Chapter 8
Hydrogen Production from Renewable Energy Sources, Storage, and Conversion into Electrical Energy

El Manaa Barhoumi, Paul C. Okonkwo, Slah Farhani, Ikram Ben Belgacem, and Faouzi Bacha

Abstract This chapter discusses the electrolysis process used to produce green hydrogen from renewable energy sources and the conversion of hydrogen into electrical energy by using fuel cells. Hydrogen can be produced from renewable energy sources, stored, and used whenever electrical energy is required by the loads. The process of electrolysis is the use of electrical energy and water to produce hydrogen. The different electrolyzers: solid oxide, alkaline, and proton exchange membrane have different characteristics and efficiencies. The cost of hydrogen production depends on the worth of renewable energy systems and hydrogen production equipment. On the other hand, the overall efficiency of hydrogen production depends on the renewable energy system efficiency. So, the optimization of the renewable energy system and the selection of adequate sites are characterized by their high renewable energy potential allow maximizing the effectiveness of hydrogen production. The design of a photovoltaic system to generate the electrical energy required to produce 100 kg of hydrogen per day highlights the potential future of green hydrogen produced from solar energy using photovoltaic systems. This hydrogen gas power station requires the installation of 2662.2 kWp of the PV system to produce 13,311

E. M. Barhoumi (✉)
Department of Electrical and Computer Engineering, College of Engineering, Dhofar University, Salalah, Oman
e-mail: ebarhoumi@du.edu.om

P. C. Okonkwo
Department of Mechanical and Mechatronics Engineering, College of Engineering, Dhofar University, Salalah, Oman
e-mail: pokonkwo@du.edu.om

S. Farhani
Laboratory of Computer for Industrial Systems, INSAT, University of Carthage, Carthage, Tunisia

I. B. Belgacem
Laboratoire de Génie Mécanique, Ecole Nationale d'Ingénieurs de Monastir, Université de Monastir, Monastir, Tunisie

F. Bacha
Department of Electrical Engineering, University of Tunis, ENSIT, Tunis, Tunisia
e-mail: faouzi.bacha@esstt.rnu.tn

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kWh of electrical energy per day to run four proton exchange membrane electrolyzers during 5 h per day. The produced hydrogen can be used to charge fuel cell vehicles, generate electricity for buildings during the night, or be transported to be consumed in any other industrial applications.

Keywords Electrolyzers · Fuel cells · Renewable energy · Photovoltaic-Hydrogen Refueling Station

Nomenclature

PV	photovoltaic
HGS	hydrogen gas station
PEM	proton exchange membrane
SOE	solid oxide electrolyzer
FCV	fuel cell vehicle
H2	hydrogen
V	volt
Wp	watt peak
Vohm	voltage of ohmic losses
O2	dioxygen
H_2O	water
OH-	hydroxide
η	Efficiency
$P_{DC\text{-}DC\ converter}$	power of one DC-DC converter
$P_{PV\text{-}System}$	power of the PV system
$N_{pv\ panels}$	number of PV panels
V_{act}	voltage of activation losses
V_{conc}	voltage of concentration losses

8.1 Introduction

The population increase, the urbanization, and industrialization development lead to an increase in electricity consumption (Yoo and Lee 2010). The excess of fossil fuels exploitation to produce electricity results in the pollution of the environment and the decrease of fuel reserve (Razmjoo et al. 2021). Renewable energy sources represent an alternative solution to produce electrical energy from clean and renewable sources (Boran et al. 2012). Thereafter, solar, wind, geothermal, and other renewable sources are exploited to produce electrical energy. However, the electrical energy produced from renewable sources is dependent on weather conditions and cannot be controlled according to load consumption (Barhoumi et al. 2019; Barhoumi et al. 2021). Therefore, the storage of the surplus of produced electrical energy from renewable sources consists of an adequate solution to maximize energy efficiency (Marano et al. 2012). (Abdin and Mérida 2019). However, the lifetime and the cost of batteries discourage the implementation of this solution (Duggal and Venkatesh 2015; Hammad and Ebaid 2015). To avoid the dependence on batteries for the storage of electrical energy, the electrical energy is converted into hydrogen to be stored in gas or liquid state (Boulmrharj et al. 2020; Gondal et al. 2018). Thereafter, hydrogen is converted into electrical energy to be used when loads required electrical energy. So, hydrogen represents an effective alternative to store electrical energy. Hydrogen energy is leading to a clear change of renewable energy exploitation. Indeed, the surplus of electrical energy is used to produce hydrogen. Hydrogen can be stored in huge quantities, transported to different locations, and used to produce electrical energy (Christensen 2020; HassanzadehFard et al. 2020). The electrolysis technologies and the fuel cells are key solutions in the conversion of energy to gas and gas to energy (Chi and Yu 2018).

This chapter discusses the electrolysis technologies used to produce hydrogen from renewable energy sources, the hydrogen industrial applications, and the conversion of hydrogen into electrical energy. Then, this chapter is organized as follows. Section 8.2 presents the electrolysis process and a comparison of three types of electrolyzers used in hydrogen production. In Sect. 8.3, the production of hydrogen from renewable energy sources is presented and discussed. The requirements of hydrogen storage are presented in Sect. 8.4. The principle of operation, modeling, and applications of the fuel cell is presented in Sect. 8.5. In Sect. 8.6, the design of the photovoltaic hydrogen station is presented and analyzed. The conclusion is given in Sect. 8.7.

8.2 Electrolysis

The processes used to produce hydrogen from renewable sources are summarized in Fig. 8.1 (Shiva Kumar and Himabindu 2019). These processes have different efficiencies and different costs. The hydrogen is called "green" when is produced from renewable energy sources (Gondal et al. 2018). In the process of water splitting, the hydrogen can be produced by photolysis, thermolysis, or electrolysis method. In electrolysis, hydrogen is produced using PEM, solid oxide, or alkaline electrolyzers. The process using electrical current to produce hydrogen is called electrolysis (Yan et al. 2020). This process is based on water-splitting using electrical current to produce hydrogen and oxygen. The different components required for the design of an electrolyzer are the cathode, the anode, the membrane, and the electrolyte (Shiva Kumar and Himabindu 2019). The anode of the electrolyzer is connected to the positive terminal of the DC power source. The negative terminal of the power source is connected to the cathode. The membrane ensures electrical separation

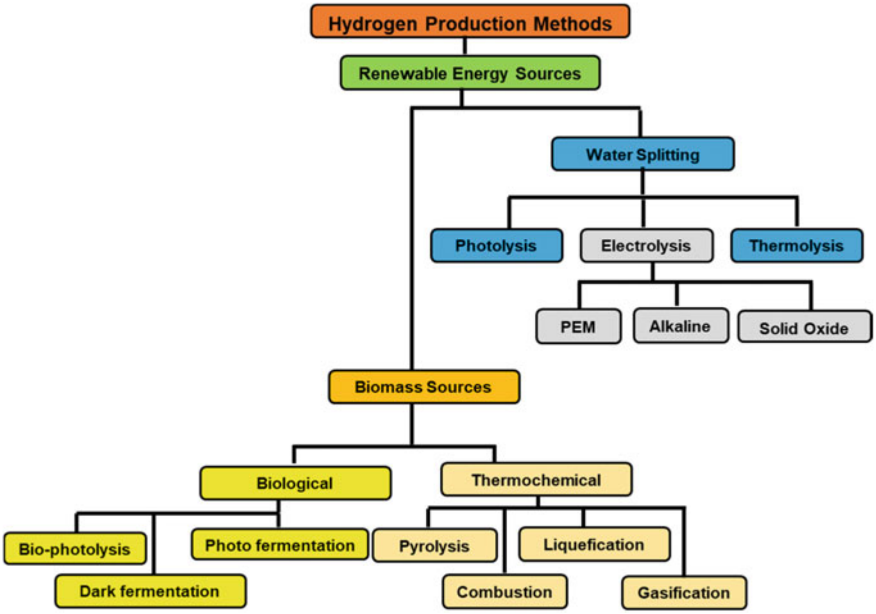

Fig. 8.1 Processes of hydrogen production (Nikolaidis and Poullikkas 2017)

between the anode and the cathode circuits. At the cathode, hydrogen gas is generated. The oxygen is generated at the cathode. The membrane requirements are ion permeability, gas-tight, chemical stability, electrically insulating, and mechanical robustness (Okonkwo et al. 2021).

