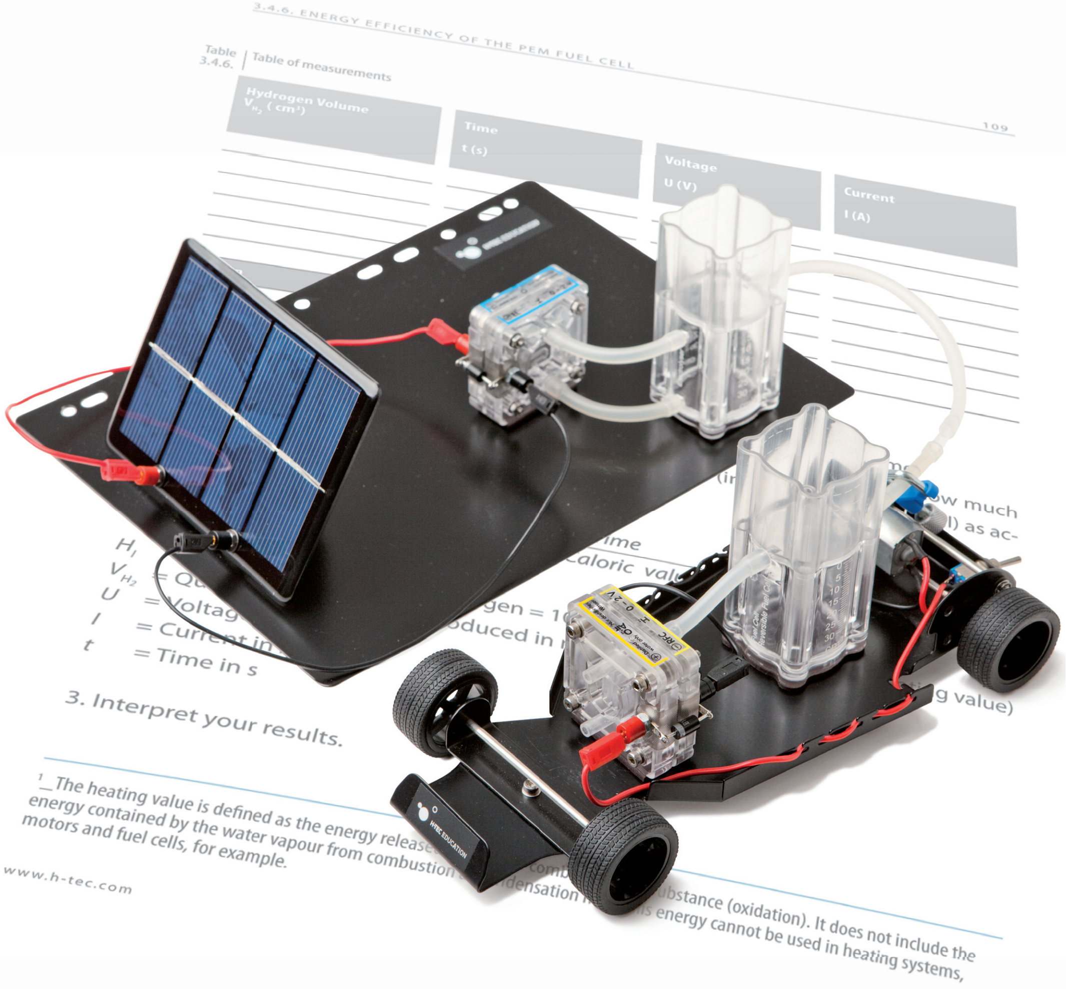
H-TEC EDUCATION

Cornelia Voigt | Stefan Hoeller | Uwe Kueter

Fuel Cell Technology for Classroom Instruction

BASIC PRINCIPLES | EXPERIMENTS | WORK SHEETS



3.4.6. ENERGY EFFICIENCY OF THE PEM FUEL CELL

109

Table 3.4.6. | Table of measurements

Hydrogen Volume V_{H_2} (cm³)	Time t (s)	Voltage U (V)	Current I (A)

H_i

V_{H_2} = Qu

U = Voltag

I = Current in

t = Time in s

3. Interpret your results.

---

[1] The heating value is defined as the energy release … substance (oxidation). It does not include the energy contained by the water vapour from combustion … condensation … is energy cannot be used in heating systems, motors and fuel cells, for example.

www.h-tec.com

Fuel Cell Technology for Classroom Instruction

Basic Principles, Experiments, Work Sheets

Cornelia Voigt, Stefan Hoeller, Uwe Kueter

Fuel Cell Technology for Classroom Instruction

Basic Principles, Experiments, Work Sheets

Cornelia Voigt, Stefan Hoeller, Uwe Kueter

With reference tables and illustrations

Please also visit the following website: **www.h-tec-education.com**

Book composition: Dipl.-Des. Andreas Wolter, Weimar, Germany

Paper was produced without using acid, wood and chlorine bleaching; non-ageing according to
ISO 9706.

PREFACE

The world is watching emerging changes in the energy infrastructure of which the advent of the Fuel Cell is of central importance. Fuel cells convert a fuel, mostly consisting of hydrogen or hydrogen containing compounds, into electric energy and heat. Due to its unique characteristics, the fuel cell has the potential to change the energy utilisation of mankind. This change will move us from an era characterised by the Carnot cycle stemming back from the steam engines, to a new and more efficient "free energy" era where electrons and protons play a direct role. Primary energy resources are of many kinds. The present challenge to humankind has to do with the primary energy sources. Fossil sources create greenhouse gas emissions. If proper and efficient solutions to carbon sequestration are not found, renewable energies will become even more important. One of the most obvious artificial fuel candidates for a renewable energy economy is of the element of hydrogen, the lightest and most common element in the universe. There is a continuing need for training a new generation of students and the public in the area of hydrogen.

This book "Fuel Cell Technology for Classroom Instruction" provides an insight into the nature and technology of fuel cells. The book is based on a simple educational philosophy of "learning-by-doing". It is based on a pioneering work of a company specialising in hydrogen education. The experiments range from for example solar production of hydrogen by electrolysis, to the utilisation of hydrogen in fuel cells for electric energy production. The reader is expected to work with real laboratory apparatus and is led through the fascinating world of this new technology in a lucid and entertaining way. The book can be used in conjunction with physics, chemistry or environmental sciences at a wide range of levels. Experiments are clearly devised and graphically illustrated.

The book should provide a valuable contribution to an emerging future technology and I wish the reader success in the exploratory journey ahead!

Professor Thorsteinn I. Sigfusson
CoChair of the IPHE ILC International Partnership for the Hydrogen Economy

CONTENTS

PART 0 INTRODUCTION

PART 1 BASIC PRINCIPLES OF FUEL CELL TECHNOLOGY

PART 2 SOLUTIONS TO EXPERIMENTS

PART 3 WORK SHEETS AND STUDENT EXPERIMENTS

0

Introduction

0.1. INSTRUCTIONS ON HOW TO USE THIS BOOK

The book consists of three parts:

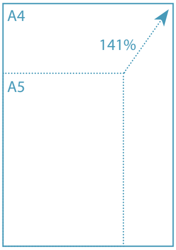
The **first part** of the book describes the basic principles of fuel cell technology.

Experiments on solar cells, electrolysis and fuel cells are described in the **second part**. Examples of the values and results have been provided to illustrate the experiments. The calculations have been performed using example values to ensure everything is easy to understand.

The **third part** consists of a large number of ***work sheets***.
3.1. The handouts summarize the most important objectives for each respective topic.
3.2. The teacher work sheets consist of useful questions with the corresponding answers.
3.3. The student work sheets reiterate the questions contained in the teacher work sheets. The answers are not provided. These work sheets can be simply copied and handed out for quizzes.
3.4. The experiment work sheets for the basic level are working instructions on how to perform experiments. They contain instructions on the necessary experiment material, setup, procedure and questions for analysis. The experimental work sheets closely follow the experiments contained in Part 2.
3.5. The experiment work sheets for the advanced level are arranged similarly to those in section 3.4; however, the experiments are somewhat more complex.

All handouts and teaching aids can be used as work sheets by copying or downloading them from the Internet at www.h-tec-education.com.

Please let us know what you think. If you have any comments or suggestions, please send us an e-mail to: *info@h-tec-education*



0.2. RENEWABLE ENERGIES

Renewable energies are energy sources that are continuously being replenished by natural processes that occur on human timescales. In contrast, fossil fuels (coal, natural gas, oil) are formed over millions of years of geological processes. Therefore, our resources of fossil fuels are limited, and nuclear fuels (e.g. uranium) also have a finite supply. Renewable energies, on the other hand, are virtually inexhaustible.

Examples of renewable energy sources include:

SOLAR ENERGY (hydrogen fusion in the Sun)

Solar energy surrounds us in different forms and can be used in a variety of ways, including:

Fig. 1 | Solar energy

- Solar radiation: photovoltaics, solar heat
- Atmospheric movement: wind energy
- Evaporation/precipitation: hydroelectric energy/ water power
- Biomass: e.g., fiber fuel, biogas

Today's most widespread applications for using renewable energies are solar panels, wind power plants and hydroelectric power plants - all of which derive their energy in some way from the sun.

TIDAL ENERGY (gravitational attraction of Sun, Earth and Moon)

Tidal power plants use the energy provided by high and low tides. Water is stored during high tide and released during low tide, powering turbines in the process.

GEOTHERMAL ENERGY (radioactivity and primordial heat in Earth's interior)

Geothermal power plants use heat released from the interior through the Earth's crust. This heat can be used directly or converted to electricity.

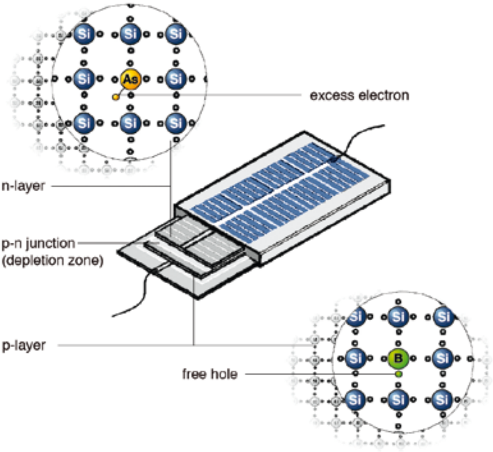
0.2.1. SOLAR ENERGY

***Photovoltaic* systems convert sunlight directly into electrical energy.**

The backbone of this technology is *semiconducting* materials such as silicon.

A typical solar cell consists of two differently doped semiconductors. *Doping* is the controlled introduction of impurities into the host material. Starting out with a pure semiconductor crystal (say, silicon) this is achieved by substituting some of the atoms in the crystal lattice with elements that have one more or one less *valence electron* than the host material (Valence electrons are the electrons that determine the chemical behavior of a material, they are located in the outermost orbital shell of the atom).

Fig. 2 | Basic principle of a solar cell



Semiconducting elements have four valence electrons, all of which are used for bonding in the crystal lattice. If the doping material has five valence electrons there will be one additional, loosely bound electron per dopant atom. These "free" atoms can move about easily in the lattice and are responsible for an increase in conductivity. Since they have a negative charge the material doped in this way is called an *n-type* semiconductor. If, on the other hand, the doping material has only three valence electrons, the lattice structure will be deficient of electrons and there will be one hole, or positive charge, per dopant atom. These ‚holes' are the inverse of the free electrons in the n-layer; they can easily move about in the lattice, again causing an increase in conductivity. Since in this case the free charge carriers are positive this kind of semiconductor is said to be of *p-type*.

When a p-type semiconductor is joined to an n-type semiconductor, a *p-n junction* is created. While each side by itself is electrically neutral (there are as many electrons as there are protons) this is not the case for certain areas of the combined configuration. The different concentrations of holes and free electrons between the n- and p-regions produce a diffusion current: electrons flow from the n-side and fill holes on the p-side. This creates a region that is almost devoid of free charge carriers (i.e. free electrons or holes) and is therefore called the *depletion zone*. In the depletion zone there is a net positive charge on the n-side and a net negative charge on the p-side, resulting in an electric field that opposes a further flow of electrons. The more electrons move from the n- to the p-side the stronger the opposing field will be and eventually an equilibrium will be reached in which no further electrons are able to move against the electric field. The potential difference of the equilibrium electric field is called the *diffusion voltage*. It cannot be used externally. However, when light hits the solar cell the equilibrium conditions are disturbed and the so-called *inner photo effect* creates additional charge carriers that are free to move in the electric field of the depletion zone. Holes move towards the p-region and electrons towards the n-region, creating an external voltage (no-load voltage) at the cell. The no-load voltage of a solar cell is material dependent and does not depend on the cell‘s surface area. A silicon solar cell has a no-load voltage of about 0.5V. Higher voltages can be obtained by connecting individual cells in series.

The current delivered by a solar cell is proportional to the intensity of the incoming light. Higher currents can be achieved by connecting cells in parallel.

The power of a solar cell depends not only on the cell itself but also on the connected electrical load. The maximum power point (MPP) can easily be determined from the power-voltage characteristic of the cell.

The efficiency of a solar cell is temperature dependent. It will decrease with increasing temperature.

The most common semiconductor material used in solar cells is silicon. A number of different degrees of lattice alignment are in use:

1 - monocrystalline silicon (cell efficiency of approx. 17 – 20 %)
2 - polycrystalline silicon (cell efficiency of approx. 14 – 16 %)
3 - amorphic silicon (cell efficiency of approx. 5 - 7 %)

0.2.2. WIND ENERGY

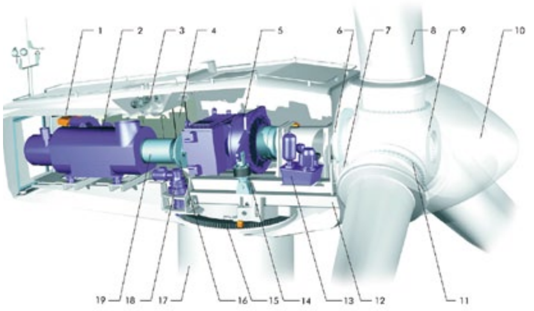
Wind energy has been used for centuries. Windmills once converted wind energy into mechanical energy which was used to perform tasks such as crushing grain to make flour. Today wind power plants harness wind energy to generate electricity.

The most important components of a wind power system are (Figure 3):

Foundation	ensures that the system has sufficient anchoring.
Mast	typically made of steel or concrete, at present between 10 and120 m high; even higher ones are planned in the future.
Gondola	provides the framework for generator, transmission and other components.
Rotor	converts wind energy with one or more rotor blades into rotational mechanical energy. The rotor shaft connects rotor and transmission.
Transmission/gear	translates the rotor‘s low rotation rate into the higher rotation rate required to operate the generator. Some wind energy systems no longer require a transmission between rotor and generator.
Generator	converts mechanical into electrical energy

Commercial wind power plants have total efficiencies of between 35 % and 43 %. The greatest energy loss occurs at the rotor (aerodynamic loss) which transfers only about 45 - 50 % of the wind energy into mechanical energy. Losses associated with the transmission (frictional) and generator (electrical) are 2.5 % and ~ 5 %, respectively.

Fig. 3 | Diagram of a typical wind power plant



WIND POWER PLANT

1. Service crane
2. Generator
3. Cooling system
4. Top controller
5. Gearbox
6. Main shaft
7. Rotor lock system
8. Blade
9. Blade hub
10. Spinner
11. Blade bearing
12. machine foundation
13. Hydraulic unit
14. Gear torque arm
15. Yaw ring
16. Brake
17. Tower
18. Yaw gear
19. Composite disc coupling

0.2.3. WATER POWER

Hydroelectric power plants convert the kinetic energy of moving water into electrical energy. A typical scenario is a hydroelectric power plant installed in combination with a river dam. The dam raises the water level in the reservoir and ensures a steady supply of water.

As water from the reservoir is allowed to fall through pipes, its potential energy is converted into kinetic energy which in turn is used to power a turbine. In other words, the turbine converts the kinetic energy into mechanical energy. A generator finally converts the mechanical into electrical energy.
Hydroelectric power plants reach efficiencies of up to 80 - 90 %.

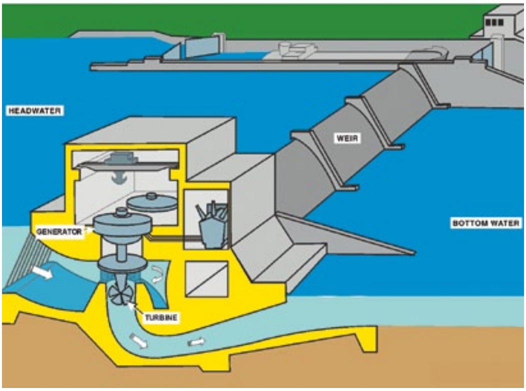
The power *P* of the system is given by:

$$P = \dot{V} \cdot h \cdot g \cdot \rho \cdot \eta$$

$\dot{V}$ = water flux
h = height of fall
g = gravitational acceleration
ρ = density of water
η = total efficiency of the system

The two main types of hydroelectric plants are run-of-river and storage plants.

Fig. 4 | Run-of-river power plant



Run-of-river power plants (Figure 4) are used in rivers with small height of fall and large flux. They operate continuously and are therefore suitable as base load power stations.

In storage power plants water is stored in natural or artificial reservoirs. This allows the plant operator to control flow irregularities as well as to adjust the electricity production to meet energy demand.

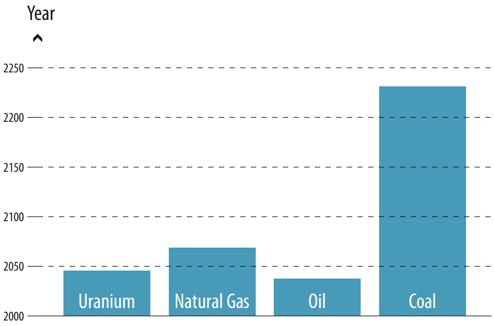
Water can be released from the reservoir during peak times when energy demands are highest. Storage power stations are therefore particularly suitable as peak load power stations.

Pump storage power stations are a special type of storage power stations. During times of low electricity demand (for example, at night) excess electricity from a base load power stations is used to pump water into a reservoir. During peak times the water is released again and used to generate electricity. Pump storage power plants have efficiencies of up to 75 %.

0.3. THE SOLAR-HYDROGEN ENERGY CYCLE

Diminishing resources, severe environmental pollution and an ever-increasing demand for energy are forcing us to reconsider the structure of our energy supply system.

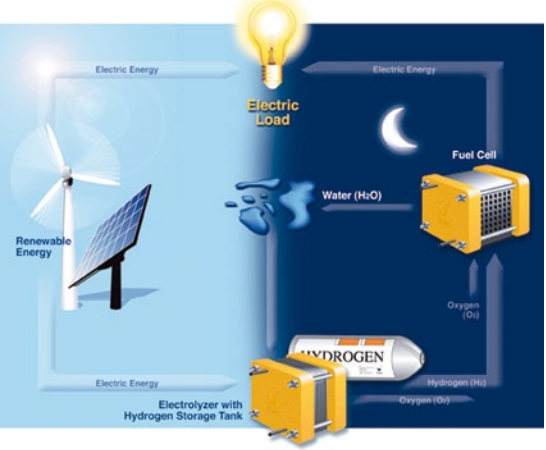
Fig. 5 | Projected availability of fossil and nuclear fuels (based on today's rate of consumption).



The necessary changes in our energy supply system can be accomplished if we are able to establish renewable energies like solar, wind and hydroelectric energy as a fundamental part of the energy market.

However, one issue we are faced with when we use solar panels or wind power plants to produce electricity is that energy supply and demand often do not coincide. For example, a solar panel will provide electricity during the day, but we might want to use electricity to power a light in the evening. Or, we might want to use wind-generated electricity in a place far away from the power plant. Hence, when supply and demand do not coincide we need a convenient way to both store and transport renewable energy. This is where hydrogen comes into play as a storage and transport medium. When excess electric energy from renewable sources is stored in hydrogen and then converted back to electricity, this is called the *solar-hydrogen energy cycle*. The key technologies are renewable energy sources, fuel cells, and electrolysers, which use excess electricity to split water into oxygen and hydrogen (bottom path in Figure 6). The hydrogen (and potentially the oxygen) can be stored and transported as necessary. Then when we need electricity the gas(es) are fed into a fuel cell which converts the chemical energy of the hydrogen (and oxygen) into electricity, water and heat. In this way our energy demands can be met anywhere and anytime.

Fig. 6 | The Solar-Hydrogen Energy Cycle



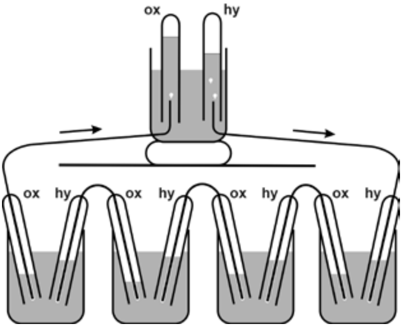
1

Basic Principles of Fuel Cell Technology

1.1. A BRIEF HISTORY OF FUEL CELL TECHNOLOGY

The fuel cell was invented more than 165 years ago. In 1839 Sir William Robert Grove (1811 - 1896) and Christian Friedrich Schoenbein (1799 - 1868) discovered that the electrolysis process can be reversed.

Fig. 7 | Fuel Cell of Sir William Robert Grove



In the electrolysis of water, electricity is used to produce hydrogen and oxygen. In a fuel cell the reverse reaction occurs: hydrogen and oxygen react to form water and electricity is produced.

Grove developed his first fuel cell in 1839. The diagram in Figure 7 shows a model built in 1842 consisting of four elements that are connected in series. Each of the four containers is filled with diluted sulfuric acid and has two glass tubes with platinum electrodes on the inside. In the top portion of the glass tubes hydrogen surrounds the anodes and oxygen surrounds the cathodes. The electricity generated can be used externally: in the diagram it is used to operate an electrolyser.

Difficulties with materials, the invention of the combustion engine and electric motor and a seemingly inexhaustible abundance of fossil fuels are among the reasons why for over a century fuel cell technology remained insignificant as a means to generate electricity. It was only in the 1960s that it was rediscovered for use in space exploration, where it was needed to provide reliable, combustion-free energy. The basic research done in this period was the crucial impulse for the development of modern fuel cell technology.

1.2. TYPES OF FUEL CELLS

A fuel cell essentially consists of two electrodes (cathode and anode) separated by an electrolyte. Usually the type of electrolyte is used to distinguish between different types of fuel cells. However, additional characteristics such as operating temperature, efficiency and application can vary significantly between different fuel cell types.

