

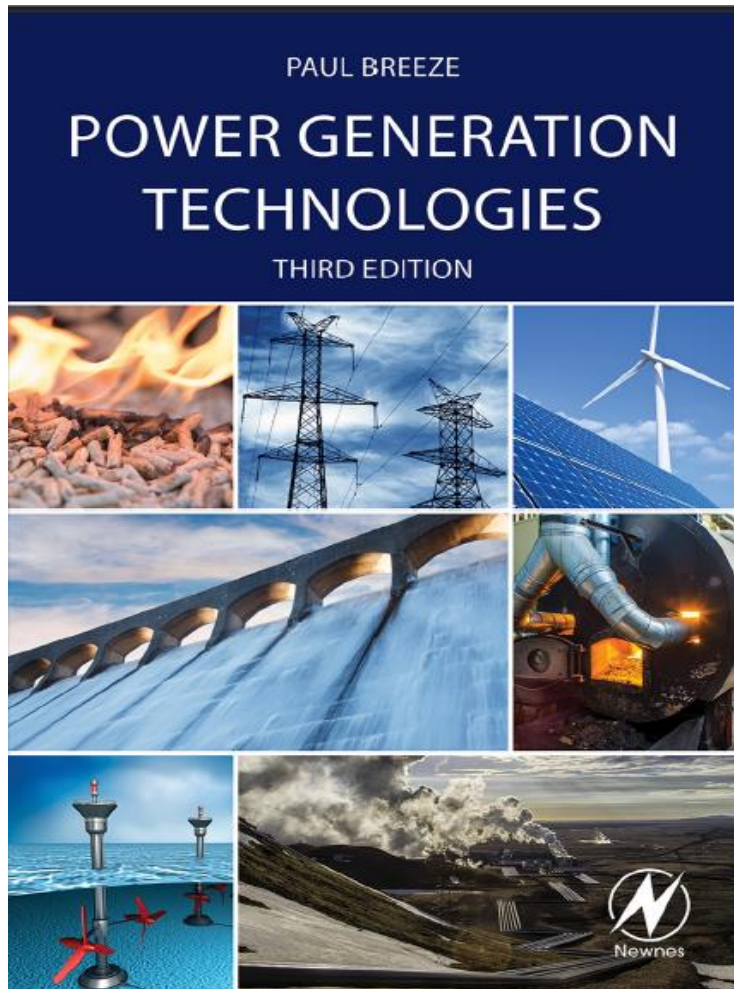
Renewable Electric Energy Systems EE—546

Fuel—Cells

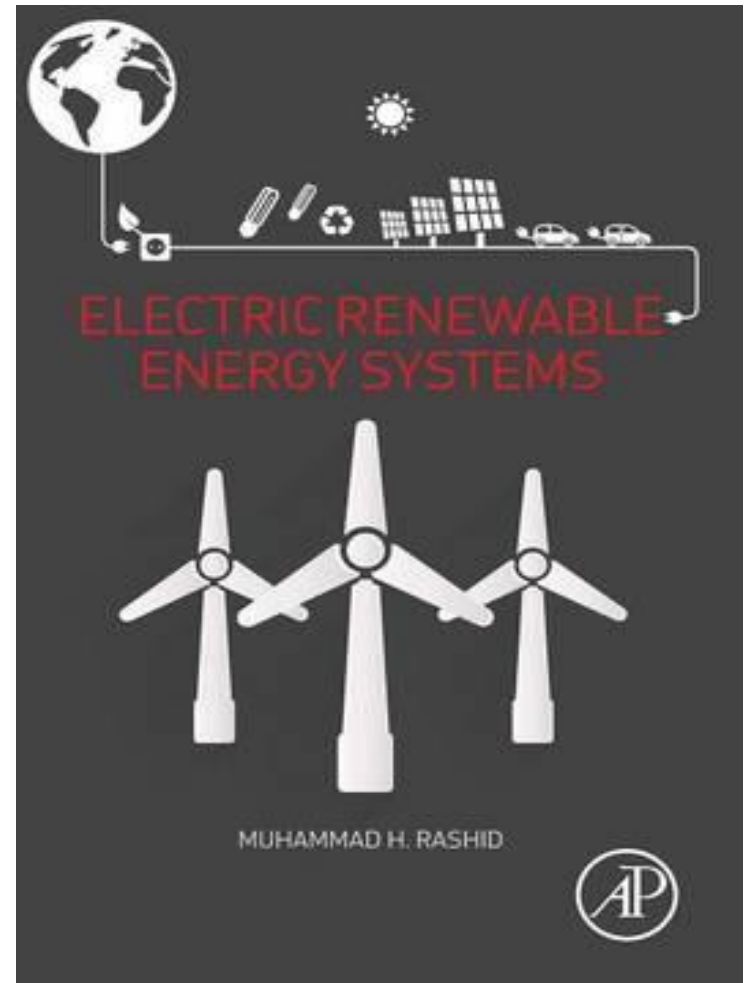
Dr. U. T. Shami



Fuel—Cells : Slides are prepared from the following books:



Paul Breeze—Power Generation Technologies (3rd Ed, 2019, Newnes)



Muhammad H. Rashid—Electric Renewable Energy Systems

Introduction

Fuel Cell Fundamentals

Modeling of Ideal Fuel Cells

Advantages and Disadvantages of Fuel Cells

Power Applications of Fuel Cells

Fuel Cell Efficiency

Fuel Cell Types

The Alkaline Fuel Cell

The Phosphoric Acid Fuel Cell

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The Molten Carbonate Fuel Cell

The Solid Oxide Fuel Cell

The Direct Methanol Fuel Cell

Fuel Cell Costs

Introduction

The fuel cell is an electrochemical device, closely related to the battery, which harnesses a chemical reaction between two reactants to produce electricity.

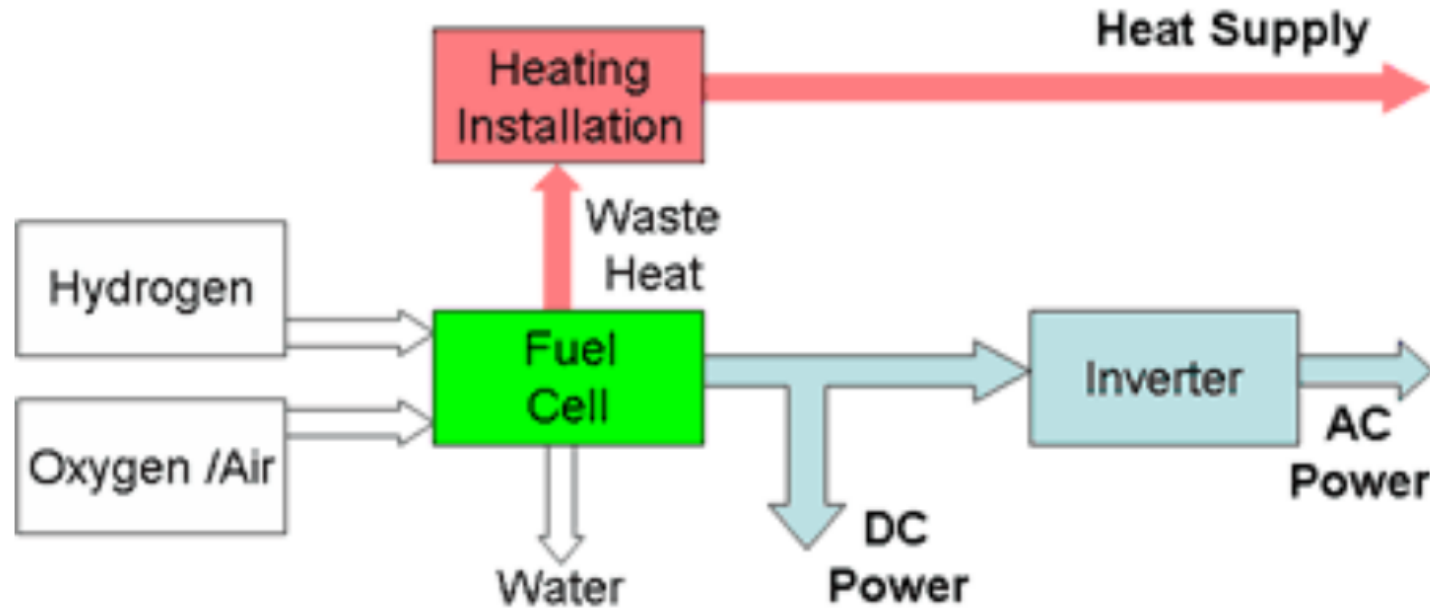
A battery is usually intended as a portable or self-contained source of electricity, and it must carry the reactants it needs to generate electricity within it.

Once they are exhausted the battery can no longer supply any power.

A fuel cell, by contrast, does not contain any chemical reactants itself but is supplied with them from an external source. So long as these reactants are made available, the cell will continue to provide power.

