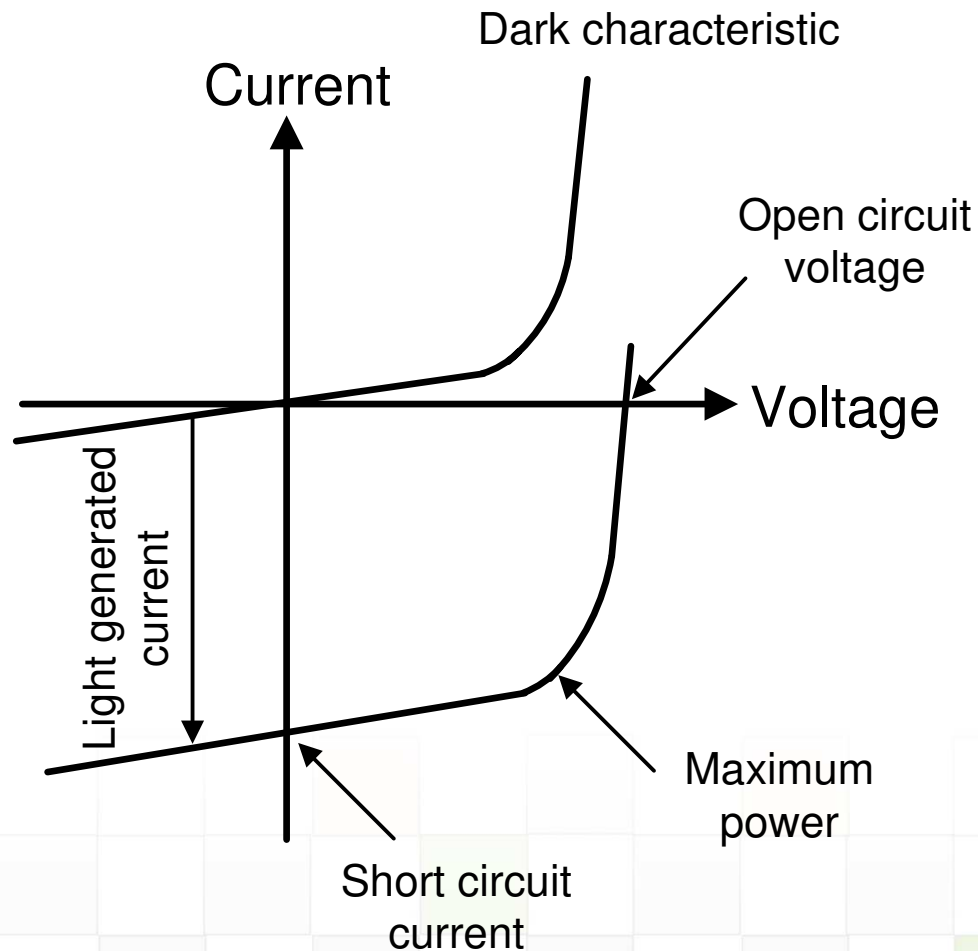


Figure 2.13 I-V characteristic



## 2.3 Photovoltaic Energy Systems

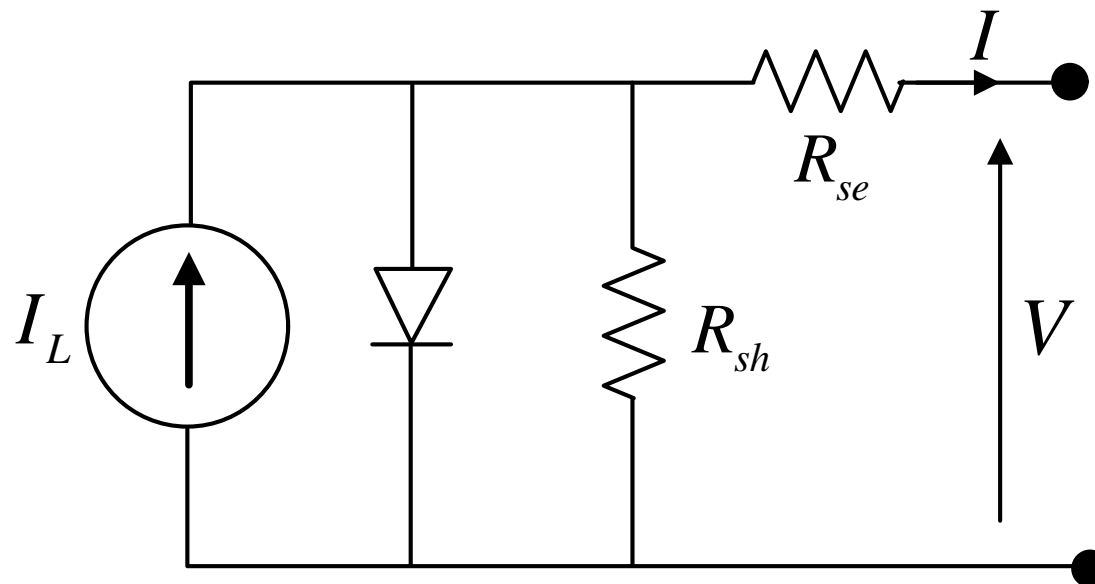


Figure 2.14 Equivalent circuit of a PV cell



## 2.3 Photovoltaic Energy Systems

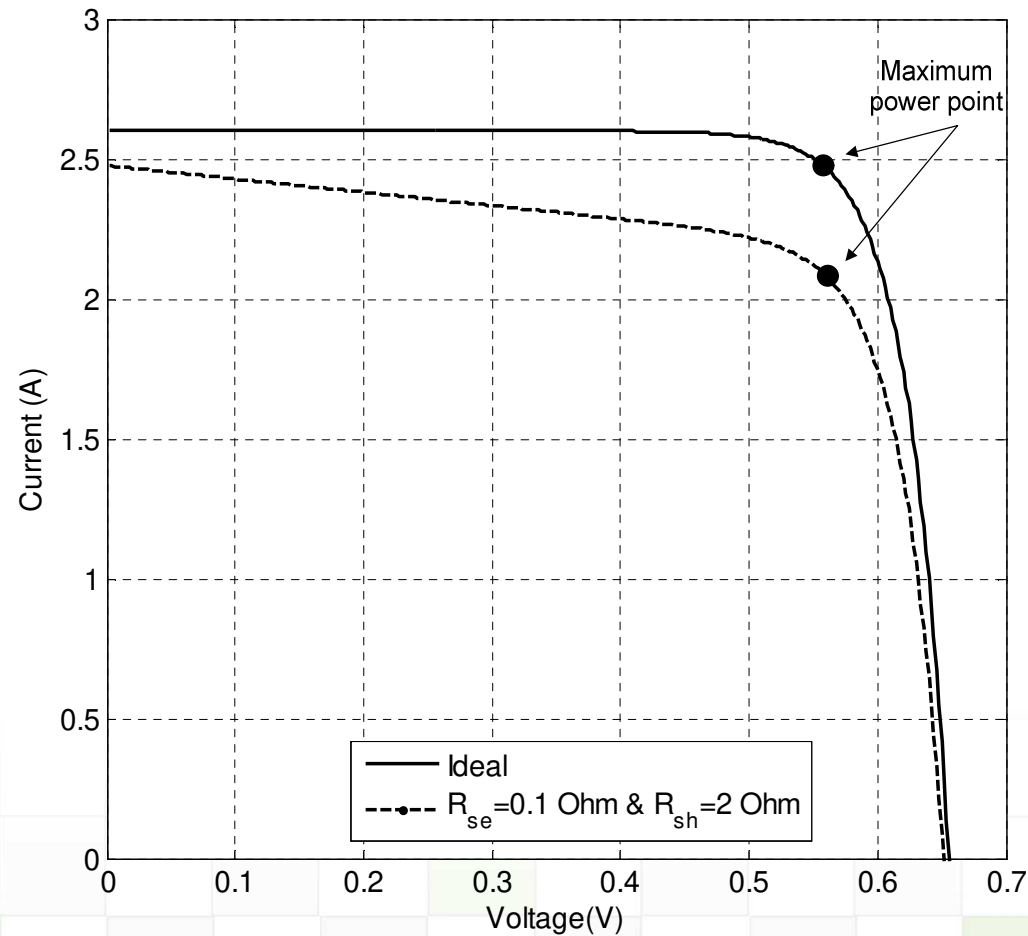