The electrolysis is described by the following chemical reaction expression (Chi and Yu 2018):

$$H_2O_{(liquid)} \rightarrow H_{2(gaz)} + \frac{1}{2}O_{2(gaz)} \tag{8.1}$$

8.2.1 PEM Electrolyzer

The PEM electrolyzer is mainly composed of anode, cathode, and membrane. In the PEM electrolyzer, the electrodes are made of platinum and the membrane is made of Nafion (Shiva Kumar and Himabindu 2019). The membrane allows separating the electrodes and the gases produced at the cathode and the anode. The flow of the current through the water leads to the apparition of hydrogen and oxygen. At the cathode, the reduction reaction takes place (Abdin et al. 2015):

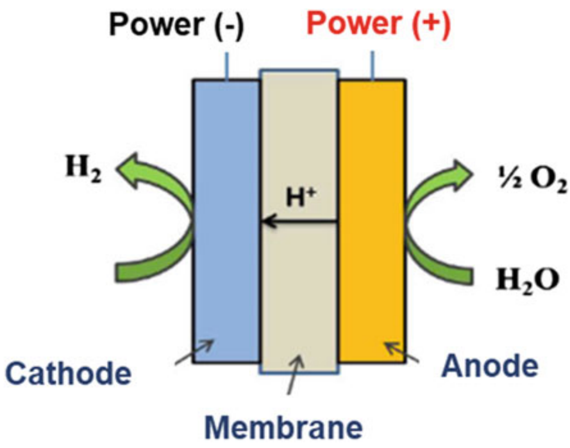

Fig. 8.2 Schematic diagram of the PEM electrolysis process (Barbir May 2005)

$$2H^+ + 2e^- \rightarrow H_{2(gaz)} \tag{8.2}$$

The cathode attracts the cations, and the anode attracts anions. At the anode, the oxidation reaction takes place.

$$H_2O_{(liquid)} \rightarrow 2H^+_{(gaz)} + \frac{1}{2}O_{2(gaz)} + 2e^- \tag{8.3}$$

The overall reaction is expressed as

$$H_2O_{(liquid)} \rightarrow H_{2(gaz)} + \frac{1}{2}O_{2(gaz)} \tag{8.4}$$

The different reactions of water splitting using the PEM electrolyzer are summarized in Fig. 8.2.

The EPM electrolysis is used and implemented in many countries to produce hydrogen from water despite it having the lowest efficiency compared to other electrolyzers.

8.2.2 Solid Oxide Electrolyzer (SOE)

The SOE consists of multiple SOE stacks, a fan for circulating oxygen, and a separator to separate produced water from the water (Wang et al. 2019). The SOEs are usually operating in exothermic condition (Nieminen et al. 2010). For lower potential operation, heat is required to start up. This heat and electricity can be generated from solar energy. The electrolysis takes place at high temperatures (400–500 °C). The SOE allows to produce pure oxygen which is considered a valuable product. The

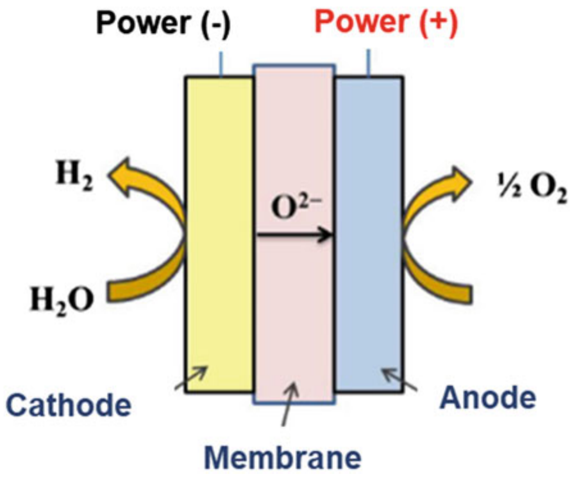

Fig. 8.3 Schematic diagram of the water electrolysis using the SOE

overall efficiency of the SOE is higher than the PEM electrolyzer (Nieminen et al. 2010). The elementary stack of the SOE is depicted in Fig. 8.3.

The chemical reactions at the anode and cathode sides, respectively, are expressed as follows (Ni et al. 2008):

$$O^{2-} \rightarrow 2e^- + \frac{1}{2}O_2 \tag{8.5}$$

$$H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{8.6}$$

The overall reaction is

$$H_2O_{(liquid)} \rightarrow H_{2(gaz)} + \frac{1}{2}O_{2(gaz)} \tag{8.7}$$

8.2.3 Alkaline Electrolyzer

The electrodes of the alkaline electrolyzer are merged in the aqueous electrolyte of approximately 30% Sodium hydroxide or potassium hydroxide (David et al. 2019; Chi and Yu 2018). The cathode is made of nickel and the anode is made of nickel or copper. At the cathode, the water is decomposed into hydrogen and anions OH-. At the anode, the oxidation of OH- taking place at the anode generates water and oxygen. The principle of operation of the alkaline electrolyzer is given in Fig. 8.4.

The chemical reactions at anode and cathode sides are expressed by David et al. (2019)

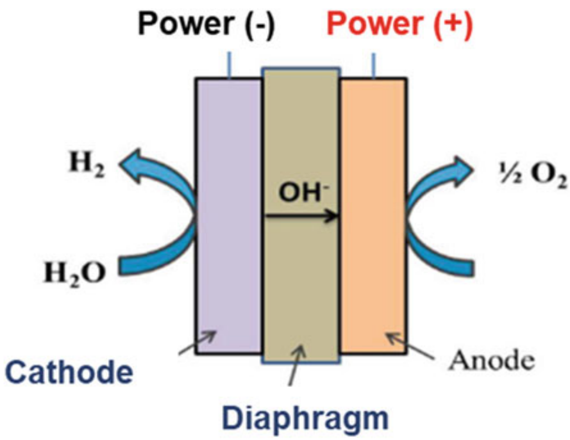

Fig. 8.4 Schematic diagram of the water electrolysis using the alkaline electrolyzer

$$2OH^- \rightarrow 2e^- + \frac{1}{2}O_2 + H_2O \tag{8.8}$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{8.9}$$

The overall reaction is

$$H_2O_{(liquid)} \rightarrow H_{2(gaz)} + \frac{1}{2}O_{2(gaz)} \tag{8.10}$$

8.2.4 Comparison of Electrolyzers

The efficiency of an electrolyzer is calculated by Nieminen et al. (2010)

$$\eta = \frac{P_{out}}{P_{input}} \tag{8.11}$$

where P_{out} is the output power calculated in kWh equivalent to the produced hydrogen P_{input} is the electrical energy required to run the electrolyzer to produce the hydrogen. In other words, the efficiency is equivalent to the energy of produced hydrogen divided by the amount of absorbed electricity. 1 kg of hydrogen is equivalent to 33.4 kWh of electrical energy. This value is called the higher heating value of hydrogen.

Example: An electrolyzer is absorbing 50 kWh of electrical energy to produce 0.5 kg of hydrogen. Then, the efficiency of the electrolyzer is.

Table 8.1 Comparison of electrolyzers' characteristics

Electrolyzer characteristics	PEM	SOE	Alkaline
Material of anode	Pt black, Ir, Ru, Rh	Lanthanum strontium manganate (LSM)	Ni or Cu
Material of cathode	Pt black, Ir, Ru, Rh	Ni-doped YSZ	Ni
Electrolyte	Solid polymer	Solid oxide or ceramic material	Potassium hydroxide (KOH) or sodium hydroxide (NaOH)
Efficiency	57–69%	80%	90%
Working temperature	50–100 °C	500–950 °C	80 °C

$$\eta = \frac{0.5 \times HeatValue(H2)}{50 \times HeatValueof\,1kWh} = 33.4\% \tag{8.12}$$

The different performances and main characteristics of electrolyzers used to produce hydrogen are summarized in Table 8.1.

