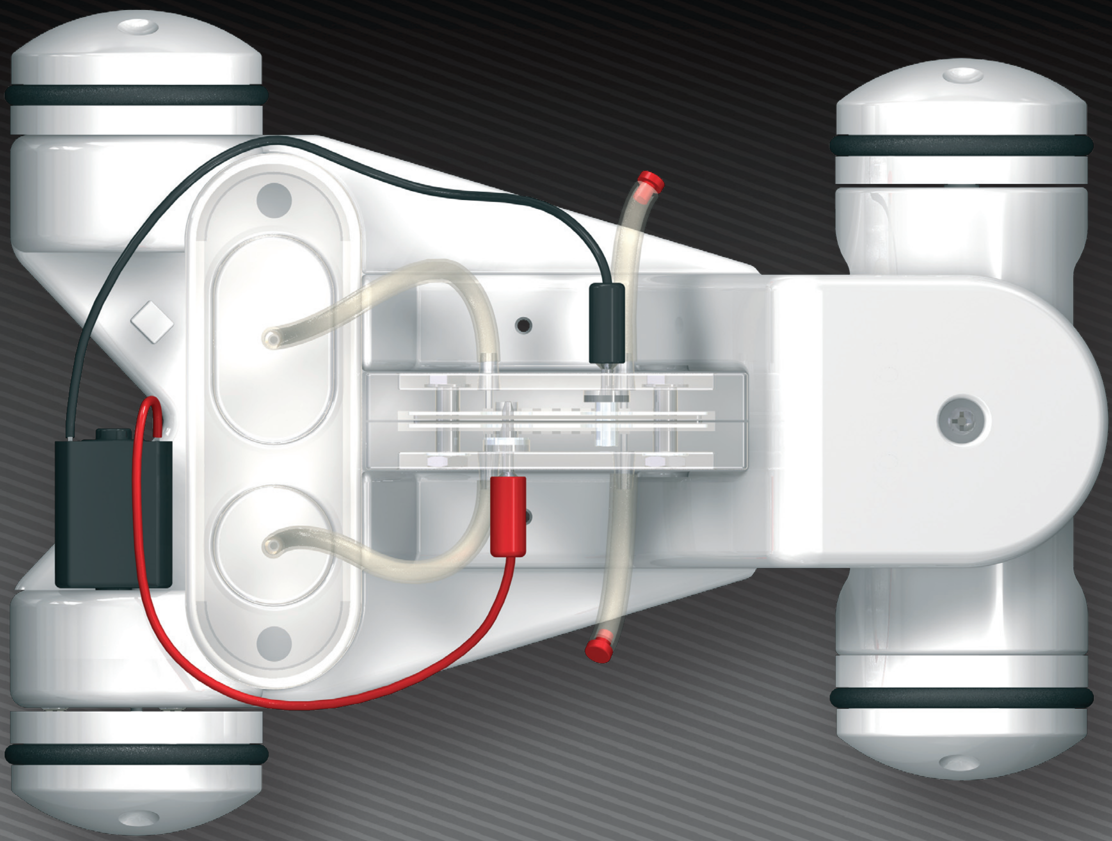
fuel cell 10

car and experiment kit



SCIENCE EDUCATION SET

WARNING — This set contains chemicals that may be harmful if misused. Read cautions on individual containers carefully. Not to be used by children except under adult supervision.

Thames & Kosmos

Experiment Manual

1st Edition, Franckh-Kosmos Verlags-GmbH & Co. KG, Stuttgart / 2009

0708283 I-I AN 170709

Project Manager: Manfred Berrer
Text and Experiments: Dr. Uwe Wandrey
Design: designstudio, www.c-r-1.de

1st English Edition, Thames & Kosmos LLC, Rhode Island, USA

Editing: Ted McGuire
Design: Dan Freitas

Distributed in North America by Thames & Kosmos, LLC.
Web Site: www.thamesandkosmos.com
Phone: 800-587-2872
Email: support@thamesandkosmos.com