Figure 2.15 The effect of series and shunt resistance



## 2.3 Photovoltaic Energy Systems

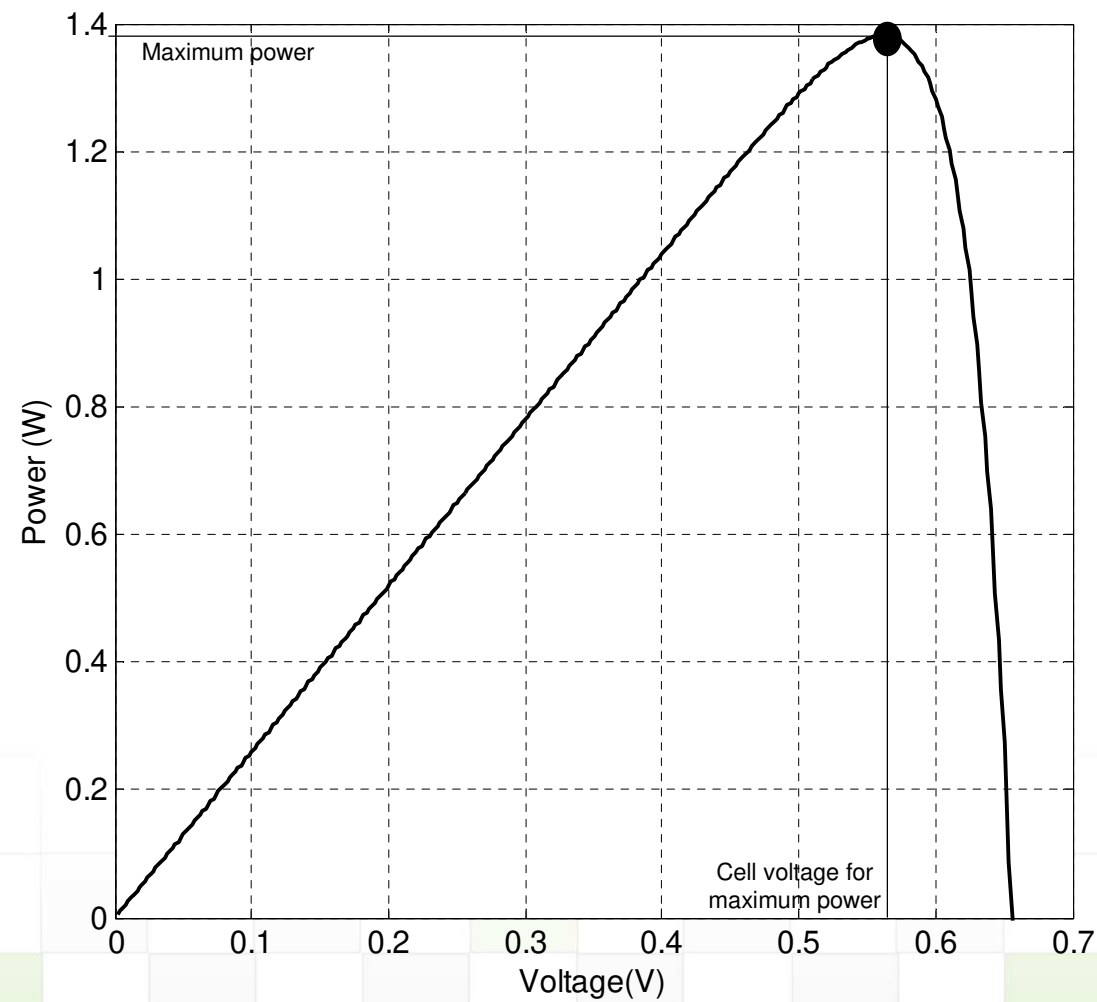
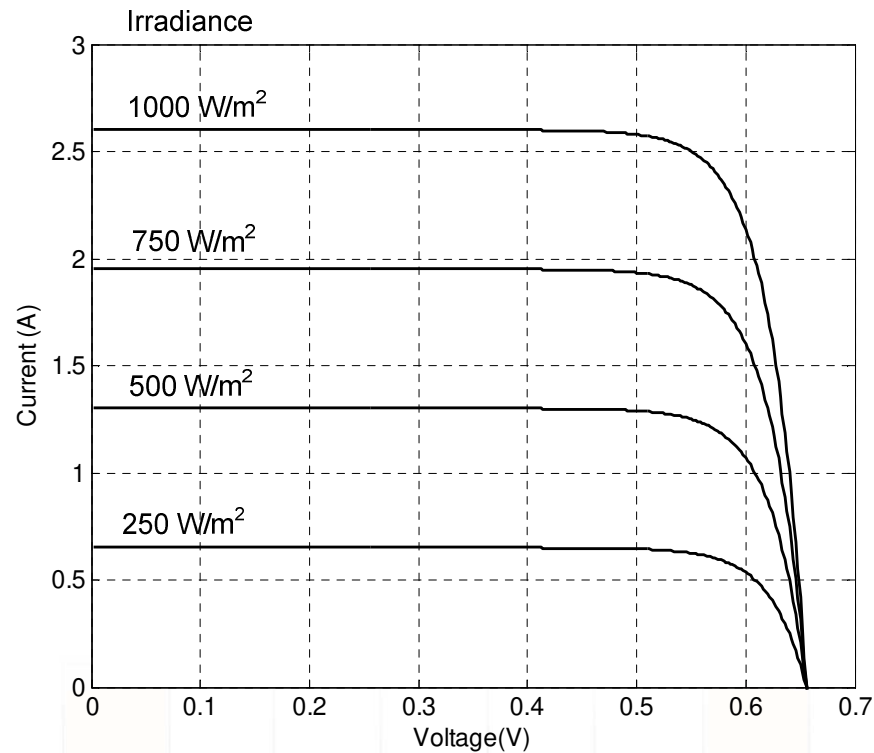


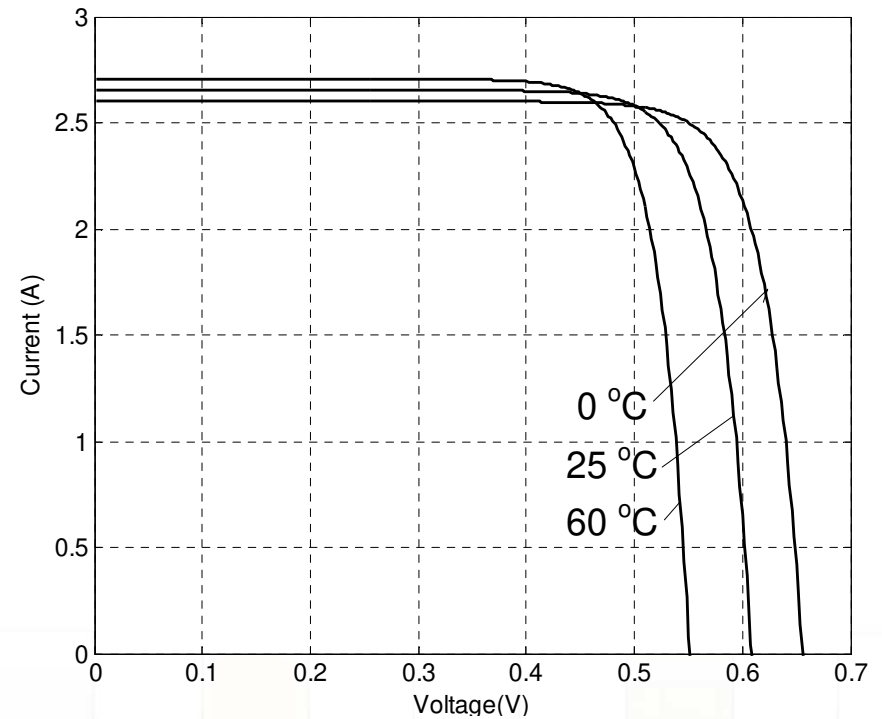
Figure 2.16 Power vs voltage characteristic