8.3 Renewable Energy Sources for Hydrogen

Even though hydrogen is produced from renewable sources using different techniques, electrolysis still considered the main process used to produce hydrogen (Barbir 2005). When the electrical current used in electrolysis is produced from classic power generating stations, e.g., thermal power station and gas power station, the process is considered a pollutant and non-green (Chi and Yu 2018). Indeed, hydrogen is produced from pollutant sources. However, electrolysis can use electrical current produced from renewable energy sources where no dioxide of carbon is produced (Yan et al. 2020). The green hydrogen is produced from carbon-free and environmentally friendly sources. Recently, governmental authorities in many countries showed interest to convert renewable energy sources into hydrogen. The process of the conversion of wind energy and solar energy into hydrogen through the electrolysis is presented in Fig. 8.5. The hydrogen produced from renewable sources by electrolysis is used on-site for refueling FCVs or transported and used in other places. Therefore, the hydrogen is considered an effective method for the storage of electrical energy produced from renewable energy sources.

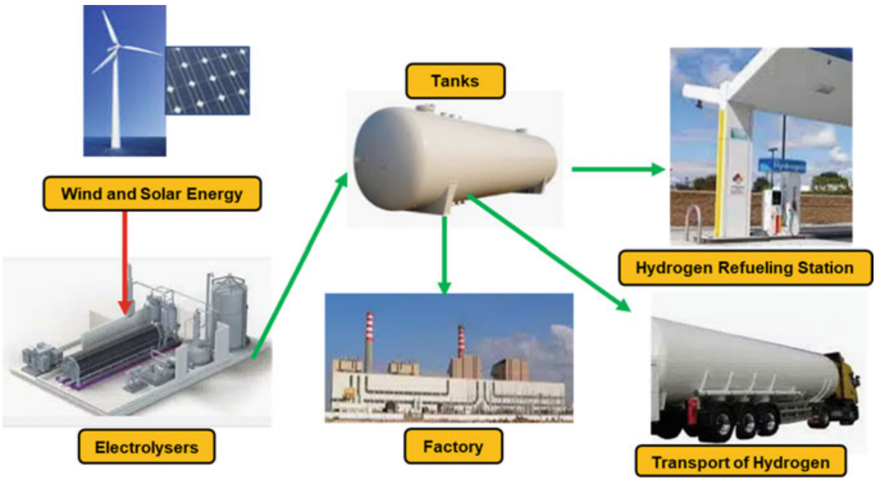

Fig. 8.5 Conversion of electrical energy produced from renewable energy sources into hydrogen

8.3.1 *Solar Energy*

Solar energy has been used to produce electrical energy to run different industrial processes (Hammad and Ebaid 2015; Albadi et al. 2019; Shaner et al. 2016). Nowadays, large-scale PV plants is installed around the world to produce electrical energy from solar energy using large-scale PV systems (El Ouderni et al. 2013). To control the flow of produced electrical energy into the power grid, the surplus of electrical energy that cannot be fed to the power grid is converted into hydrogen (Shaner et al. 2016). The hydrogen will be used later to produce electrical energy when required. A photovoltaic system feeding an electrolyzer to provide 58,400 kg of hydrogen in London city on a yearly basis required the installation of 2.98 MWp as DC capacity of PV system (Abdin and Mérida 2019). The results show that 47.82 kWh of electrical energy is required to produce 1 kg of hydrogen. The economic analysis shows that 1 kg of hydrogen costs between 3 and 8 Euro according to the price of the PV systems, civil works, compressors, and storage tanks.

8.3.2 *Wind Energy*

Recently, several plants are used to produce hydrogen from wind power (Xiao et al. 2020). The basic idea consists of the production of electricity from wind energy using wind turbines, electric generators, and power converters. In the second stage, electricity produced is used to produce hydrogen (Schnuelle et al. 2020). The method has a lot of advantages. Indeed, hydrogen is produced from clean and cost-free sources. The hydrogen is then stored in special tanks to be used to produce electricity by the fuel cell. Xcel Energy in cooperation with NREL's installed the wind turbines to produce the hydrogen (Givler and Lilienthal 2005). The project, Wind2H2, uses two wind turbines 1of 00-kW and one turbine of 10-kW. The project uses two PEM and one alkaline electrolyzer. The hydrogen produced during the electrolysis is stored in special tanks for later use through the conversion back to electrical power to be fed into the utility grid ("Wind-to-Hydrogen Project" 2021).

8.3.3 Hydroelectric Energy

Hydrogen can be produced from hydroelectric electric energy by converting the hydro energy into electrical power to fed electrolyzers (Edwards et al. 2021). In Canada, the company Air Liquide has built the largest PEM electrolyzer with a total capacity of 20 MW.

8.3.4 Geothermal Energy

Geothermal energy consists of an essential renewable source of electrical energy around the world. So, the production of green hydrogen using geothermal energy represents another effective alternative to green hydrogen (Balta et al. 2010).

8.4 Storage of Hydrogen

The electrical energy to hydrogen energy to electrical energy process can be summarized in three stages: hydrogen production by electrolysis, storage in special tanks, and electricity generation by fuel cells. The hydrogen is converted later into electrical energy to feed fuel cells and produce electrical energy. The storage stage of hydrogen represents a delicate step due to the safety requirements and exigencies. The hydrogen gas storage process is described in Fig. 8.6. The heat exchanger is shown in Fig. 8.6. allowing to minimize the compression work during the compression and intercooling, which allows the increasing of the efficiency of the storage process. Hydrogen can be stored in gas or liquid state. The storage of hydrogen in the gas state shall be done in tanks that can resist high pressure (350–700 Bar). The boiling temperature of hydrogen is -252.8 °C at one-atmosphere pressure. Therefore, cryogenic temperatures are required to perform the storage of hydrogen in the liquid state.

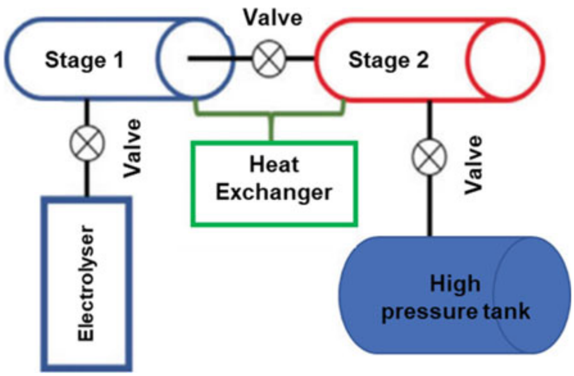

Fig. 8.6 Storage of hydrogen

8.5 The Generation of Electrical Energy from Hydrogen

8.5.1 The Fuel Cells

The Alkaline and the PEM fuel cells are the main fuel cells used in the production of electrical energy from hydrogen. These two types operate at temperatures below 100 °C. Other fuel cells are characterized by electrolytes requiring higher temperatures to become ion-conducting. The two electrodes where the chemical reactions take place are indispensable. These two electrodes emerge in a solution called electrolyte. To produce electrical energy, two chemical elements are required which are hydrogen and oxygen. The hydrogen (H_2) reaches the fuel cell at the anode. Then, a chemical reaction takes place to strip the hydrogen molecules of their electrons. Hence, the atoms become ionized to form the ion H+ . The electrons produced at the anode from the chemical reaction will flow through wires to constitute the electrical current. On the other side, the oxygen reaches the cathode. The oxygen is usually coming from the air. The oxygen attracts the electrons that flow through the wires connecting the anode and the cathode. The voltage produced in a single fuel cell from a chemical reaction is only about 0.7 V. Single cells are usually stacked in series to obtain a higher voltage at the terminal of the fuel cell and make the fuel cell used in residential applications, fuel cell cars, and any other equipment requiring electrical power.

The chemical reactions happening in a single fuel cell stack are as described by the following expressions. At the anode side, an oxidation reaction described by the following equation will take place.

$$H_2 \rightarrow 2H^+ + 2e^- \tag{8.13}$$

At the cathode side, a chemical reaction called a reduction reaction will take place.