Introduction

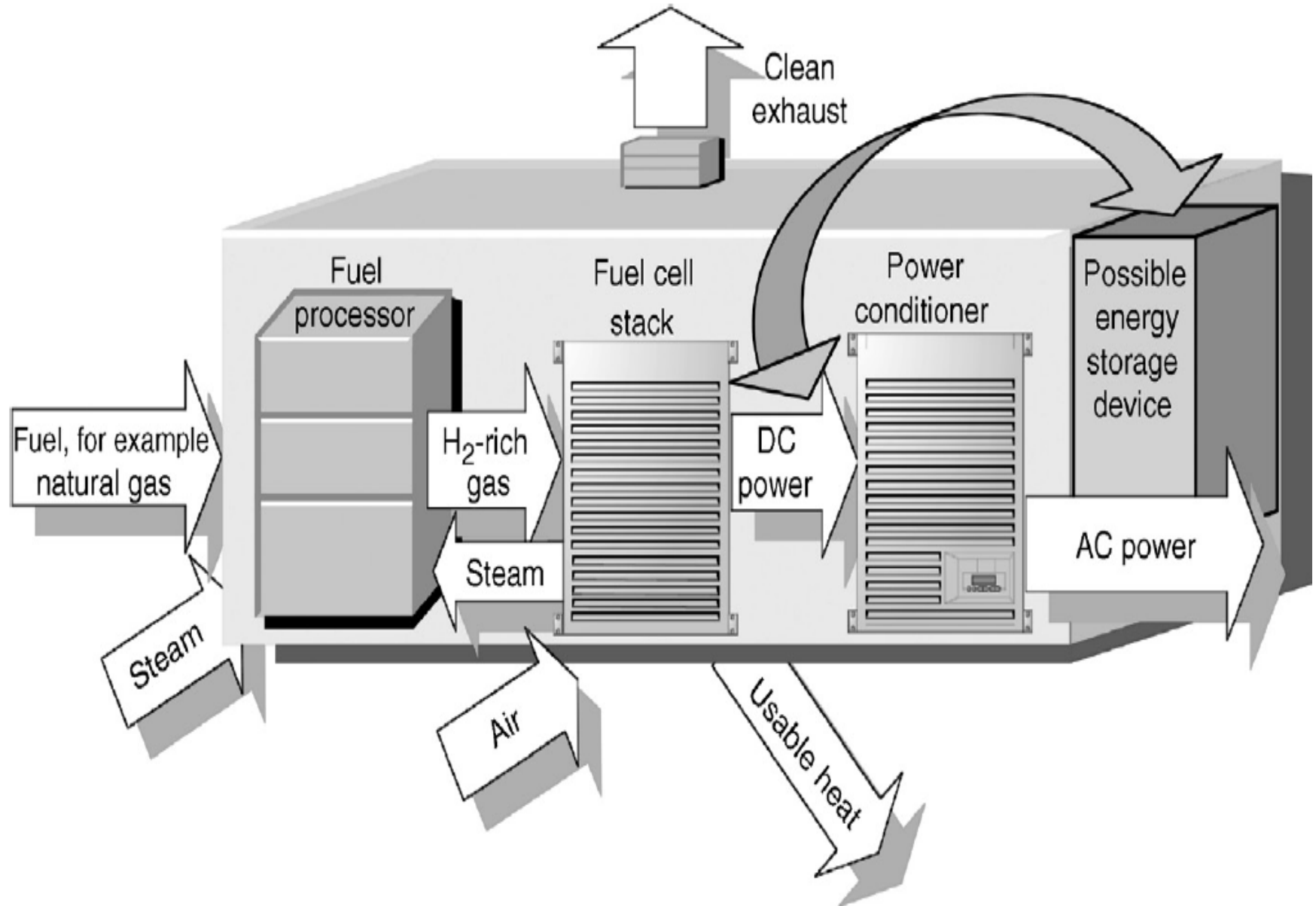
Energy from fuel cells can be used, **normally by means of** power electronic converters, for a wide variety of applications, for example, electric transportation as main and/or auxiliary power sources, stationary power for buildings, cogeneration applications, and power generation sources for standalone systems (e.g., standalone microgrids) and grid-connected applications.



Fuel Cells used in CHP Applications

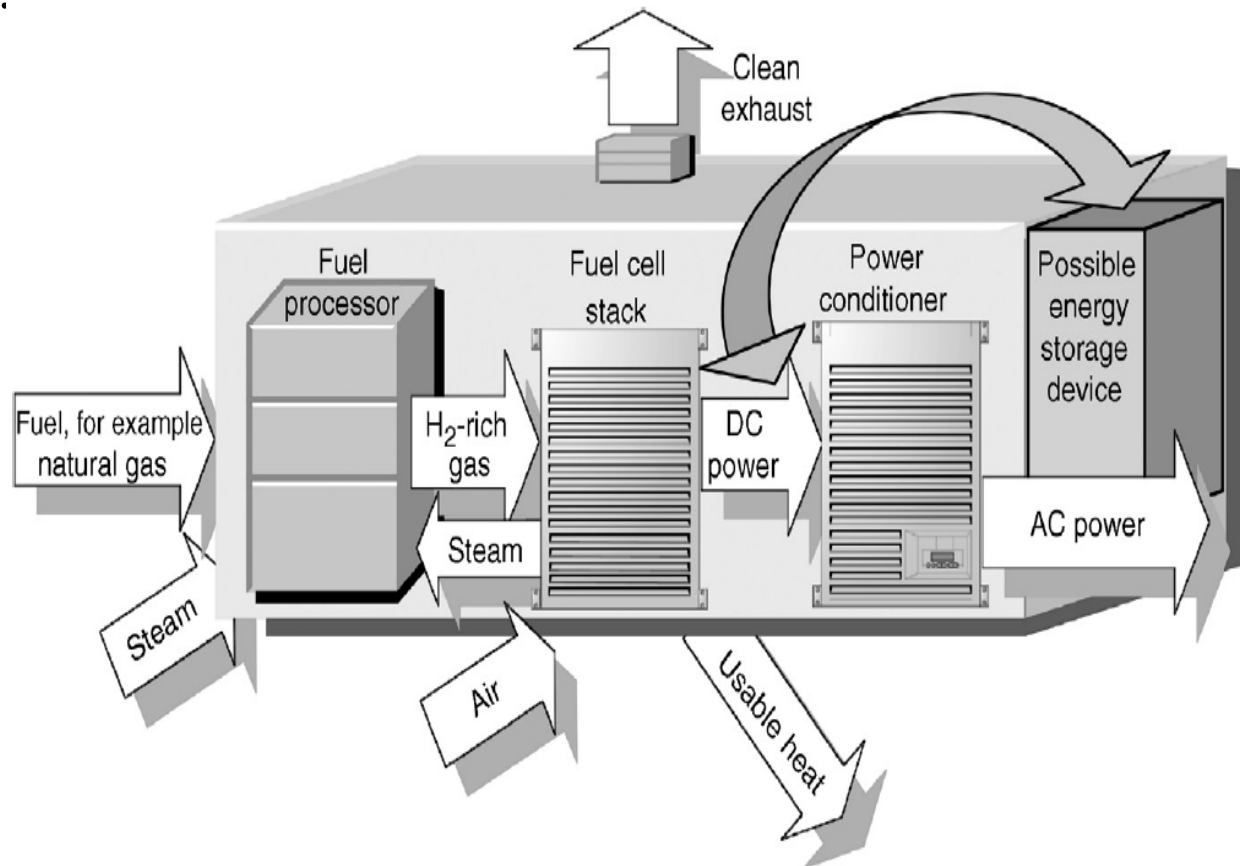
Combined Heat and Power (CHP) application overall system efficiencies of 80% approx

Major components and processes in a generic fuel cell energy system



Fuel—Cells Fundamentals

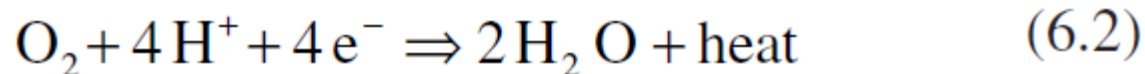
The main fuel for fuel cells is **hydrogen**, though some fuel cells can work on natural gas or methanol directly; it can be pure hydrogen or that obtained from other fuels, such as natural gas and methanol. The **hydrogen fuel combines with oxygen** in air inside the fuel cell and produces **electricity, water (steam), and heat**, as shown in Figure 6.1.



Fuel—Cells Fundamentals

In a simple fuel cell, **hydrogen molecules are split** at the anode, through electrochemical processes, to generate **hydrogen ions** and **electrons**. The hydrogen ions move from the cathode to the anode through the membrane (electrolyte), but the electrons cannot. The electrons travel through an **external electrical circuit (load)** to recombine with the hydrogen protons and oxygen molecules at the cathode to produce water. The chemical reactions at the anode and cathode are given in (6.1) and (6.2), respectively.