## 2.3 Photovoltaic Energy Systems



(a) Variation with irradiance



(b) Variation with cell temperature

Figure 2.17 The effect of series and shunt resistance



## 2.3 Photovoltaic Energy Systems

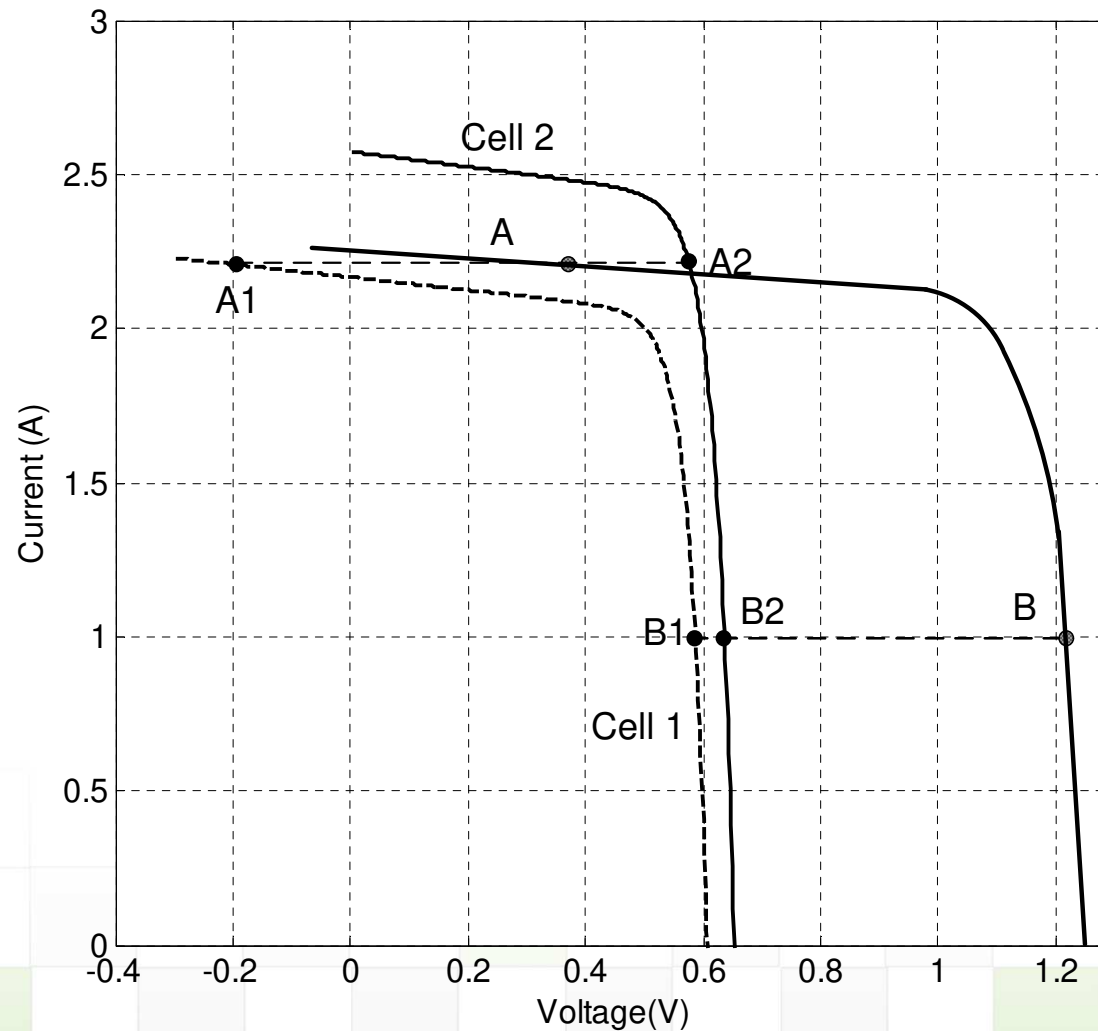


Figure 2.18 The effect of connection of non-identical PV cells in series



## 2.3 Photovoltaic Energy Systems

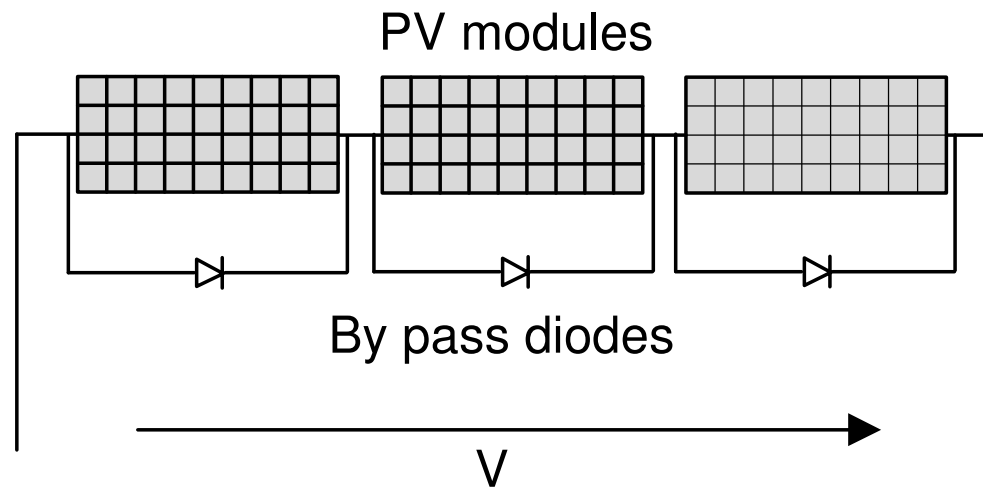


Figure 2.19 Connection of a string of PV modules



## 2.3 Photovoltaic Energy Systems

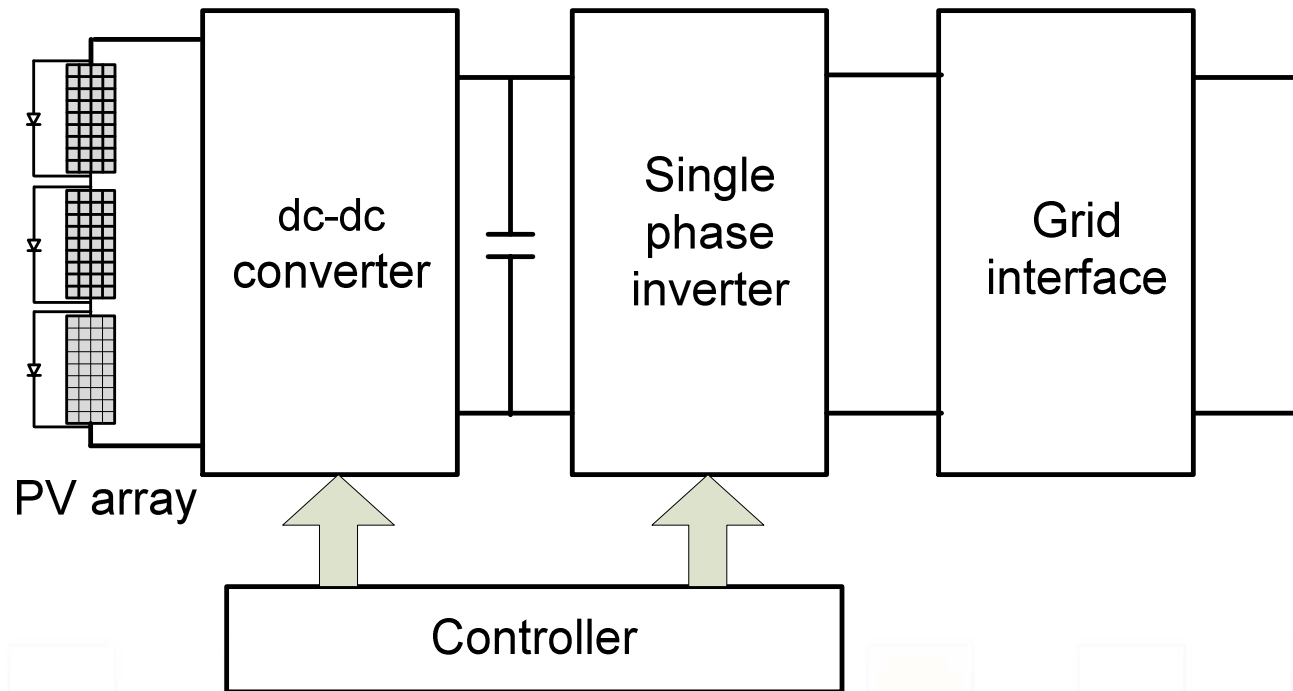