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{8.14}$$

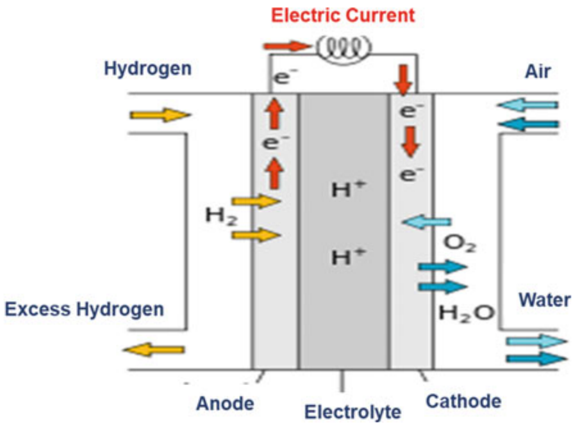

Fig. 8.7 Principle of working of the fuel cell

The net reaction, called the oxidation–reduction or redox reaction, is described by

$$\frac{1}{2}O_2 + 2H^+ \rightarrow H_2O \tag{8.15}$$

Figure 8.7 shows the main components and the fuel cell principle of working.

8.5.2 *Comparison of Fuel Cells and Batteries*

Fuel cells are distinct from batteries in dependence on integrating elements required to produce electricity. In the battery, there is no external fuel source. Indeed, the battery should be charged and after that connect to the load until a defined discharging point. The fuel cells are not charged or discharged. Indeed, the hydrogen and oxygen required to produce electrical energy are provided from external tanks. This property gives the fuel cell more effectiveness in terms of working hours and avoiding the charging time. Moreover, fuel cells can provide electricity when hydrogen is available, only hydrogen tanks need to be charged. In conventional batteries, the battery components are the basis of energy generation, where the reaction of chemical components of the battery produces electricity. This process continues until the end of the battery reactant chemicals, while the fuel cells operate on a continuous basis as the hydrogen and the oxygen are provided from external sources. The principles of operation made a big difference in terms of lifetime and cost. Therefore, fuel cells have more lifetime and high cost due to their high reliability and efficiency. Moreover, the fuel cells have high efficiency and showed better performances in transportation applications.

8.5.3 Modeling of the Fuel Cell

During the phase of generating current, the voltage of the fuel cell Vcell is less than the voltage produced in open-circuit Vnern (Barhoumi et al. 2020):

$$V_{Cell} = E_0 - \Delta V_{act} - \Delta V_{ohm} - \Delta V_{con} \tag{8.16}$$

The voltage drop is due to the Ohmic losses, activation, and concentration losses. The activation losses are described by the activation overvoltage, Vact:

$$\frac{d\Delta V_{act}}{dt} = \frac{\Delta V_{act} I}{\eta_{act} CdI} + \frac{I}{CdI} \tag{8.17}$$

The cathodic activation drop, ηact, is given by the following equation:

$$\eta_{act} = -(\xi_1 + \xi_2 T + \xi_3 T \ln C_{O2} + \xi_4 T \ln I) \tag{8.18}$$

where:

I: is the current produced by the fuel cell,

$$\xi_1 = -0.948$$
$$\xi_2 = 0.00286 + 0.0002 \ln(A_{cell}) + 4.3\ 10^{-5} \ln(C_{H2})$$
$$\xi_3 = 7.6\ 10^{-3}$$
$$\xi_4 = -1.93\ 10^{-4}$$

The Ohmic voltage is given by

$$\Delta V_{ohm} = iR_{ohm} = i(R_{mem} + R_e) \tag{8.19}$$

where: $R_{ohm} = \frac{t_m}{\sigma_m}$.

The membrane conductivity is given by Yoo and Lee (2010)

$$\sigma_m = b_1 \exp\left[b_2\left(\frac{1}{303} - \frac{1}{T_{fc}}\right)\right] \tag{8.20}$$

The concentration voltage is expressed by

$$\Delta V_{act} = \frac{RT}{nF} \ln\left(1 - \frac{I_{fc}}{I_{lim}}\right) \tag{8.21}$$

This voltage drop is due to the concentration of reactants consumed during the chemical e reaction.

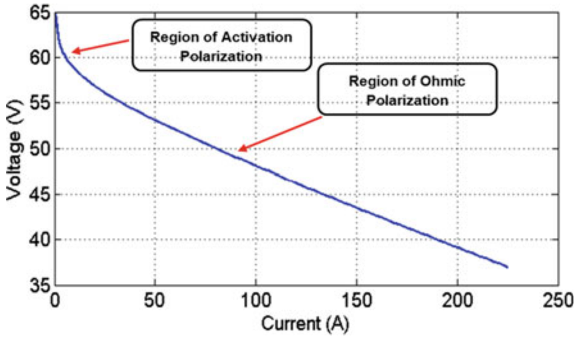

Fig. 8.8 Voltage–current (V–I) characteristic of the fuel cell

I_{lim} is the maximum current density of the cell. The practical characteristic of voltage–current (V–I) of the fuel cell type PEM 1.6 kW is presented in Fig. 8.8.

8.5.4 Characteristics of the PEM Fuel Cell

The output voltage and power of a PEMFC depend on the membrane thickness. To determine the effect of the thickness variation on the output power and the output voltage, a simulation using MATLAB/Simulink was carried out. All parameters are fixed and only, the thickness was varied from 10 to 200 mm. The results presented in (Fig. 8.9) show the variation of the output voltage versus the membrane thickness when the electrical current delivered by the PEMFC is more than 20A. Indeed, for a current equal to 30 A, the voltage decreases from 60 to 30 V when the thickness varies from 10 to 200 mm. This study shows the important effect of the membrane thickness on the output voltage. Hence, a judicious choice for this parameter will be selected depending on the required performances of the PEMFC.

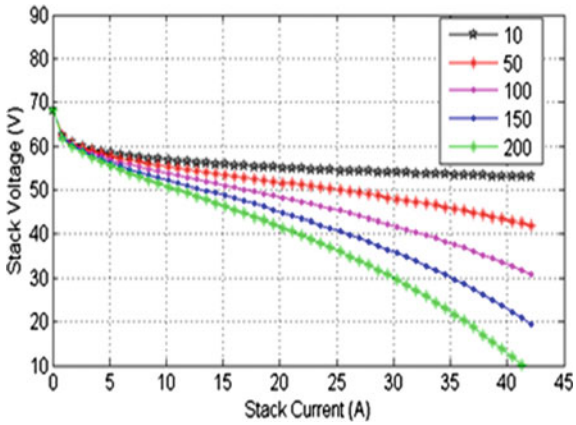

Fig. 8.9 Output voltage versus the current for different values of the membrane thickness

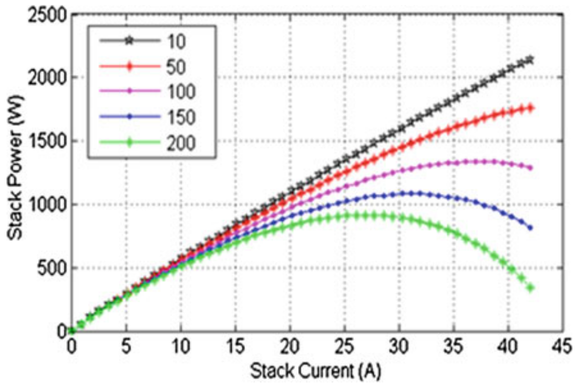

Fig. 8.10 Output power versus the current for different values of the membrane thickness

Figure (8.10) shows the variation of the output power versus the stack current for different membrane thicknesses. The presented results show a maximum output power corresponding to a minimum membrane thickness and maximum stack current.

Figure (8.11) shows the variation of the output voltage versus the hydrogen concentration for different levels of electrical current. The variation of the hydrogen does not affect considerably the output power and voltage. The voltage increases with the same rate when the current increases with the same rate for all levels of the hydrogen concentration.

The variation of the power generated by the fuel cell versus the variation of the temperature is given in Fig. 8.12. The power increases when the temperature increases, especially at high values of generated current. The power reaches a maximum value for a temperature 353 K and a current generated equal to 35A. Hence, it is better to operate at a selected temperature level and optimum current to generate optimum power from the fuel cell.