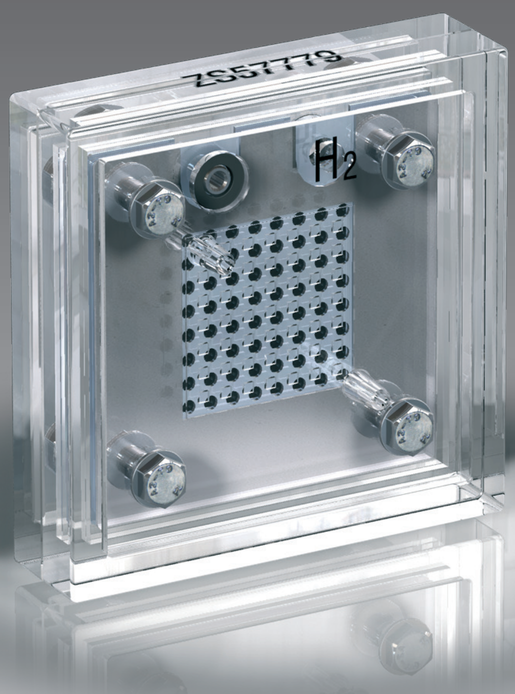
Image Credits: Adam Opel AG, GM General Motors, NASA, Solar Impulse, Solarboot Hamburg, Hochschule Bochum, Tesla, BMW, Mercedes Benz, Biokraftwerk MVV, NUNA3, PEGE, Bundesverband Solarwirtschaft.

Dr. Uwe Wandrey

fuel cell 10

car and experiment kit

The Energy of Tomorrow



Experiments with a Fuel Cell

Franckh-Kosmos Verlags-GmbH & Co. KG, Stuttgart, Germany
Thames & Kosmos LLC, Rhode Island, USA

Thames & Kosmos

Experiment Manual

Safety Information

Please read the following safety statements.

Warning!

All of the electrical experiments in this kit are performed with the solar panel, battery holder containing AA batteries, and/or fuel cells using only very low, safe voltages of less than two volts. Do not use any other energy sources.

This set contains chemicals that may be harmful if misused. Read cautions on individual containers carefully. Not to be used by children except under adult supervision.

The assembly of the models is not difficult. It is however important to review the individual components before beginning the assembly. Parents and other supervising adults should support their children with assistance and encouragement. Before you start your experiments, review the manual together and follow it. Please note also that the kit should be kept away from small children who could swallow the small parts.

Please Note!

Keep the kit box, since it contains important information. Certain parts of this kit have pointed or sharp corners or edges related to their functions. There is danger of injury!

Environmental Protection

The electric and electronic components in this kit should not be disposed of in normal household trash at the end of their useful life but rather should be brought to a collection point for the recycling of electric and electronic devices.

The materials are recyclable as indicated by their labeling. By re-using, recycling, or otherwise using old devices, you are making an important contribution to the protection of our environment. Please ask your local government about the appropriate disposal site.

Precautions and Notes

The right to technical alterations is reserved.

Caution!

The fuel cell produces small quantities of hydrogen and oxygen, which are extremely flammable gases. Read, follow, and keep this instruction manual.

Attention

This experiment kit contains technically advanced components. To preserve the functionality of the technical and electrical components you must ensure that the parts are handled carefully and only used as described in the instructions. Experiments other than those in this manual are not recommended. The kit is not a toy. The models are intended for educational purposes only.

The enclosed electrical measuring device, a digital multimeter, must only be used as described in this kit. Do not use it with high voltages.

Warning!

Only to be used for educational purposes by children who are at least 10 years old. Use only under the close supervision of adults who have familiarized themselves with the warnings and precautions in this manual. Keep small children and pets away from the experiments. Keep the fuel cell out of reach of small children. Read the instructions before use, follow them, and keep them for ready reference.

Additionally Required

1. ***One liter of distilled water, which is sold in markets and pharmacies.***
2. ***For some experiments, you will need two 1.5-volt AA batteries. (Type LR6/AA/Mignon)***

This Science Education Set Is Not a Toy!

Table of Contents

Overview

Short Description

In the first chapter, an innovative, environmentally friendly method of energy production and transformation for use in vehicles is introduced.
There is an overview of the kit components and the models that will be built.

The design of the experiment vehicle and the display stand is explained. The components of the car and display stand are assembled step by step.
The two assemblies are joined together and their functionality is tested.
The placement of the model on the display stand is explained.