Figure 2.20 Grid connected PV arrays



## 2.3 Photovoltaic Energy Systems

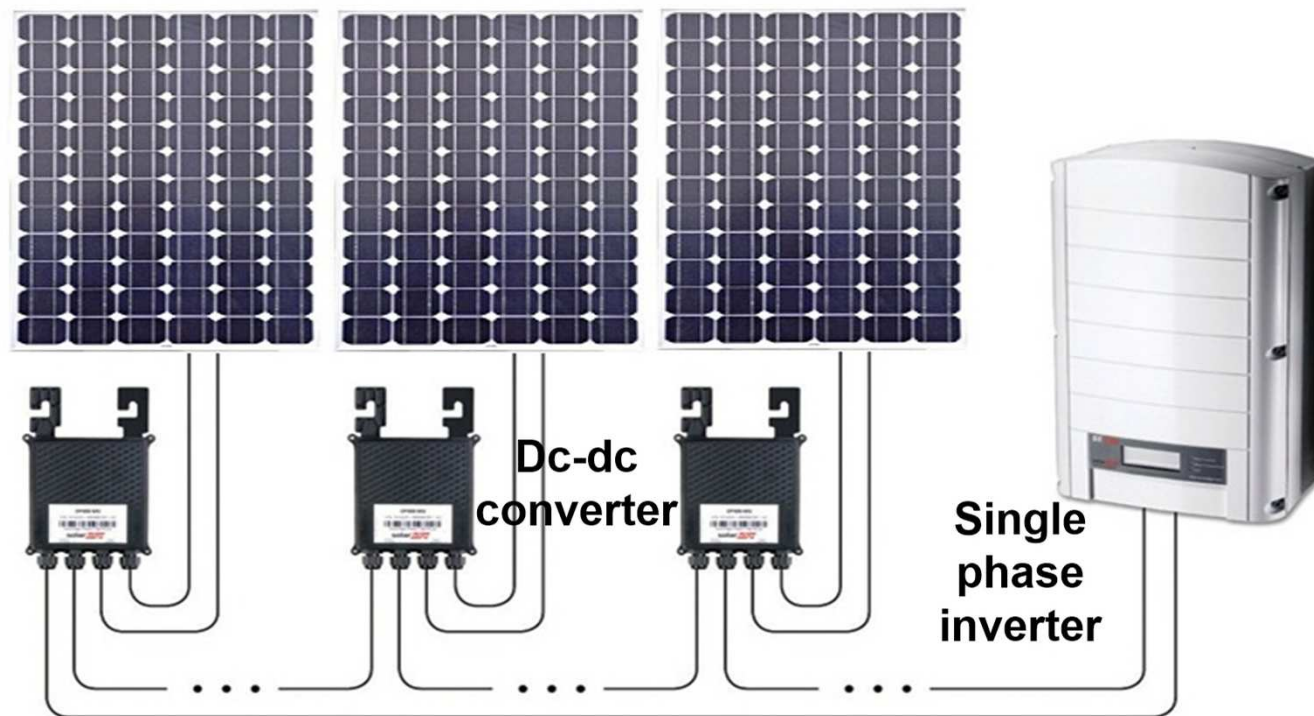


Figure 2.21 PV array with a single inverter and dc-dc converter for each module



## 2.3 Photovoltaic Energy Systems

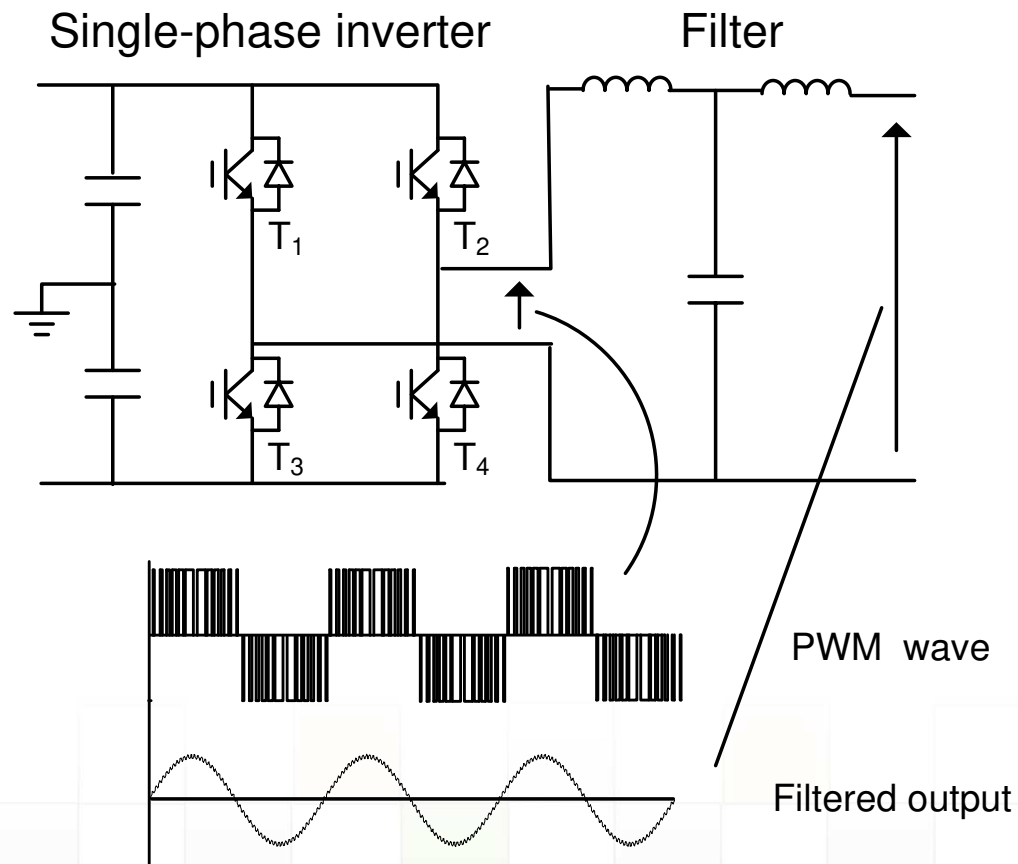
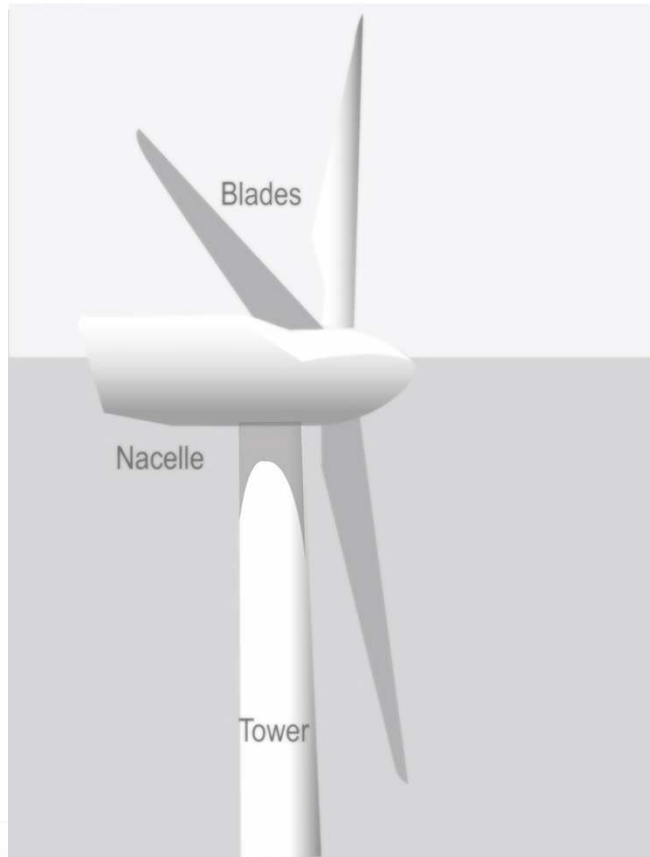


Figure 2.22 Single phase inverter



## 2.4 Wind Energy Systems



(a) Horizontal axis wind turbine (Courtesy of Wind Force (Pvt) Ltd)