A fuel cell is an electrochemical machine used for the generation of electrical energy according to a chemical reaction between hydrogen and oxygen. The output

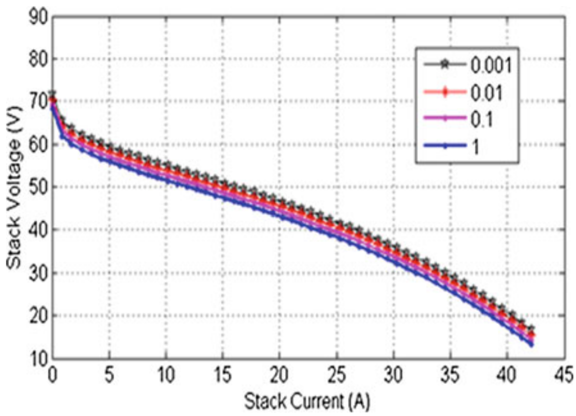

Fig. 8.11 Variation of the output voltage versus the current for different values of hydrogen concentration

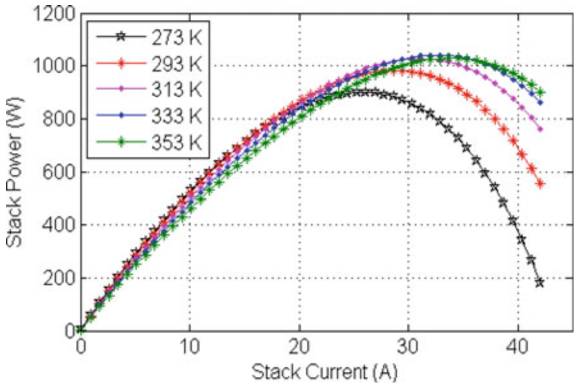

Fig. 8.12 Output power versus the current for different values of the temperature

power generated depends on the geometrical parameters and the pressure and concentration of the hydrogen and the temperature variation. Hence, the output power is variable. To maintain the power and the voltage at a given value, it is usually required to associate the fuel cell stack with a power converter to control the power flow.

8.5.5 Applications of Fuel Cell

Fuel cells were used in the beginning in space applications and then began to evolve and spread more in military circles, where they had been relying on fuel cells as a source of reserves because of their high reliability. Currently, all auto companies developed new hybrid products that use fuel cells in addition to classic engines used to run vehicles. Fuel cells began to spread in buses, trains, planes, and scooters. Fuel cells are also used in small applications such as telephones, cellular phones, and laptops. In the near future, the fuel cells will be used to feed hospitals, banks, and ATMs. The fuel cells will be installed in the waste treatment plants to convert methane gas into electricity. Multiple fuel cell applications do not end with the technical development of the areas of increased use (Barhoumi et al. 2018).

Many auto manufacturers are working to develop new hybrid or fuel cell vehicles (FCV), where fuel cells are used to provide electrical power to electrical motors used in these cars. In addition, many companies are installing commercial hydrogen stations for recharging vehicles with hydrogen gas. All vehicles that run on fuel cells, (General Motors) (Toyota) Daimler-Chrysler)), which consists of about 40% of the total investments in the field of FCV in the world, they are supporting the development of research on fuel cell and hydrogen production, in order to make the hydrogen the best eco-friendly choice. Figure (8.13) shows the main elements used in the FCV. The vehicle contains a fuel tank for the storage of hydrogen, batteries used as a buck up source of electrical energy, and power converters to control the flow of the power from the fuel cell and batteries to the electrical motor.

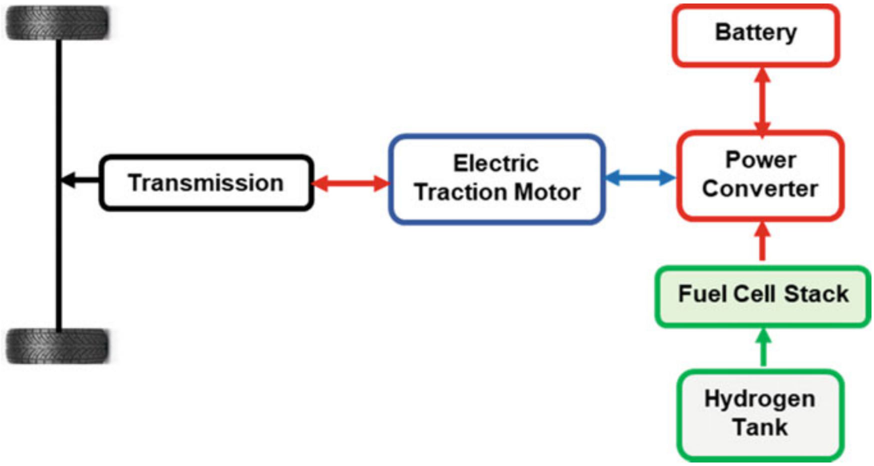

Fig. 8.13 Hydrogen fuel cell car

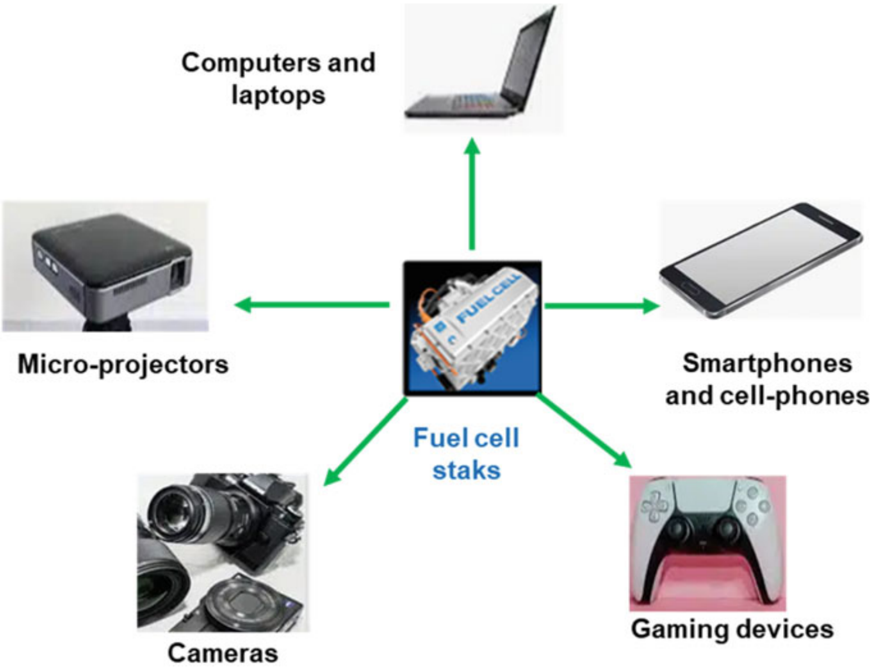

Fig. 8.14 Portable power applications of fuel cells

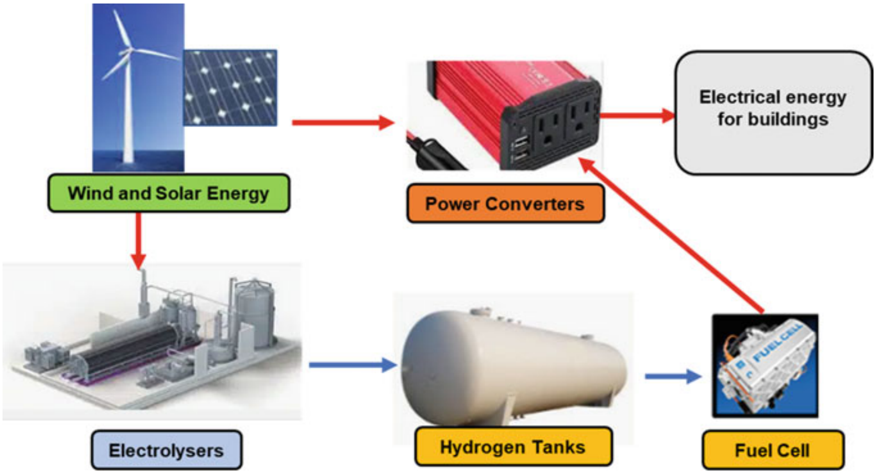

Fig. 8.15 Fixed applications of the fuel cells

Nowadays, fuel cells are used in military planes because of their low noise and compact size. One of the largest companies that developed this technique is the Boeing Company. The fuel cell can provide electrical power to the fed electric power grid in fault cases and emergency situations. Indeed, the fuel cells are more efficient than batteries working longer and lighter. Hence, they are used in a lot of industrial applications (Fig. 8.14).