Tab. 1 | Types of Fuel Cells

Fuel Cell	**Electrolyte**	**Operating Temperature**	**Electrical Efficiency**	**Fuel** ***Oxydant***
Alcaline Fuel Cell = AFC	Potassium hydroxide (KOH) solution	Room temperature to 90 °C	60 - 70 %	H_2 *O_2*
Proton Exchange Membrane Fuel Cell = PEMFC	Proton exchange membrane	Room temperature to 80 °C	40 - 60 %	H_2,Hydrocarbons e.g. natural gas *O_2, Air*
High Temperature Proton Exchange Membrane Fuel Cell = HT-PEMFC	Proton exchange membrane	130 - 200 °C	40 - 60 %	Hydrocarbons, H_2 *O_2, Air*
Direct-Methanol-Fuel Cell = DMFC	Proton exchange membrane	Room temperature to 200 °C	20 - 30 %	CH_3OH *O_2, Air*
Phosphoric Acid Fuel Cell = PAFC	Phosphoric acid	160 - 220 °C	55 %	Hydrocarbons, H_2 *O_2, Air*
Molten Carbonate Fuel Cell = MCFC	Molten mixture of alkali metal carbonates	620 - 660 °C	65 %	Hydrocarbons, H_2 *O_2, Air*
Solix Oxide Fuel Cell = SOFC	Oxid ion conducting ceramic	800 - 1000 °C	60 - 65 %	Hydrocarbons, H_2 *O_2, Air*

ALKALINE FUEL CELL [AFC]

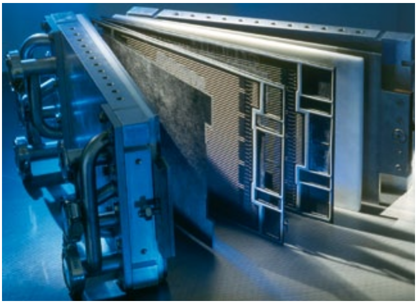
The electrolyte in an Alkaline Fuel Cell is caustic potash solution (KOH). Operating temperatures range from room temperature to 90° C (but can be higher depending on electrolyte concentration). AFCs are highly efficient and make use of inexpensive catalysts. The major challenge with AFCs is their incompatibility with carbon dioxide. CO_2 reacts with the electrolyte and forms an insoluble carbonate. This means that AFCs can only be operated with fuels that are extremely pure (highly pure hydrogen and oxygen), but not with air (which contains CO_2).

Applications: military, space travel

Anode reaction: $2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$
Cathode reaction: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

POLYMER ELECTROLYTE MEMBRANE FUEL CELL [PEMFC]

Fig. 8 | PEM Fuel Cell Stack (General Motors)



Depending on the electrolytes used, the PEM fuel cell (see section 1.2.1) operates in the temperature range between 60 and 80° C (low-temperature PEMFC) or between 130 and 200°C (high-temperature PEMFC).

A proton-conducting membrane is used as an electrolyte.

The advantages include an excellent cold start behavior and high efficiency.

In addition, the individual cells can be easily connected to a larger stack (the so-called fuel cell stack) to achieve higher outputs. The cathode is supplied with oxygen (e.g. from the air), and the anode is supplied with hydrogen. If the hydrogen is supplied by reforming coal-derived fuel, it must be ensured that the carbon monoxide (CO) does not enter the cell, since this would present a strong catalyst poison for the low-temperature PEMFC. The high-temperature PEMFC is not sensitive to carbon monoxide. Furthermore, this prevents the membrane from becoming wet. In contrast to the low-temperature PEMFC, a water management system is not required.

Regardless of the temperature range, the very expensive catalyst material (platinum) is a disadvantage of the PEM fuel cell.

Applications: electrical power systems, e.g. for automobiles, space travel, portable power supplies, battery replacement, residential power generation systems (combined heat and power generation).

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

DIRECT METHANOL FUEL CELL [DMFC]

The Direct Methanol Fuel Cell is a special PEMFC. Both fuel cells have similar structures, however, the DMFC uses methanol (CH_3OH) as fuel, rather than hydrogen. This has the advantage that methanol can be used as a liquid. On the other hand, methanol is poisonous and corrosive and DMFCs have low efficiencies.

Applications: electrical power systems, portable electricity supplies, battery replacement

Anode reaction: $2CH_3OH + 2H_2O \rightarrow 2CO_2 + 12H^+ + 12e^-$
Cathode reaction: $3O_2 + 12H^+ + 12e^- \rightarrow 6H_2O$
Total reaction: $2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O$

PHOSPORIC ACID FUEL CELL [PAFC]

The electrolyte in a PAFC is phosphoric acid. Operating temperatures range between 160 - 220° C. Compared to other types of fuel cells (except DMFCs), PAFCs have low efficiencies.

Applications: stationary electricity supplies, block-type thermal power stations (electricity-heat coupling)

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

MOLTEN CARBONATE FUEL CELL [MCFC]

Fig. 9 | HotModule (MTU Fiedrichshafen)

The electrolyte in an MCFC is a molten alkali carbonate that is retained in a ceramic matrix 01 lithium aluminum oxide. MCFCs have high operating temperatures (600 - 700° C) and high efficiencies. They can be operated not only with hydrogen but also with other gases including natural gas and biogas.

Applications: block-type thermal power stations (electricity-heat coupling). utility power plants

Anode reaction: $2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$
Cathode reaction: $O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

SOLID OXIDE FUEL CELL [SOFC]

Fig. 10 | SOFC (Siemens AG)

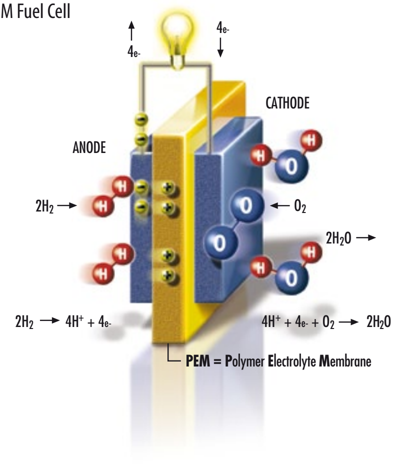
The electrolyte in this fuel cell is a solid metal oxide, usually yttrium-stabilized zirconium oxide ($Zr0_2$). SOFCs are high-temperature fuel cells. They can be operated with hydrogen but also other gases including natural gas and biogas.

Applications: block-type thermal power stations (electricity-heat coupling), utility power plants and also home electricity generation

Anode reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$
Cathode reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

1.2.1. PEM FUEL CELLS

Fig. 11 PEM Fuel Cell



The PEM fuel cell converts chemical energy into electrical energy efficiently, with low noise, and no harmful emissions. The electrolyte is a thin proton-conducting polymer membrane. The membrane is coated with catalyst material on both sides. These two layers form the cathode and the anode of the fuel cell. Individual cells can be connected together to form compact stacks (see section 1.2.2.) in order to match the power requirements of a given application.

Stackability, high efficiency, and the good cold-start behavior of the PEM fuel cell make it suitable for a wide range of applications, e.g. for electric drives in cars, as a replacement for batteries and accumulators, and for domestic energy supplies (see section 1.3).

How a PEM fuel cell works

In a PEM fuel cell two electrodes (typically platinum, blue in Figure 11) are separated by a proton-conducting polymer membrane, the electrolyte (yellow). Hydrogen gas (in red, left side) is supplied to one electrode and oxygen gas (in blue, right side) to the other. The anode is a catalyst for the dissociation of hydrogen into protons (H^+ ions) and electrons (indicated by the yellow + and -). Both protons and electrons now travel to the cathode side (on the right) but – very importantly – on different paths. While the H^+ ions pass through the cell's proton-conducting membrane, the electrons move through the (closed) external circuit and thereby provide the fuel cell's electric power (indicated by the light bulb). At the cathode the protons and electrons finally react with the oxygen to form water (in red and blue), the fuel cell's only byproduct.

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction: $4H^+ + 4e^- + O_2 \rightarrow 2H_2O$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

PEM fuel cells are named after their electrolyte material, a proton-conducting polymer membrane. The acronym PEM stands for proton exchange-membrane or polymer-electrolyte-membrane. A PEM consists of a Teflon-like polymer structure to which sulfonic acid groups (SO_3H) are attached. When the membrane becomes wet the sulfonic acid dissociates, and the membrane becomes acidic and thereby proton-conducting. This allows for easy transport of protons (H^+ ions), but anions (negatively charged ions) cannot pass through the membrane.

1.2.2. FUEL CELL STACKS

In order to achieve appreciable output voltages several individual fuel cells must be combined into a unit called a fuel cell stack.

Fig. 12 | PEM Fuel Cell Stack

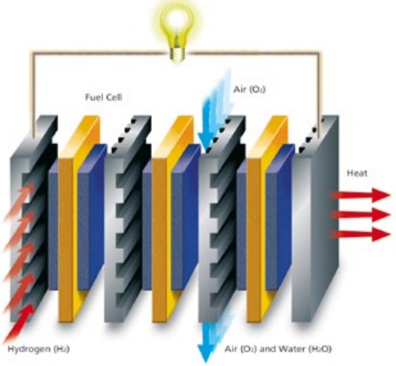


Figure 12 shows a fuel cell stack consisting of three individual fuel cells. These are represented as yellow and blue units, where the electrolyte (or PEM) is shown in yellow and the electrodes in blue. adjacent cells are connected by a separator plate (gray with horizontal and vertical grooves) which has a number of tasks: 1) to provide the electrical connections between the cells, 2) to facilitate gas transport to and away from the cells, 3) to dissipate the heat produced in the cells, and 4) to seal off adjacent cells and prevent fuel and oxidant leakage. In the fi-gure the electrical connections are not shown explicitly, the gas transport channels are represented by horizontal (hydrogen) and vertical (oxygen supply and water exhaust) grooves. Special end plates are attached to the end cells of the stack (left and right side, gray). The end plates have electrical connectors for the external circuit as well as hook-ups for gas supply and (if necessary) coolant. Stacks are either air- or water-cooled, depending on the stack's total output power and the heat generation associated with it.

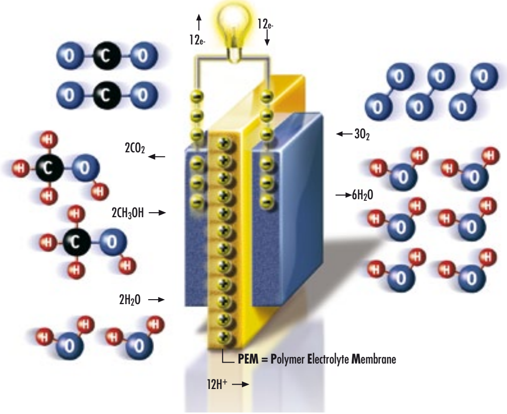
Simply by varying the number of individual cells, stacks can be designed for any desirable output voltage. Since the cells are electrically connected in series, adding a cell will increase the output voltage. The total output voltage is given by the sum of all of the individual voltages.

1.2.3. DIRECT METHANOL FUEL CELLS

The Direct Methanol Fuel Cell is a special type of PEM fuel cell. DMFCs and PEMFCs have similar structures, two electrodes are separated by an electrolyte consisting of a proton-conducting polymer membrane that is impermeable to electrons.

The Direct Methanol Fuel Cell is a special type of PEM fuel cell. DMFCs and PEMFCs have similar structures, two electrodes are separated by an electrolyte consisting of a proton-conducting polymer membrane that is impermeable to electrons.

Fig. 13 | Direct Methanol Fuel Cell



The difference between a DMFC and a PEMFC is that the DMFC uses methanol (CH3OH), rather than hydrogen, as fuel. At ambient pressures (101.3 kPa) methanol is liquid at temperatures between -97 °C and 64 °C. Thus the major advantage of a DMFC is that its fuel can be handled, stored and transported similarly to conventional liquid fuels like gasoline or diesel. On the other hand, methanol is poisonous and corrosive and DMFCs have low electrical efficiencies compared to most other fuel cell types. The chief applications for DMFCs are: electrical power systems, portable electricity supplies, battery replacement.

How a DMFC works

Figure 13 shows a schematic diagram of a DMFC. The electrolyte (PEM) is shown in yellow, the electrodes on either side of it in blue (anode on the left, cathode on the right). The anode is supplied with a methanol/water mixture (red/ blue/black and red/blue molecules on the left). Due to the electrode's catalytic effect hydrogen is separated from the mixture and reduced to protons (H^+ ions, yellow +), yielding free electrons (yellow -) to the anode. Both protons and electrons now travel to the cathode side but – very importantly – on different paths. While the H+ ions pass through the cell's pro-ton-conducting membrane, the electrons move through the (closed) external circuit and thereby provide the fuel cell's electric power (indicated by the light bulb).

At the anode the oxygen and carbon left over from the methanol react with the oxygen from the water and form carbon dioxide (CO_2).

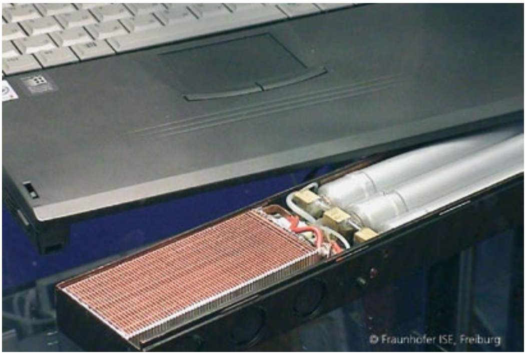
At the cathode the protons that passed through the membrane and electrons from the external circuit react with the supplied oxygen (blue) to form water (red and blue).

Anode reaction: $2CH_3OH + 2H_2O \rightarrow 2CO_2 + 12H^+ + 12e^-$
Cathode reaction: $3O_2 + 12H^+ + 12e^- \rightarrow 6H_2O$
Total reaction: $2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O$

1.3. APPLICATIONS

Fuel cells for portable applications

Fig. 14 | Fully integrated fuel cell system powering a laptop. The dimensions of the system are equivalent to those of typical rechargeable batteries.



For portable applications fuel cells are an alternative to typical batteries. Their major advantage is that, unlike batteries, they do not run down. Batteries are energy storage devices; the electrical energy they can supply is determined by the amount of chemical reactant stored within. When its reactant is used up a battery has to be either recharged (if it is rechargeable) or discarded. Rechargeable batteries also lose capacity over time. Fuel cells, on the other hand, are energy conversion devices and do not store their own fuel. They will provide electrical energy for as long as they are supplied with fuel (hydrogen or methanol).

There is a wide range for possible applications of fuel cell technology in portable devices, for example, fuel cells could provide electricity to low-power devices such as laptops (Figure 14) or measuring instruments, or they might even supply power to camping equipment.

Low-temperature fuel cells like PEMFCs and DMFCs are the most suitable for portable low-power devices because they are operable at low temperatures, work immediately after start-up (i.e. no warm-up phase is required) and allow for a compact design.

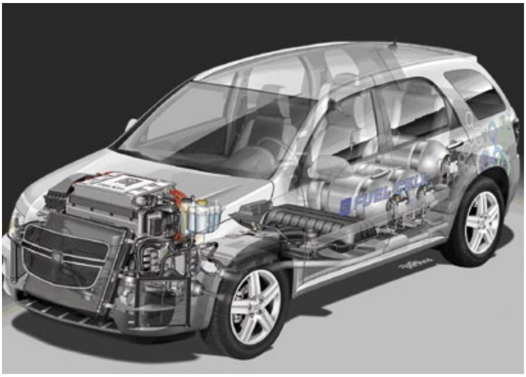
The only byproduct of a PEMFC is water while a DMFC – in addition to water – also produces small amounts of carbon dioxide.

Fuel cells for mobile applications

Mobile applications are dominated by PEM fuel cells. Since they have low operating temperatures PEMFCs can deliver power immediately after start-up. This is particularly important for use in automobiles.

Power requirements for mobile applications range from a few kilowatts to several hundred kilowatts.

Fig. 15 | Fuel cell powered car: The HydroGen4 can accelerate from 0 to 100 km/h in 12 seconds and has a top speed of 160 km/h



Small boats typically require onboard power supplies of a few kilowatts, while electric power on the order of several hundred kilowatts is needed to equip a submarine with adequate propulsion as well as on-board electricity and emergency energy supply systems.

Due to their modular character, fuel cell stacks can be adapted to meet the most diverse power requirements imaginable.

The HydroGen4 made by General Motors is powered by a fuel cell stack consisting of 440 individual fuel cells that are connected in series. As there are no moving parts in a fuel cell the energy conversion is done noiselessly and without wear and tear.

There are also other concept vehicles that use hydrogen technology, e.g. the BMW Hydrogen 7 and the Daimler F-Cell.

The BMW Hydrogen 7 uses a hydrogen combustion engine instead of a fuel cell stack and an electric motor. This technology is based on the conventional four-stroke internal combustion engine, the difference being that the engine burns hydrogen instead of gasoline.

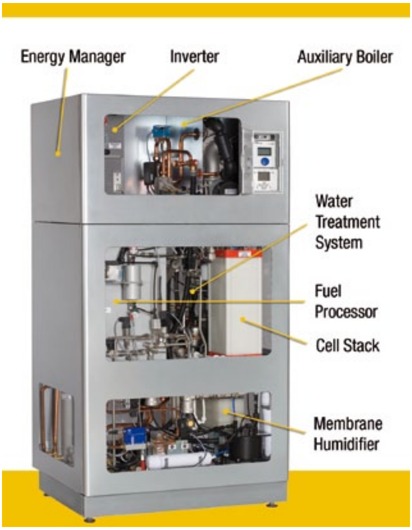
While the NECAR 5 from DaimlerChrysler still fuels with methanol, the F-Cell uses hydrogen.

In the meantime, all automobile manufacturing companies have discontinued the original preferred practice of on-board reforming of hydrocarbon compounds (such as methanol).

Fuel cells for stationary applications

Stationary applications range from residential power and heat generation (output starting at 1 KW) to heat and power supplies for entire residential areas by means of heat-and-power block units (with outputs in the MW range).

Fig. 16 | Fuel cell heating system: At present powered by natural gas, but could be powered by renewable hydrogen in the future. This device supplies two kinds of usable energy: electrical and thermal.



The first pilot projects for domestic energy supply have already been implemented.

A complete fuel cell system for generating power and heat consists not only of the fuel cell stack, but also of a number of other components:

Systems for conditioning the gas: if the fuel needed to run the fuel cell is of inadequate quality, it has to be conditioned first. This may involve reforming and CO purification as well as desulfurization and the removal of excess oxygen.

Heat exchangers: serve to couple out the heat generated by the cell reaction.

Other power-generating components: depending on output, these may be expansion turbines, gas turbines or combined gas- and steam turbines

Piping, pumps and condensers required for gas and heat management

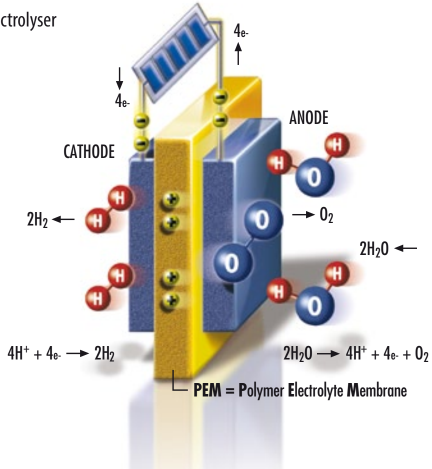
Electrical connections between system units as well as controls and interfaces

Invertors and transformers to convert and transform the DC voltage of the fuel cell stack to AC voltage.

1.4. PEM ELECTROLYSERS

Hydrogen and oxygen gases can be produced by the electrolysis of water. Electrolysis is an electrochemical process through which a substance (the electrolyte)

Fig. 17 | PEM Electrolyser



is decomposed when an external DC voltage is applied to two electrodes (cathode and anode) that are in contact with the electrolyte. For electrolysis to happen the DC voltage must be equal to or exceed a certain material-dependent threshold voltage known as the decomposition voltage. Different types of electrolysers are usually distinguished by their type of electrolyte and/or electrodes.

PEM electrolysers (Figure 17) have a particularly simple and compact design. The central component is a proton-conducting polymer membrane which is coated with a layer of catalyst material on either side. These two layers are the electrodes of the cell.

When a DC voltage greater than the decomposition voltage of water is applied to its electrodes, the PEM electrolyser splits pure water into hydrogen and oxygen. The theoretical decomposition voltage of water is 1.23 V, however, because of transition resistances, somewhat higher voltages are necessary in practice.

Higher power electrolysers are built as stacks in which individual electrolysers are connected in series and voltages are added. PEM electrolysers have efficiencies of up to ~85 %.

How PEM electrolysers work

When a DC voltage is applied to the PEM electrolyser electrodes (e.g. via the solar panel in *Figure 17*), water is oxidized at the anode (electrode on the right), leaving oxygen, protons (H^+ ions) and free electrons. While the oxygen gas can be collected directly at the anode, the protons (yellow +) migrate through the proton-conducting membrane to the cathode where they are reduced to hydrogen (the electrons for this are provided by the external circuit).

Anode reaction $2H_2O \rightarrow 4H^+ + 4e^- + O_2$
Cathode reaction: $4H^+ + 4e^- \rightarrow 2H_2$
Total reaction: $2H_2O \rightarrow 2H_2 + O_2$

PEM electrolysers are named after their electrolyte material, a proton-conducting polymer membrane. The acronym PEM stands for proton exchange-membrane or polymer-electrolyte-membrane. A PEM consists of a Teflon-like polymer structure to which sulfonic acid groups (SO_3H) are attached. When the membrane becomes wet the sulfonic acid dissociates, and the membrane becomes acidic and thereby proton-conducting. This allows for easy transport of protons (H^+ ions), but anions (negatively charged ions) cannot pass through the membrane.

1.5. HYDROGEN STORAGE

Pressure storage

The easiest and most economical method of storing hydrogen is simply to compress the gas and store it in containers that can withstand the high pressure that results (Figure 18). Unless space or weight are issues this is the storage method of choice.

Fig. 18 | Pressure storage tank

Conventional pressure tanks are designed to withstand pressures of up to 200 bar and can therefore hold a high volume of a given gas (as compared to the gas volume at ambient pressures). They are mainly used for indoor and stationary applications. Among the more recent developments in this area are tanks made of carbon composites. Not only are these more lightweight than their conventional counterparts but they can also withstand pressures of up to 350 bar (700 bar in the future).

Cryogenic storage (liquid hydrogen storage)

In this method hydrogen is stored as a liquid at temperatures below -253° C. The major advantage is the high energy storage density per volume (and mass), i.e. a given volume of liquid hydrogen con-tains many times the energy of the same volume of hydrogen gas. This is parti-cularly important when there is limited space (e.g. during transport on tankers).

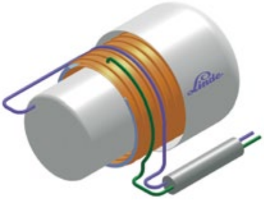


Fig. 19 | Cryogenic storage tank

Hydrogen changes into its liquid phase at a temperature of - 253° C. At temperatures this low it can only be stored in special cryogenic storage tanks that are sufficiently well insulated (Figure 19). But even in these tanks the liquid hydrogen can be stored for only a few days before evaporation losses begin. These occur when - due to a slight temperature increase - a small portion of the hydrogen evaporates and thus returns to the gas phase. To avoid the build-up of high pressures in the tank the gaseous hydrogen has to be released. The losses due to this process amount to about 0.4 % of the tank volume per day. Another significant loss is associated with the li-quefaction process: the energy required to liquefy the hydrogen amounts to appro-ximately one third of the total energy stored.

Metal hydride storage

Fig. 20 | Metal hydride storage

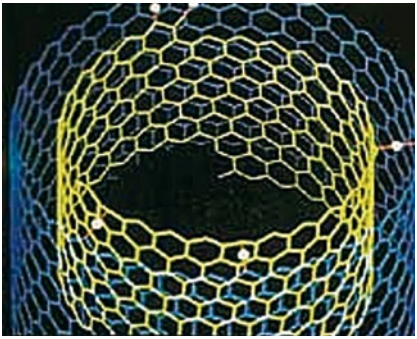
Hydrogen can be stored as a metal hydride, in the crystal lattice of certain metals or metal alloys (*Figure 20*). At pressures slightly exceeding the ambient pressure the hydrogen is pumped into the storage medium where it bonds to the metal (metal alloy) to form a metal hydride, releasing heat in the process (exothermic reaction). The reaction is reversible: by applying heat the hydrogen can be released from the tank for use in, for example, a fuel cell.

Compared to the methods above, hydrogen stored as a metal hydride is safer and easier to handle. Metal hydride storage has a high energy storage density per volume. This could make it suitable for use in automobiles as enough fuel can be stored in a small volume to provide a sufficient range for the vehicle. However, there is one major issue: the energy storage density per mass is low and, consequently, metal hydride storage tanks are heavy. This continues to be a problem for its widespread use in automobiles.