(b) Vertical axis wind turbine

Figure 2.23 Vertical axis wind turbine



## 2.4 Wind Energy Systems

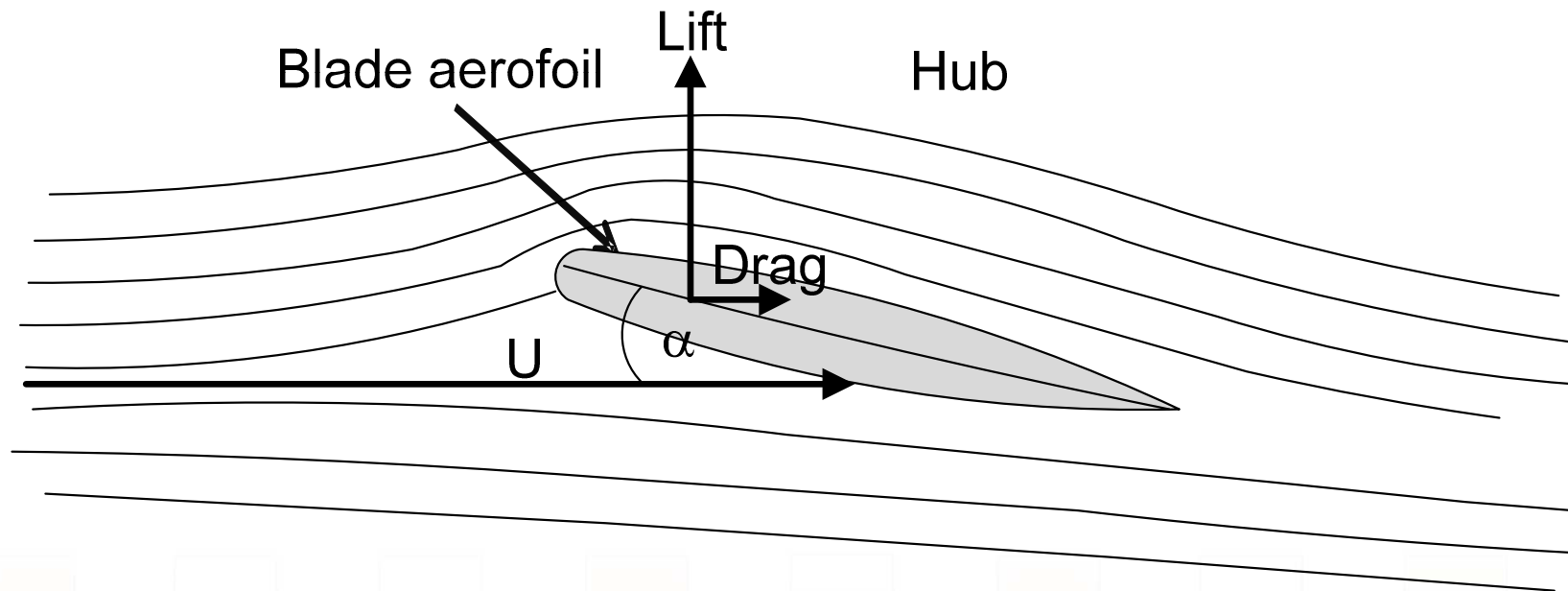


Figure 2.24 Flow of air past an aerofoil



## 2.4 Wind Energy Systems

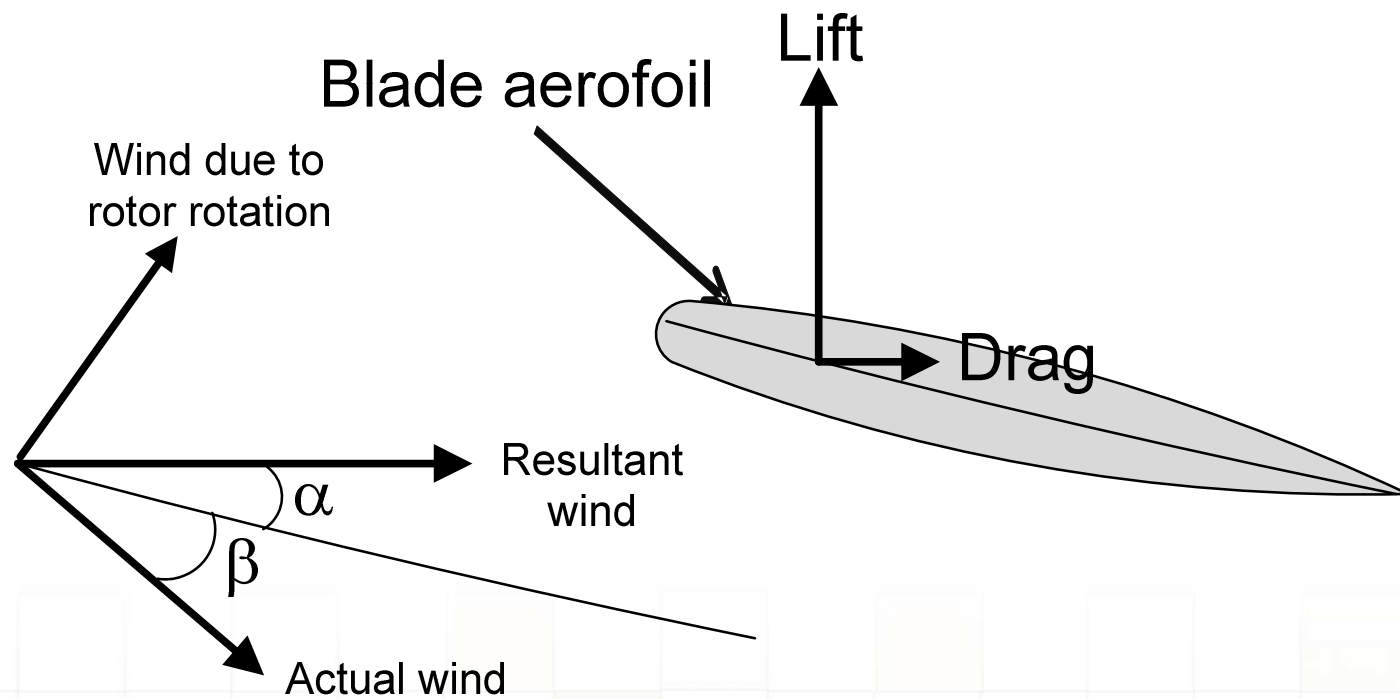


Figure 2.25 Relative wind



## 2.4 Wind Energy Systems

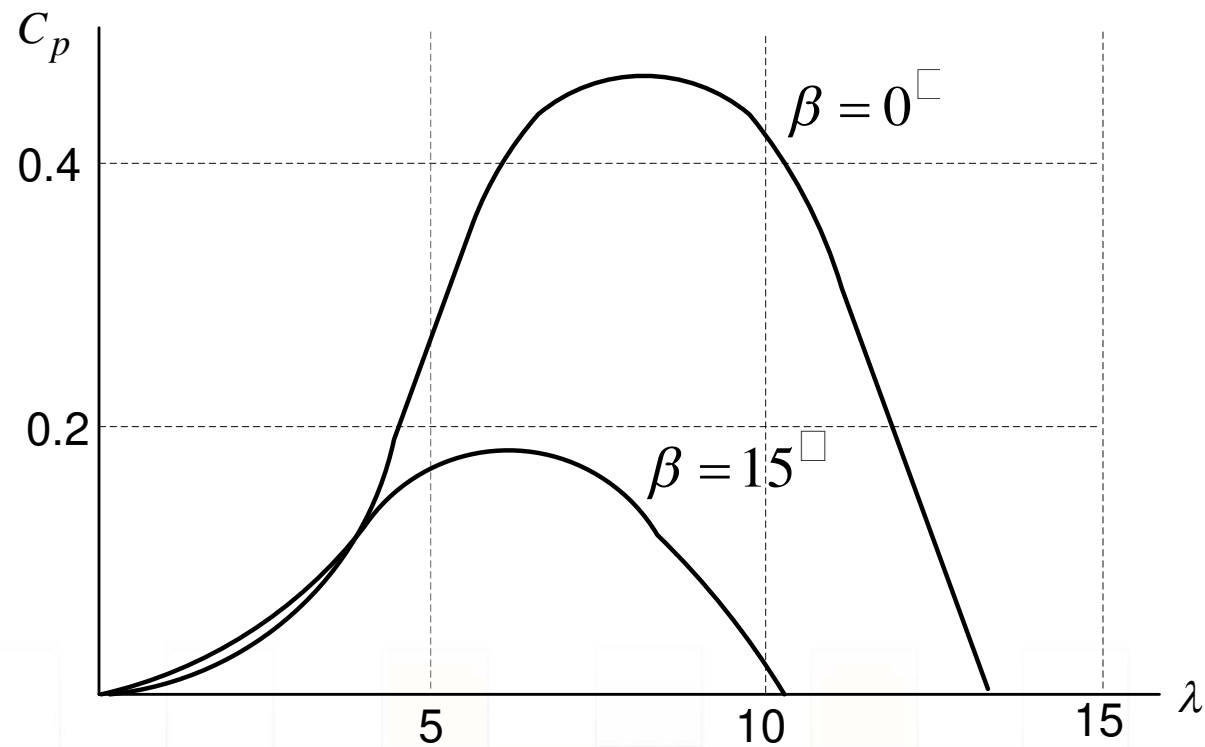


Figure 2.26 Variation of power coefficient with  $\alpha$  and  $\beta$