More than 2500 applications of the fuel cell are developed around the world, in hospitals, hotels, offices, and schools. Fuel cell stations are connected to the public electricity grid to secure the support of the network or independent power stations in areas that are difficult to connect with the network.

Fuel cell systems operate efficiently 40%, without noise, without polluting the air. When using fuel cells in a co-generation power system where taking advantage of the thermal energy produced can increase the efficiency to 85%. Figure (8.15) shows the principle of fixed application of the fuel cell system where the fuel cell is used to produce the electricity required to run the different equipment and lighting in this building. Another advantage of this application is to convert the surplus of electrical energy produced from renewable sources into hydrogen. Hydrogen is used to produce electrical energy during cloudy days and nights.

The fuel cells are used in telecommunications applications to generate electrical energy required by the communications equipment in case of emergency, as shown in Fig. 8.16. With the increased use of computers, the Internet, and telecommunications networks emerged the need for a more reliable source of electrical power. As a source of electrical energy, fuel cells have shown high reliability.

Overall, the fuel cell consists of a reliable source of electrical power for telecommunications systems. They are silent and environmentally friendly and can be designed to be robust bear any ambient conditions. They are currently being used

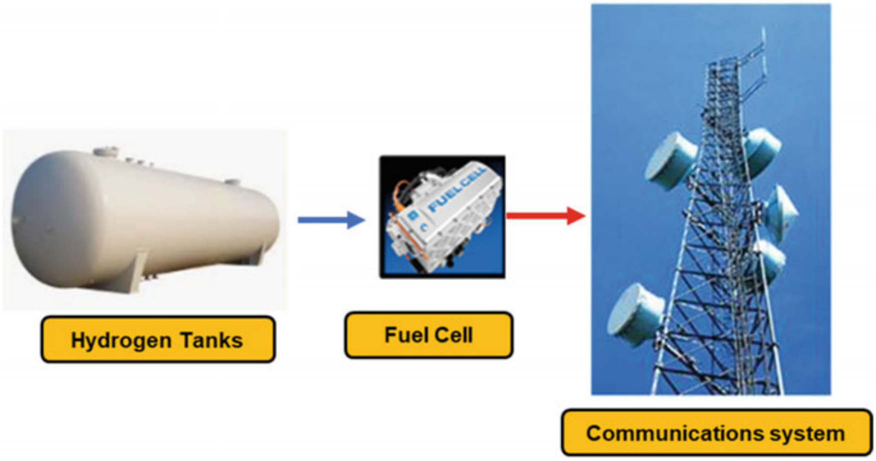

Fig. 8.16 Fuel cell application in the telecommunication system

mainly as a source of energy or support in the communication towers cell towers as the source, point of conversion telecom switch nodes.

The fuel cells are currently installed in waste and water treatment plants all over the world. This technique has proven its ability to reduce emissions where using methane gas produced from these sites as fuel. As it has been installed in several factories for the production of beer, where alcohol is passed untreated breaks organic compounds, and generates methane, which is rich in hydrogen.

8.6 Design of a Photovoltaic-Hydrogen Gas Station

8.6.1 Solar to Hydrogen

The conversion of solar energy into hydrogen energy is possible through the production of electrical energy using PV systems and the production of hydrogen by electrolysis process. The exponential growth of the price of car fuels has pushed researchers and engineers to look at cheap sources of fuels. On the other hand, the production of hydrogen from renewable energy sources leads to a decline in the cost of hydrogen production. In many countries around the world, e.g., Europe and United States of America, renewable energy has been used to produce green hydrogen. In Tunisia, the government sets a plan to produce electrical energy from renewable energy sources. In this context, the implementation of many small-scale and medium-scale PV stations is ongoing. The FCVs consist of a key solution for the transport problems by reducing the cost of fuel prices. The efficiency of such projects depends mainly on the PV potential and the cost of PV panels, MPPT converters, electrolyzers, and storage

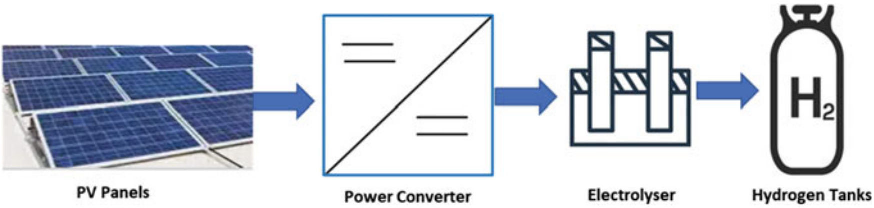

Fig. 8.17 Hydrogen production using PV system

tanks. According to the PV potential distribution in Tunisia, 4 to 5 kWh of electrical energy can be produced daily by installing only 1kWp of the PV system. Moreover, hydrogen production stations using PV systems can be implemented near the main highways for refueling FCV. The main idea is to produce green hydrogen from solar energy to feed FCVs. In the next section, the sizing of the PV system and hydrogen gas station to produce a quantity of hydrogen of 100 kg daily is discussed in detail.

8.6.2 Sizing of Hydrogen Gas Station

The sizing of different components is performed for one hydrogen gas station producing 100 kg of hydrogen daily. The hydrogen PV power station requires the PV system, the power converters, the electrolyzers, and the storage tanks. The process of hydrogen production from solar energy using PV panels is depicted in Fig. 8.17.

- The electrolyzer

A 400 kW PEM electrolyzer with a capacity of production of 5 kg of hydrogen/hour for each electrolyzer is proposed for this example. As the solar energy is approximately available only for 5 h per day, then the electrolyzer will operate only 5 h per day. Therefore, one electrolyzer produces about 25 kg of hydrogen per day. The total number of required electrolyzers is calculated as follows:

$$N_{\text{Electrolysers}} = \frac{\text{Total required hydrogen}}{\text{Daily capacity of one electrolyser}} = \frac{100}{25} = 4 \qquad (8.22)$$

Then, 4 electrolyzers are required to produce 100 kg of hydrogen per day.

With an efficiency of 50%, an electrolyzer requires 80 kWh of electrical energy to produce 1 kg of H2. So, to produce 5 kg of H2 per hour, one electrolyzer requires 400 kWh. The 4 electrolyzers consume 1600 kWh of electrical energy per hour.

- The power converter

The power converters required are DC–DC converters controlled with maximum power point tracking system (MPPT). The DC–DC converters allow to optimize the flow of the power from the PV system to the electrolyzers. The rated power of one electrolyzer is 400 kW. Considering a coefficient of 0.25 to model the losses in the DC–DC converter, then the rated power of one DC–DC converter feeding one electrolyzer is calculated using the following expression:

$$P_{DC-DCconverter} = P_{Electrolyser} \times 1.25 = 400 \times 1.25 = 500\text{kW} \quad (8.23)$$

Each electrolyzer is connected in series with one DC–DC converter. So, 4 (500 kW) DC–DC converters are required. The total input power required for the 4 electrolyzers is 2000 kW.

- The PV panels

The PV panels convert solar energy into electrical energy. Then, the PV panels represent the power source, and they should provide the required power to the load. A coefficient of 0.25 is added to the power of the DC–DC converter for modeling the cable losses, then the rated power of the PV system is calculated as follows:

$$P_{PV-system} = P_{DC-DCconverter} \times N_{DC-DCconverter} \times 1.25 = 500 \times 4 \times 1.25 = 2500\text{kW} \quad (8.24)$$

As many other equipment are required for the hydrogen gas station, like dispensers, compressors, and others, a total capacity of 2662.2 kW of the PV system is proposed to provide electrical energy to all equipment in the hydrogen station.

The technical characteristics of the selected PV panels are given in Table 8.2.