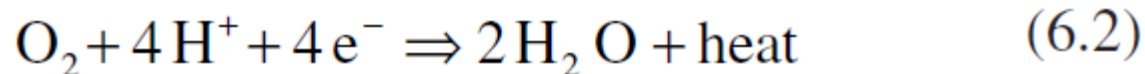
Functioning Electricity (current)



Fuel—Cells Fundamentals

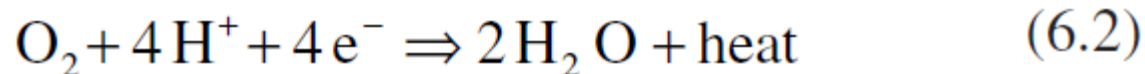
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Functioning Electricity (current)

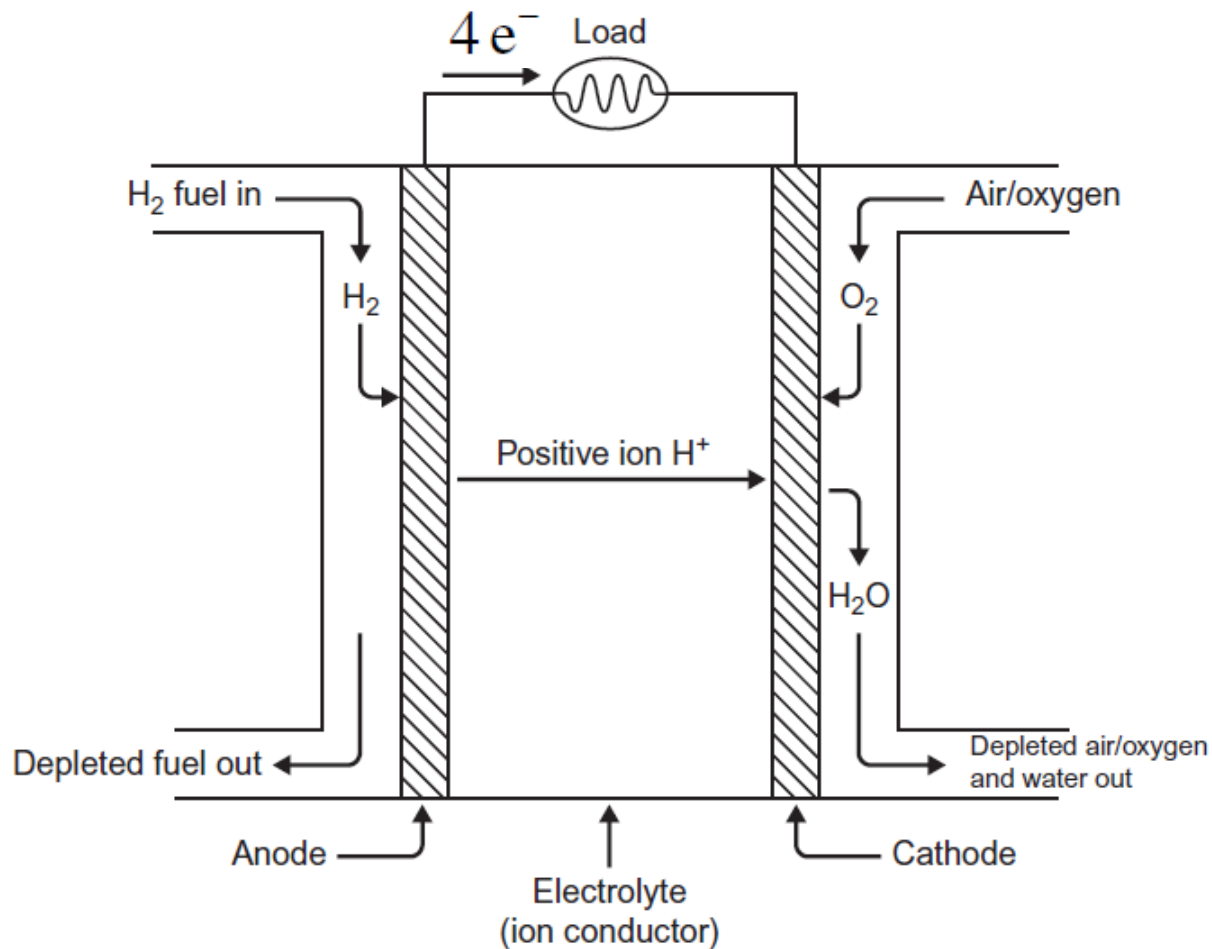
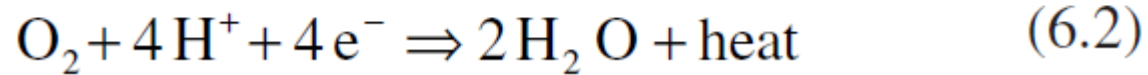


Fuel—Cells Fundamentals

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Fuel—Cells Fundamentals



Fuel—Cells Fundamentals

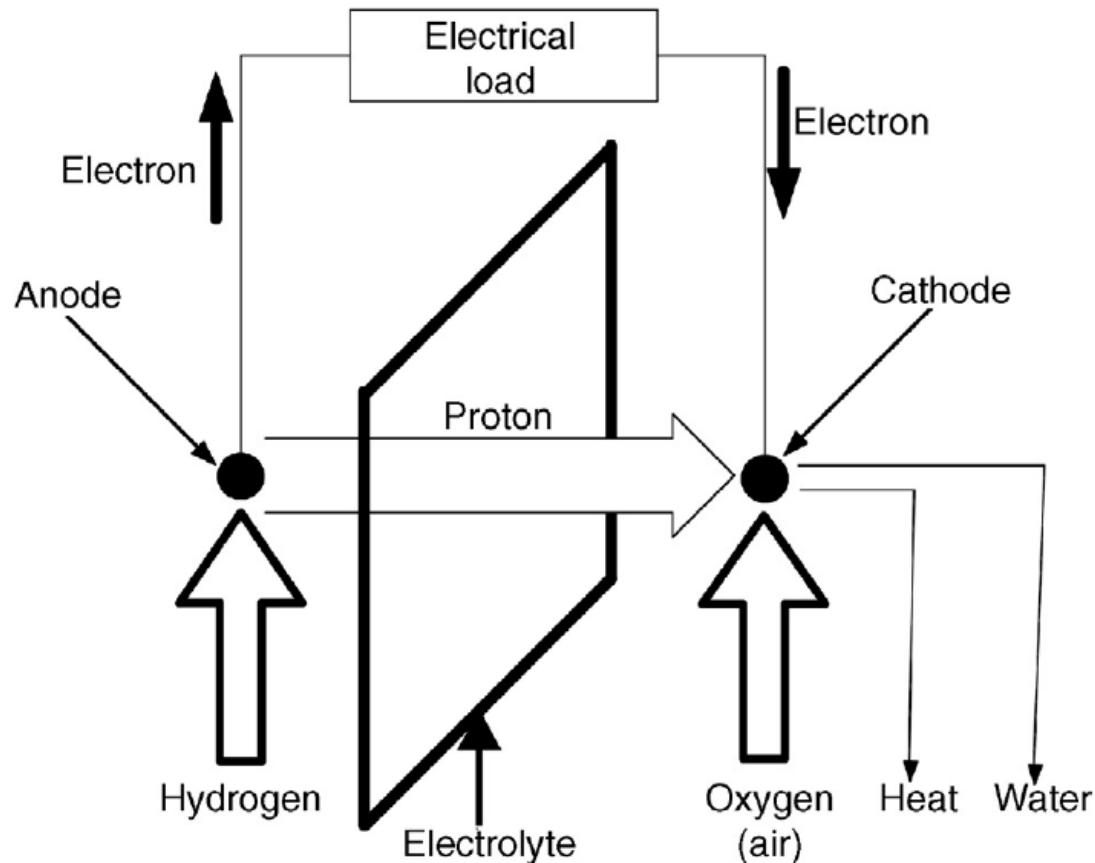
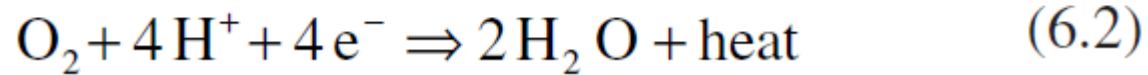


Diagram of a simple hydrogen fuel cell.