## 2.4 Wind Energy Systems

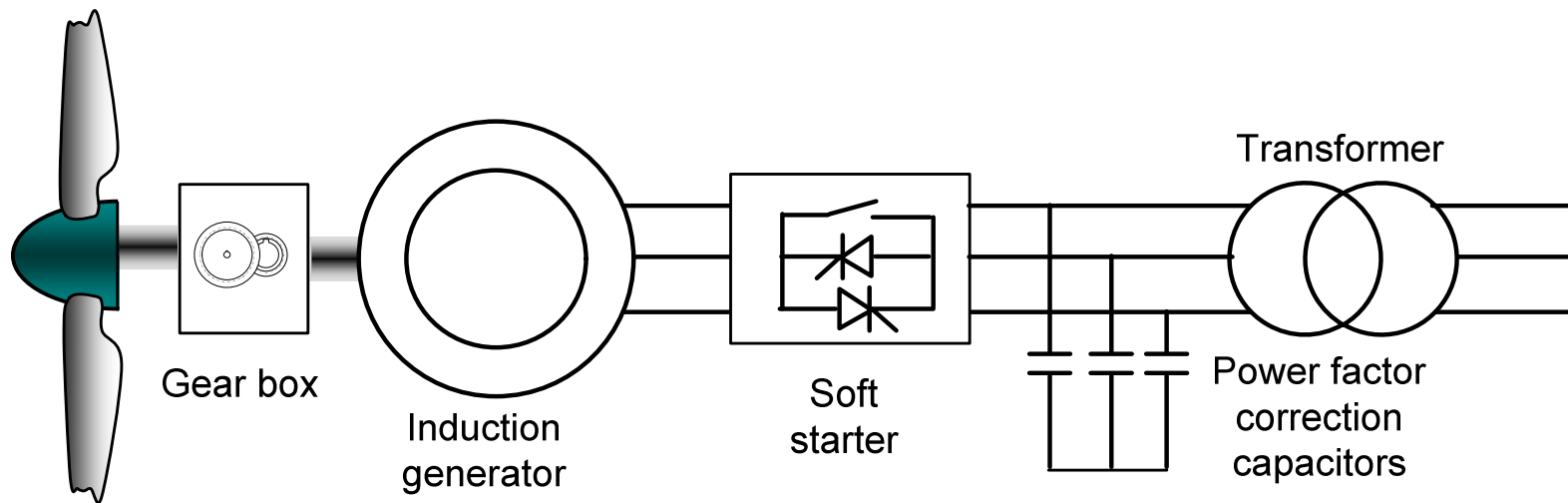


Figure 2.27 Component of a fixed speed wind turbine



## 2.4 Wind Energy Systems

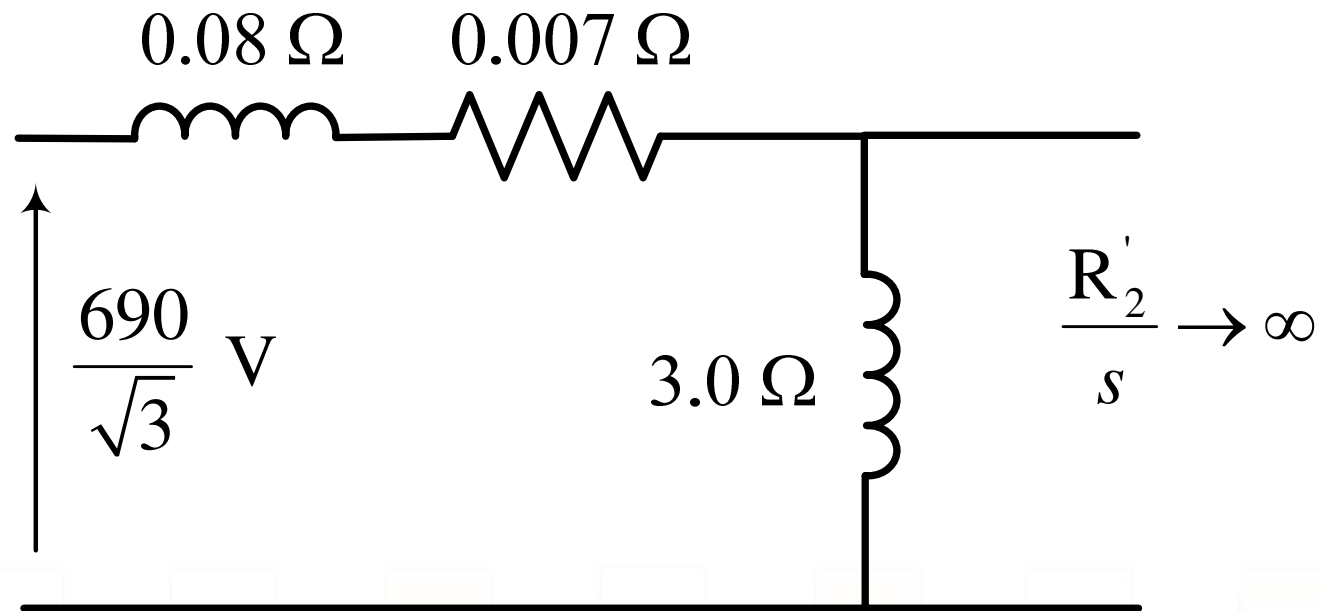


Figure 2.28 No-load equivalent circuit of the induction generator



## 2.4 Wind Energy Systems

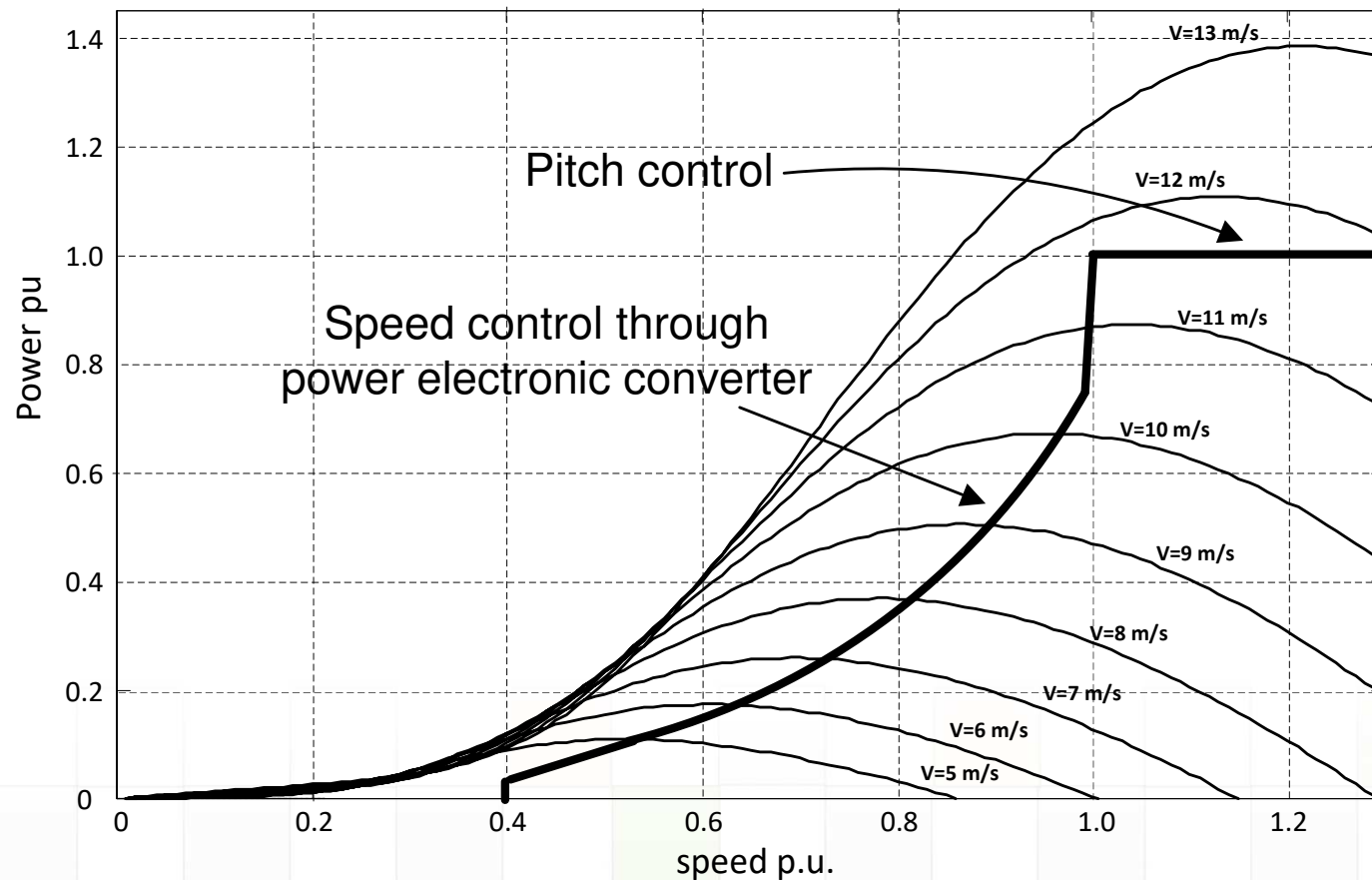


Figure 2.29 Operation of a variable speed wind turbine