Based on the data given in Table 8.2, the number of required panels is calculated as follows:

$$N_{PV\,panels} = \frac{P_{PV-system}}{P_{Panel}} = \frac{2662,200}{435} = 6120\,\text{panels} \quad (8.25)$$

Then, 6120 panels (435 Wp each) provide the electrical power to the hydrogen gas station. The connection of PV panels is performed according to the requirements of the DC input voltage of the DC–DC converter. In case of the maximum voltage of the DC–DC converter is 1250 V, the maximum number of panels per string is calculated as follows:

Table 8.2 Technical characteristics of PV panels (Canadian_Solar-Datasheet 2021)

Technical characteristics	Specifications
Rated power	435 W
Open circuit voltage	48.6 V
Short circuit current	11.35 A
MPP voltage	40.1 V
MPP current	10.85 A

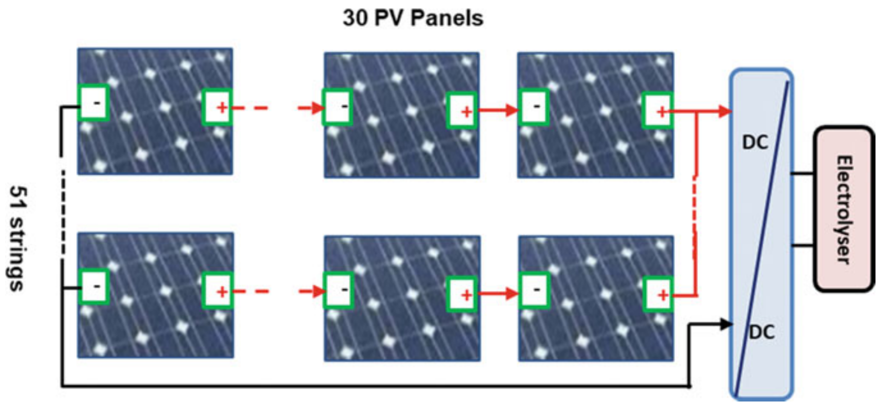

Fig. 8.18 Connection of PV panels to the DC–DC converter

$$N_{\text{PV panels per string}} = \frac{\text{Maximum Voltage of DC} - \text{DC converter}}{\text{Mpp Voltage of PV panel}} = \frac{1250}{40.1} = 31.17\ \text{panels} \tag{8.26}$$

Then, the proposed number of panels connected in series to form one string is 30 panels.

The number of strings connected to each converter depends on the maximum input current of the converter. The maximum input current of the DC–DC converter is 600 A, then, the maximum number of strings is given by Eq. (8.27).

$$N_{\text{strings per converter}} = \frac{\text{Max input current of the converter}}{\text{Mpp current of PV panel}} = \frac{600}{10.85} = 55.29\ \text{strings} \tag{8.27}$$

According to Eq. (8.27), 55 strings are the maximum number of strings that can be connected to each power converter.

The total number of PV panels is distributed between the four converters. Then, 1530 panels are connected to each converter. So, for each converter, the PV panels will be distributed into 51 strings connected in parallel, each string is formed by 30 PV panels connected in series. The connection of PV strings to DC–DC converters and electrolyzers is clarified in Fig. 8.18. The hydrogen station formed by 4 electrolyzers, 4 DC–DC converters, and PV systems is given in Fig. 8.19.

8.7 Conclusion

This chapter has discussed the life cycle of hydrogen. Indeed, the electricity generated from renewable energy sources is converted into hydrogen through the electrolysis

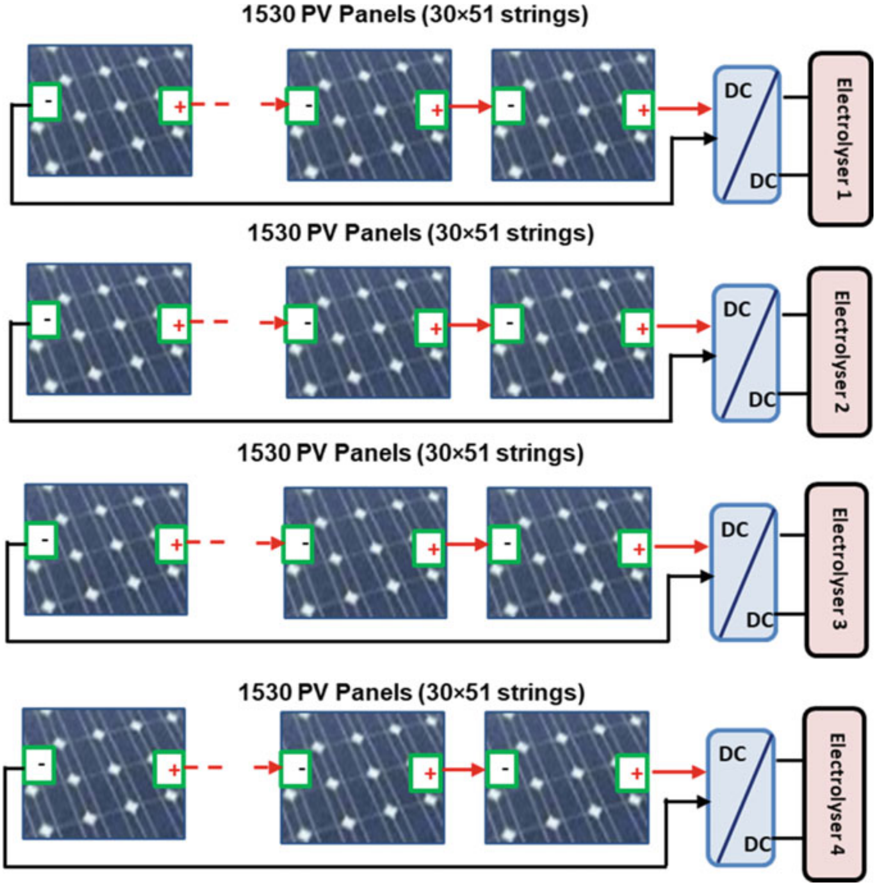

Fig. 8.19 Connection of all PV panels to the DC–DC converters and electrolyzers

process. The hydrogen is converted into electrical energy using PEMFC. The main electrolyzers used to produce hydrogen are the PEM, the solid oxide, and the alkaline electrolyzers. Among these three electrolyzers, the alkaline electrolyzer has the highest efficiency.

The hydrogen produced from renewable energy sources represents an effective solution for the storage of the surplus of electrical energy produced from renewable energy sources. Indeed, the hydrogen is converted into electrical energy using fuels cells. The applications of hydrogen are continuously increasing to cover a wide range of industrial applications, mobile applications, and transportation sectors.

The principle of operation, the characteristics of the PEMFC were presented and analyzed in this chapter. The PEMFC power and output voltage depend on different parameters, especially the operation temperature, the hydrogen concentration, and the membrane thickness.

To shed the light on the principle of sizing of the PV systems for hydrogen production, the design of a hydrogen gas station was presented and discussed in this chapter. The obtained results showed that a standalone PV system with a total capacity of 2662.2 Wp is required to provide electricity to the hydrogen station. The PV system produces about 13.311 MWh of electrical energy per day. The quantity of hydrogen produced per day is 50 kg.

References

Abdin Z, Webb CJ, MacA E, Gray (2015) Modelling and simulation of a proton exchange membrane (PEM) electrolyser cell. Int J Hydrog Energy 40(39):13243–13257, Oct. https://doi.org/10.1016/j.ijhydene.2015.07.129

Abdin Z, Mérida W (2019) Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: a techno-economic analysis. Energy Convers Manag 196:1068–1079, Sep. https://doi.org/10.1016/j.enconman.2019.06.068

Albadi MH, Al-Hinai AS, Maharbi MJA, Hosni AMA, Hajri MAA (2019) Economic dispatch of Oman's main interconnected system in presence of 500MW solar PV plant in Ibri. In: 2019 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT), Apr., pp. 204–208. https://doi.org/10.1109/JEEIT.2019.8717418.