Fuel—Cells Fundamentals

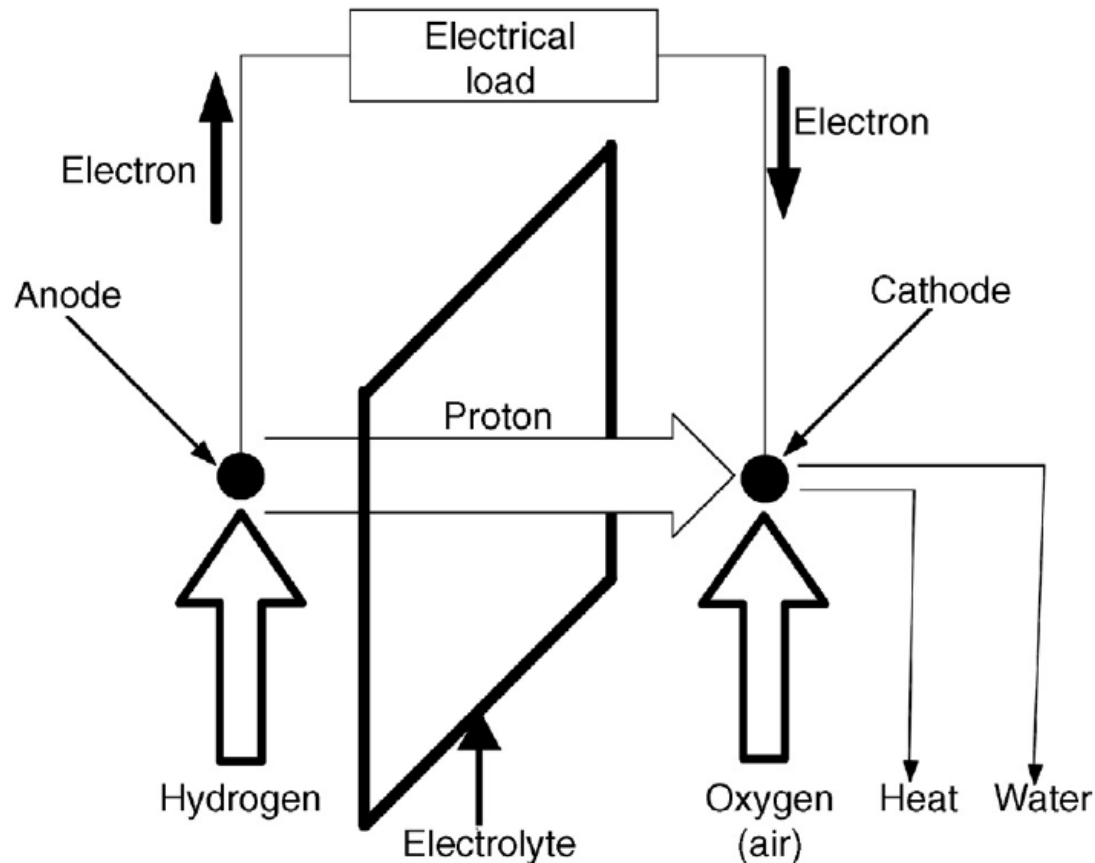
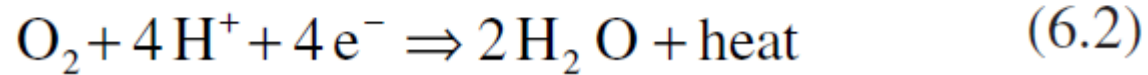
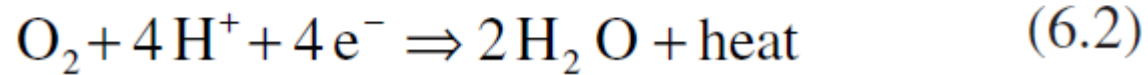


Diagram of a simple hydrogen fuel cell.

Fuel—Cells Fundamentals



The polarity of an ion and its transport direction can differ across different fuel cells, determining the site of water production and removal. If the ions transferred through the electrolyte are positive, as shown in Figure 6.2, then water is produced at the cathode. On the other hand, if the working ion is negative, as in solid-oxide and molten-carbonate fuel cells (discussed later), water is formed at the anode.

In both the cases, electrons pass through an external circuit and produce electric current.

Fuel—Cells Fundamentals

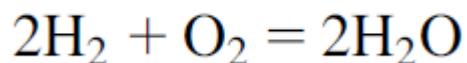
The fuel cell principle belongs to a branch of chemistry called electrochemistry. This explores how electricity can be derived from a chemical reaction. In nature, certain materials will react with one another spontaneously if the conditions are correct. For example, a strong acid such as Sulphuric acid will react vigorously with a variety of different materials if they are mixed with it.

Typical of these is the reaction of hydrogen with oxygen. The two gases can be mixed at ambient temperatures without any reaction but once the temperature is raised beyond a certain point, with a spark for example, the reaction will proceed explosively.

Spontaneous reactions of this type are called **exothermic reactions** because they all release **heat energy** when they are allowed to proceed freely.

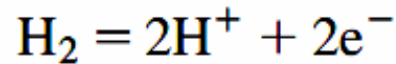
All the chemical reactions that can be exploited to generate electrical energy are **spontaneous reactions**.

The reaction between hydrogen and oxygen is exothermic. This reaction can be expressed by a simple chemical formula:

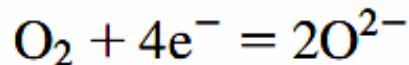


The formula shows two hydrogen molecules and one oxygen molecule reacting to create two molecules of water. Although the formula looks simple, this is in fact a complex process but it can be broken down into three simple partial reactions, each of which must take place for the reaction to run to completion. The first of these involves the hydrogen molecule, **H₂**, splitting into two hydrogen atoms, H, and the each of these releasing an electron to form a positively charged hydrogen ion, a proton:

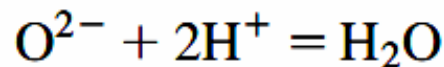




A parallel second partial reaction involves the oxygen molecule, O_2 , which splits into two oxygen atoms, O . Each of these absorbs two electrons released from two hydrogen atoms to produce a doubly negatively charged oxygen ion, O^{2-} :



The third and final part of the reaction involves the negatively charged oxygen ion attracting two positively charged hydrogen atoms and the three ions coalescing to form a water molecule, H_2O :



Then the reaction is complete.

The Electrolyte.

When hydrogen burns in air, the various steps of the reaction occur in the same place at the same time. However in a fuel cell the hydrogen and oxygen are not allowed to mix. Instead the reacting gases are introduced separately with hydrogen supplied to one electrode of the cell and oxygen to the other. The two electrodes are separated by a material called **the electrolyte**.

The electrolyte is the key element in any electrochemical cell because it acts like a **filter to both stop** the cell reactants mixing directly with one another and to control how the charged ions created during the partial cell reactions are allowed to reach each other.

The **electrolyte** in a fuel cell is **resistant to the gases, hydrogen and oxygen**. It will neither conduct electricity in the form of electrons nor (provided it is an acidic electrolyte) conduct the negatively charged oxygen ions. What it will do is conduct positively charged hydrogen ions.

Therefore, at the hydrogen electrode (which is called the anode), the hydrogen molecules first follow to the electrode material and then separate into atoms, each subsequently releasing an electron to form a positively charged ion as shown in the equation above. In this ionic form the hydrogen can cross the electrolyte boundary and reach the oxygen at the second electrode.

The electrons, however, are left behind at the electrode. At the second electrode (called the cathode), oxygen atoms will also adhere to the electrode surface and dissociate, each leaving two oxygen atoms. These require a supply of electrons if they are to form oxygen ions.

Only in this form can they coalesce with the hydrogen ions travelling through the electrolyte from the anode to create water molecules. The electrons must come from the anode, but these electrons cannot pass through the electrolyte.

Fuel—Cells Efficiency

The reaction between hydrogen and oxygen to create water releases a precisely quantified amount of energy. Not all this energy can be converted into electricity because some is required to overcome the energy barrier that normally prevents the reaction proceeding. When this reaction takes place between gaseous oxygen and hydrogen, each provided at a pressure of one atmosphere and at room temperature, the theoretical maximum chemical to electrical energy conversion efficiency that can be achieved is **83%**.

The precise reaction conditions will affect the potential efficiency. If the pressure of the reacting gases is increased, then conversion efficiency can be increased. However, increasing the operational temperature of the cell will reduce the net efficiency that can be achieved.

The actual conversion efficiency of a fuel cell is reflected in the voltage that the cell produces. The theoretical maximum cell voltage at open circuit for a fuel cell operating, when the cell is delivering no current, is **1.229 V**.

Fuel—Cells Efficiency

This **theoretical maximum** voltage only applies to a cell where the cell reaction product is water in liquid form. In most practical cells, where the product is actually water vapour, this maximum falls to **1.18 V**. At **100°C** this falls to **1.16 V** and at **800°C** the ideal cell voltage is only **0.99 V**. This is equivalent to a maximum ideal efficiency of **67%**. In practice, high temperature cells might approach **50%** efficiency. Low-temperature cells can do better than this and **60%**, or more, is feasible.

Fuel—Cells Types

There are **six major types of fuel cells**, classified by their electrolyte, such as follows.

1. Polymer electrolyte membrane (also called proton exchange membrane) fuel cell (**PEMFC**)
2. Alkaline fuel cell (**AFC**)
3. Phosphoric acid fuel cell (**PAFC**)
4. Direct methanol fuel cell (**DMFC**)
5. Solid oxide fuel cell (**SOFC**)
6. Molten carbonate fuel cell (**MCFC**).