Preparations for the experiments are made. Initial tests with battery power, among other things, show us the function of the transmission and electric motor. After that, there are explanations of the solar cell and the operation of the vehicle with solar power.
The operational fuel cell car is assembled. The fuel cell is connected to the gas tanks. The system is filled with distilled water.

We learn the procedure for the production of hydrogen with the fuel cell.
We see how the hydrogen and oxygen gases are stored in the gas tanks. We see how we can power our car with this environmentally friendly fuel.

After assembling and experimenting with the car, we get a glimpse into the world of environmentally friendly vehicles. We get to know solar cars and solar planes, electric cars, and fuel cell technology in modern vehicles. This chapter offers both an overview of future alternative energy possibilities as well as what is already a reality.

This chapter gives some background information explaining why environmentally friendly energy technology is so important. Examples of renewable energies from the real world are presented.

In this chapter, we learn the science behind solar hydrogen production and the electrolysis of water.

The theory and functionality of the fuel cell is explained.

The theory and functionality of the solar cell is explained.
To understand the electrical measurements, this chapter takes us on a small excursion into the topics of electronics and energy.
The digital multimeter is explained and we use it to take electrical measurements with the solar panel and fuel cell.

The Car of the Future

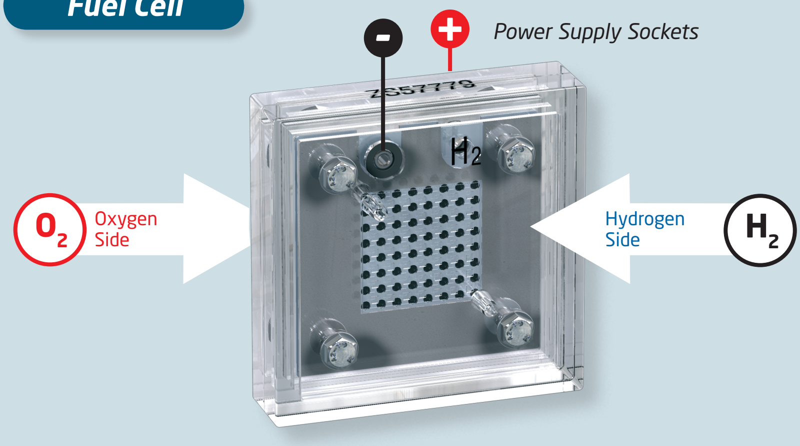
Take a moment to envision the car of the future. Instead of revving up with a loud roar of the engine, it will hum quietly along. Nothing but water vapor will escape from its cool exhaust pipe. Stretching out on the roofs and fields along the roadways will be photovoltaic modules – "green" power plants creating electricity for the future car's fuel: hydrogen.

Under the hood, you will find an engine made of a fuel cell, battery, and electric motor, along with a hydrogen tank. Gone will be the days when cars spewed toxins into the atmosphere. Is this image of a pollutant-free electric car charged by solar energy just a dream or wishful thinking? Well, the first hydrogen-powered vehicles are already on the road today, but the technology is stilled being perfected and a large-scale hydrogen distribution system still needs to be developed.

Solar-Hydrogen Fuel Cell

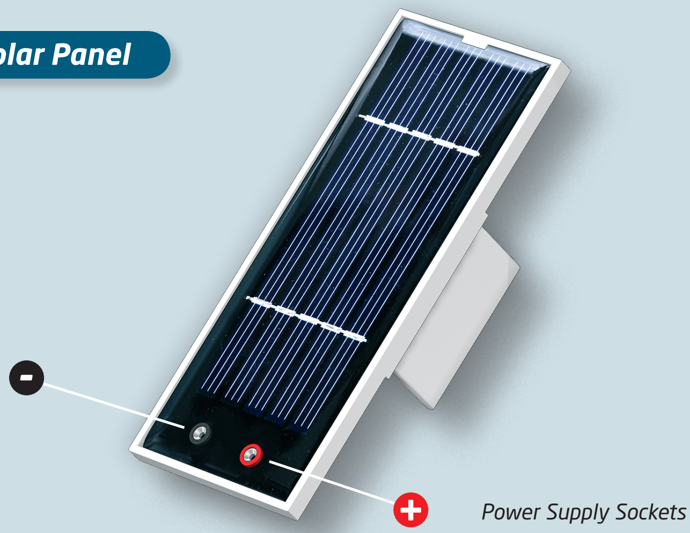
With the fuel cell car model in this kit, you will see that an environmentally friendly car is achievable. Its heart is the fuel cell, which turns hydrogen gas and oxygen into water and supplies electricity to the motor in the process.