Nanotubes

The chemical element carbon can take on various structures with different properties. Diamond, for example, is very hard, while graphite is very soft and can be used as a lubricant. The so-called Fullerenes that are made up of carbon atoms have just been discovered in recent years. This matter has a hexagonal atomic structure similar to honeycombs.

Fig. 21 | Nanotubes



This atomic structure can form layers that in turn can be rolled up into cylindrical nanotubes. If the tubes have several layers, they are called multi-wall nanotubes. It is also possible to make tubes that have only one carbon layer and are thus called single-wall nanotubes. Compared to single-wall nanotubes, multi-wall nanotubes have a 10-fold larger diameter (30 to 50 nm). Research has shown that it is possible to store gaseous hydrogen between the wall layers of multi-wall nanotubes. However, depending on the temperature, the storage capacity is only between 1 and 5 percent of its weight, which is why much development work must still be invested to enable practical usage.

Methanol

Methanol contains hydrogen in bonded form. Methanol (CH_3OH) was formerly called methyl alcohol or wood alcohol. It is a water-soluble alcohol that, in contrast to ethanol, is poisonous and can cause blindness. Just a few milliliters of methanol can cause blindness. The quantity of formic acid created when the human body breaks down methanol determines its toxicity. Frequently repeated exposure in small doses (for example, occupational inhalation of vapors) causes mucous membrane irritation, lightheadedness, vertigo, headaches, cramps as well as digestion and gastric disorders. Methanol is an important chemical base product and is primarily used for producing formaldehyde. It can be technically produced from any source of carbon. Today, methanol is produced primarily from natural gas or by gasifying coal, so it is therefore not linked to the primary energy carrier, crude oil.

2

Solutions to experiments

2.1. DECOMPOSITION OF WATER WITH REGARD TO THE RESULTING VOLUME OF HYDROGEN AND OXYGEN GAS

Read the safety instructions contained in the operating instructions before performing the experiment!

BACKGROUND

In electrolysis, chemical compounds are decomposed (broken down) using electrical energy. This allows water to be split into its elements hydrogen and oxygen. Since every water molecule H_2O is made up of two hydrogen atoms and one oxygen atom, the volume of hydrogen and oxygen gas produced is expected to have a ratio of 2:1. In the subsequent sections of this book, volume is always used to describe the volumes of gas, since hydrogen and oxygen are always gaseous at normal ambient temperatures and ambient pressure.

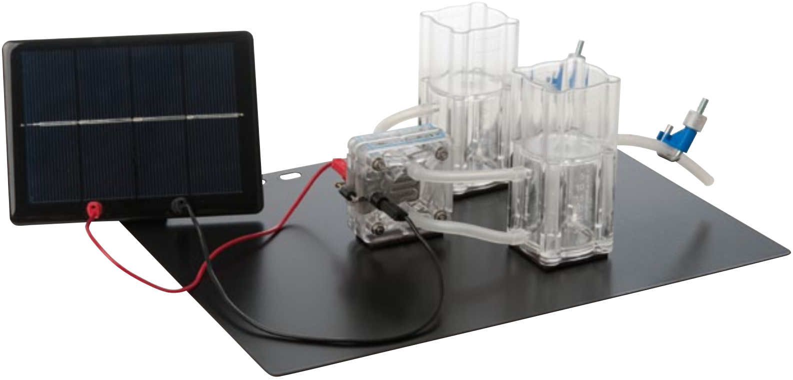
APPARATUS

- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Power source, such as a solar module, laboratory power supply
- A light, if necessary, for operating the solar module

SETUP *(See also operating instructions)*

Connect the electrolyser to the power source.
Perform the work using a voltage value greater than 1.5V and less than 2V for example 1.9V. For multi-cell electrolysers (electrolyser stack), the voltage must be high-er, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum.

Setup
2.1



PROCEDURE

Switch on the device as described in the operating instructions.
Before beginning the experiment, the gas storage containers must be completely filled with deionised water.

Produce, for example, $10 cm^3$ of hydrogen. Disconnect the electrolyser from the power source and record the volume of oxygen produced.

Example:

Volume of hydrogen produced	Volume of oxygen produced
$10 cm^3$	$5 cm^3$

ANALYSIS

The electrolyser splits water into its elements hydrogen and oxygen. As stated in the Background chapter, a hydrogen/oxygen volume ratio of 2:1 is expected. The test result confirms this assumption. $10 cm^3$ of hydrogen and $5 cm^3$ of oxygen are created at the same time.

2.2. CURRENT-VOLTAGE CHARACTERISTIC, POWER CURVE AND EFFICIENC OF SOLAR MODULE

Read the safety instructions contained in the operating instructions before performing the experiment!

BACKGROUND

The current-voltage characteristic provides information on the performance of the solar module. The so-called Maximum Power Point (MPP) can be determined from the current-voltage characteristic and the power curve. The efficiency of the solar module indicates the amount of incident radiant power that the solar module converts into electrical energy.

$$Efficiency\ \ \eta = \frac{electrical\ \ power\ output}{Incident\ \ \ radiant\ \ \ power} = \frac{P_{out}}{P_{in}}$$

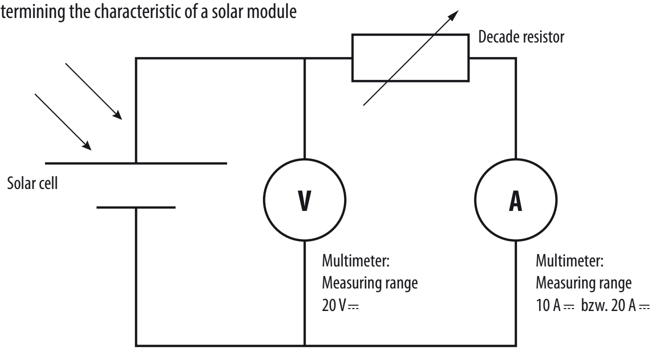
APPARATUS

- Solar module
- A light, if necessary, for operating the solar module
- Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Instrument for determining the radiant power of the light:
  - a| Measuring instrument for the direct measurement of the radiant power of the light, e.g.: Pyranometer
  - b| *Alternative:* The radiant power of the light is determined using the short-circuit current of the solar module

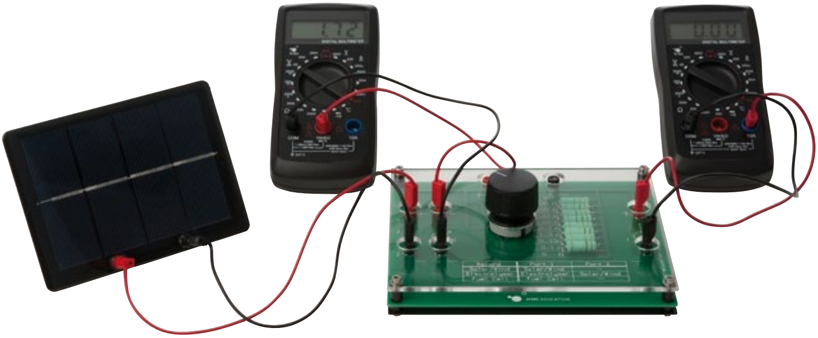
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram.

Circuit Diagram 2.2 | Setup for determining the characteristic of a solar module



Setup 2.2



PROCEDURE

Set up the experiment as shown above (Setup 2.2). Point the lamp at the solar module at a right angle (90° angle). In order to prevent errors due to temperature fluctuations, wait at least 1 minute after switching the lamp on. Start recording the current-voltage characteristic using the open-circuit voltage (R = ∞) and switch the decade resistor to successively lower resistances. Record the voltage and current for the re-spective resistance in a table. Wait between each individual measurement until the values have stabilised.

Example:

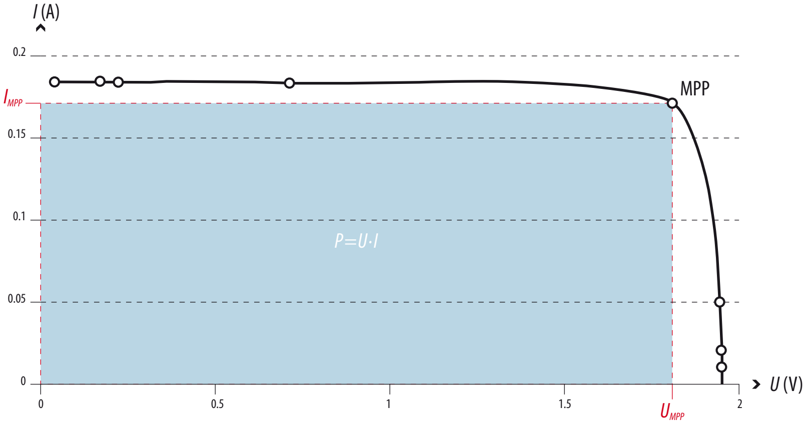
Table 2.2 | Table of measurements: Measurement of voltage and current for the respective resistance (performed using the H-TEC TUTORIAL hydrogen experimentation system)

R (Ω)	U (V)	I (A)	P (W) calculated P = U · I
∞	1.95	0	0
330	1.94	0.01	0.019
100	1.93	0.02	0.039
33	1.91	0.05	0.096
10	1.83	0.17	0.311
3.3	0.71	0.18	0.128
1	0.22	0.18	0.04
0.33	0.17	0.18	0.031
0.1	0.04	0.18	0.007
0	0.02	0.18	0.004

ANALYSIS

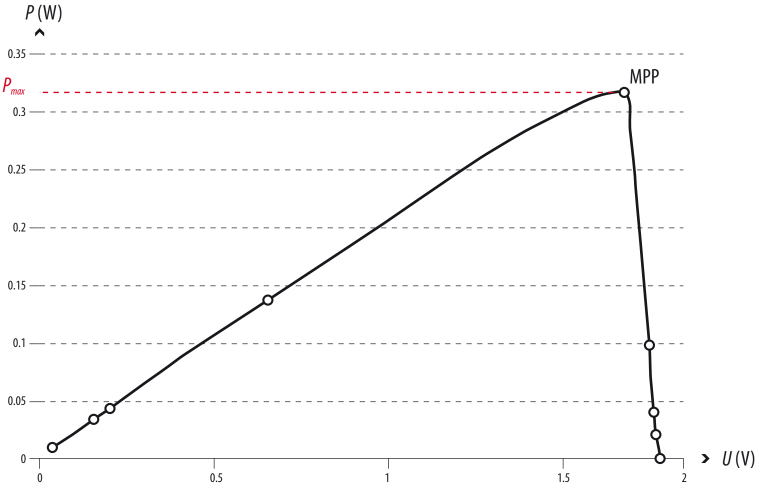
Using the table of measurements, plot a graph showing the relationship between the current and the voltage:

Diagram 2.2.a | Current-voltage characteristic of the solar module



Plot a graph showing power as a function of voltage:

Diagram 2.2.b | Power curve of solar module



The point that outputs the maximum electrical power (Maximum Power Point = MPP) is the turning point of the power curve. It occurs where the product of voltage and current is greatest: $P_{MPP} = U_{MPP} \cdot I_{MPP}$

In this example, the turning point is at: $P_{MPP} = 1.83\ V \cdot 0.17\ A = \underline{\underline{0.311\ W}}$

The MPP can also be determined from the current-voltage characteristic by forming the rectangles (products) of the voltage and associated current whose areas indicate the respective power value. The rectangle with the greatest area corresponds to the maximum power output with the respective current and voltage values.

EFFICIENCY OF THE SOLAR MODULE

The efficiency η is defined as the ratio of the incident radiant power P_{in} and the electrical power output P_{out} by the solar cell at the maximum power point.

The solar cell outputs the maximum electrical power at the maximum power point. Thus, the value for P_{out} is already known (in this example, $P_{out} = 0.311W$).

a| Use the radiant power measuring instrument to measure the radiant power of the light per unit area (irradiance E_E). This value must be multiplied by the effective area of the solar module to determine P_{in}, the power that strikes the solar cell.

$$P_{in} = E_E \cdot A$$

P_{in} = *Power of the light that strikes the solar module (W)*

E_E = *Irradiance* $\left(\frac{W}{m^2}\right)$

A = Effective area of the solar module (m^2)

The efficiency can now be calculated using $\eta = \frac{P_{out}}{P_{in}}$

b| If there is no measuring instrument available to measure the radiant power, the multimeter can be used to estimate the incident radiant power of the light. This method uses the fact that the short-circuit current (maximum photoelectric current) is proportional to the photons (radiation) that strike the solar cell. The short-circuit current is therefore proportional to the incident radiant power of the light.

The open circuit voltage depends on the semiconductor material of which the solar cell is made. It is not proportional to the incident radiant power of the light and therefore cannot be used for this measurement. To use the multimeter to measure the power of the light, the short-circuit current displayed on the multimeter must be multiplied by the factor F to obtain a quantitative statement. This factor depends on the maximum value of the short-circuit current of the solar cell. The maximum irradiance under sunny summer conditions is approximately 1000 W/m^2. The maximum value specified by the manufacturer for the short-circuit current is reached at this irradiation. The characteristics of the solar modules are based on the standard test conditions of 1000 W/m^2 solar irradiation at a cell temperature of 25°C.

Based on this assumption, the maximum short-circuit current is 600 mA under standard test conditions. You can now easily calculate the factor F using the following formula:

$$F = \frac{P_{\max}(m^2)}{I_{K\max}} = \frac{1000\frac{W}{m^2}}{600\,mA} = 1.67\frac{W}{m^2 \cdot mA}$$

If you now multiply the short-circuit current displayed on the multimeter by the factor

$$F = 1.67\frac{W}{m^2 \cdot mA}$$

you have the approximate value of the incident radiant power per unit area that strikes the solar module. To calculate the incident radiant power on the solar module, you must measure the effective area of the solar module and multiply it by the incident radiant power per unit area.

Example:
Solar module area: 4 cells that are each 26 mm x 77 mm, $A = 8 \cdot 10^3\ m^2$
Short-circuit current: I_K=200 mA

$$P_{in} = F \cdot I_K \cdot A = 1.67\frac{W}{m^2 \cdot mA} \cdot 200\,mA \cdot 8 \cdot 10^{-3}\,m^2 = 2.67W$$

As already determined, the maximum power point is
P_{out} = 0.311 W (at an incident radiant power of 2.67 W).

The efficiency can now be calculated *using* $\eta = \frac{P_{out}}{P_{in}}$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{0.311}{2.67} = 0.116 = \underline{\underline{11.6\%}}$$

A = Effective area of the solar module (m^2)
I_K = Short-circuit current (mA)
P_{in} = Power of the light that strikes the solar module (W)
P_{out} = Maximum power output (W)
η = Efficiency of the solar module

DISCUSSION

The maximum output can very easily be read from the power curve. This point is called MPP (Maximum Power Point). On the current-voltage characteristic, the MPP describes the greatest possible rectangular area that can be stretched between the coordinate axes (*U* and *I*) and enclosed by the characteristic. The resistance R_{MPP}, the point where maximum output power is greatest, can be calculated using the following formula:

$$R_{MPP} = \frac{U_{MPP}}{I_{MPP}}$$

The efficiencies of polycrystalline solar cells range between 14% and 16%. The calculated efficiency at 11.6% is slightly less. This is due to measuring errors and inaccuracies in determining the incident radiant power.

In addition, the efficiency of solar modules is lower than the efficiency of individual solar cells. This is caused by matching losses that occur because not all solar cells have identical properties. If the solar cells are connected in series to create one module, they do not all have the same maximum power point.

The efficiency of the solar cell is reduced by losses that occur during the following process: not all photons that strike the solar cells can be converted into charge carriers; part of the light is reflected once it strikes the solar cell surface; furthermore, the metal contacts also cast shadows. Since the photon energy does not correspond to the energy gaps, more than half of the incident energy is not used. In addition, energy carriers are recombined (atomic rebinding of electrons) and there are also electrical losses at the internal resistances (ohmic losses in the semiconductor material) of the solar cells as well as their contacts.

2.3. CURRENT-VOLTAGE CHARACTERISTIC OF PEM ELECTROLYSER

Read the safety instructions contained in the operating instructions before performing the experiment!

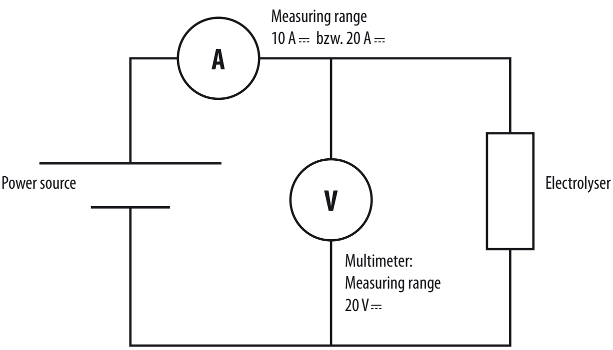
BACKGROUND

The PEM electrolyser splits water into hydrogen and oxygen. The voltage applied to the electrolyser must exceed a specific value, the decomposition voltage of water, for this to be achieved. Water cannot be split below this voltage. The following experiment is designed to determine the magnitude of this voltage.

APPARATUS

- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Measuring instrument for current and voltage, e.g.:
  - Two multimeters
- Power source
  - a| Adjustable power source, e.g. laboratory power supply
  - b| *Alternative:* solar module, in which case, the following are also needed:
    - A light, if necessary, for operating the solar module
    - Variable resistor as well as a measuring instrument for current and voltage, e.g.:
      - Decade resistor, various resistors, potentiometer and two multimeters

Circuit Diagram 2.3.a | Setup for determining the current-voltage characteristic of the electrolyser using an adjustable power source

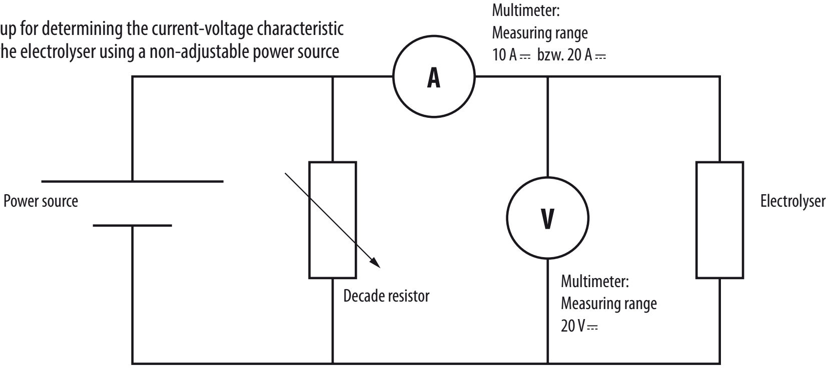


SETUP *(See also operating instructions)*

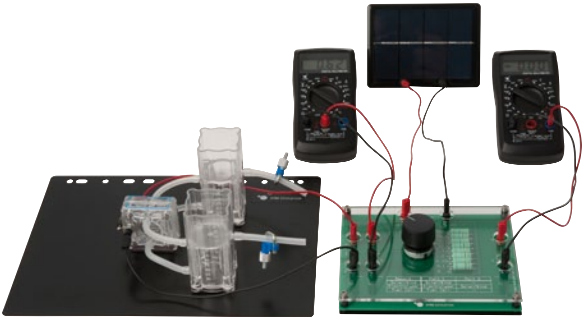
a| Connect the electrolyser directly to the variable DC power source.
Set this DC power source to 0V and then increase it to a maximum of 2.0V. For multi-cell electrolysers (electrolyser stack), the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum.

b| Create the circuit as shown in the following circuit diagram.

Circuit Diagram 2.3.b | Setup for determining the current-voltage characteristic of the electrolyser using a non-adjustable power source



Setup 2.3.b



PROCEDURE

Switch on the device as described in the operating instructions.

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system).

Table 2.3.a Table of measurements:
The PEM electrolyser does not produce hydrogen and oxygen gas continuously until a specific DC voltage value has been exceeded. From this point, the current increases with increasing voltage. The table displays the respective currents for the different voltages applied.

U (V)	I (A)
0.1	0
0.2	0
0.3	0
0.4	0
0.5	0
0.6	0
0.7	0
0.8	0
0.9	0
1	0
1.1	0
1.2	0
1.3	0.01
1.4	0.02
1.5	0.05
1.6	0.38
1.7	0.78
1.8	1.21
1.9	1.73
2	2.16

a| Continually increase the voltage on the power source in 0.1 V increments from 0V to 2V and record both the respective voltage and corresponding current in a table. Wait between measurements until the values have stabilized to achieve representative values. Observe the start of gas pro-duction and mark down the corresponding voltage in the table.

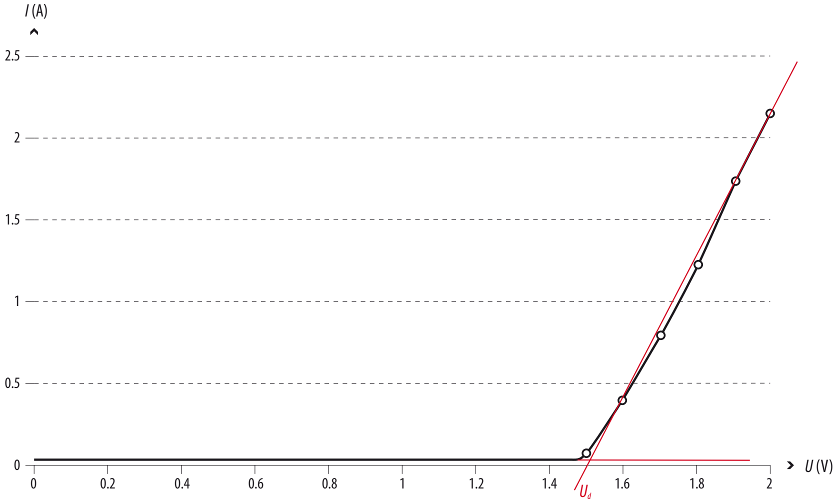
b| Gradually switch the decade resistor from low to high resistances and record the respective voltage and the corresponding currents in a table. Single-cell electrolysers must not exceed the maximum value of 2V. For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum. Wait between measurements until the values have stabilised to achieve representative values. Observe the start of gas production and mark down the corresponding voltage in the table..

ANALYSIS

Plot a graph of the recorded value pairs in a diagram. The resulting curve is the voltage-current characteristic of the electrolyser that can be approximated by two intersecting straight lines (see diagram 2.3.a). Draw the 2 straight lines and mark the intersection point of the sloped line with the X-axis. The intersection point indicates the decomposition voltage U_d.

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system):

Diagram 2.3.a | Current-voltage characteristic of the electrolyser



DISCUSSION

The relationship between the currents and the applied voltage is plotted in Diagram 2.3.a. The curve clearly shows that no current flows until a specific voltage begins to flow.

The water did not begin to split into hydrogen and oxygen until measurable current began to flow. In our example, this occurs at 1.5V (see table 2.3.a).

The decomposition voltage is located at the intersection point of the steeper line and the abscissa (X-axis).

The theoretical decomposition voltage of water is 1.23V. Water does not split below this voltage. In practice, however, this voltage is higher due to losses in the electrolyser. The difference between the theoretical and practical value depends on several parameters, e.g. the type and composition of the electrode material, the electrolytes and the temperature.

2.4. ENERGY EFFICIENCY AN D FARADAY EFFICIENCY OF PEM ELECTROLYSER

Read the safety instructions contained in the operating instructions before performing the experiment!