Balta MT, Dincer I, Hepbasli A (May 2010) Potential methods for geothermal-based hydrogen production. Int J Hydrog Energy 35(10):4949–4961. https://doi.org/10.1016/j.ijhydene.2009.09.040

Barbir F (2005) PEM electrolysis for production of hydrogen from renewable energy sources. Sol Energy 78(5):661–669, May. https://doi.org/10.1016/j.solener.2004.09.003

Barhoumi E, Ben Belgacem I, Khiareddine A, Zghaibeh M, Tlili I (2018) A neural network-based four phases interleaved boost converter for fuel cell system applications. Energies 11(12):3423, Dec. https://doi.org/10.3390/en11123423

Barhoumi EM et al (2019) Renewable energy resources and workforce case study Saudi Arabia: review and recommendations. J Therm Anal Calorim, Dec. https://doi.org/10.1007/s10973-019-09189-2

Barhoumi EM, Chukwuleke Okonkwo P, Belgacem IB, Zghaibeh M (2020) MPPT control of an interleaved boost converter for a polymer electrolyte membrane fuel cell applications. In: 2020 International Conference on Electrical and Information Technologies (ICEIT), Mar, pp. 1–5. https://doi.org/10.1109/ICEIT48248.2020.9113228

Barhoumi EM, Farhani S, Okonkwo PC, Zghaibeh M, Bacha F (2021) Techno-economic sizing of renewable energy power system case study Dhofar Region-Oman. Int J Green Energy 1–10, Feb. https://doi.org/10.1080/15435075.2021.1881899

Boran FE, Boran K, Menlik T (2012) The evaluation of renewable energy technologies for electricity generation in Turkey using intuitionistic fuzzy TOPSIS. Energy Sources Part B Econ. Plan Policy 7(1):81–90, Jan. https://doi.org/10.1080/15567240903047483

Boulmrharj S, Khaidar M, Bakhouya M, Ouladsine R, Siniti M, Zine-dine K (2020) Performance assessment of a hybrid system with hydrogen storage and fuel cell for cogeneration in buildings. Sustainability 12(12):4832, Jun. https://doi.org/10.3390/su12124832

Canadian_Solar-Datasheet-BiHiKu_CS3W-PB-AG_High-Efficiency_1000V1500V_EN-2.pdf (2021) Accessed 21 Apr, 2021. https://www.canadiansolar.com/wp-content/uploads/2019/12/Canadian_Solar-Datasheet-BiHiKu_CS3W-PB-AG_High-Efficiency_1000V1500V_EN-2.pdf

Chi J, Yu H (2018) Water electrolysis based on renewable energy for hydrogen production. Chin J Catal 39(3):390–394, Mar. https://doi.org/10.1016/S1872-2067(17)62949-8

Christensen, A (2020) Assessment of hydrogen production costs from electrolysis: United States and Europe, p. 73

David M, Ocampo-Martínez C, Sánchez-Peña R (2019) Advances in alkaline water electrolyzers: a review. J. Energy Storage 23:392–403, Jun. https://doi.org/10.1016/j.est.2019.03.001

Duggal I, Venkatesh B (2015) Short-term scheduling of thermal generators and battery storage with depth of discharge-based cost model. IEEE Trans Power Syst 30(4):2110–2118, Jul. https://doi.org/10.1109/TPWRS.2014.2352333

Edwards RL, Font-Palma C, Howe J (2021) The status of hydrogen technologies in the UK: a multi-disciplinary review. Sustain. Energy Technol. Assess. 43, Feb. https://doi.org/10.1016/j.seta.2020.100901

El Ouderni AR, Maatallah T, El Alimi S, Ben Nassrallah S (2013) Experimental assessment of the solar energy potential in the gulf of Tunis, Tunisia. Renew. Sustain. Energy Rev., vol. 20, pp. 155–168, Apr. https://doi.org/10.1016/j.rser.2012.11.016

Givler T, Lilienthal P (2005) Using HOMER software, NREL's micropower optimization model, to explore the role of gen-sets in small solar power systems; case study: Sri Lanka. National Renewable Energy Lab., Golden, CO (US), NREL/TP-710–36774, May. https://doi.org/10.2172/15016073

Gondal IA, Masood SA, Khan R (2018) Green hydrogen production potential for developing a hydrogen economy in Pakistan. Int J Hydrog Energy 43(12):6011–6039, Mar. https://doi.org/10.1016/j.ijhydene.2018.01.113

Hammad M, Ebaid MSY (2015) Comparative economic viability and environmental impact of PV, diesel and grid systems for large underground water pumping application (55 wells) in Jordan. Renew. Wind Water Sol. 2(1):12, Jul. https://doi.org/10.1186/s40807-015-0012-2

HassanzadehFard H, Tooryan F, Collins ER, Jin S, Ramezani B (2020) Design and optimum energy management of a hybrid renewable energy system based on efficient various hydrogen production. Int J Hydrog Energy 45(55):30113–30128, Nov. https://doi.org/10.1016/j.ijhydene.2020.08.040

Marano V, Rizzo G, Tiano FA (2012) Application of dynamic programming to the optimal management of a hybrid power plant with wind turbines, photovoltaic panels and compressed air energy storage. Appl Energy 97:849–859, Sep. https://doi.org/10.1016/j.apenergy.2011.12.086

Ni M, Leung MKH, Leung DYC (2008) Technological development of hydrogen production by solid oxide electrolyzer cell (SOEC). Int J Hydrog Energy 33(9):2337–2354, May. https://doi.org/10.1016/j.ijhydene.2008.02.048

Nieminen J, Dincer I, Naterer G (2010) Comparative performance analysis of PEM and solid oxide steam electrolysers. Int J Hydrog Energy 35(20):10842–10850, Oct. https://doi.org/10.1016/j.ijhydene.2010.06.005

Nikolaidis P, Poullikkas A (2017) A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 67:597–611, Jan. https://doi.org/10.1016/j.rser.2016.09.044

Okonkwo PC et al. (2021) Platinum degradation mechanisms in proton exchange membrane fuel cell (PEMFC) system: a review. Int J Hydrog Energy 46(29):15850–15865, Apr. https://doi.org/10.1016/j.ijhydene.2021.02.078

Razmjoo A, Gakenia Kaigutha L, Vaziri Rad MA, Marzband M, Davarpanah A, Denai M (2021) A technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO2 emissions in a high potential area. Renew. Energy, vol. 164, pp. 46–57, Feb. https://doi.org/10.1016/j.renene.2020.09.042

Schnuelle C, Wassermann T, Fuhrlaender D, Zondervan E (2020) Dynamic hydrogen production from PV & wind direct electricity supply – Modeling and techno-economic assessment. Int J Hydrog Energy 45(55):29938–29952, Nov. https://doi.org/10.1016/j.ijhydene.2020.08.044

Shaner MR, Atwater HA, Lewis NS, McFarland EW (2016) A comparative technoeconomic analysis of renewable hydrogen production using solar energy. Energy Environ Sci 9(7):2354–2371. https://doi.org/10.1039/C5EE02573G

Shiva Kumar S, Himabindu V (2019) Hydrogen production by PEM water electrolysis–a review. Mater. Sci. Energy Technol, vol. 2, no. 3, pp. 442–454, Dec. https://doi.org/10.1016/j.mset.2019.03.002.

Wang L et al. (2019) Power-to-fuels via solid-oxide electrolyzer: operating window and techno-economics. Renew Sustain Energy Rev 110:174–187. https://doi.org/10.1016/j.rser.2019.04.071

Wind-to-Hydrogen Project (2021) https://www.nrel.gov/hydrogen/wind-to-hydrogen.html, 20 Apr 2021

Xiao P, Hu W, Xu X, Liu W, Huang Q, Chen Z (2020) Optimal operation of a wind-electrolytic hydrogen storage system in the electricity/hydrogen markets. Int J Hydrog Energy 45(46):24412–24423, Sep. https://doi.org/10.1016/j.ijhydene.2020.06.302

Yan Z, Hitt JL, Turner JA, Mallouk TE (2020) Renewable electricity storage using electrolysis, p. 6

Yoo S-H, Lee J-S (2010) Electricity consumption and economic growth: a cross-country analysis. Energy Policy 38(1):622–625, Jan. https://doi.org/10.1016/j.enpol.2009.05.076