## 2.4 Wind Energy Systems

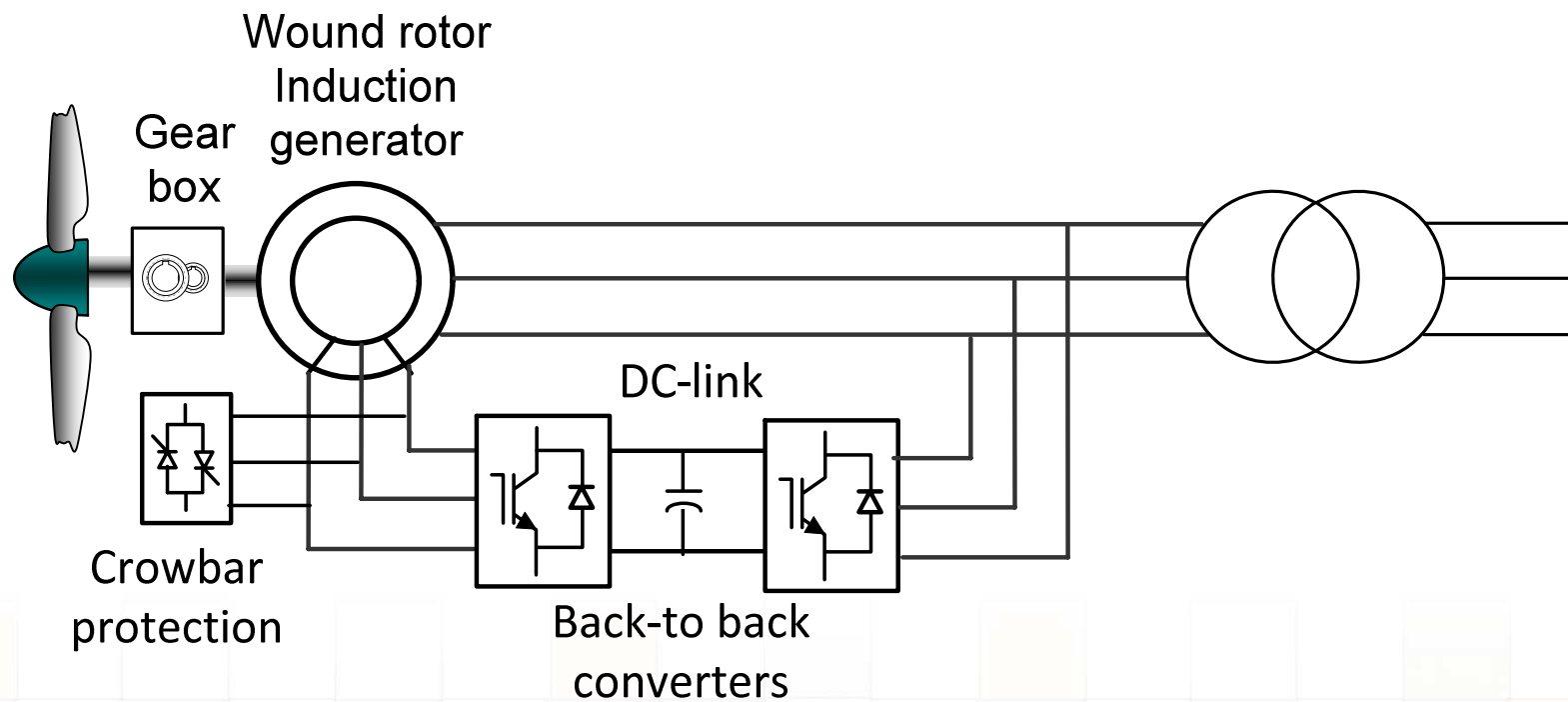


Figure 2.30 DFIG wind turbine



## 2.4 Wind Energy Systems

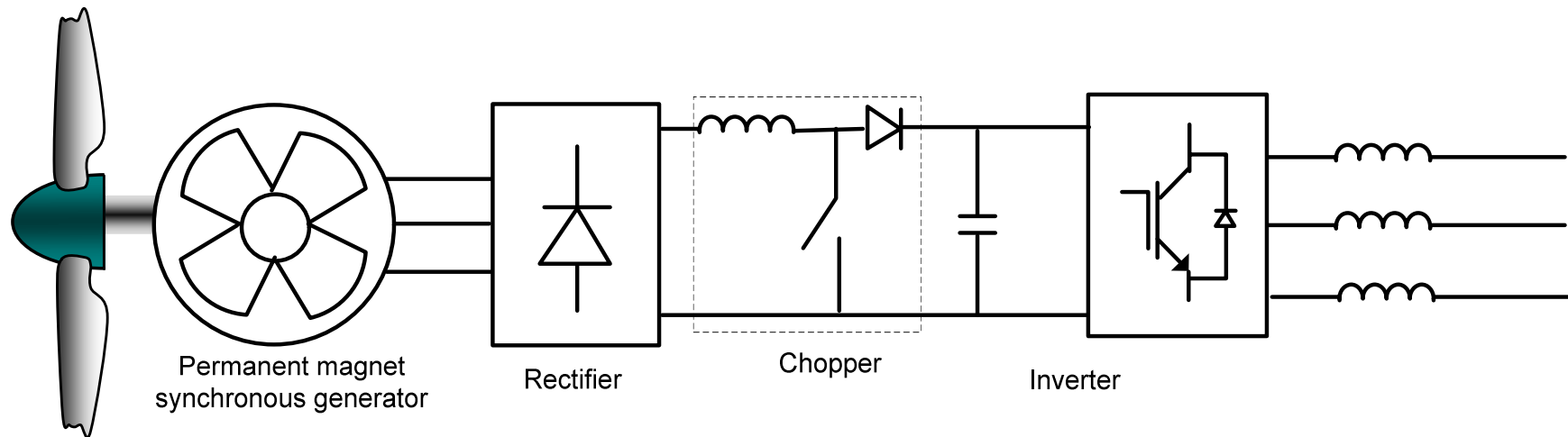


Figure 2.31 Gearless FSFC wind turbine with a diode rectifier



## 2.4 Wind Energy Systems

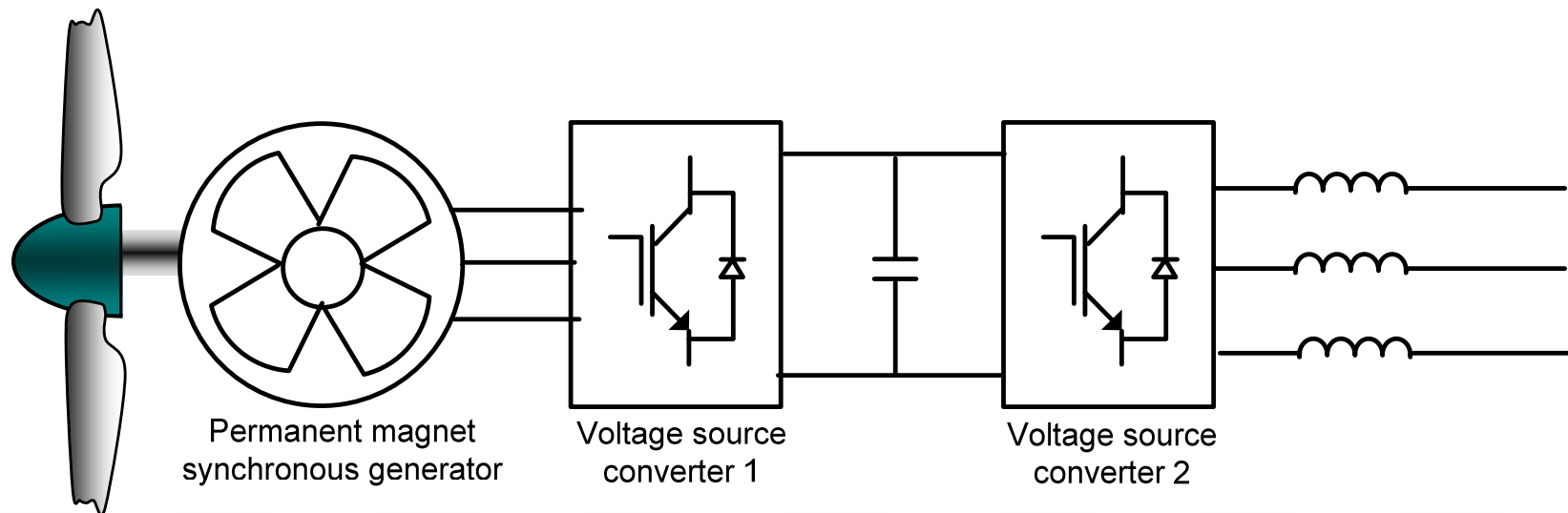


Figure 2.32 Gearless FCFS wind turbine with back-to-back converters