APPARATUS

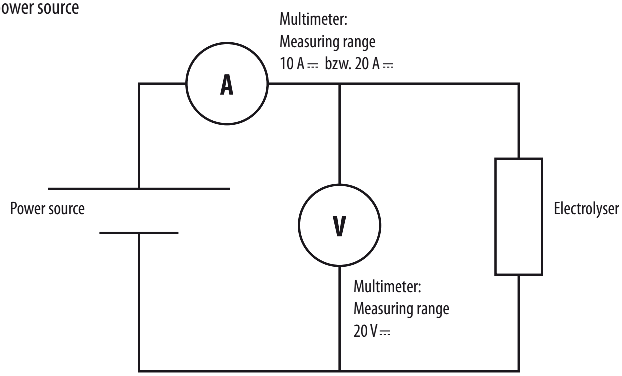
- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Stopwatch
- Measuring instrument for current and voltage, e.g.:
  - Two multimeters
- Power source
  - a| Adjustable power source, e.g. laboratory power supply
  - b| *Alternative:* solar module, in which case, the following are also needed:
    - A light, if necessary, for operating the solar module
    - Variable resistor as well as a measuring instrument for current and voltage, e.g.:
      - Decade resistor, various resistors, potentiometer and two multimeters

SETUP *(See also operating instructions)*

a| Connect the electrolyser to the adjustable power source. Set a voltage, e.g. 1.9V (greater than 1.5V and less than 2V).
For multi-cell electrolysers (electrolyser stack), the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum.

b| Connect the electrolyser to the solar module and illuminate the solar module. This will create a voltage between 1.5V and 2V.

Circuit Diagram 2.4.a Setup for determining the energy efficiency and Faraday efficiency of the electrolyser using an adjustable power source



PROCEDURE AND DATA

Switch on the device as described in the operating instructions.

Allow several minutes of gas production before starting to record the data. Interrupt the power supply to the electrolyser. Open the outlet valves of the gas storage tanks to completely release the gases produced. Once the gases have been removed, fill the storage tanks completely with deionised water. The water level must coincide with the 0 cm^3 graduation mark, when viewed horizontally. Now close the gas storage tank outlet valves.

Begin measuring the time from the moment you connect the electrolyser to the power source. Record the time, the voltage applied to the electrolyser and the current flowing through it once gas quantities can be easily read.

(e. g. 5 cm^3, 10 cm^3, etc.). Take the last measurements when the hydrogen storage tank is completely filled with gas. This is 30 cm^3 in our example.

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system):

Table 2.4.a

Table of measurements:
A PEM electrolyser continuously produces hydrogen and oxygen gas once the applied DC voltage exceeds a specific value. The time, voltage and current were recorded in the following table for volumes (at 5cm^3 increments) of hydrogen gas produced..

V_{H_2} (cm^3)	t (s)	U (V)	I (A)	P (W) P = U · I
0	0	1.94	1.02	1.98
5	40	1.94	1.01	1.96
10	80	1.94	1.01	1.96
15	119	1.95	1.01	1.97
20	160	1.95	1.01	1.97
25	200	1.95	1.00	1.95
30	238	1.94	1.01	1.96

BACKGROUND

The energy efficiency η_{energy} indicates how much of the input energy E_{input} is dissipated in the system (in this case, the electrolyser) as actual usable energy E_{usable}.

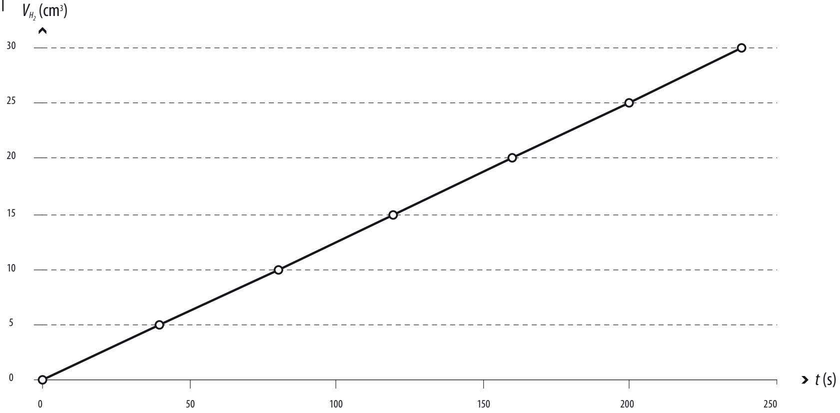
$$\eta_{energy} = \frac{E_{usable}}{E_{input}} = \frac{E_{Hydrogen}}{E_{electric}}$$

The greater the efficiency is, the better the energy use.

ANALYSIS PART I

Plot a graph showing the produced volume of gas as a function of time.

Diagram 2.4.a | Gas volume/time graph of an electrolyser (at $\bar{P} = 1.96\,W$)



ANALYSIS PART II

Calculate the energy efficiency of the electrolyser.

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system):

$$\eta_{energy} = \frac{E_{Hydrogen}}{E_{electric}} = \frac{V_{H_2} \cdot H_h}{\bar{U} \cdot \bar{I} \cdot t}$$

$$\eta_{energy} = \frac{3 \cdot 10^{-5} m^3 \cdot 12.745 \cdot 10^6 \frac{J}{m^3}}{1.94V \cdot 1.01A \cdot 238s} = 0.82 = \underline{\underline{82\%}}$$

---

[1] _The energy that is released during the combustion of a substance (oxidation) is defined as the calorific value H_h (also called higher heating value). It also includes the energy contained by the water vapor from combustion as condensation heat. This energy cannot by used in conventional combustion systems. Therefore, a value is also formulated that does not inclulde the condensation heat. This variable is called a heating value H_l and is used to calculate the efficiency for heating systems, motors and fuel cells.

H_h = Caloric value[1] of hydrogen = $12.745 \cdot 10^6 \frac{J}{m^3}$

V_{H_2} = Quantity of hydrogen produced in m^3

U = Voltage in V

I = Current in A

t = Time in s

DISCUSSION

Table 2.4.a shows that the electrical power consumption of the electrolyser is constant over time. The hydrogen production is also constant, since the gas volume/time graph shows that the volume of gas produced is linearly dependent on time.

In this example, the energy efficiency of the electrolyser is 82%. This means that 82% of the electrical energy that we use to operate the electrolyser is stored in hydrogen gas.

Losses occur during over-voltages due to particular electrodes (over-voltage is generally defined as the deviation of the theoretical from the actual experimentally determined decomposition voltage), the internal resistance of the electrolyser cell and the diffusion losses of the gases within the cell.

Faraday efficiency of the PEM electrolyser

BACKGROUND

Using Faraday's second law and the ideal gas law, a relationship can be established between the flowing current and the electrolyser's theoretical volume of gas produced.

The Faraday efficiency of the electrolyser can be derived from the ratio of the actual volume of gas produced to the calculated theoretical volume of gas.

ANALYSIS

The second Faraday law states:

$Q = I \cdot t = n \cdot z \cdot F$

The ideal gas law states:

$p \cdot V = n \cdot R \cdot T$

By combining the formulas, the volume of gas can be calculated as follows:

$$V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}$$

V = Theoretical volume of gas produced in m^3

R = Universal gas constant = $8.314 \frac{J}{mol \cdot K}$

p = Ambient pressure in Pa (1 Pa = $1 \frac{N}{m^2}$)

F = Faraday constant = $96485 \frac{C}{mol}$ (1C=1As)

T = Ambient temperature in K
I = Current in A
t = Time in s
Q = Electrical charge in C
n = Quantity of substance in mol
z = Number of electrons to release a molecule:
  z (H_2) = 2, i.e. 2 moles of electrons are required to release 1 mol of hydrogen.
  z (O_2) = 4

If an electrolyser stack (several electrolyser cells electrically connected in series) is used for this experiment, please take into consideration when calculating the volume that the current flows through each individual cell, i.e. each individual cell produces a gas volume and added together they equal the stack volume.

$$V(calculated) = \frac{R \cdot \bar{I} \cdot T \cdot t}{F \cdot p \cdot z} = \frac{8.314 \frac{J}{mol \cdot K} \cdot 1.01A \cdot 298K \cdot 238s}{96485 \frac{C}{mol} \cdot 1.013 \cdot 10^5 \, Pa \cdot 2}$$

$$V(calculated) = 3.05 \cdot 10^{-5} \, m^3 = 30.5 cm^3$$

The Faraday efficiency is obtained from the following equation:

$$\eta_{Faraday} = \frac{V_{H_2}(produced)}{V_{H_2}(calculated)}$$

The volume of hydrogen produced in this experiment is:

$$V_{H_2}(produced) = 30cm^3$$

Therefore, the Faraday efficiency is:

$$\eta_{Faraday} = \frac{30\ cm^3}{30.5\ cm^3} = 0.98$$

$$\eta_{Faraday} = \underline{\underline{98\%}}$$

DISCUSSION

The difference between the theoretical and actual volume of gas produced is very small, i.e. the electrical current is almost entirely converted for the intended reaction (splitting the water into hydrogen and oxygen). No side reactions occur. Very small diffusion losses of gas may occur within the cell. The diffusion losses occur as a result of a very small portion of gas diffusing through the membrane of the electrolyser and reacting with the catalyst to form water. A small portion of the gases produced is therefore directly converted without it being able to escape from the cell.

EXPERIMENTS WITH THE PEM FUEL CELL

The fuel cell must be well moistened for this experiment (see operating instructions). However, if there are too many water drops inside the cell, they may obstruct the gas flow so that the cell cannot perform as it should. We therefore recommend the following:

- Switch on the fuel cell as described in the operating instructions.
- Temporarily stop the fuel cell by interrupting the power supply to the electrolyser and disconnect the load from the fuel cell.
- Remove the gas supply hoses on the storage tanks that lead to the fuel cell, open the ventilating clamps on the fuel cell, then take a short and powerful breath of air and blow through the cell. This will force out the water drops.

Close the fuel cell outputs again and reconnect the hoses to the storage tanks.

2.5. CURRENT-VOLTAGE CHARACTERISTIC AND POWER CURVE OF FUEL CELL

Read the safety instructions contained in the operating instructions before performing the experiment!

BACKGROUND:

Hydrogen and oxygen are fed into the fuel cell and react to produce water and release heat and electricity in the process.

The output power of the fuel cell depends on the load resistance. The following experiment is designed to determine at which resistance and which current the maximum power output is achieved.

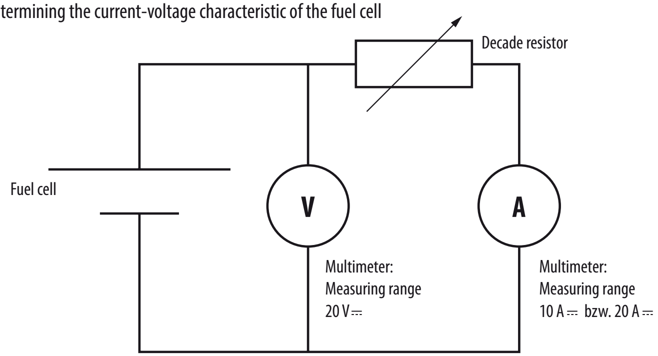
APPARATUS

- PEM fuel cell
- Variable resistor as well as a measuring instrument for current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Hydrogen source
  - a| Electrolyser or RFC in Electrolysis mode with gas storage tanks, in which case, the following is also needed:
    - Power source, such as a solar module, laboratory power supply
    - A light, if necessary, for operating the solar module
  - b| Hydrogen storage tank, e.g. pressurized gas canister, metal hydride storage tank

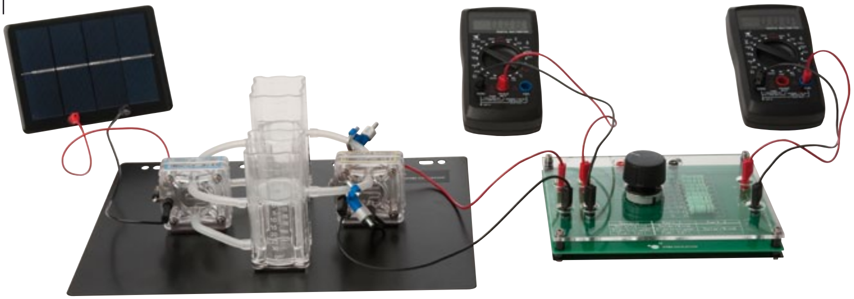
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 2.5.a | Setup for determining the current-voltage characteristic of the fuel cell



Setup 2.5.a



PROCEDURE

Switch on the device as described in the operating instructions.

Note that no additional oxygen is required in the hydrogen/air mode, i.e. the following description only refers to hydrogen.

a| Connect the electrolyser to the power source to produce hydrogen and oxygen

Connect the outlet connections of the electrolyser to the input connections of the gas storage tanks and connect their outputs to the input connections of the fuel cell. Close the fuel cell outlets. After you have produced approximately 5 cm^3 of hydrogen gas, open the fuel cell outlets, purge them with gas and close them again. This removes the residual gases that distort the measurement. To prevent the fuel cell from using any hydrogen before the measurement is taken, the fuel cell must be switched to open circuit. Start re-cording the current-voltage characteristic in a table using the open circuit voltage (R = ∞). Gradually switch the decade resistor from higher to lower resistances and record each voltage and current value. Wait 20 seconds in between individual measurements to achieve representative results.

2

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system):

Table 2.5.a | Table of Measurements: measurements of the voltage and current values for the fuel cell at different load resistances

R (Ω)	U (V)	I (A)	P (W) calculated $P = U \cdot I$
∞	0.99	0	0
330	0.97	0.01	0.01
100	0.95	0.01	0.01
33	0.9	0.03	0.027
10	0.84	0.08	0.067
3.3	0.76	0.22	0.167
1	0.62	0.56	0.347
0.33	0.47	1.05	0.494
0.1	0.32	1.43	0.458
0	0.24	1.61	0.386

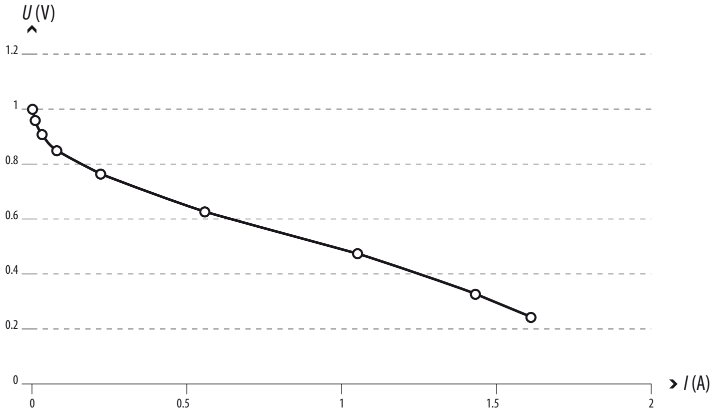
b| Close the fuel cell outlet. Connect the outlet connection of the hydrogen source to the input connection of the fuel cell (see operating instructions). Open the fuel cell outlet, briefly purge the cell with hydrogen and close the outlet again. This removes the residual gases that distort the measurement. To prevent the fuel cell from using any hydrogen before the measurement is taken, the fuel cell must be switched to open circuit (open clamps, no flowing current).

Start recording the current-voltage characteristic in a table using the open circuit voltage (R = ∞). Gradually switch the decade resistor from higher to lower resistances and record each voltage and current value. Wait 20 seconds in between individual measurements to achieve representative results.

ANALYSIS

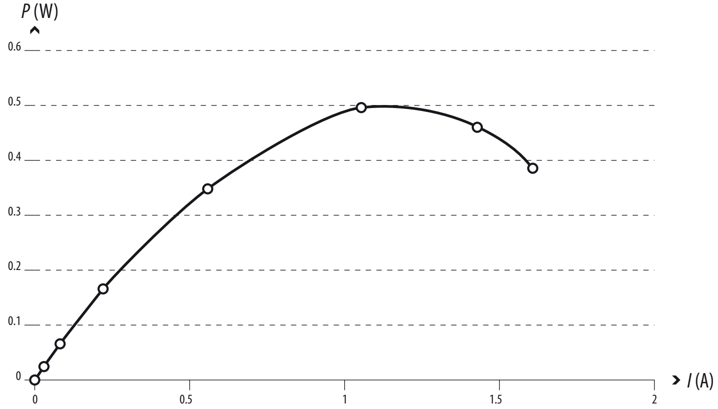
Plot a graph using recorded values as a current-voltage characteristic.

Diagram 2.5.a | Current-voltage characteristic of the fuel cell



Plot a graph showing the power as a function of current.

Diagram 2.5.b | Power curve of the fuel cell



DISCUSSION

The power curve clearly shows the current at which the fuel cell provides the greatest power output. The fuel cell provides the maximum power output at 1.05 A, which corresponds to a load resistance of 0.33 Ω.

2.6. ENERGY EFFICIENCY AND FARADAY EFFICIENCY OF PEM FUEL CELL

Read the safety instructions contained in the operating instructions before performing the experiment!

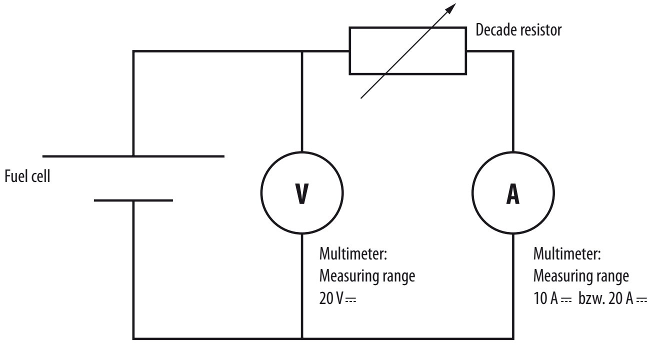
APPARATUS

- PEM fuel cell
- Hydrogen source, e.g. PEM electrolyser or RFC in Electrolysis mode
- Gas storage tanks
- Power source, such as a solar module or laboratory power supply for the electrolyser
- A light, if necessary, for operating the solar module
- Variable resistor as well as a measuring instrument for current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Stopwatch

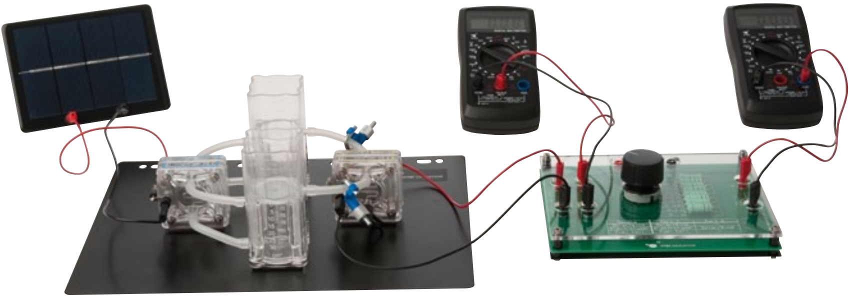
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 2.6. Setup for determining the energy efficiency and Faraday efficiency of the fuel cell



Setup
2.6.



PROCEDURE

Switch on the device as described in the operating instructions.

Connect the outlet connections of the hydrogen storage tank of the electrolyser to the input connections of the fuel cell. Close the fuel cell outlets. Produce hydrogen gas, then briefly open the fuel cell outlets to vent the system and then close them again. Produce the maximum volume of hydrogen possible with the system (in this example, 30 cm^3). Interrupt the power supply to the electrolyser and disconnect the electrical connection between the fuel cell and the decade resistor. Switch the decade resistor to the resistance at which you want to determine the energy efficiency (e.g. 3.3 Ω). Reconnect the circuit between the fuel cell and the decade resistor and start measuring the time from this moment.

Record the measured time, voltage and current at constant volume increments (e.g. 5 cm^3). Do not change the resistance. Make sure that the current values do not fluctuate too much. Any substantial reduction in the current during the measurement may be due to residual gases in the storage tank that impair the operation of the fuel cell. This problem may also occur if only a small quantity of hydrogen is left in the storage tank (e.g. only 5 cm^3).

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system):

Table 2.6. Table of measurements
If hydrogen gas is fed into a fuel cell, the cell continuously converts it into electrical energy. The time, voltage and current values were recorded in the following table for the specific volumes (at 5cm^3 increments) of hydrogen gas consumed.

Storage tank content V_{H_2} (cm^3)	t (s)	U (V)	I (A)	P (W) calculated $P = U \cdot I$
30	0	0.73	0.22	0.161
25	175	0.72	0.21	0.151
20	356	0.72	0.21	0.151
15	534	0.71	0.21	0.149
10	712	0.72	0.20	0.144
Mittelwert		$\bar{U} = 0.72$	$\bar{I} = 0.21$	$\bar{P} = 0.151$

Energy efficiency of the PEM fuel cell

BACKGROUND

The energy efficiency η_{energy} indicates how much of the input energy E_{input} is dissipated in the system (in this case the fuel cell) as actual usable energy E_{usable}.

$$\eta_{energy} = \frac{E_{usable}}{E_{input}} = \frac{E_{electric}}{E_{Hydrogen}}$$

The greater the efficiency is, the better the energy use.

ANALYSIS PART I

Plot a graph showing the storage tank content or the consumed volume of gas as a function of time.

Diagram 2.6.a | Storage tank content/time diagram of a fuel cell at $\overline{P} = 0.151\ W$

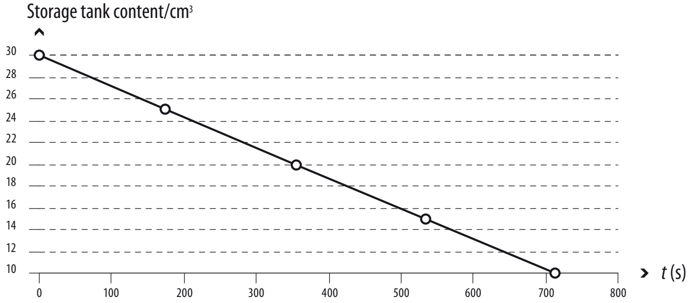
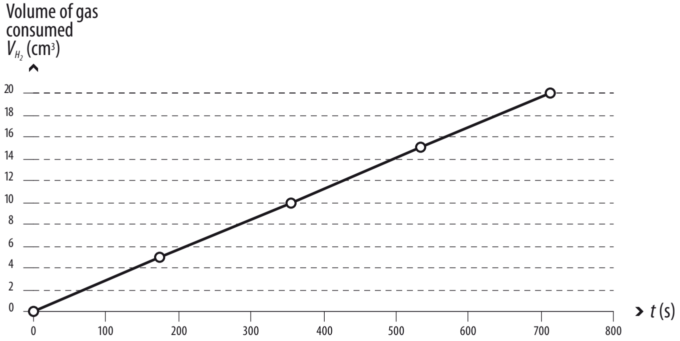


Diagram 2.6.b | Hydrogen consumption/time diagram of a fuel cell at $\overline{P} = 0.151\ W$



ANALYSIS PART II

Calculate the energy efficiency of the fuel cell.

$$\eta_{energy} = \frac{E_{electric}}{E_{Hydrogen}} = \frac{\bar{U} \cdot \bar{I} \cdot t}{V_{H_2} \cdot H_l}$$

$$\eta_{energy} = \frac{0.72V \cdot 0.21A \cdot 712s}{20 \cdot 10^{-6}\, m^3 \cdot 10.8 \cdot 10^6\, \frac{J}{m^3}} = 0.498 \approx 50\%$$

H_l = Heating value[1] of the hydrogen = $10.8 \cdot 10^6 \frac{J}{m^3}$ (also called lower heating value)
V_{H_2} = Quantity of hydrogen produced in m^3
U = Voltage in V
I = Current in A
t = Time in s

DISCUSSION

Diagrams 2.6.a and 2.6.b show that the volume of gas consumed is directly proportional to time. The energy efficiency of the fuel cell in our example is 50%. This means that 50% of the energy stored in the hydrogen with which we operate the fuel cell is output as electrical energy. The fuel cell also outputs heat. If this heat is not used, it is regarded as lost energy. This limits the energy efficiency from the outset. To account for ideal efficiency η_{id} is defined as the ratio of the free reaction enthalpy ΔG (the work released during the reaction, e.g. in the form of electrical energy) and the reac-tion enthalpy ΔH (the energy released during the reaction).

$$\eta_{id} = \frac{\Delta G}{\Delta H}$$

---

[1] The heating value is defined as the energy released during the combustion of a substance (oxidation). It does not include the energy contained by the water vapor from combustion as condensation heat. This energy cannot be used in heating systems, motors and fuel cells, for example.