Self-Study of Fuel—Cells Types

Fuel—Cells types

TABLE 7.4 Fuel Cell Characteristics

| | Operating Temperature (°C) | Catalyst | Efficiency (%) |
|---------------|----------------------------|----------------------------------|----------------|
| AFC | 25–200 | Noble metal catalyst | 60 |
| PAFC | 150–200 | Platinum | 35–42 |
| PEM fuel cell | 80 | Platinum | 30–50 |
| MCFC | 650 | Nickel | 47 |
| SOFC | 750–1000 | None needed at temperatures used | 35–43 |
| DMFC | 60–130 | Platinum/ruthenium | 25–40 |

Table 6.1 Comparison of the chemical reaction of major types of fuel cells [1]

| Type | Mobile ion | Cathode reaction | Anode reaction | Overall reaction | Efficiency (%) | Operating temperature range (°C) |
|-------|--------------------|---|---|---|----------------|----------------------------------|
| AFC | OH^- | $\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{e}^- \Rightarrow 2(\text{OH})^-$ | $\text{H}_2 + 2(\text{OH})^- \Rightarrow 2\text{H}_2\text{O} + 2\text{e}^-$ | $\text{H}_2 + \frac{1}{2}\text{O}_2 \Rightarrow \text{H}_2\text{O}$ | 60–70 | 50–200 |
| PEMFC | H^+ | $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \Rightarrow \text{H}_2\text{O}$ | $\text{H}_2 \Rightarrow 2\text{H}^+ + 2\text{e}^-$ | $\text{H}_2 + \frac{1}{2}\text{O}_2 \Rightarrow \text{H}_2\text{O}$ | 35–60 | 30–100 |
| PAFC | H^+ | $\frac{1}{2}\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \Rightarrow \text{H}_2\text{O}$ | $\text{H}_2 \Rightarrow 2\text{H}^+ + 2\text{e}^-$ | $\text{H}_2 + \frac{1}{2}\text{O}_2 \Rightarrow \text{H}_2\text{O}$ | ~40 | Around 200 |
| DMFC | H^+ | $\frac{3}{2}\text{O}_2 + 6\text{H}^+ + 6\text{e}^- \Rightarrow 3\text{H}_2\text{O}$ | $\text{CH}_3\text{OH} + \text{H}_2\text{O} \Rightarrow 6\text{H}^+ + 6\text{e}^- + \text{CO}_2$ | $\text{CH}_3\text{OH} + \frac{3}{2}\text{O}_2 \Rightarrow 2\text{H}_2\text{O} + \text{CO}_2$ | Up to 40% | 50–130 |
| MCFC | CO_3^{2-} | $\frac{1}{2}\text{O}_2 + \text{CO}_2 + 2\text{e}^- \Rightarrow \text{CO}_3^{2-}$ | $\text{H}_2 + \text{CO}_3^{2-} \Rightarrow \text{H}_2\text{O} + \text{CO}_2 + 2\text{e}^-$ | $\text{H}_2 + \frac{1}{2}\text{O}_2 + \text{CO}_2 \Rightarrow \text{H}_2\text{O} + \text{CO}_2$ | 50–60* | Around 600 |
| SOFC | O_2^- | $\frac{1}{2}\text{O}_2 + 2\text{e}^- \Rightarrow \text{O}_2^-$ | $\text{H}_2 + \frac{1}{2}\text{O}_2^- \Rightarrow \text{H}_2\text{O} + 2\text{e}^-$ | $\text{H}_2 + \frac{1}{2}\text{O}_2 \Rightarrow \text{H}_2\text{O}$ | 45–65* | 500–1000 |

AFC, alkaline fuel cell; PEMFC, polymer electrolyte membrane fuel cell; PAFC, phosphoric acid fuel cell; DMFC, direct methanol fuel cell; MCFC, molten carbonate fuel cell; SOFC, solid oxide fuel cell.

*Efficiency of these fuel cells could reach or exceed 80% in CHP operation mode.

Modeling of Ideal Fuel—Cells

Fuel cell modeling involves the modeling of thermal, chemical, and electric processes. A brief qualitative description of these processes is given in the following subsections.

6.3.1 *Thermal–electrical processes of fuel cells*

Fuel cells are energy conversion devices converting the energy stored in the fuel into electrical energy and heat through electrochemical and thermal processes. The electrochemical processes for different types of fuel cells are briefly covered in the previous section. In this subsection, thermodynamics governing the transformation of energy stored in the fuel to electrical energy, has been briefly described. The thermodynamics of fuel cells can predict the ideal maximum electrical output that can be generated in a reaction.

Rules, called *thermodynamic potentials*, can be written to specify how energy is transferred from one form to another. These potentials are described further [2].

Internal energy (U) is the energy needed to create a system without any change in the temperature and volume of the system. That is, the change in internal energy of the system is equal to the change in heat transferred to the system (dQ), lesser the work done by the system (dW):

$$dU = dQ - dW \quad (6.3)$$

where dU is the change in internal energy that can be transferred between the system and its surrounding through heat (dQ) or work (dW).

Enthalpy (H) is the energy needed to create a system plus the work needed to make room for it at volume V and pressure P :

$$H = U + PV \quad (6.4)$$

Helmholtz free energy (F) is the energy needed to create a system, less the energy that can be obtained from the system's environment at a constant temperature T :

$$F = U - TS \quad (6.5)$$

where S is the entropy of the system. Entropy can be interpreted as how change in heat transfer within a system can take place at constant temperature. For a reversible (ideal) heat transfer at constant pressure, the system entropy can change as:

$$dS = \frac{dQ_{\text{rev}}}{T} \quad (6.6)$$

where dS is the change in entropy of the system for a reversible heat transfer (dQ_{rev}) at a constant temperature T . For a thorough explanation on entropy of a system, interested readers can refer any standard book on thermodynamics.

Gibbs free energy (G) is the energy needed to create a system, less the energy that is obtained from its environment due to heat transfer. It represents the work potential of the system:

$$G = U + PV - TS = H - TS \quad (6.7)$$

It can be shown that for an electrochemical reaction (as in fuel cells), the maximum electricity production (W_e) is equal to the change in the Gibbs free energy [2]:

$$W_e = -\Delta G = n_e F E \quad (6.8)$$

where n_e is the number of participating electrons, F is Faraday's constant (96,485.3 C/mol), and E is the potential difference across the electrodes. Therefore, as a result of thermochemical reaction in fuel cells, a potential difference is induced across the fuel cell electrodes:

$$E = \frac{-\Delta G}{n_e F} \quad (6.9)$$

The above potential difference is a function of the fuel cell temperature and pressure of hydrogen and oxygen gases inside the fuel cell [2].

6.3.2 Fuel cell equivalent circuit

Like in a battery, the voltage at the terminals of a fuel cell is lower than the internal voltage induced in the cell. This is because of different losses due to electrochemical reactions and the ohmic loss, which is due to a current flow over resistance. There are three different losses (voltage drops) caused due to activation, ohmic, and concentration voltage drops inside a fuel cell, as shown in Figure 6.6. These voltage drops are