## 2.5 Electrical Energy Storage

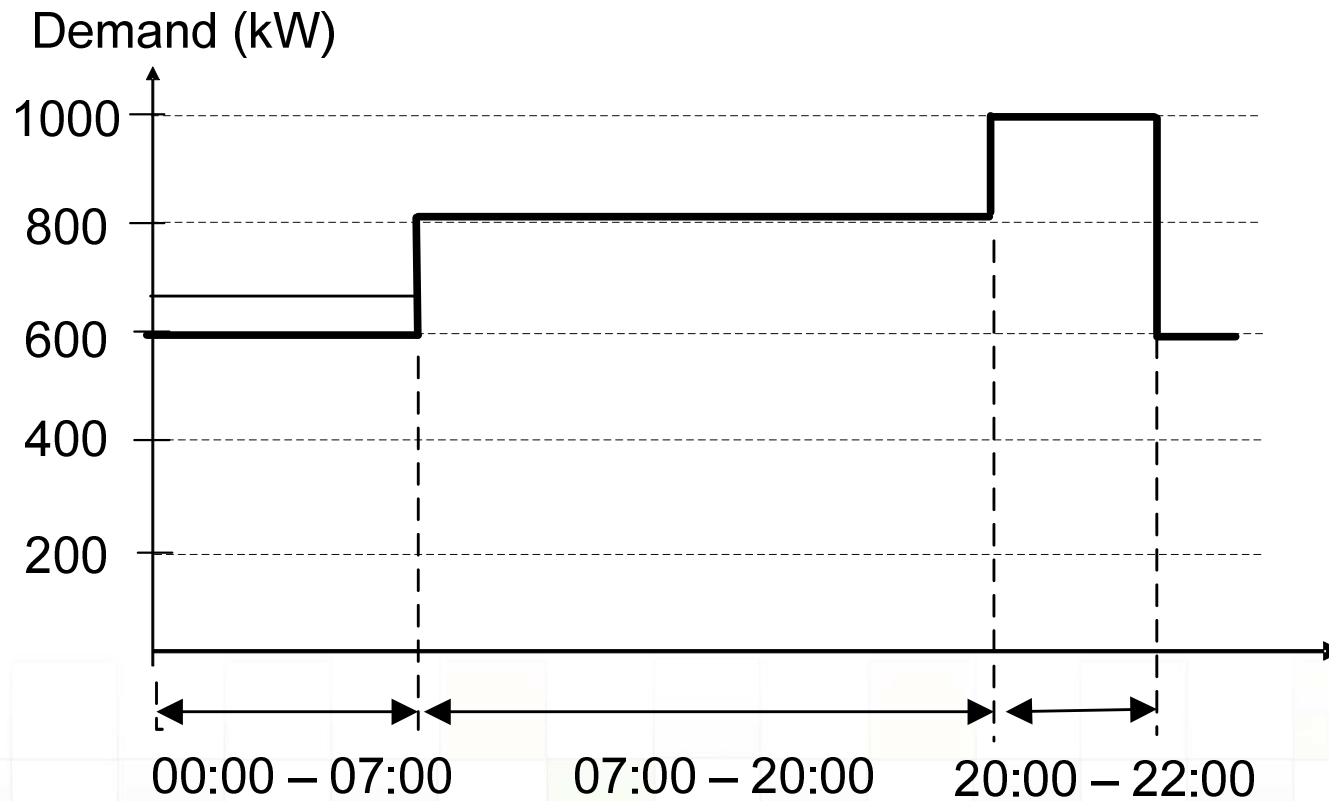


Figure 2.33 Demand profile



## 2.5 Electrical Energy Storage

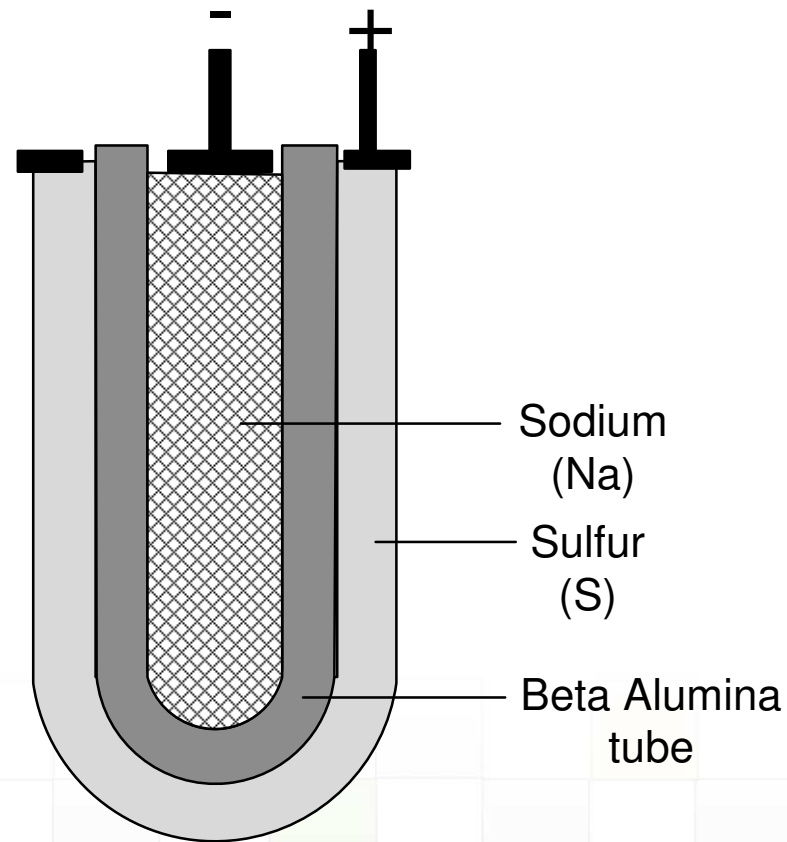


Figure 2.34 NaS battery



## 2.5 Electrical Energy Storage

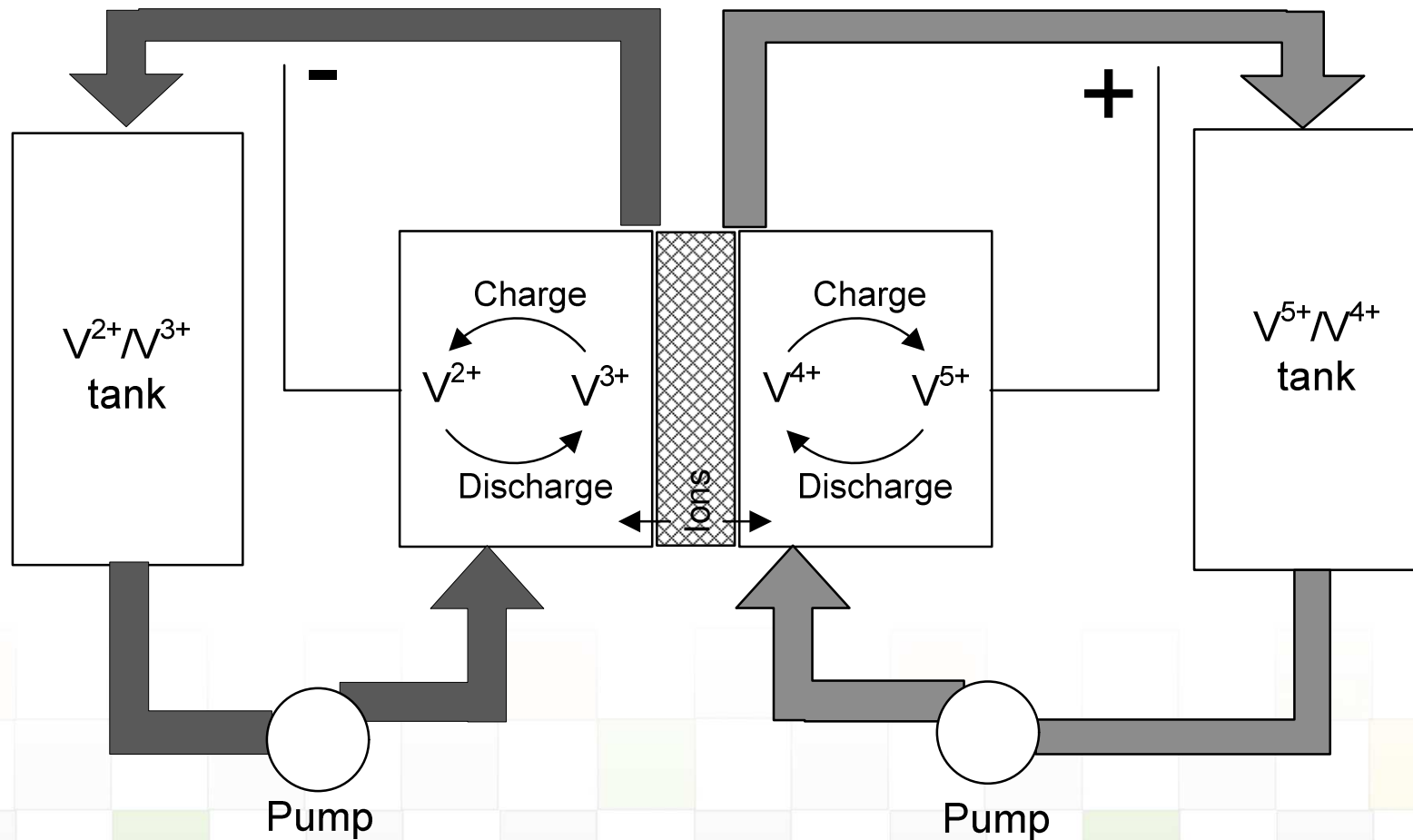


Figure 2.35 VRB flow battery system



## 2.6 Flexible Demand

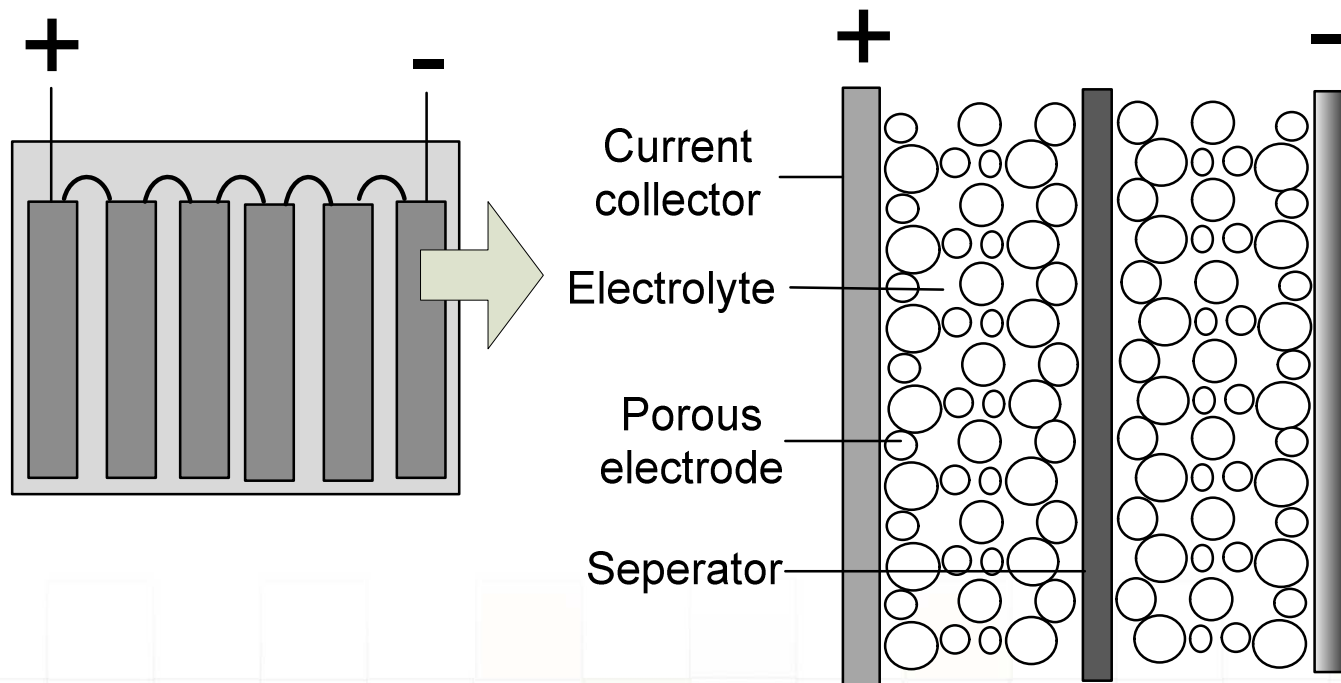


Figure 2.36 Ultra-capacitor module and cell



# Thank You!