The difference between free reaction enthalpy ΔG and the reaction enthalpy ΔH is the heat released Q. The heat can be described as a product of the temperature T and the reaction entropy ΔS.

$$Q = T \cdot \Delta S$$

The reaction enthalpy can be calculated using the following equation:

$$\Delta H = \Delta G + T \cdot \Delta S$$

The ideal efficiency η_{id} is calculated using the following formula:

$$\eta_{id} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T \cdot \Delta S}{\Delta H} = 1 - \frac{T \cdot \Delta S}{\Delta H} = 1 - \frac{298K \cdot \left(-162.985 \frac{J}{K \cdot mol}\right)}{-285840 \frac{J}{mol}}$$

$$\eta_{id} = 0.83 = \underline{\underline{83\%}}$$

$T = 298$ K

$\Delta S = -162.985 \ \frac{J}{K \cdot mol}$ (at standard pressure and temperature)

$\Delta H = -285840 \ \frac{J}{mol}$ (at standard pressure and temperature)

The energy efficiency of 83% is reduced further due to voltage losses that are manifested as heat. As a result of the overvoltages due to particular electrodes, the internal resistance of the fuel cell and diffusion loses within the fuel cell, the ideal cell voltage of 1.23V will never be reached.

The energy efficiency of the fuel cell, like that of the electrolyser, is closely related to the power level. Although the efficiency of the fuel cell is high, if the load has a high electrical resistance, it only operates in the partial-load range. The power extracted is therefore less than it can produce.

To ascertain the load resistance at which the energy efficiency of the fuel cell is greatest, this experiment can be repeated with different resistances (we recommend 10 Ω to 0.1 Ω).

Faraday efficiency of the PEM fuel cell

BACKGROUND

Using Faraday's second law and the ideal gas law, a relationship can be established between the flowing current and the fuel cell's theoretical volume of gas consumed.

The Faraday efficiency of the fuel cell can be derived from the ratio of the calculated theoretical volume of gas to the actual volume of gas consumed.

ANALYSIS

The second Faraday law states:

$$Q = I \cdot t = n \cdot z \cdot F$$

The ideal gas law states:

$$p \cdot V = n \cdot R \cdot T$$

By combining the formulas, the volume of gas can be calculated as follows:

$$V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}$$

V = Theoretical volume of gas produced in m^3

R = Universal gas constant = 8.314 $\frac{J}{mol \cdot K}$

p = Ambient pressure in Pa (1 Pa = 1$\frac{N}{m^2}$)

F = Faraday constant = 96485 $\frac{C}{mol}$ (1C=1As)

T = Ambient temperature in K
I = Current in A
t = Time in s
Q = Electrical charge in C
n = Quantity of substance in mol

z = Number of electrons to release a molecule:
z (H_2) = 2, i.e. 2 moles of electrons are required to release 1 mol of hydrogen.
z (O_2) = 4

If a fuel cell stack (several fuel cells electrically connected in series) is used for this experiment, please take into consideration when calculating the volume that the current flows through each individual cell, i.e. the gas volumes are consumed in each individual cell. The Faraday efficiency is obtained from the following equation:

$$\eta_{Faraday} = \frac{V_{H_2}(calculated)}{V_{H_2}(consumed)}$$

Example (performed using the H-TEC TUTORIAL hydrogen experimentation system):

$$V_{H_2}(consumed) = 20cm^3$$

$$V_{H_2}(calculated) = \frac{R \cdot \bar{I} \cdot T \cdot t}{F \cdot p \cdot z} = \frac{8.314\frac{J}{mol \cdot K} \cdot 0.21A \cdot 298K \cdot 712s}{96485\frac{C}{mol} \cdot 1{,}013 \cdot 10^5\,Pa \cdot 2}$$

$$V_{H_2}(calculated) = 18.96 \cdot 10^{-6}\,m^3 = \underline{\underline{18.96cm^3}}$$

$$\eta_{Faraday} = \frac{18.96cm^3}{20cm^3} = 0.948 \approx 95\%$$

DISCUSSION

The volume of gas actually consumed is slightly greater than the calculated volume, since diffusion losses similar to those with the electrolyser occur in the fuel cell.

However, according to the experiment results, the Faraday efficiency of the fuel cell is slightly less than that of the electrolyser. This is due to a smaller flowing current. It takes more time to form a given quantity of water than to split it. Over a longer time period, more hydrogen diffuses through the membrane and is then no longer available to produce electricity.

3

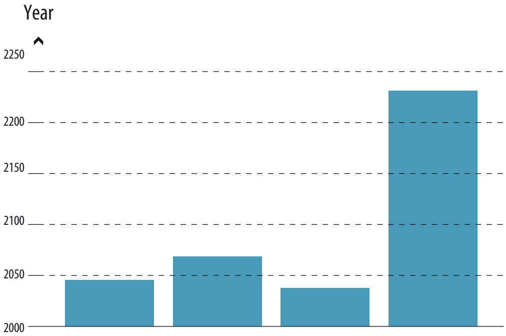
Work sheets and student experiments

3.1. INFORMATION FOR HANDOUT

3.1.1. THE SOLAR-HYDROGEN ENERGY CYCLE

Our global resources of fossil and nuclear fuels are limited.

Fig. 3.1.1. | Projected availability of fossil and nuclear fuels (based on today's rate of consumption).



The necessary changes in our energy supply system can be accomplished if we are able to establish renewable energies like solar, wind and hydroelectric energy as a fundamental part of the energy market.

One issue we are faced with when we use solar panels or wind power plants to produce electricity is that energy supply and demand often do not coincide. For example, a solar panel will provide electricity during the day but we might want to use electricity to power a light in the evening. Or, we might want to use wind-generated electricity in a place far away from the power plant. Hence, when supply and demand do not coincide we need a convenient way to both store and transport renewable energy. This is where hydrogen comes into play, as a future storage and transport medium for energy. The combination of solar energy for electricity production and hydrogen for energy transport and storage is called the solar-hydrogen energy cycle. During times when solar panels and wind power plants supply more energy than needed, the excess energy is used to produce hydrogen. This is accomplished with electrolysers that use electricity to split water into oxygen and hydrogen. The hydrogen (and potentially the oxygen) can be stored and transported as necessary. When we need electricity the gas(es) are fed into a fuel cell which converts the chemical energy of the hydrogen (and oxygen) into electricity, water and heat. In this way our energy demands can be met anywhere and anytime.

Renewable energies: what they are and how we can use them.

Renewable energies have energy sources that are continuously being replenished by natural processes that occur on human timescales. In contrast, fossil fuels (coal, natural gas, oil) require millions of years of geological processes to form. Our resources of fossil and nuclear fuels (e.g. uranium) are limited. Renewable energies, on the other hand, are virtually inexhaustible.

Today's most widespread applications for using renewable energies are solar panels, wind power plants and hydroelectric power plants.

SOLAR ENERGY (hydrogen fusion in the Sun)

Solar energy surrounds us in different forms and can be used in a variety of ways, including:

- Solar radiation: photovoltaics, solar heat
- Atmospheric movement: wind energy
- Evaporation/precipitation: hydroelectric energy/water power
- Biomass: e. g., fibre fuel, biogas

TIDAL ENERGY (gravitational attraction of Sun, Earth and Moon)

Tidal power plants use the energy provided by high and low tides. Water is stored during high tide and released during low tide, powering turbines in the process.

GEOTHERMAL ENERGY (radioactivity and primordial heat in Earth's interior)

Geothermal power plants use heat released from the interior through the Earth's crust.

3.1.2. HYDROGEN

Properties of hydrogen

Hydrogen is a colorless, odorless and non-toxic gas. It has a very low melting and boiling point. Hydrogen is the element with the simplest atomic structure. The most common isotope of hydrogen has only one proton and no neutron in its nucleus and one electron in its shell. Deuterium and tritium are less abundant isotopes, deuterium having one additional neutron in its nucleus and tritium two. Hydrogen is not only the smallest and lightest, but also the most abundant element in the universe. On Earth it is almost exclusively found in compound form.

Table 3.1.2. Properties of hydrogen

Density (at 0 °C and 1013 hPa) H_2 - gaseous	0.08988 kg/m^3
Melting point (101.3 kPa)	- 259 °C
Boiling point (101.3 kPa)	- 252.8 °C
H_h Calorific value (higher heating value)	12745 kJ/m^3
H_L Heating value (lower heating value)	10800 kJ/m^3
Valency z	1

Methods of hydrogen manufacture

In *electrolysis*, chemical compounds are decomposed by electrical current. For example, electrolysis can be used to decompose water into its constituents: hydrogen and oxygen.

Hydrogen is released from complex hydrocarbon compounds - such as methane or natural gas - by *reforming*.

In *cracking*, a method for refining crude oil, the gas is produced as a by-product at high pressure and high temperature.

Iron reacts with water vapor at high temperatures, likewise with the formation of hydrogen.

In the *"water gas" process*, coke and water vapor react at high temperatures to form water gas.

Hydrogen storage

The development of efficient hydrogen storage tanks is one of the key challenges in hydrogen management. Here, the decisive factors are storage capability, storage behavior, manufacturing effort and manufacturing costs. Three major technologies have emerged to date to address these needs the development of which is consistently promoted.

Tab. 3.1.2.a. High-pressure containers made from carbon composite materials (for pressures up to 350 bar)

Compressed gas storage

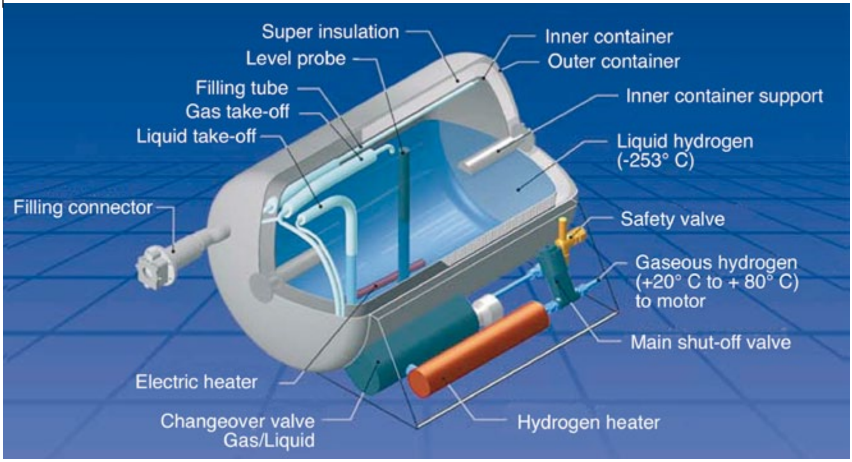
With its low manufacturing effort and cost, the conventional compressed gas bottle is the favorite when there is no shortage of space and high weight is acceptable. Several times the bottle's volume of gas can be stored in compressed gas bottles, as they are designed for pres-sures up to 200 bar. Compressed gas bottles are mainly used in fixed installations.

High-pressure containers made from carbon composite materials are the latest development in the area of compressed gas storage. They are lighter than conventional compressed gas bottles and, in addition, are designed for pressures up to 350 bar (in the future, pressures up to 700 bar will be possible).

Liquid hydrogen storage (cryostorage)

Hydrogen changes to the liquid phase at temperatures of -253° C. This deep-frozen hydrogen is stored in "cryostorage tanks", which maintain the liquid hydrogen at the appropriate temperature (-253° C) due to their excellent insulation. For the first few days after filling, the hydrogen can be stored without loss. After that, however, so-called evaporation losses can become a significant factor. Evaporation losses occur when, due to the slight temperature increase, a small amount of hydrogen changes back to the gaseous phase. The excess gaseous hydrogen must be released in order to avoid high pressure in the container. With today's technology, this loss is approximately 0.4 % of the tank volume per day.

Fig. 3.1.2.b. Liquid hydrogen tank



Additional energy, which is equivalent to approximately one-third of the stored energy, is required to liquefy the hydrogen.

Metal hydride storage tank

Fig. 3.1.2.c. Metal hydride storage tank

A metal hydride storage tank consists of special metal alloys that have to capability of storing hydrogen atoms in their crystal lattice. In order to obtain as large a surface area as possible for this, the metal alloys are pulverized. The hydrogen is introduced into the storage tank under slight positive pressure, and reacts with the metal alloy to form the metal hydride. This process is exothermic, i. e. heat is dissipated. Heat must be reintroduced in order to discharge hydrogen from the storage tank.

Metal hydride storage tanks have a high storage density with respect to the volume. However, they have a low storage density with respect to the weight. New, lighter storage materials are being developed. The use of these lighter materials could lead to a considerable improvement of weight-related storage density.

3.1.3. FUEL CELLS

The fuel cell's principle of operation is the reverse of that of an electrolytic cell (electrolyser). Like the electrolytic cell, a fuel cell consists of a negative and positive electrode and an electrolyte.

Types of fuel cells:

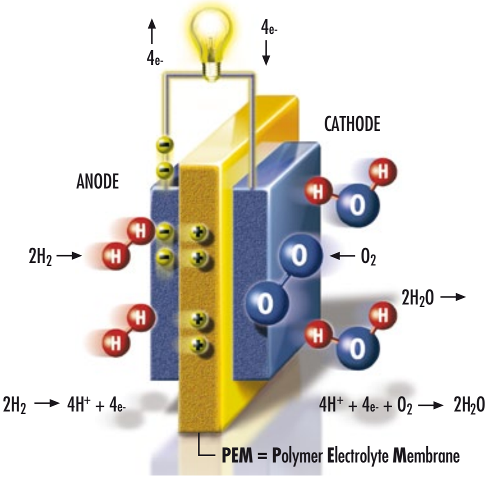
Table 3.1.3.

Fuel Cell	Electrolyte	Operating Temperature	Electrical Efficiency	Fuel *Oxydant*
Alcaline Fuel Cell = AFC	Potassium hydroxide (KOH) solution	Room temperature to 90 °C	60 - 70 %	H_2 O_2
Proton Exchange Membrane Fuel Cell = PEMFC	Proton exchange membrane	Room temperature to 80 °C	40 - 60 %	H_2,Hydrocarbons e.g. natural gas O_2, *Air*
High Temperature Proton Exchange Membrane Fuel Cell = HT-PEMFC	Proton exchange membrane	130 - 200 °C	40 - 60 %	Hydrocarbons, H_2 O_2, *Air*
Direct-Methanol-Fuel Cell = DMFC	Proton exchange membrane	Room temperature to 200 °C	20 - 30 %	CH_3OH O_2, *Air*
Phosphoric Acid Fuel Cell = PAFC	Phosphoric acid	160 - 220 °C	55 %	Hydrocarbons, H_2 O_2, *Air*
Molten Carbonate Fuel Cell = MCFC	Molten mixture of alkali metal carbonates	620 - 660 °C	65 %	Hydrocarbons, H_2 O_2, *Air*
Solix Oxide Fuel Cell = SOFC	Oxid ion conducting ceramic	800 - 1000 °C	60 - 65 %	Hydrocarbons, H_2 O_2, *Air*

The **PEM fuel cell** converts chemical energy into electrical energy efficiently. The electrolyte is a thin proton-conducting polymer membrane. The membrane is coated with catalyst material on both sides. These two layers form the cathode and the anode of the fuel cell. Individual cells are connected together to form compact stacks in order to match different power requirement. Stackability high efficiency, and good cold-start behavior of the PEM fuel cell make it suitable for a wide range of applications, e.g. for electric drives in cars, as a replacement for disposable and rechargeable batteries, and for residential electricity production.

PEM fuel cell: how it works

Fig. 3.1.3. The PEM fuel cell is an electrochemical energy converter, in which chemical energy is directly converted into electrical energy and heat. In this case, hydrogen and oxygen react spatially separately and noiselessly to form pure water, the only „emission" from the fuel cell..



The hydrogen gas fed to the anode breaks down into protons and electrons due to the catalytic action of the electrode (platinum), even at room temperature. The protons (H^+ ions) migrate through the proton-conducting membrane to the cathode side. When the external circuit is closed, the electrons migrate to the cathode and, in this way, perform electrical work. Protons, electrons and oxygen combine at the cathode to form water.

Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction: $4H^+ + 4e^- + O_2 \rightarrow 2H_2O$
Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

3.1.4. ELECTROLYSERS

In electrolysis, chemical compounds are decomposed by electrical current. For example, electrolysis can be used to decompose water into its constituents: hydrogen and oxygen.

In principle, an electrolyser consists of:
- a negatively charged cathode, to which the positive ions migrate
- a positively charged anode, to which the negative ions migrate
- an electrolyte, a material which conducts due to ion migration

Different types of electrolysers are categorized in terms of their electrode and electrolyte material:

Fig. 3.1.4.a. | Electrolyser with liquid electrolyte

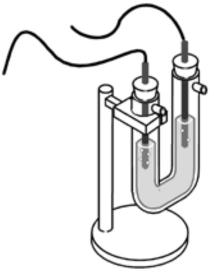
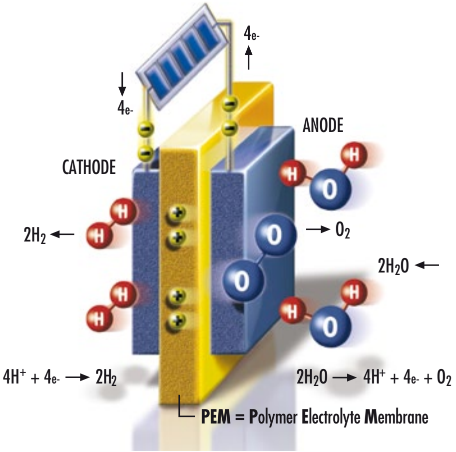


Fig. 3.1.4.b. | Electrolyser with solid electrolyte, the so-called Polymer Electorlyte Membrane



PEM electrolysers are distinguished by a very simple and compact design. The core of the PEM electrolyser is a thin, proton-conducting polymer membrane, which is coated on both sides with a layer of catalyst material. These two layers form the cathode and the anode of the cell. When a direct voltage is applied, the PEM electrolyser splits pure water into hydrogen and oxygen. To do this, the voltage must exceed the so-called decomposition voltage of the water. The theoretical decomposition voltage of water is 1.23 V. In practice, however, this voltage is higher as a result of contact resistances. Power electrolysers are built in the form of stacks. This is a series connection of electrolysers, which results in an addition of the voltages. PEM electrolysers achieve electrical efficiencies of up to approximately 85 %.

PEM electrolyser: how it works

When a direct voltage is applied to the anode, water molecules are oxidized to form oxygen and protons, and electrons are released. The protons (H^+ ions) migrate through the proton-conducting membrane to the cathode where they form hydrogen gas with the electrons flowing in the external circuit. Oxygen gas collects at the anode side.

Anode reaction $2H_2O \rightarrow 4H^+ + 4e^- + O_2$

Cathode reaction $4H^+ + 4e^- \rightarrow 2H_2$

Total reaction $2H_2O \rightarrow 2H_2 + O_2$

The name *PEM* is derived from the electrolyte used. In this case, this is a proton-conducting polymer foil. The letters PEM stand for Proton Exchange Membrane (sometimes also called Polymer Electrolyte Membrane). The membrane itself consists of a Teflon-polymer support frame, which has a sulphonic acid group (SO_3H) at the ends of its side chains. If the membrane is moistened, it acquires an acidic character and becomes conducting to protons. Anions (negatively charged ions and electrons) are unable to pass through the membrane.

3.2. SOLUTIONS TO STUDENT WORK SHEETS

3.2.1. THE SOLAR-HYDROGEN ENERGY CYCLE

***Question 1:* How long are conventional sources of energy expected to last?**

The reserves of natural uranium, natural gas and crude oil are expected to still be available more for 50 years (coal probably for more than 200 years). Keep in mind, however, that the reserves will not run out abruptly. Reserves will dwindle to ever more critical levels. Furthermore, these reserves are also required for other areas of application, e.g. crude oil is a basic building block of the plastics industry.

***Question 2:* Which components are included in the solar-hydrogen cycle?**

- Solar cells, wind power systems etc.
- Electrolyser
- Hydrogen storage tank
- Fuel cell
- Electrical consumer

***Question 3:* How can the solar-hydrogen cycle be described?**

Solar cells, wind power systems etc. convert the sun‘s energy into electrical energy. When energy is converted by solar cells and wind power systems, the availability of energy and the demand for energy often do not coincide in time or place. If they do coincide, the consumer can use the electrical energy directly. But, in order to be able to make the electrical energy available around the clock, an intermediate storage device is required. In the future, hydrogen could take over the task of intermediate storage. When supply exceeds demand, the electricity provided by solar cells and wind power systems is used to produce hydrogen. This is done with electrolysers which are supplied with direct current and decompose water into hydrogen and oxygen. Electrical energy is converted to chemical energy (hydrogen). The hydrogen (and, if required, the oxygen) is stored until demand exceeds supply. Now the hydrogen (and oxygen) is fed to the fuel cell, which converts the chemical energy of the hydrogen back into electricity, water and heat. In this way electricity can be supplied at any time.

***<u>Question 4:</u>* What are the three different primary renewable energy sources?**

- **Solar energy** *(nuclear fusion in the sun: conversion of hydrogen into helium)*
- **Tidal energy** *(gravitational interaction of earth, sun and moon)*
- **Geothermal energy** *(radioactivity and primordial heat in the Earth's interior)*

***<u>Question 5:</u>* How are the three primary renewable energy sources used to obtain energy?**

Solar energy *(nuclear fusion in the sun: conversion of hydrogen into helium)*
The sun's energy occurs in different forms due to natural energy conversion, such as:

- Solar radiation (photovoltaics, solar heat)
- Wind power from atmospheric movement
- Water power from evaporation/precipitation
- Biomass from photosynthesis

Ultimately, fossil fuels are only stored solar energy. In contrast to renewable energy sources, however, they are not renewable on human timescales, but require millions of years to form. The most frequently used energy converters for renewable energy today are solar cells, wind power systems and hydroelectric power stations.

Tidal energy *(gravitational interaction of earth, sun and moon)*
Tidal power stations use the ebb and flow of currents caused by the rising and falling of the water level.

Geothermal energy *(radioactivity and primordial heat in the Earth's interior)*
Geothermal systems use the natural heat of the earth's crust. The temperature increases with increasing depth into the earth.
In geothermal systems, hot water from the deep is used for heating purposes or for producing electrical energy (steam turbine).

3.2.2. HYDROGEN

<u>Question 1:</u> Name the 7 properties of natural hydrogen:

1 - Colorless gas
2 - Odorless
3 - Non-toxic
4 - Very low melting point (- 259 °C)
5 - Very low boiling point (- 252.8 °C)
6 - Simplest atomic structure consisting of only one proton and one electron
7 - Smallest and lightest element

<u>Question 2:</u> What are the known isotopes of hydrogen?

1. Natural hydrogen, consisting of one electron in the atomic shell and one proton in the atomic nucleus (${}^{1}_{1}H$); most frequently occurring hydrogen isotope (frequency greater than 99.9%).
2. Deuterium, also known as heavy hydrogen, consisting of one electron in the atomic shell and one proton and one neutron in the atomic nucleus (${}^{2}_{1}H$).
3. Tritium, consisting of one electron in the atomic shell and one proton and two neutrons in the atomic nucleus (${}^{3}_{1}H$).