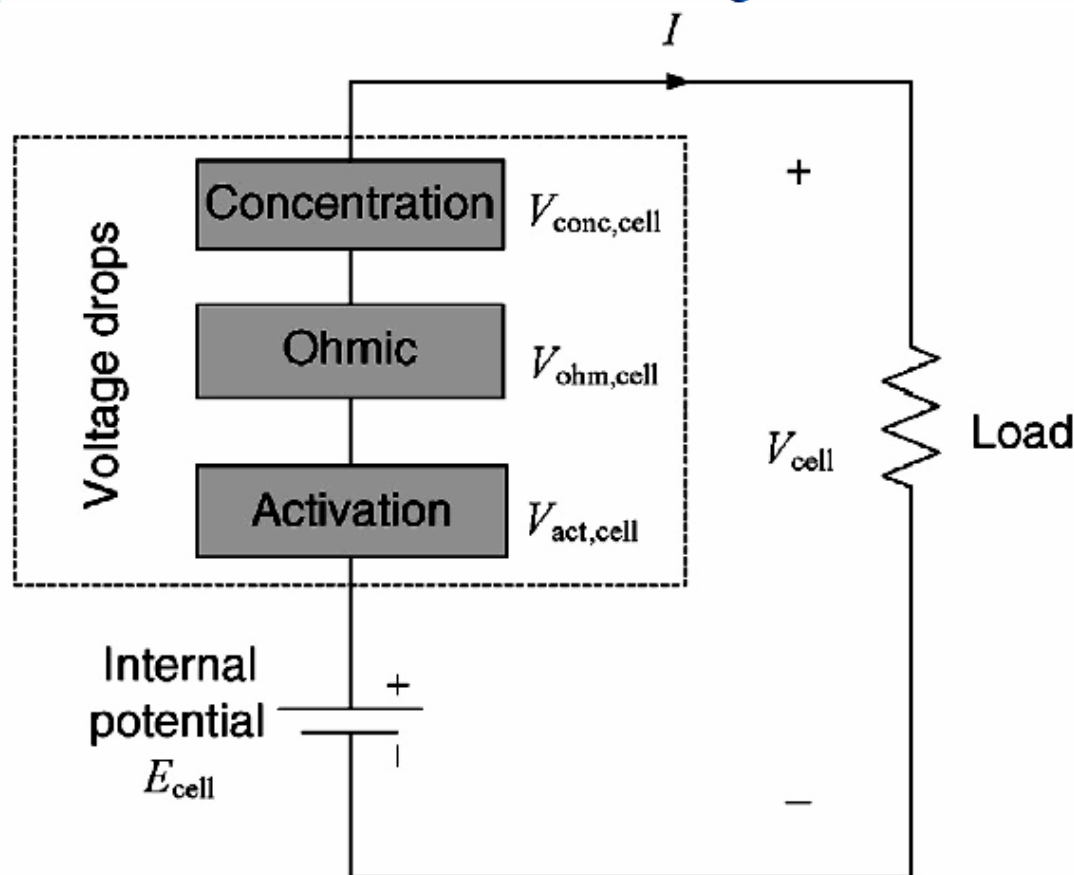


Figure 6.6 Fuel cell voltage drops [1].

functions of load current and fuel cell temperature and/or pressure. The ohmic voltage drop is a linear function of fuel cell load current at a certain operating point, but the ohmic resistance ($R_{\text{ohm,cell}}$) is normally a function of fuel cell temperature. The activation and concentration voltage drops are nonlinear functions of load current as well as pressure and/or temperature inside the fuel cell.

From Figure 6.6, the output voltage of a fuel cell can be written as [1]:

$$V_{\text{cell}} = E_{\text{cell}} - V_{\text{act,cell}} - V_{\text{ohm,cell}} - V_{\text{conc,cell}} \quad (6.10)$$

where V_{cell} and E_{cell} are the fuel cell output voltage and internal voltage, respectively, and $V_{\text{act,cell}}$, $V_{\text{ohm,cell}}$, and $V_{\text{conc,cell}}$ are the voltage drops discussed earlier.

Assuming that the parameters for individual cells can be lumped together to represent a fuel cell stack, we can obtain the output voltage of a fuel cell stack as:

$$V_{\text{out}} = N_{\text{cell}} V_{\text{cell}} = E - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}} \quad (6.11)$$

where V_{out} is output voltage of a fuel cell stack (V); N_{cell} is number of cells in the stack; E is fuel cell stack internal potential (V); V_{act} is the overall activation voltage drop (V); V_{ohm} is the overall ohmic voltage drop (V); and V_{conc} is the overall concentration voltage drop (V).

The activation voltage drop is a function of the fuel cell current and temperature, as described empirically by the Tafel equation given here:

$$V_{\text{act}} = \frac{RT}{\alpha z F} \ln\left(\frac{I}{I_0}\right) = T [a + b \ln(I)] \quad (6.12)$$

where α is the electron transfer coefficient; I_0 is the exchange current (A); R is the gas constant, 8.3143 (J/(molK)); T is the temperature in Kelvin; z is the number of participating electrons; and a and b are two empirical constants.

V_{act} can be further described as the sum of V_{act1} and V_{act2} as:

$$V_{\text{act}} = \eta_0 + (T - 298)a + Tb \ln(I) = V_{\text{act1}} + V_{\text{act2}} \quad (6.13)$$

where η_0 is temperature invariant part of V_{act} (V). $V_{\text{act1}} = (\eta_0 + (T-298) \times a)$ is the voltage drop affected only by the fuel cell internal temperature (that is not current dependent), and $V_{\text{act2}} = (T \times b \times \ln(I))$ is both current and temperature dependent.

The equivalent resistance of activation is defined by the ratio of V_{act2} and the fuel cell current. From Equation (6.14), it is noted that the resistance is both temperature and current dependent:

$$R_{\text{act}} = \frac{V_{\text{act2}}}{I} = \frac{Tb \ln(I)}{I} \quad (6.14)$$

The overall ohmic voltage drop can be expressed as:

$$V_{\text{ohm}} = IR_{\text{ohm}} \quad (6.15)$$

where R_{ohm} is a function of current and temperature and can be expressed by [1],

$$R_{\text{ohm}} = R_{\text{ohm}0} + k_{\text{RI}}I - k_{\text{RT}}T \quad (6.16)$$

where $R_{\text{ohm}0}$ is the constant part of R_{ohm} ; k_{RI} is the empirical constant for calculating R_{ohm} (Ω/A); and k_{RT} is the empirical constant for calculating R_{ohm} (Ω/K).

The concentration overpotential in the fuel cell is defined as follows [1]:

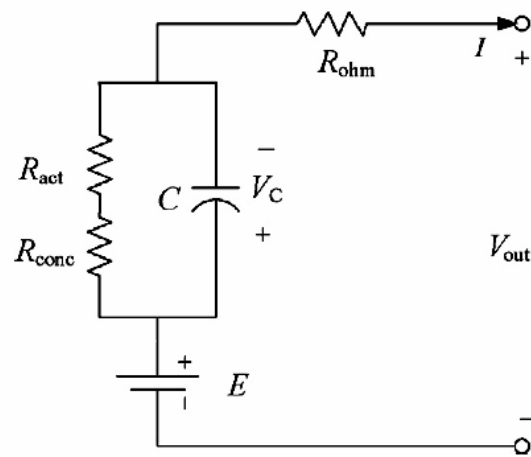
$$V_{\text{conc}} = -\frac{RT}{zF} \ln\left(1 - \frac{I}{I_{\text{limit}}}\right) \quad (6.17)$$

where I_{limit} is the fuel cell current limit (A).

The corresponding equivalent resistance for the concentration loss can therefore be defined as:

$$R_{\text{conc}} = \frac{V_{\text{conc}}}{I} = -\frac{RT}{zFI} \ln\left(1 - \frac{I}{I_{\text{limit}}}\right). \quad (6.18)$$

Because of the structure of fuel cells, where the electrodes are separated by electrolyte/membrane, which only allows one form of ion (positive or negative) flow through it, there is always charge accumulation on both sides of the electrolyte/membrane, which results in energy stored in the electric field inside cell. This phenomenon is represented by a capacitor, representing the *double-layer charge effect* [1,3]. The equivalent circuit of a fuel cell considering the double-layer charge effect is shown in Figure 6.7, where R_{act} , R_{conc} , and R_{ohm} are resistances corresponding to the activation, concentration, and ohmic voltage drops, C is the capacitance of the double-layer charge effect, and E is the



cell internal voltage (6.11). From Figure 6.7, the voltage across the capacitor and cell output voltage can be written as follows:

$$V_C = (I - C \frac{dV_C}{dt})(R_{act} + R_{conc}) \quad (6.19)$$

$$V_{out} = E - V_{act1} - V_C - V_{ohm} \quad (6.20)$$

where V_{act1} is the temperature-dependent part of V_{act} .

In practice, the capacitance of double-layer charge effect appears only in the transient response of the fuel cell. The fuel cell voltage is constant DC at steady state, and there is no current through the capacitor. Therefore, the capacitor acts as an open circuit and does not affect the fuel cell steady-state response.

Steady-state Electrical Characteristics of Fuel Cells

Since all the voltage drops in eq. (6.11) are a function of load current and temperature, the output terminal voltage of the fuel cell is also a nonlinear function of load current and temperature.

$$V_{\text{out}} = N_{\text{cell}} V_{\text{cell}} = E - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}} \quad (6.11)$$

Modeling of Actual Fuel—Cells

Modeling of different types of fuel cells depends on their electrochemical characteristics and can be different from one another. Therefore, to be accurate, each fuel cell type should be modeled independently.

The block diagram for building the electrical circuit model for PEMFC, considering the electro-thermo-chemical characteristics of the fuel cell, is shown in Figure 6.9.

The output voltage of the fuel cell as a function of load current, which is based on (6.20), and its output power (the product of the output voltage and load current), simulated in Matlab/Simulink, are shown in Figure 6.10 [1].

The active, ohmic, and concentration zones of the fuel cell are also shown in the Figure 6.10. It is noted that the output voltage of the fuel cell decreases as its load current increases, and the maximum power it can deliver is almost near the rated current of the fuel cell, just before the fuel cell enters the concentration mode. This phenomenon holds for different types of fuel cells.