<u>Question 3:</u> Name different ways of producing hydrogen gas:

- Electrolysis
- Reforming
- Cracking of hydrocarbons
- Iron/water vapor reaction
- "Water gas" process

<u>Question 4:</u> Name the three most common methods of storing hydrogen:

1 – Under high pressure (e. g. 200 bar) in compressed gas tanks
2 – Deep-frozen (- 253 °C) liquefied in cryogenic tanks
3 – By storing hydrogen atoms in metal lattices in so-called metal hydrides.

3.2.3. FUEL CELLS

***Question 1:* What are the main components of all fuel cells?**

Electrodes (cathode and anode) and electrolyte.

***Question 2:* What are the main differences in the types of fuel cells?**

The type of electrolyte and the operating temperature.

***Question 3:* Name some types of fuel cells.**

AFC, PEMFC, DMFC, PAFC, MCFC, SOFC

***Question 4:* How does a hydrogen-operated PEM fuel cell work?**

The hydrogen gas fed to the anode breaks down into protons and electrons due to the catalytic action of the electrode even at room temperature. The protons (H^+ ions) migrate through the proton-conducting membrane to the cathode side. The electrons are not allowed to pass through. If an external circuit is connected, they migrate to the cathode. An electric current flows. The hydrogen ions impinge on the oxygen from the air and the electrons from the external circuit at the cathode. They combine and react to form water.

***Question 5:* What material is the catalyst layer in a PEM fuel cell made of?**

Platinum.

***Question 6:* What is the chemical equation for the reaction in a hydrogen-operated PEM fuel cell?**
a| at the anode side, b| at the cathode side, and c| for the total reaction?

a| Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
b| Cathode reaction: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$
c| Total reaction: $2H_2 + O_2 \rightarrow 2H_2O$

***Question 7:* What are the advantages of a hydrogen-operated PEM fuel cell with regard to environmental pollution?**

It has a higher efficiency and the "emission" it produces is pure water.

Question 8: ***What is the maximum efficiency of a PEM fuel cell?***

The electrical efficiency of the PEM fuel cell is about 50 %. If the heat produced in the fuel cell is also used, e. g. by means of power-heat coupling, a total efficiency of approximately 85 % can be achieved.

Question 9: ***What do engineers describe as a stack?***

The interconnection of several fuel cells to achieve higher power.

Question 10: ***In what areas are fuel cells already being used and developed today?***

In manned and unmanned space travel, for generating electricity in electric vehicles, and in heat and power stations with electricity generation.

3.2.4. ELECTROLYSERS

***Question 1:** What is electrolysis?*

The use of an electrical current to break down a liquid into its component elements.

***Question 2:** What does an electrolyser consist of?*

Negatively charged cathode, positively charged anode, electrolyte.

***Question 3:** In the future how can hydrogen be obtained on a large scale with new technologies?*

By electrolysis in the PEM electrolyser.

***Question 4:** Where does the term PEM come from?*

PEM is derived from the electrolyte used, a proton-conducting polymer foil. The letters **PEM** stand for **P**olymer **E**lectrolyte **M**embrane or also **P**roton **E**xchange **M**embrane.

***Question 5:** What is the electrical efficiency of a PEM electrolyser?*

The electrical efficiency of PEM electrolysers can be up to 85 %.

***Question 6:** How does a PEM electrolyser work?*

When a direct voltage is applied to the anode, water molecules are oxidized to form oxygen, protons and electrons. The protons (H^+ ions) migrate through the proton-conducting membrane to the cathode where they form hydrogen gas with the electrons flowing in the external circuit. Oxygen gas collects at the anode side.

***Question 7:** What is the chemical equation for the reaction in a hydrogen-operated PEM electrolyser*

a| at the anode side, b| at the cathode side, and c| for the total reaction?

a| Anode reaction: $2H_2O \rightarrow 4H^+ + 4e^- + O_2$

b| Cathode reaction: $4H^+ + 4e^- \rightarrow 2H_2$

c| Total reaction: $2H_2O \rightarrow 2H_2 + O_2$

***Question 8:* What is the decomposition voltage of water?**

The theoretical decomposition voltage of water is 1.23 V.

***Question 9:* Name other ways of producing hydrogen gas.**

Reforming, cracking of hydrocarbons, iron/water vapor reaction, "water gas" process.

3.3. STUDENT WORK SHEETS (BASIC AND ADVANCED LEVEL)

3.3.1. THE SOLAR-HYDROGEN ENERGY CYCLE

In any energy system we need to convert energy to be able to use it. For example coal by itself is not useful. But by burning it, we get thermal energy and can heat our homes, or we can convert the thermal energy to electricity to power our electrical appliances.

Major components of any energy systems are:
- Primary Energy
- Conversion of primary energy to usable form of energy (e.g. electricity)
- Storage and transport, to be able to use energy anywhere and anytime
- Conversion of stored energy to usable form of energy (e.g. electricity)

Question 1: ***How long are conventional sources of energy expected to last?***

Question 2: ***Which components are included in the solar-hydrogen cycle?***

Question 3: ***How can the solar-hydrogen cycle be described?***

Question 4: ***What are the three different primary renewable energy sources?***

Question 5: ***How are the three primary renewable energy sources used to obtain energy?***

3.3.2. HYDROGEN

Question 1: ***Name the 7 properties of natural hydrogen:***

Question 2: ***What are the known isotopes of hydrogen?***

Question 3: ***Name different ways of producing hydrogen gas:***

Question 4: ***Name the three most common methods of storing hydrogen:***

3.3.3. FUEL CELLS

Question 1: ***What are the main components of all fuel cells?***

Question 2: ***What are the main differences in the types of fuel cells?***

Question 3: ***Name some types of fuel cells.***

Question 4: ***How does a hydrogen-operated PEM fuel cell work?***

Question 5: ***What material is the catalyst layer in a PEM fuel cell made of?***

Question 6: ***What is the chemical equation for the reaction in a hydrogen-operated PEM fuel cell***
a| at the anode side, b| at the cathode side, and c| for the total reaction?

Question 7: ***What are the advantages of a hydrogen-operated PEM fuel cell with regard to environmental pollution?***

Question 8: ***What is the maximum efficiency of a PEM fuel cell?***

Question 9: ***What do engineers describe as a stack?***

Question 10: ***In what areas are fuel cells already being used and developed today?***

3.3.4. ELECTROLYSERS

Question 1: *What is electrolysis?*

Question 2: *What does an electrolyser consist of?*

Question 3: *In the future how can hydrogen be obtained on a large scale with new technologies?*

Question 4: *Where does the term PEM come from?*

Question 5: *What is the electrical efficiency of a PEM electrolyser?*

Question 6: *How does a PEM electrolyser work?*

Question 7: *What is the chemical equation for the reaction in a hydrogen-operated PEM electrolyser*
a| at the anode side, b| at the cathode side, and c| for the total reaction?

Question 8: *What is the decomposition voltage of water?*

Question 9: *Name other ways of producing hydrogen gas.*

3.4. EXPERIMENT WORK SHEETS (BASIC LEVEL)

3.4.1. DECOMPOSITION OF WATER WITH REGARD TO THE RESULTING VOLUME OF HYDROGEN AND OXYGEN GAS

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

BACKGROUND

In electrolysis, chemical compounds are decomposed (broken down) using electrical current. This allows water to be split into its elements hydrogen and oxygen. Since every water molecule H_2O is made up of two hydrogen atoms and one oxygen atom, the volume of hydrogen and oxygen gas produced is expected to have a ratio of 2:1. In the subsequent sections of this book, volume is always used to describe the volumes of gas, since hydrogen and oxygen are always gaseous at normal ambient temperatures and ambient pressure.

APPARATUS

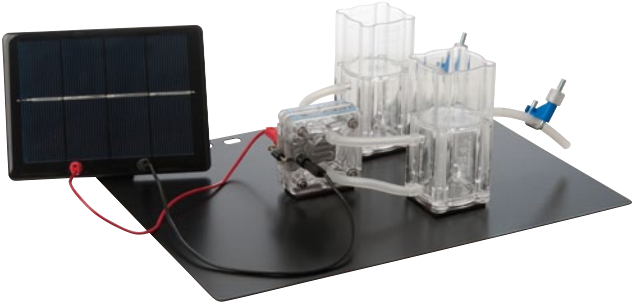
- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Power source, such as a solar module, laboratory power supply
- A light, if necessary, for operating the solar module

SETUP *(See also operating instructions)*

Connect the electrolyser to the power source.

Perform the work using a voltage value greater than 1.5V and less than 2V, for example 1.9V. For multi-cell electrolysers (electrolyser stack), the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum.

Setup 3.4.1.



PROCEDURE

Switch on the device is described in the operating instructions.

Before beginning the experiment, the gas storage tanks must be completely filled with distilled water.

Produce, for example, 10cm^3 of hydrogen. Disconnect the electrolyser from the power source and record the volume of oxygen produced.

Example:

Volume of hydrogen produced	Volume of oxygen produced

ANALYSIS

1. Compare the volume of the hydrogen gas produced with the volume of oxygen gas.

Do the test results confirm your expectations?

3.4.2. CURRENT-VOLTAGE CHARACTERISTICS, POWER CURVE AND EFFICENCY OF SOLAR MODULE

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed intructions!

Follow all written safety instructions as well as any provided by the instructor!

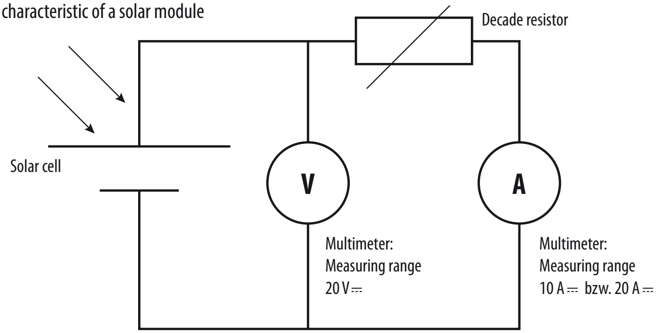
APPARATUS

- Solar module
- A light, if necessary, for operating the solar module
- Variable resistor as well as a measuring instrument for current and voltage, e.g.:
  - Decade resistor, various resistors, potentiomete and two multimeters
- Instrument for determining the radiant power of the light:
  - a| Measuring instrument for the direct measurement of the radiant power of the light, e.g.: Pyranometer
  - b| *Alternative:* The radiant power of the light is determined using the short-circuit current of the solar module.

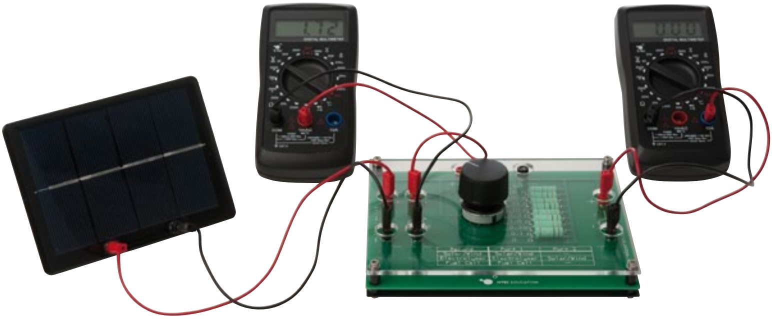
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram.

Circuit Diagram 3.4.2. | Setup for determining the characteristic of a solar module



Setup 3.4.2.



PROCEDURE

Point the lamp at the solar module at a right angle (90° angle). Observe the safety clearances. Once the setup is complete, wait one minute to avoid errors due to temperature fluctuations.

Start recording the current-voltage characteristic using the open-circuit voltage (R = ∞) and successively switch the decade resistor to the lower resistances. Record the voltage and current for the respective resistance in a table. After changing the resistance, wait for approximately 20 seconds in between measurements.

Table 3.4.2. Table of measurements

Resistance R (Ω)	Voltage U (V)	Current I (A)	Power calculated P (W) calculated $P = U \cdot I$
∞			
330			
100			
33			
10			
3.3			
1			
0.33			
0.1			
0			

ANALYSIS

1. Using the measurements in the table, plot a graph showing the relationship between the photoelectric current and the photoelectric voltage. Identify the maximum power point (MPP) in this diagram.
2. Plot a graph showing the power as a function of the voltage.
3. Calculate the efficiency of the solar module.
4. Interpret your results.

3.4.3. CURRENT-VOLTAGE CHARACTERISTIC OF PEM ELECTROLYSER

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

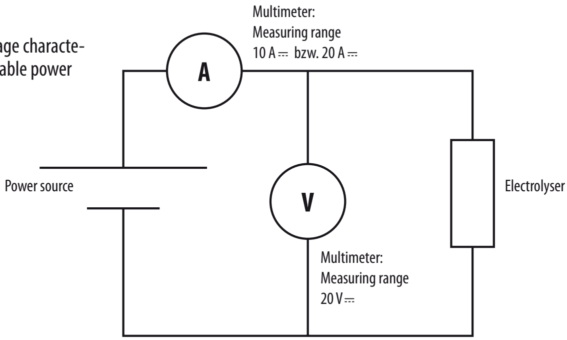
Follow all written safety instructions as well as any provided by the instructor!

APPARATUS

- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Measuring instrument for current and voltage, e.g.:
  - Two multimeters
- Power source
  - a| Adjustable power source, e.g. laboratory power supply
  - b| *Alternative:* solar module, in which case, the following are also needed:
    - A light, if necessary, for operating the solar module
    - Variable resistor as well as a measuring instrument for current and voltage, e.g.:
      - Decade resistor, various resistors, potentiometer and two multimeters

SETUP *(See also operating instructions)*

a| Connect the electrolyser directly to the adjustable power source. Set this DC power source to 0V and then increase it to a maximum of 2.0V.

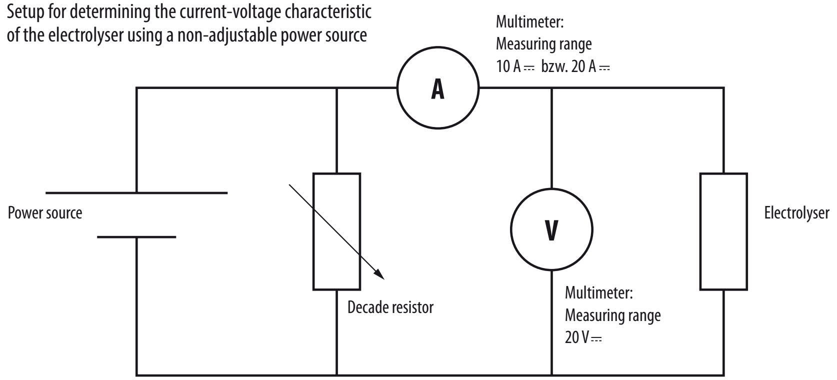


Circuit Diagram 3.4.3.a | Setup for determining the current-voltage characteristic of the electrolyser using an adjustable power source

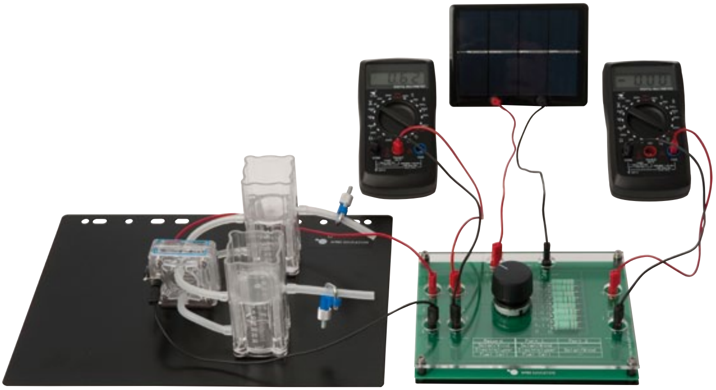
For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, it would be 4V, for 3 cells, it would be 6V, etc.

b| Create the circuit as shown in the following circuit diagram.

Circuit Diagram 3.4.3.b | Setup for determining the current-voltage characteristic of the electrolyser using a non-adjustable power source



Setup 3.4.3.b



PROCEDURE

Switch on the device as described in the operating instructions.

a| Continually increase the voltage on the power supply in 0.1-volt increments from 0V to 2V and record the respective voltage and the corresponding current in a table.

After changing the voltage, wait for 20 seconds in between measurements to obtain representative values. Observe the start of gas production and mark down the corresponding voltage in the table.

b| Gradually switch the decade resistor from low to high resistances and record the respective voltage and the corresponding currents in a table. Single-cell electrolysers must not exceed the maximum value of 2V. For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum. After changing the resistance, wait for 20 seconds in between measurements to obtain representative values. Observe the start of gas production and mark down the corresponding voltage in the table.

Table 3.4.3.b. | Table of measurements

Resistance *R* / Ω	Voltage *U* / V	Current *I* / A
0		
0.1		
0.33		
1		
3.3		
10		
33		
100		
330		
∞		

ANALYSIS

1. Plot the recorded value pairs in a graph.
2. The resulting curve is the voltage-current characteristic of the electrolyser that can be approximated by two intersecting straight lines. Draw the 2 straight lines and mark the intersection point of the sloped line with the *U*-axis. This intersection point marks the practical decomposition voltage of water. Record the value and compare it with the theoretical decomposition voltage.
3. Interpret your results.

3.4.4. ENERGY EFFICIENCY OF PEM ELECTROLYSER

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

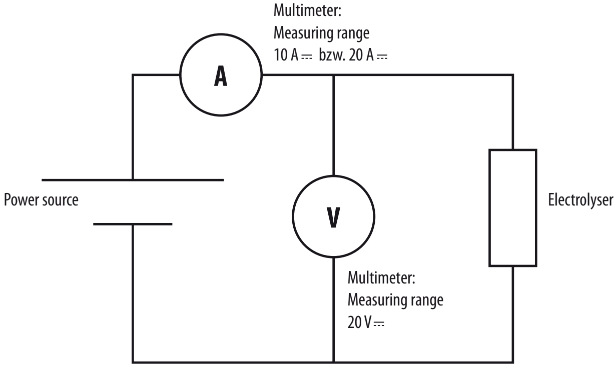
APPARATUS

- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Measuring instrument for current and voltage, e.g.:
  - Two multimeters
- Power source
  - a| Adjustable power source, e.g. laboratory power supply
  - b| Alternative: solar module, in which case, the following are also needed:
    - A light, if necessary, for operating the solar module
    - Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
      - Decade resistor, various resistors, potentiometer and two multimeters

SETUP *(See also operating instructions)*

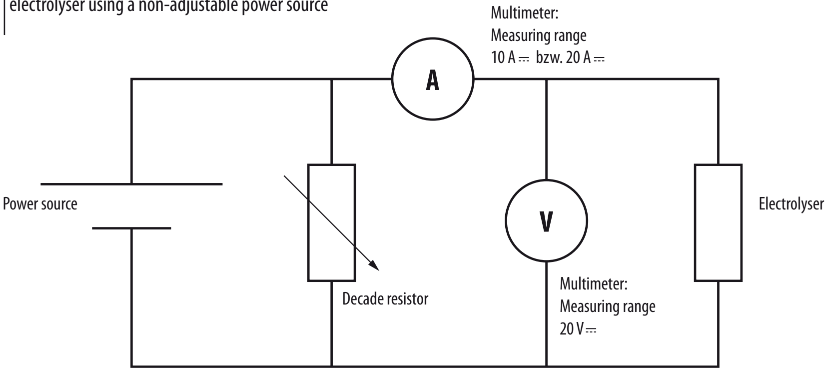
a| Connect the electrolyser directly to the adjustable power source. Set a voltage greater than 1.5V and lower than 2V (e.g. 1.8V).
For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, the maximum is 4V, for 3 cells, the maximum is 6V, etc.

Circuit Diagram 3.4.4.a | Setup for determining the energy efficiency of the electrolyser using an adjustable power source

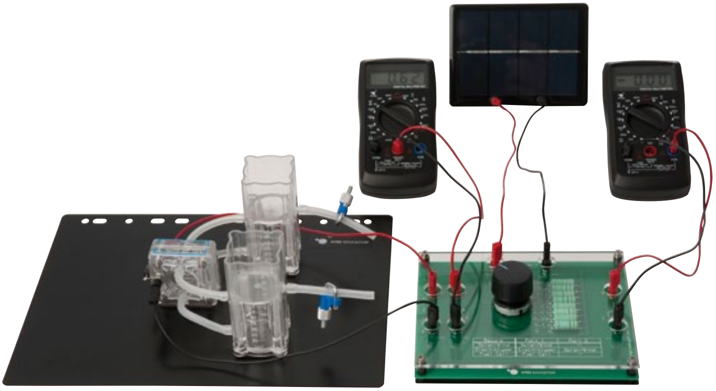


b| Create the circuit as shown in the following circuit diagram. apply a voltage greater than 1.5V and less than 2V to the electrolyser (e.g. 1.8V). For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, the maximum is 4V, for 3 cells, the maximum is 6V, etc.

Circuit Diagram 3.4.4.b | Setup for determining the energy efficiency of the electrolyser using a non-adjustable power source



Setup
3.4.4.b



PROCEDURE

Switch on the device as described in the operating instructions.

Allow several minutes of gas production before starting to record the data. Interrupt the power supply to the electrolyser. Open the gas outlet of the hydrogen storage tank to completely release the gases produced. Once the gases have been removed, fill the storage tanks completely with distilled water. The water level must coincide with the 0 cm^3 graduation mark, when viewed horizontally. Now close the gas outlet of the hydrogen storage tank.

Begin measuring the time from the moment you connect the electrolyser to the power source. Record the voltage applied to the electrolyser and the current flowing through it. Record the time, voltage and current values at each of the graduation marks. Take the last measurements when the hydrogen storage tank is completely filled with gas.

Table 3.4.4. Table of measurements

Produced hydrogen V_{H_2} (cm^3)	**Time t (s)**	**Voltage U (V)**	**Current I (A)**

ANALYSIS

1. Plot a graph showing the volume of gas produced as a function of time.
2. Calculate the energy efficiency of the electrolyser. The efficiency indicates how much of the input energy E_{input} is dissipated in the system (in this case, the electrolyser) as actual usable energy E_{usable}.

$$\eta_{energy} = \frac{E_{Hydrogen}}{E_{electric}} = \frac{Hydrogen \cdot volume \cdot Calorific \cdot value}{Voltage \cdot Current \cdot Time} = \frac{V_{H_2} \cdot H_h}{\bar{U} \cdot \bar{I} \cdot t}$$

H_h = Caloric value[1] of hydrogen = $12.745 \cdot 10^6 \frac{J}{m^3}$
V_{H_2} = Quantity of hydrogen produced in m^3
U = Voltage in V
I = Current in A
t = Time in s

3. Interpret your results.

---

[1] The energy that is released during the combustion of a substance (oxidation) is defined as the calorific value H_h (also called higher heating value). It also includes the energy contained by the water vapor from combustion as condensation heat. This energy cannot be used in conventional combustion systems. Therefore, a value is also formulated that does not include the condensation heat. This variable is called a heating value H_l and is used to calculate the efficiency for heating systems, motors and fuel cells.

3.4.5. CURRENT-VOLTAGE CHARACTERISTIC AND POWER CURVE OF PEM FUEL CELL

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

APPARATUS

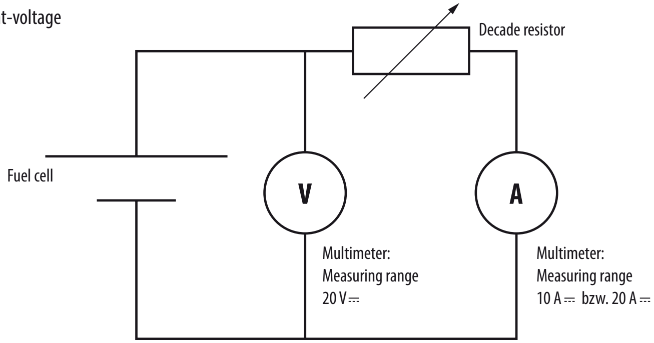
- PEM fuel cell
- Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Hydrogen source

  Electrolyser or RFC in Electrolysis mode with gas storage tanks, in which case, the following is also needed:
  - Power source, such as a solar module, laboratory power supply
  - A light, if necessary, for operating the solar module

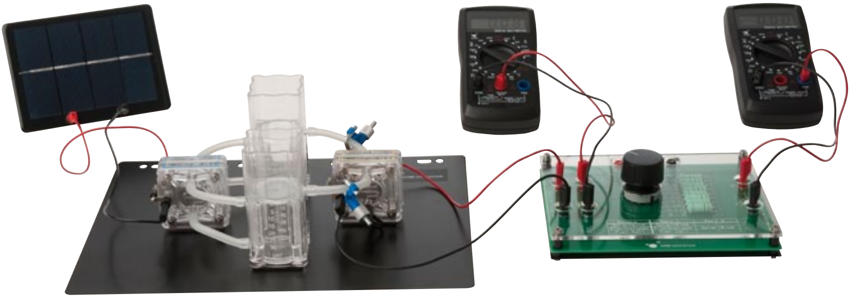
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 3.4.5. Setup for determining current-voltage characteristic of the fuel cell



Setup
3.4.5.



PROCEDURE

Switch on the device as described in the operating instructions. Note that no additional oxygen is required in hydrogen/air mode, i.e. the following description only refers to hydrogen.

Connect the electrolyser to the power source to produce hydrogen and oxygen. Connect the outlet connections of the electrolyser to the input connections of the gas storage tanks and their outputs to the input connections of the fuel cell. Close the fuel cell outlets. After you have produced approximately 10 cm^3 of hydrogen gas, open the fuel cell outlets, purge them with gas and close them again. This removes the residual gases that distort the measurement. To prevent the fuel cell from using any hydrogen before the measurement is taken, the fuel cell must be switched to open circuit (open clamps, no flowing current). Start recording the current-voltage characteristic in a table using the open circuit voltage ($R = \infty$). Switch the decade resistor from higher to lower resistances and record the corresponding voltage and current value at the resistances. After changing the resistance, wait for approximately 20 seconds in between measurements to obtain representative results.

Table 3.4.5. Table of measurements

Resistance R (Ω)	Voltage U (V)	Current I (A)	Power P (W) calculated P = U · I
∞			
330			
100			
33			
10			
3.3			
1			
0.33			
0.1			
0			

ANALYSIS

1. Plot a graph using recorded values as a current-voltage characteristic.
2. Plot a graph showing the power as a function of the current. Mark the maximum power point.
3. Interpret your results.

3.4.6. ENERGY EFFICIENCY OF THE PEM FUEL CELL

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

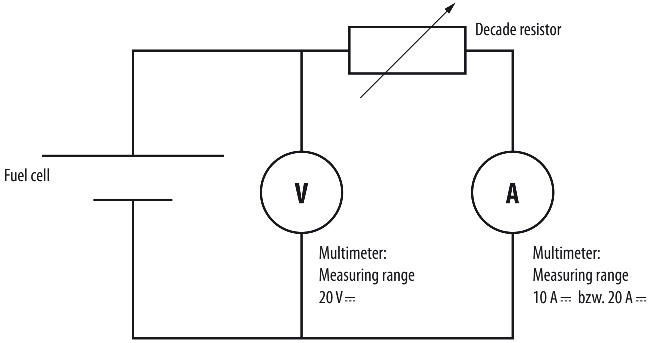
APPARATUS

- PEM fuel cell
- Hydrogen source, e.g. PEM electrolyser or RFC in Electrolysis mode
- Gas storage tanks
- Power source, such as a solar module or laboratory power supply for the electrolyser
- A light, if necessary, for operating the solar module
- Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Stopwatch

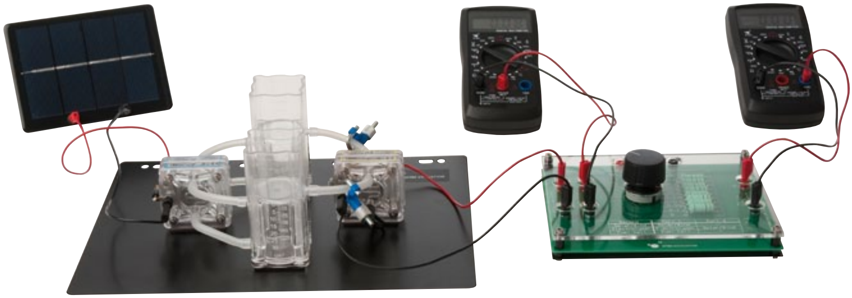
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 3.4.6. | Setup for determining the energy efficiency of the fuel cell



Setup 3.4.6.



PROCEDURE

Switch on the device as described in the operating instructions.

Note: *No additional oxygen is required for hydrogen/air fuel cells, i.e. the following description only refers to hydrogen.*

Connect the connections on the electrolyser side of the gas storage tanks to the electrolyser or the RFC and the outlet connections of the gas storage tanks to the input connections of the fuel cell. To prevent the fuel cell from using any hydrogen before the measurement is taken, the fuel cell must be switched to open circuit (open clamps, no current flow). Close the fuel cell outlets. Produce approximately 10 cm^3 of hydrogen gas, then briefly open the fuel cell outlets to vent the system and then close them again. Produce the maximum volume of hydrogen possible with the system (in this example, 30 cm^3). If necessary, interrupt the power supply to the electrolyser and disconnect the electrical connection between the fuel cell and the decade resi-stor. Switch the decade resistor to the resistance at which you want to determine the energy efficiency (e.g. 3.3 Ω). Reconnect the circuit between the fuel cell and the decade resistor and start measuring the time from this moment.

Record the measured time, voltage and current at constant volume increments (e.g. 5 cm^3). Do not change the resistance. Make sure that the current values do not fluctuate too much (take the measurement again if necessary). Any substantial reduction in the current during the measurement will probably be due to residual gases in the storage tank that impair the operation of the fuel cell. This problem may also occur if only a small quantity of hydrogen is left in the storage tank
(e.g. only 5 cm^3).

Table 3.4.6. | Table of measurements

Hydrogen Volume V_{H_2} (cm^3)	Time t (s)	Voltage U (V)	Current I (A)
Mean			

ANALYSIS

1. Plot a graph showing the volume of gas produced as a function of time.
2. Calculate the energy efficiency of the fuel cell. The efficiency indicates how much of the input energy E_{input} is dissipated in the system (in this case, the fuel cell) as actual usable energy E_{usable}.

$$\eta_{energy} = \frac{E_{electric}}{E_{Hydrogen}} = \frac{Voltage \cdot Current \cdot Time}{Hydrogen\ \ volumes \cdot Caloric\ \ value} = \frac{\bar{U} \cdot \bar{I} \cdot t}{V_{H_2} \cdot H_l}$$

H_l = Heating value[1] of the hydrogen = $10.8 \cdot 10^6 \frac{J}{m^3}$ (also called lower heating value)
V_{H_2} = Quantity of hydrogen produced in m^3
U = Voltage in V
I = Current in A
t = Time in s

3. Interpret your results.

---

[1] The heating value is defined as the energy released during the combustion of a substance (oxidation). It does not include the energy contained by the water vapor from combustion as condensation heat. This energy cannot be used in heating systems, motors and fuel cells, for example.

3.5. EXPERIMENT WORKSHEETS FOR ADVANCED LEVEL

3.5.1. CURRENT-VOLTAGE CHARACTERISTIC, POWER CURVE-AND EFFICIENCY OF SOLAR MODULE

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

PRE-LAB QUESTIONS

What behavior do you expect from the current-voltage characteristic and the power curve? Draw a sketch of the expected characteristic.

What information can you find for the efficiencies of solar cells made of amorphous, polycrystalline and monocrystalline silicon?

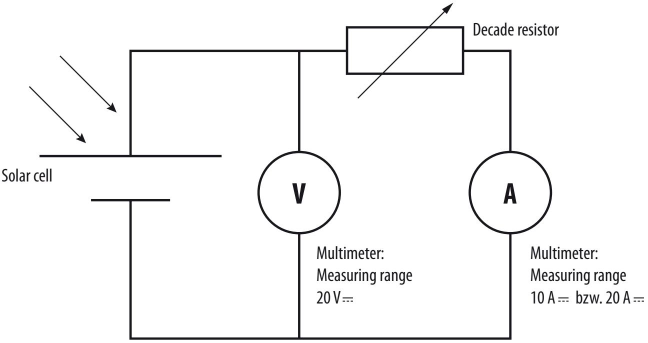
APPARATUS

- Solar module
- A light, if necessary, for operating the solar module
- Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Instrument for determining the radiant power of the light:
  - a| Measuring instrument for the direct measurement of the radiant power of the light, e.g.: Pyranometer
  - b| *Alternative:* The short-circuit current of the solar module is used to determine the radiant power of the light.

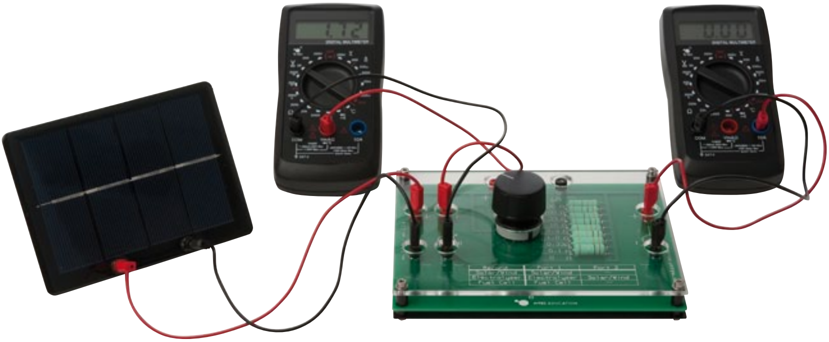
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 3.5.1. | Setup for determining the characteristic of a solar module



Setup 3.5.1. |



PROCEDURE

Point the lamp at the solar module at a right angle (90° angle). Observe the safety clearances. In order to prevent errors due to temperature fluctuations, wait at least 1 minute after switching the lamp on. Start recording the current-voltage characteristic using the open-circuit voltage (R = ∞) and switch the decade resistor to successively lower resistances. Record the voltage and current for the respective resistance in a table. After changing the resistance, wait for approximately 20 seconds in between measurements.

Table 3.5.1. Table of measurements

Resistance **R (Ω)**	**Voltage** **U (V)**	**Current** **I (A)**	**Power** **P(W) calculated** **P = U · I**
∞			
330			
100			
33			
10			
3.3			
1			
0.33			
0.1			
0			

ANALYSIS

1. Using the data from the table of measurements, plot a graph showing the photoelectric current as a function of the photoelectric voltage.
   Identify the maximum power point (MPP) in this diagram.
2. Plot a graph showing the power as a function of the voltage.
3. Calculate the efficiency of the solar module. Describe the loss processes that reduce the efficiency of solar cells.
4. Interpret your results and compare them with your answers to the pre-lab questions.

3.5.2. CURRENT-VOLTAGE CHARACTERISTIC OF PEM ELECRTOLYSER

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

PRE-LAB QUESTIONS

What behaviour do you expect from the current-voltage characteristic? Draw a sketch of the expected characteristic.

APPARATUS

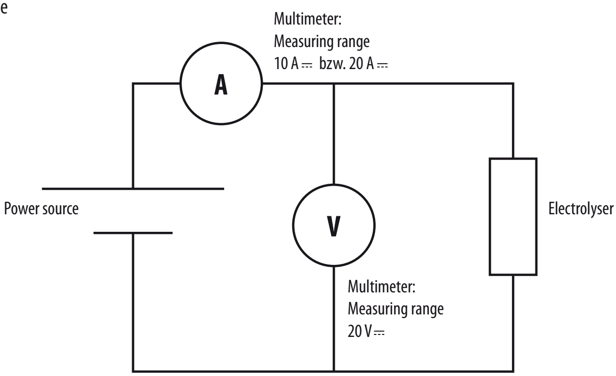
- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Measuring instrument for current and voltage, e.g.:
  - Two multimeters
- Power source
  - a| Adjustable power source, e.g. laboratory power supply
  - b| *Alternative:* solar module, in which case, the following are also needed:
    - A light, if necessary, for operating the solar module
    - Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
      - Decade resistor, various resistors, potentiometer and two multimeters

SETUP *(See also operating instructions)*

a| Connect the electrolyser directly to the adjustable power source.

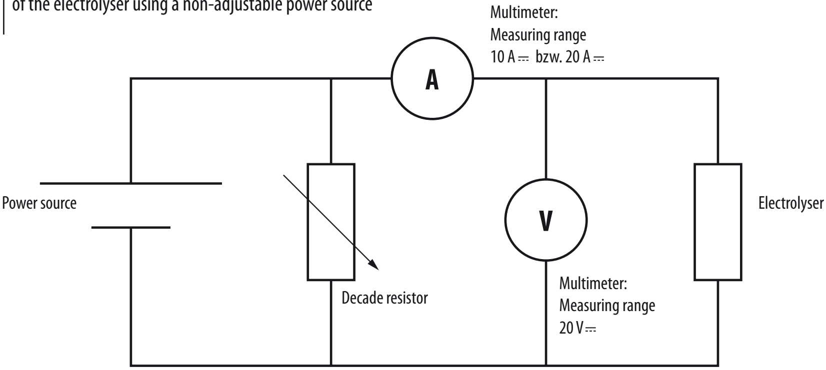
Set this DC power source to 0V and then increase it to a maximum of 2.0V. For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum.

Circuit Diagram 3.5.2.a | Setup for determining the current-voltage characteristic of the electrolyser using an adjustable power source

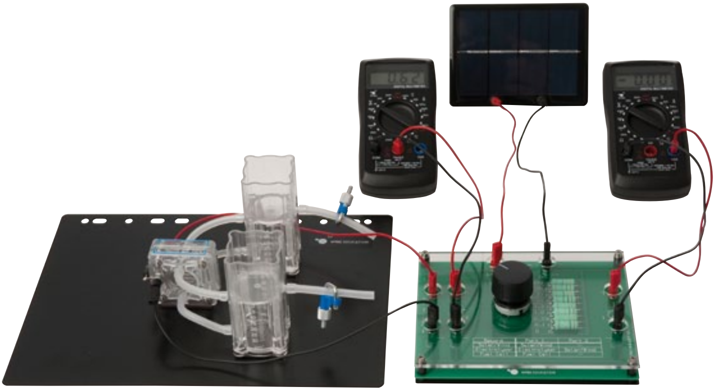


b| Create the circuit as shown in the following circuit diagram.

Circuit Diagram 3.5.2.b | Setup for determining the current-voltage characteristic of the electrolyser using a non-adjustable power source



Setup
3.5.2.b.



PROCEDURE

Switch on the device as described in the operating instructions.

a| Continually increase the voltage on the power source in 0.1-V increments from 0V to 2V and record both the respective voltage and corresponding current in a table. After changing the voltage, wait for 20 seconds in between measurements to obtain representative values. Observe the start of gas production and mark down the corresponding voltage in the table.

b| Gradually switch the decade resistor from low to high resistances and record the respective voltage and the corresponding currents in a table. (Single-cell electrolysers must not exceed the maximum value of 2V. For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells 4V is the maximum and for 3 cells 6V is the maximum.) After changing the resistance, wait for 20 seconds in between measurements to obtain representative values. Observe the start of gas production and mark down the corresponding voltage in the table.

Table 3.5.2. Table of measurements

Resistance **R (Ω)**	**Voltage** **U (V)**	**Current** **I (A)**
0		
0.1		
0.33		
1		
3.3		
10		
33		
100		
330		
∞		

ANALYSIS

1. Plot a graph of the recorded value pairs in a diagram.
2. The resulting curve is the voltage-current characteristic of the electrolyser that can be approximated by two intersecting straight lines.
   Draw the 2 straight lines and mark the intersection point of the sloped line with the *U*-axis. The intersection point marks the practical decomposition voltage of water. Note the value and compare it with the theoretical decomposition voltage.
3. Explain the energy conversion in relation to the decomposition of water.
4. Specify the appropriate reaction equations.
5. Interpret your results and compare them with your answers to the pre-lab questions.

3.5.3. ENERGY EFFICIENCY AND FARADAY EFFICIENCY OF PEM-ELECRROLYSER

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

PRE-LAB QUESTIONS

What information can you find for the efficiency of the PEM electrolysers?
Does the efficiency depend on the power of the electrolyser?

APPARATUS

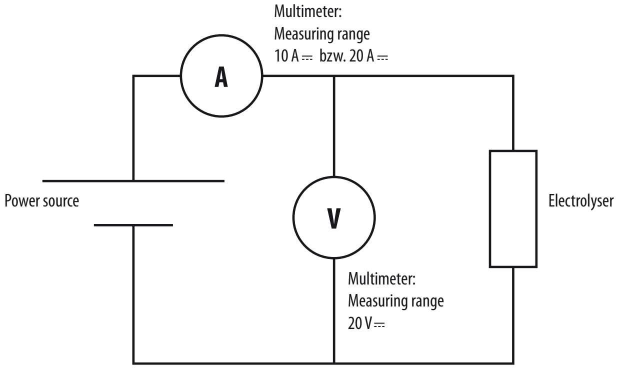
- PEM electrolyser or PEM RFC in Electrolysis mode
- Two gas storage tanks
- Measuring instrument for current and voltage, e.g.:
  - Two multimeters
- Power source
  - a| Adjustable power source, e.g. laboratory power supply
  - b| *Alternative:* solar module, in which case, the following are also needed:
    - A light, if necessary, for operating the solar module
    - Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
      - Decade resistor, various resistors, potentiometer and two multimeters

SETUP *(See also operating instructions)*

a| Connect the electrolyser to the adjustable power source. Set a voltage greater than 1.5V and less than 2V.

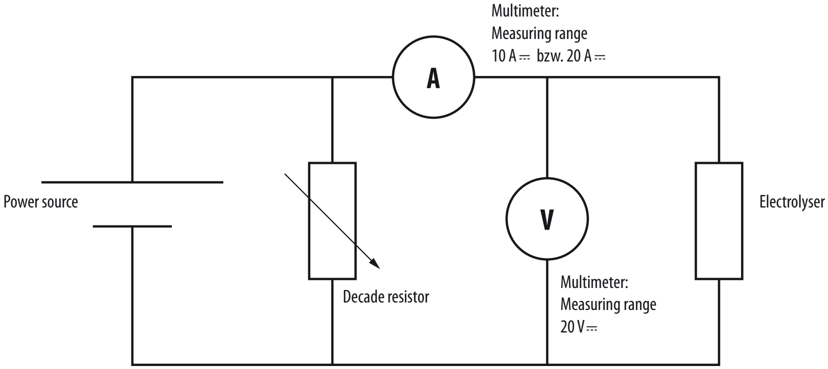
For multi-cell electrolysers, the voltage must be higher, depending on the number of cells. To obtain the maximum value, multiply 2V by the number of cells, e.g. for 2 cells, 4V is the maximum and for 3 cells, 6V is the maximum.

Circuit Diagram 3.5.3.a | Setup for determining the efficiency of the electrolyser using an adjustable power source

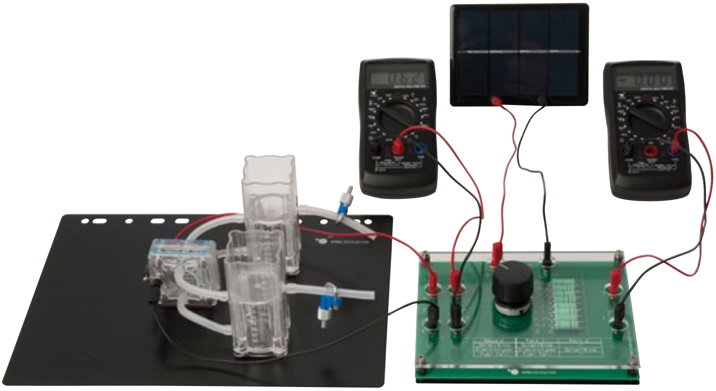


b| Connect the electrolyser to the solar module and illuminate the solar module. This will create a voltage between 1.5V and 2V.

Circuit Diagram 3.5.3.b | Setup for determining the efficiency of the electrolyser using a non-adjustable power source



Setup
3.5.3.b.



PROCEDURE

Switch on the device as described in the operating instructions.

Allow several minutes of gas production before starting to record the data. Interrupt the power supply to the electrolyser. Open the outlet valves of the gas storage tanks to completely release the gases produced. Once the gases have been removed, fill the storage tanks completely with distilled water. The water level must coincide with the 0 cm^3 graduation mark, when viewed horizontally. Now close the gas storage tank outlet valves.

Begin measuring the time from the moment you connect the electrolyser to the power source. Record the voltage applied to the electrolyser and the current flowing through it. Record the time, voltage and current values at each of the graduation marks. Take the last measurements when the hydrogen storage tank is completely filled with gas.

Table 3.5.3.a. | Table of measurements

Produced hydrogen **V_{H_2} (cm^3)**	**Time** **t (s)**	**Voltage** **U (V)**	**Current** **I (A)**

Energy efficiency of the PEM electrolyser

ANALYSIS

1. Plot a graph showing the volume of gas produced as a function of time.
2. Calculate the energy efficiency of the electrolyser.

$$\eta_{energy} = \frac{E_{Hydrogen}}{E_{electric}} = \frac{V_{H_2} \cdot H_h}{\bar{U} \cdot \bar{I} \cdot t}$$

H_h = Caloric value[1] of hydrogen = $12.745 \cdot 10^6 \frac{J}{m^3}$
V_{H_2} = Quantity of hydrogen produced in m^3
U = Voltage in V
I = Current in A
t = Time in s

---

[1] The energy that is released during the combustion of a substance (oxidation) is defined as the calorific value H_h (also called higher heating value). It also includes the energy contained by the water vapor from combustion as condensation heat. This energy cannot be used in conventional combustion systems. Therefore, a value is also formulated that does not include the condensation heat. This variable is called a heating value H_l and is used to calculate the efficiency for heating systems, motors and fuel cells.

3. Interpret your results and compare them with your answers to the pre-lab questions.

Faraday efficiency of the PEM electrolyser

ANALYSIS

1. Calculate the Faraday efficiency of the electrolyser.

Using Faraday's second law and the ideal gas law, the gas volumes are calculated as follows:

$$V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}$$

V = Theoretical volume of gas produced in m^3

R = Universal gas constant = $8.314 \frac{J}{mol \cdot K}$

p = Ambient pressure in Pa ($1\ Pa = 1 \frac{N}{m^2}$)

F = Faraday constant = $96485 \frac{C}{mol}$ (1C=1As)

T = Ambient temperature in K

I = Current in A

t = Time in s

z = Number of electrons to release a molecule:

$z(H_2) = 2$, i.e. 2 moles of electrons are required to release 1 mol of hydrogen.

$z(O_2) = 4$

The Faraday efficiency is obtained from the following equation:

$$\eta_{Faraday} = \frac{V_{H_2}(produced)}{V_{H_2}(calculated)}$$

2. Interpret your results.
3. Compare the energy efficiency with the Faraday efficiency.

3.5.4. CURRENT-VOLTAGE CHARACTERISTIC AND POWER CURVE OF FUEL CELL

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

PRE-LAB QUESTIONS

What behavior do you expect from the current-voltage characteristic and the power curve? Draw a sketch of the expected characteristic.