Modeling of Actual Fuel—Cells

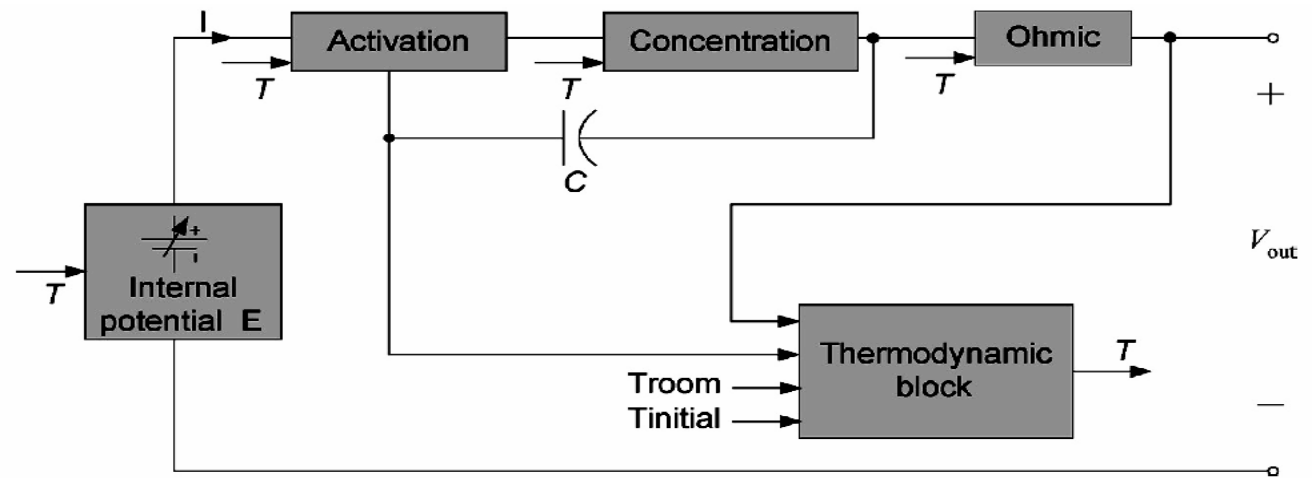


Figure 6.9 Block diagram for building an electrical circuit model for PEMFC.

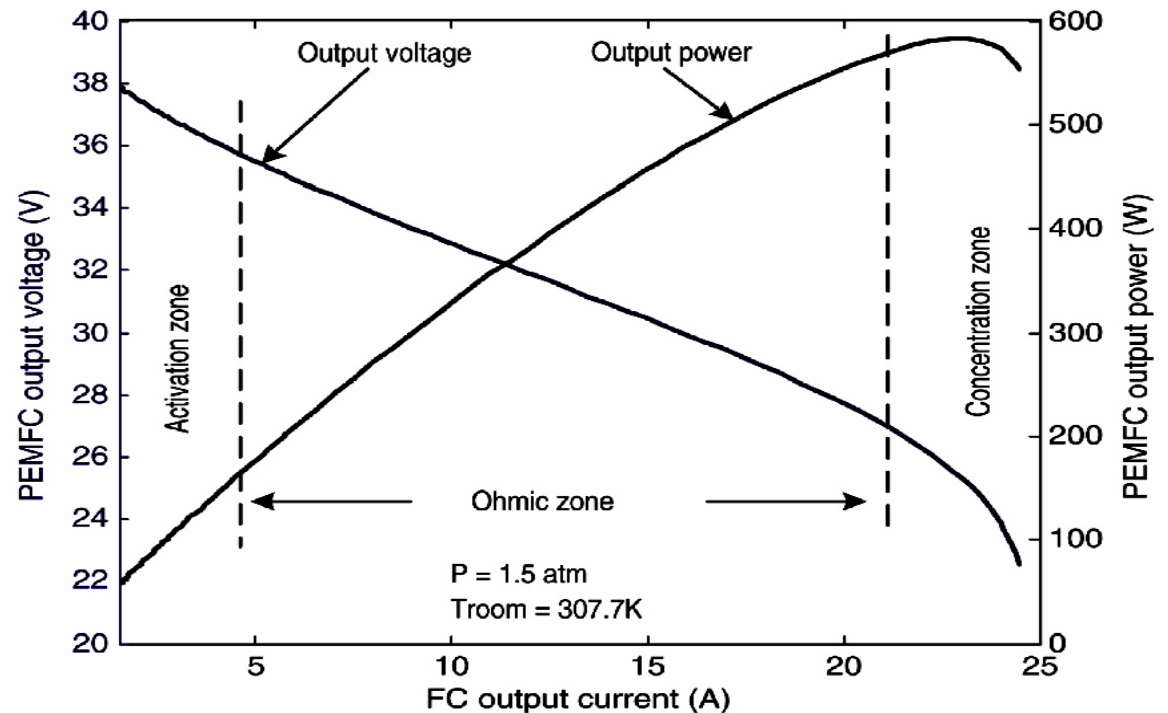


Figure 6.10 Simulated V - I - and P - I -characteristic curves for the 500-W PEM fuel cell stack [1].

Power Applications of Fuel—Cells

The most common type of fuel cells, which have large-scale power applications are PEMFC, SOFC, and MCFC. They can be connected to the power grid or operated independently in standalone mode. In both configurations, they are often referred to as fuel cell distributed generation systems. These two operation modes are discussed below.

Grid-Connected Fuel—Cell Configuration

The interface is very important as it affects the operation of the fuel cell system as well as the power grid. DC/DC converters are necessary to boost and regulate fuel cell output voltage and adapt it to a voltage that can be supplied to a DC/AC converter (inverter) to convert the regulated DC voltage of the fuel cell, to a desired AC voltage.

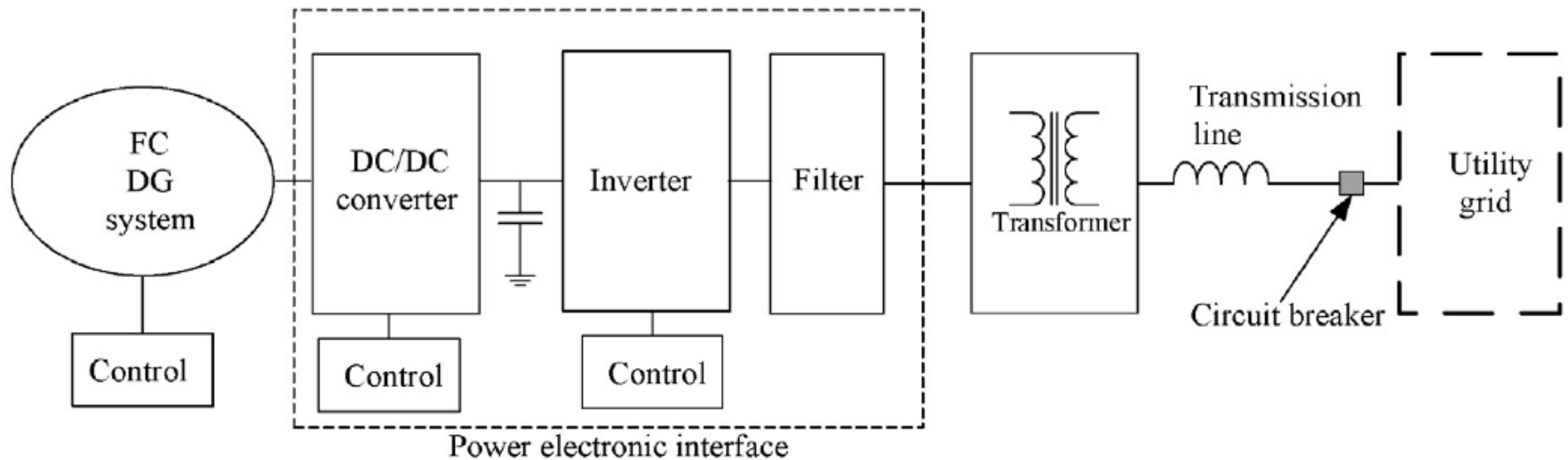


Figure 6.13 Block diagram of a grid-connected fuel cell DG system.

Grid-Connected Fuel—Cell Configuration

The harmonics of AC voltage are then filtered and the voltage is stepped up, if needed, through a transformer and connected to the grid through a transmission line. The AC voltage must be synchronized with the grid. Figure 6.13 shows the block diagram of a grid-connected fuel cell stack with the power electronic converters, electrical filter, transformer, and transmission line. It should be noted that in a fuel cell power plant, a number of fuel cell stacks are connected in series to provide the required voltage and a number of stacks are connected in parallel to provide the rated current. The regulated output voltage of the DC/DC converter is stabilized with a battery bank, and converted into AC voltage. The AC voltage is then filtered, stepped up, and connected (synchronized) to the utility grid. The amount of real and reactive power delivered by the fuel cell to the grid can be controlled by the controller of the inverter and by controlling the fuel cell stacks.

Standalone Fuel—Cell Configuration

Block diagram of a **standalone fuel cell system** is shown in Figure 6.14. The components of these systems are basically the same as those for the grid-connected system, except that the system serves independent loads and is **not connected to the utility grid**. A battery bank is also used to provide sufficient storage capacity to handle fast power variations due to load transients. An inverter is to invert the DC voltage to AC when fuel cell is to supply AC loads.