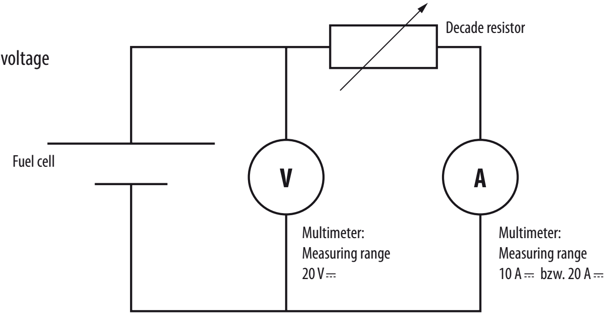
APPARATUS

- PEM fuel cell
- Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Hydrogen source, e.g. electrolyser or RFC in electrolysis mode with gas storage tanks. If you use an electrolyser, you will also need the following:
  - Power source, such as a solar module, laboratory power supply
  - A light, if necessary, for operating the solar module

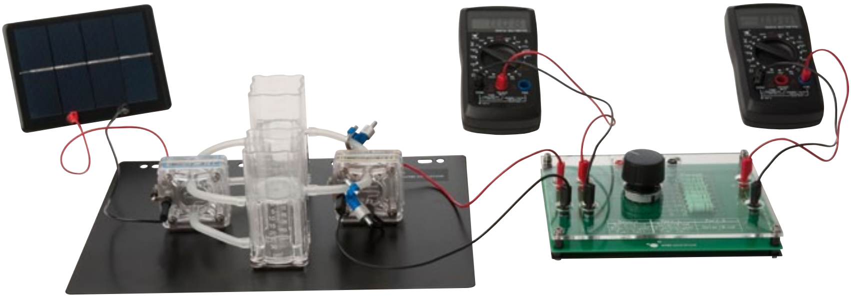
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 3.5.4. Setup for determining the current-voltage characteristic of the fuel cell



Setup
3.5.4.



PROCEDURE

Switch on the device as described in the operating instructions.

Note that no additional oxygen is required for hydrogen/air fuel cells, i.e. the following description only refers to hydrogen.

Connect the electrolyser to the power source to produce hydrogen and oxygen. Connect the outlet connections of the electrolyser to the input connections of the gas storage tanks and their outputs to the input connections of the fuel cell. To prevent the fuel cell from using any hydrogen before the measurement is taken, the fuel cell must be switched to open circuit (open clamps, no current flow). Close the fuel cell outlets using the sealing caps. After you have produced approximately 5 cm^3 of hydrogen gas, open the fuel cell outlets, purge them with gas and close them again. This removes the residual gases that distort the measurement. Start re-cording the current-voltage characteristic in a table using the open circuit voltage ($R = \infty$). Switch the decade resistor from higher to lower resistances and record the corresponding voltage and current values at the resistances. After changing the re-sistance, wait for approximately 20 seconds in between measurements.

Table 3.5.4. Table of measurements

Resistance R (Ω)	Voltage U (V)	Current I (A)	Power P (W) calculated $P = U \cdot I$
∞			
330			
100			
33			
10			
3.3			
1			
0.33			
0.1			
0			

ANALYSIS:

1. Plot a graph of the recorded values as a current-voltage characteristic.
2. Plot a graph showing the power as a function of current. Mark the maximum power point.
3. Explain the energy conversion in relation to the formation of water.
4. Specify the appropriate reaction equations.
5. Interpret your results and compare them with your answers to the pre-lab questions.

3.5.5. ENERGY EFFICIENCY AND FARADAY EFFICIENCY OF PEM FUEL CELL

Before beginning the experiment, read the information about the device and the potential safety hazards!

Carefully read through the operating instructions and the experiment instructions. Do not begin the experiment until after the instructor or supervisor has provided detailed instructions!

Follow all written safety instructions as well as any provided by the instructor!

PRE-LAB QUESTIONS

What information can you find for the efficiency of the PEM fuel cells?

Does the efficiency depend on the power of the fuel cell?

APPARATUS

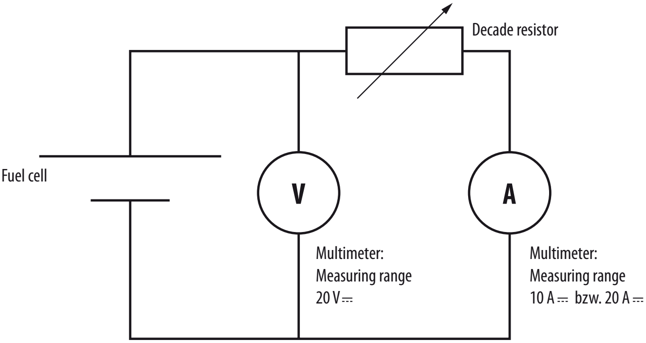
- PEM fuel cell
- Hydrogen source, e.g. PEM electrolyser or RFC in electrolysis mode
- Gas storage tanks

  The following is also needed:
  - Power source, such as a solar module, laboratory power supply
  - A light, if necessary, for operating the solar module
- Variable resistor as well as a measuring instrument for electric current and voltage, e.g.:
  - Decade resistor, various resistors, potentiometer and two multimeters
- Stopwatch

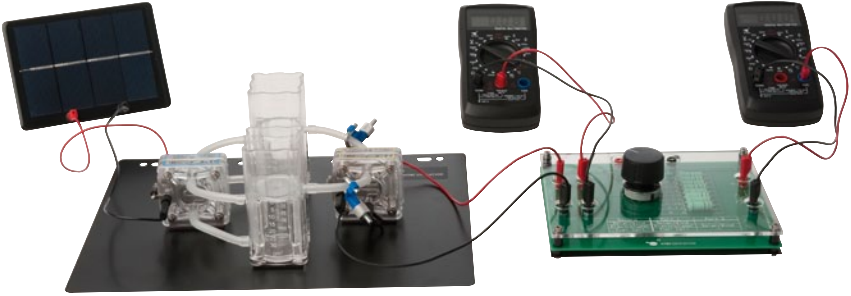
SETUP *(See also operating instructions)*

Create the circuit as shown in the following circuit diagram:

Circuit Diagram 3.5.5. | Setup for determining the energy efficiency and Faraday efficiency of the fuel cell



Setup 3.5.5.



PROCEDURE

Switch on the device as described in the operating instructions.

Note that no additional oxygen is required for hydrogen/air fuel cells, i.e. the following description only refers to hydrogen.

Connect the electrolyser to the power source to produce hydrogen and oxygen. Connect the outlet connections of the electrolyser to the input connections of the gas storage tanks and their outputs to the input connections of the fuel cell. To prevent the fuel cell from using any hydrogen before the measurement is taken, the fuel cell must be switched to open circuit (open clamps, no current flow). Close the fuel cell outlets. Produce hydrogen gas, then briefly open the fuel cell outlets to vent the system and then close them again. Produce the maximum volume of hydrogen possible with the device (in this example, 30 cm^3). If necessary, interrupt the power supply to the electrolyser and disconnect the electrical connection between the fuel cell and the decade resistor. Switch the decade resistor to the resistance at which you want to determine the energy efficiency (e.g. 3.3 Ω). Reconnect the circuit between the fuel cell and the decade resistor and start measuring the time from this moment. Record the measured time, voltage and current at constant volume increments (e.g. 5 cm^3). Do not change the resistance. Make sure that the current values do not fluctuate too much (take the measurement again if necessary). Any substantial reduction in the current during the measurement will probably be due to residual gases in the storage tank that impair the operation of the fuel cell. This problem also occurs if only a small quantity of hydrogen is left in the storage tank (e.g. only 5 cm^3).

Table 3.5.5. Table of measurements

Hydrogen Volume V_{H_2} (cm^3)	**Time** t (s)	**Resistance** U (V)	**Current** I (A)
Mean			

Energy efficiency of the PEM fuel cell

ANALYSIS

1. Plot a graph showing the volume of gas produced as a function of time.
2. Calculate the energy efficiency of the fuel cell.

$$\eta_{energy} = \frac{E_{electric}}{E_{Hydrogen}} = \frac{Voltage \cdot Current \cdot Time}{Hydrogen\ volumes \cdot Caloric\ \ value} = \frac{\overline{U} \cdot \overline{I} \cdot t}{V_{H_2} \cdot H_l}$$

H_l = Heating value[1] of the hydrogen = $10.8 \cdot 10^6 \frac{J}{m^3}$ (also called lower heating value)
V_{H_2} = Quantity of hydrogen produced in m^3
U = Voltage in V
I = Current in A
t = Time in s

3. Interpret your results and compare them with your answers to the pre-lab questions.

Faraday efficiency of the PEM fuel cell

ANALYSIS

1. Calculate the Faraday efficiency of the fuel cell.

Using Faraday's second law and the ideal gas law, the gas volumes are calculated as follows:

$$V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}$$

---

[1] _The heating value is defined as the energy released during the combustion of a substance (oxidation). It does not include the energy contained by the water vapor from combustion as condensation heat. This energy cannot be used in heating systems, motors and fuel cells, for example.

V = Theoretical volume of gas produced in m^3

R = Universal gas constant = $8.314 \frac{J}{mol \cdot K}$

p = Ambient pressure in Pa ($1\ Pa = 1 \frac{N}{m^2}$)

F = Faraday constant = $96485 \frac{C}{mol}$ (1C=1As)

T = Ambient temperature in K
I = Current in A
t = Time in s

z = Number of electrons to release a molecule:
  $z(H_2) = 2$, i.e. 2 moles of electrons are required to release 1 mol of hydrogen.
  $z(O_2) = 4$

The Faraday efficiency is obtained from the following equation:

$$\eta_{Faraday} = \frac{V_{H_2}(produced)}{V_{H_2}(calculated)}$$

2. Interpret your results.
3. Compare the energy efficiency with the Faraday efficiency.

4

Appendix

GLOSSARY

Alkaline Fuel Cell (AFC): Alkaline fuel cells belong to the low temperature fuel cells (operating temperature range between 20 °C and 90 °C). AFCs have an alkaline electrolyte (typically potassium hydroxide) and are operated with pure hydrogen and oxygen.

BTPS: Block-type thermal power station. This type of power plant supplies both electricity and heat energy. The latter can be used for residential heating, for example. In a conventional BTPS, electricity is produced by a generator which is typically powered by a combustion engine. The thermal energy produced is simply the engine waste heat. Instead of combustion engines, a BTPS can be powered by fuel cells. In this scenario, the fuel cells will provide both electricity and thermal energy.

Calorific Value: The calorific value is defined as the energy released during the combustion (oxidation) of a substance. It also includes the energy contained by the water vapor from the combustion as condensation heat. This energy cannot be used in conventional combustion systems. A value that neglects the condensation heat is therefore also formulated. This is called the heating value, which is used for calculating the efficiency of heating systems, engines and fuel cells.

Carbon Dioxide CO_2: Colorless and odorless gas that is produced during combustion or oxidation of carbon-containing substances (it is also released into the environment when we exhale). During photosynthesis plants use CO_2 and produce oxygen. Carbon dioxide is a greenhouse gas, i.e. it contributes to global warming.

Carbon Monoxide CO: Poisonous, colorless and odorless gas. Produced during incomplete combustion of carbon-containing substances.

Carbon nanofiber: Carbon-based materials that have structures made of carbon fibers with diameters of about 10-100 nm. In the future, these might be able to be used for low pressure hydrogen storage. At present, carbon nanofiber technology is still in the research and development phase.

Catalyst: Substance that facilitates or accelerates a chemical reaction without being used up in the process.

Catalytic Poison: Substance that disables the function of a catalyst.

CGH_2 : Compressed Gaseous Hydrogen

CO: See carbon monoxide.

CO_2: See carbon dioxide.

Cold Start Performance: Describes the initial performance of devices like engines or fuel cells, at the beginning of operation when the optimum operating temperature has not yet been reached.

Compressed Gas Storage: Method for storing gases at ambient temperature and under high pressures (e.g., 200 bar).

Compressed Gas Tank: See compressed gas storage.

Cryogenic storage: See Liquid Hydrogen Storage.

Decomposition Voltage: In order to decompose water by electrolysis into hydrogen and oxygen, the voltage applied to the electrolyser must exceed 1.23V. This threshold voltage is called the decomposition voltage.

Direct Methanol Fuel Cell (DMFC): Specialized version of a PEM fuel cell. DMFC and PEM fuel cells have similar structures. Their main difference is that the fuel in a DMFC is methanol (CH_3OH) and not hydrogen. Hence, in a DMFC, methanol reacts at the anode while the cathode is supplied with oxygen (or air).

Efficiency: The efficiency of a system is given by the ratio of usable energy released by the system and the energy consumed by the system.

Electrolysis: Electrochemical decomposition of liquid compounds. E.g., the decomposition of water into hydrogen and oxygen.

Electrolyte: Medium for ion transport. In a fuel cell it also spatially separates the reacting substances. In a PEMFC a special polymer foil is used for this purpose.

Electron: Negatively charged particle with a mass of 9.1×10^{-31} kg.

First Law of Thermodynamics: Energy can neither be created nor destroyed. It can only be converted from one form to another.

Fuel: A fuel is a substance containing usable energy. Examples include hydrogen, hydrocarbons (e.g., methane, gasoline, diesel, coal) and uranium (nuclear energy).

Fuel Cell (FC): A fuel cell transforms energy electrochemically. In a controlled fashion, without the use of an open flame, a fuel cell converts the chemical energy stored in fuels like hydrogen, methanol or methane, directly into electric energy (reverse process of electrolysis). In the process, water and heat are also produced.

Fuel Cell Stack: A fuel cell stack is a unit consisting of several individual fuel cells that are connected in parallel and/or in series.

Fuel Gas: Gaseous fuel.

GH_2: Gaseous hydrogen.

Heating Value: The heating value is defined as the energy released during the combustion (oxidation) of a substance. This does not include the energy contained by the water vapor from the combustion as condensation heat. This energy cannot be used in heating systems, engines and fuel cells, for example.

High-Power Electrolyser: Electrolyser with high power (e.g., with power in the kW range).

Hydrocarbons: Compounds that consist of only hydrogen and carbon.

Hydrogen: Colorless and odorless gas. Hydrogen is the smallest and lightest element in the periodic table. A hydrogen atom consists of a negatively charged electron and a positively charged proton. Hydrogen is the most abundant element in the universe. However, due to its high reactivity it is mostly found in compounds, including water (H_2O), hydrocarbons (e.g., natural gas which is mostly methane, CH_4), or crude oil.

Ion: Electrically charged particle (charge can be positive or negative) consisting of one or more atoms.

LH_2: Liquid hydrogen.

Liquid Hydrogen Storage: Hydrogen is stored cryogenically, in liquid form. At ambient pressures, hydrogen becomes liquid below -253 °C.

Metal Hydride: Storage medium for pure hydrogen. Metals or metal alloys that can store gaseous hydrogen in their lattice are suitable for this purpose. The gas enters the storage tank under pressure and chemically bonds to the storage medium while releasing heat in the process. The resulting compounds are called metal hydrides. The reaction is reversible: by applying heat the hydrogen gas is released again and the metal (alloy) is left in the state it was in before storage. Advantages of this storage method include excellent operating safety and high storage density. Disadvantageous, however, is the large weight of the storage tank.

Methanol: CH_3OH; clear liquid with characteristic odor; poisonous. Methanol is used as liquid fuel in direct methanol fuel cells. Hydrogen can be produced from methanol through reforming.

Molten Carbonate Fuel Cell (MCFC): MCFCs belong to the high temperature fuel cells (operating temperature between 600 °C and 660 °C). The electrolyte is an alkali-carbonate melt. MCFCs allow for electricity production with high efficiencies. MCFCs can be operated with hydrogen as well as other fuel gases (including, for example, natural gas and biogas).

Oxidation: Oxidation is the loss of electrons. In a fuel cell, a hydrogen molecule is oxidized (i.e. releases two electrons), leaving two protons.

Power Density: Power density is the ratio of power and volume (units of kW per liter) or power and weight (units of kW per kg) of a device (e.g., a fuel cell stack).

PEM: Polymer Electrolyte Membrane, Proton Exchange Membrane: a PEM is a proton-conducting polymer foil used in PEM electrolysers and PEM fuel cells.

Phosphoric Acid Fuel Cell (PAFC): This type of fuel cell operates at medium temperatures (160 °C to 220 °C) and uses phosphoric acid as its electrolyte.

Polymer Electrolyte Membrane Fuel Cell (PEMFC): This type of fuel cell uses a proton-conducting polymer membrane as its electrolyte. It has an operating temperature between 60 °C and 80 °C and uses pure hydrogen as its fuel. PEMFCs are characterized by their high power density and efficiency. They are particularly promising for use in automobile technology.

Primary Energy: Energy form that is directly supplied by natural processes (e.g., solar energy).

Proton: Positively charged particle with a mass of 1.67×10^{-27} kg.

Reduction: Reduction is the gain of electrons. In a fuel cell oxygen is reduced (i.e. accepts electrons).

Reformer: In a reformer, methanol, modified gasoline or synthetic fuels are converted to hydrogen, carbon dioxide and small quantities of carbon monoxide. The carbon monoxide is subsequently further oxidized in a catalytic converter where it reacts with oxygen to form carbon dioxide.

Reforming: Conversion of hydrocarbons to hydrogen, CO_2 and CO.

Renewable (Regenerative) Energy: Energy with a natural source that is continuously being replenished and that is therefore practically inexhaustible to human activity. The most common example is solar energy which is evident in several forms including solar radiation as well as wind and water power.

Secondary Energy: Energy is produced through conversion of primary energy. Examples include hydrogen and gasoline.

Second Law of Thermodynamics: A system, if left on its own, will change from a more ordered to a less ordered state.

Serial Connection: In a serial connection several e.g. fuel cells are connected in series such that the total voltage is increased with each addition of another fuel cell.

Solar-Hydrogen Economy: Energy system in which solar energy is the primary energy and hydrogen is used as the secondary energy carrier.

Solid Oxide Fuel Cell (SOFC): SOFCs operate at high temperatures (800 °C to 1000 °C) and have a solid electrolyte that consists of ceramic zirconium oxide. SOFCs can be operated with hydrogen as well as other fuel gases (including, for example, natural gas and biogas).

Stack: Individual cells (fuel cells or electrolyser cells) combined to a unit and electrically connected in series are called a cell stack.

INDEX

LINKS

www.fuelcells.org

www.h-tec-education.com

www.hyweb.de

www.solarserver.de

TABLE OF FIGURES AND SOURCES

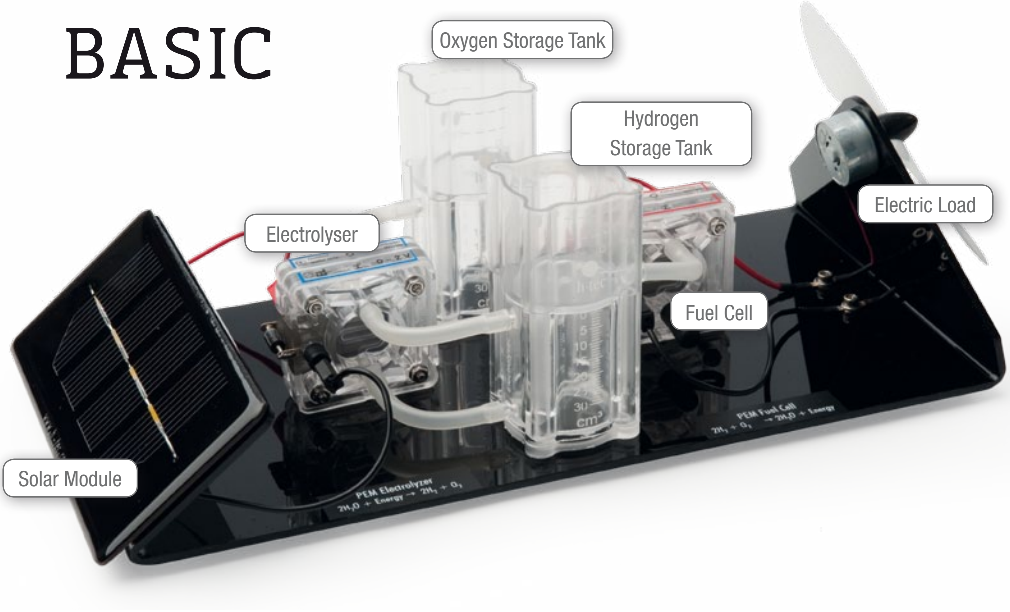
1 H-TEC EDUCATION
2 H-TEC EDUCATION
3 Vestas Deutschland GmbH
4 RWE Power AG
5 Ludwig-Boelkow-Systemtechnik GmbH
6 H-TEC EDUCATION
7 H-TEC EDUCATION
8 General Motors Corp.
9 MTU Friedrichshafen GmbH
10 Siemens Power Generation
11 H-TEC EDUCATION
12 H-TEC EDUCATION
13 H-TEC EDUCATION
14 Fraunhofer ISE
15 General Motors Corp.
16 Vaillant GmbH
17 H-TEC EDUCATION
18 Dynetek Industries Ltd.
19 Linde AG
20 Treibacher Industries AG
21 GKSS-Forschungszentrum Geesthacht GmbH

3.1.1 Ludwig-Boelkow-Systemtechnik GmbH
3.1.2.a Dynetek Industries Ltd.
3.1.2.b Linde AG
3.1.2.c Treibacher Industries AG
3.1.3 H-TEC EDUCATION
3.1.4.a H-TEC EDUCATION
3.1.4.b H-TEC EDUCATION

H-TEC EDUCATION

Innovation Fuel Cell

JUNIOR BASIC



Solar hydrogen experimentation system, consisting of solar module, PEM electrolyser, Hydrogen and oxygen storage tanks, PEM fuel cell (for electric load); mounted on a black base plate. Textbook included.

Specifications: *Electrolyser: 1 W, Fuel cell: 500 mW, Gas storage: 30 cm*^{3} *-* H_2*; 30 cm*^{3} *-* O_2*, Solar module: 2.0 V / 350 mA, Fan: 10 mW, H x B x T: 100 mm x 300 mm x 150 mm, Weight: 600 g, Item: J101*

H-TEC EDUCATION · 1902 PINON DR. STE. B · COLLEGE STATION, TX 77845 · USA
T: +1 979 703 1925 · F: +1 979 314 1122 · EMAIL: INFO@H-TEC-EDUCATION.COM

Cornelia Voigt | Stefan Hoeller | Uwe Kueter

Fuel Cell Technology for Classroom Instruction

BASIC PRINCIPLES | EXPERIMENTS | WORK SHEETS

This book provides a clear introduction and overview to fuel cell technology and its associated subject areas.

Examples of experiments using solar cells, electrolysis and fuel cells convey the knowledge for forthcoming tests in an understandable manner.

The preperation of classroom experiments is made considerably easier for the teacher thanks to the experiment work sheets. These contain the necessary information concerning the material, set-up and execution of the experiment, and questions for evaluation purposes.

The training documents and student work sheets combine the basic knowledge, questions and answers, and are ideal for copying.

A comprehensive glossary at the end of the book explains all the important technical terms.

H-TEC EDUCATION
a GP JOULE company

H-TEC EDUCATION GmbH
Maria-Goeppert-Str. 9a
D-23562 Lübeck · Germany
Telefon: +49 (0) 451-39 941-0
Telefax: +49 (0) 451-39 941-798
E-mail: info@h-tec-education.com
Website: h-tec-education.com