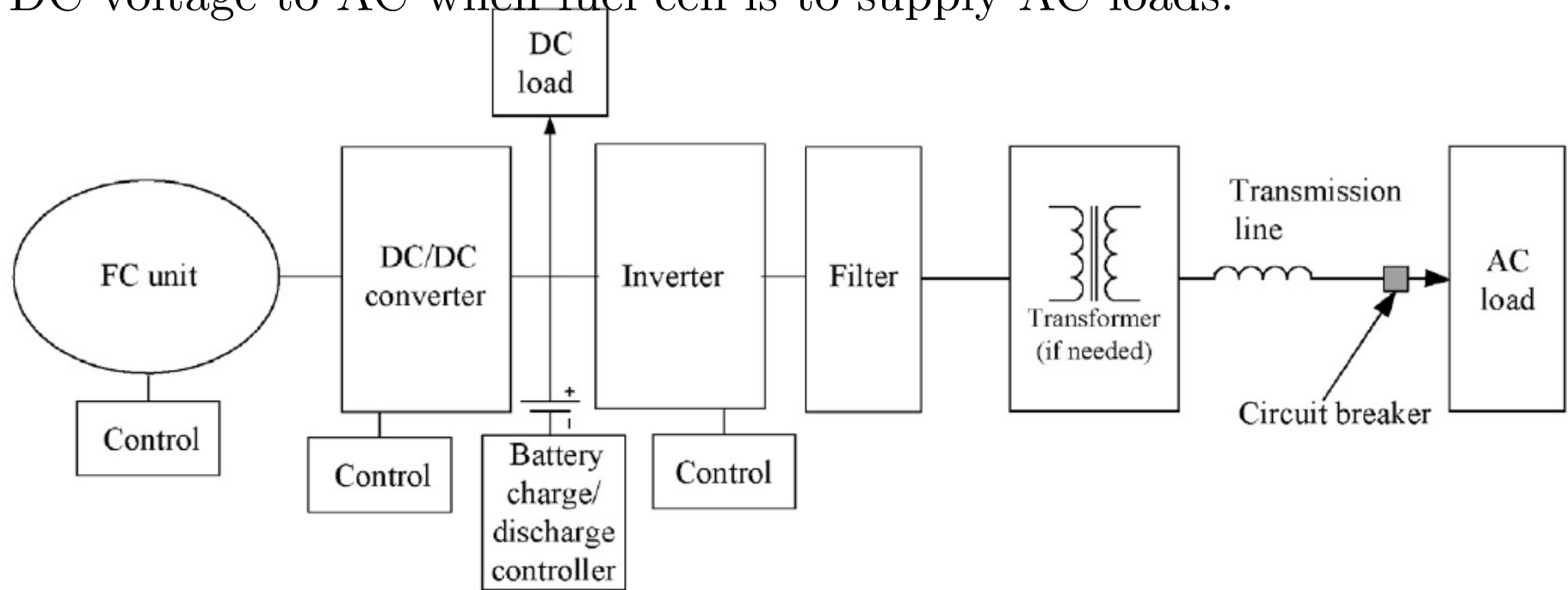


Figure 6.14 Block diagram of a standalone fuel cell DG system.

Hydrogen Production From Renewable Energy

Wind- and solar photovoltaic generated electricity can be used for water electrolysis for the production of a significant amount of hydrogen.

Figure 6.16 shows the schematic diagram of a standalone hybrid wind-solar-fuel-cell-electrolyzer energy system with the associated power electronic (AC/DC, DC/AC, and/or DC/DC) converters.

The system can be designed such that the wind-/solar-generated power supplies the load, and any excess available power is used first to charge the battery and then supplied to the electrolyzer to generate hydrogen, which is compressed and stored in the reservoir and backup tanks, respectively.

During periods when wind- and solar-generated power is not sufficient to supply the load, hydrogen fuel is used to power the fuel cell to generate electricity.

Hydrogen Production From Renewable Energy

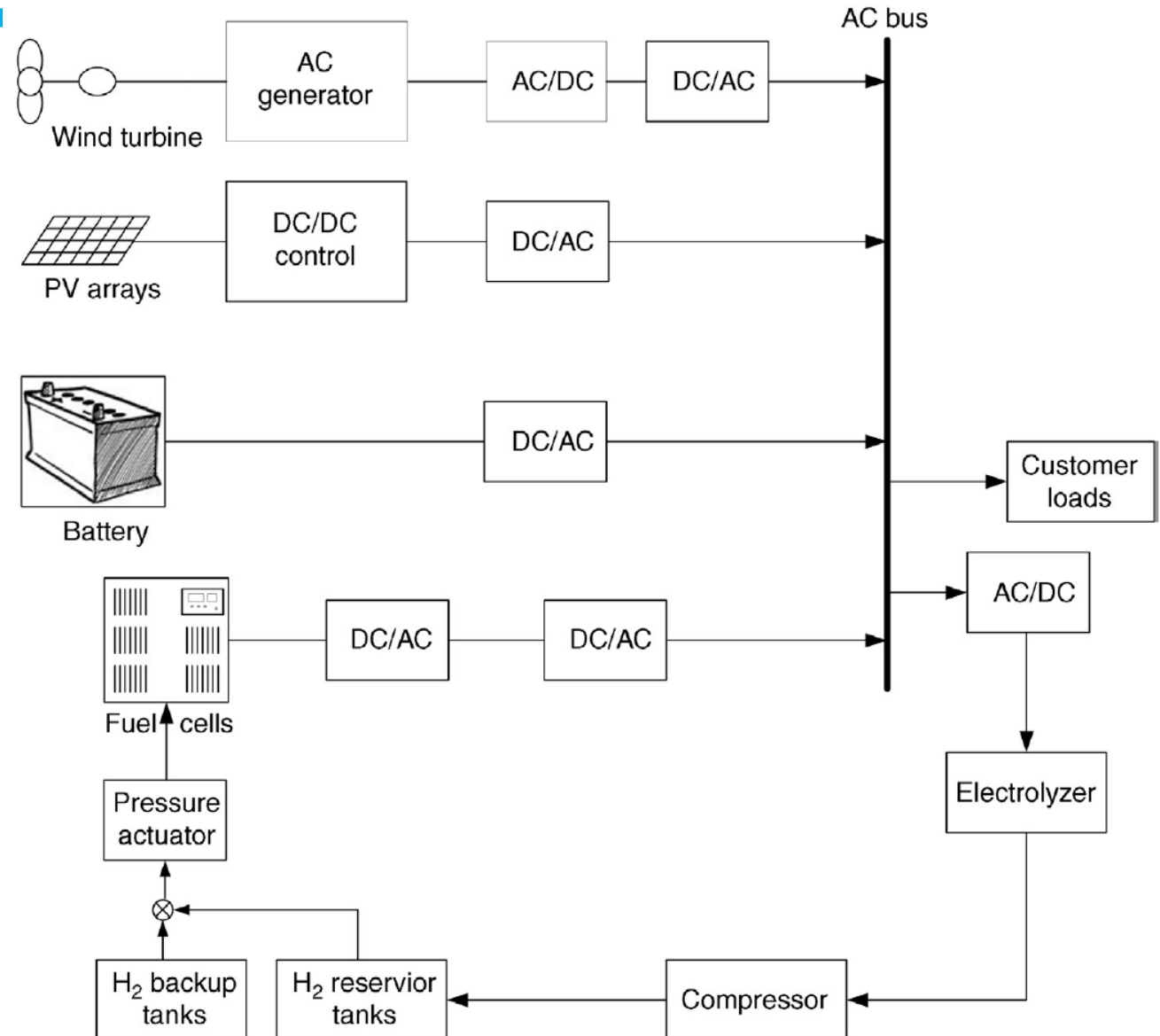


Figure 6.16 Schematic diagram of a standalone hybrid wind-solar-fuel cell energy system.

End of Fuel—Cell Course Work









Power Equations Summary

- Hydroelectric: $P = \rho Qgh$
- Wind: $P = C_p A(\frac{1}{2} \rho v^3)$
- Wave front: $P = \frac{1}{2} \rho LvgA^2$
- NOVA Program: Energy Surge
<http://www.pbs.org/wgbh/nova/tech/power-surge.html>



1

Hydroelectric Dam

Site C
1,100 MW

=



12

Natural Gas Plants

McMahon Co-Generation
120MW

=

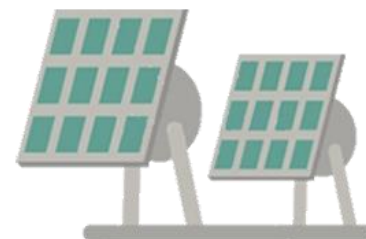


990

Wind Turbines

Leitwind LTW77-1500
1.5 MW

=



30,000,000

m² of Solar Panels

Canadian Solar
500 W

EnergyBC