Fuel Cell



It can also work in reverse to separate water into its elements hydrogen and oxygen, thereby creating its own fuel. The solar panel supplies the energy for that.

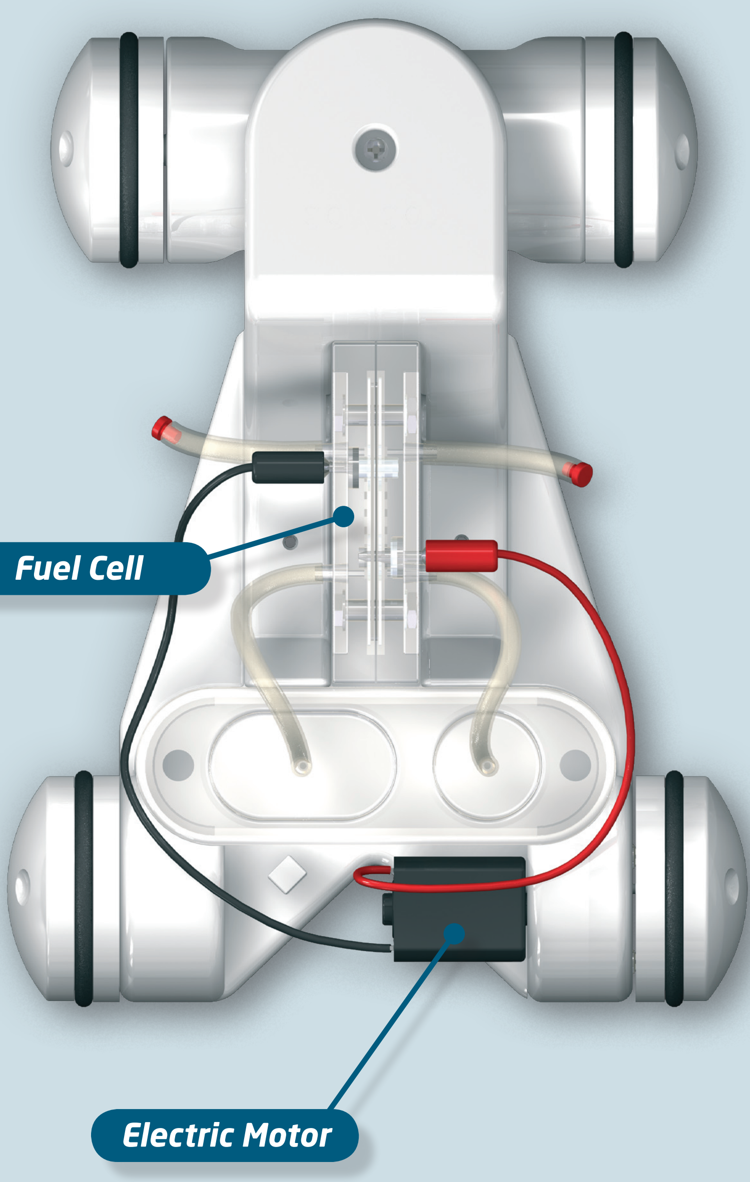
Solar Panel



Fuel cell and solar panel

Concept — Fuel Cell Car

This fuel cell car works in a two-step process. First, the fuel cell splits water into hydrogen and oxygen and those gases are stored in tanks. When the electric motor is connected to the fuel cell, the fuel cell combines those two gases into water, which produces electricity to run the motor. We can also use our car to investigate other alternative electric car concepts.

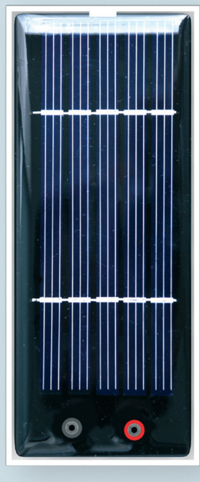


Fuel cell technology in the model

Process

To power the fuel cell, we will start with the sun, because the fuel for the fuel cell car is generated using solar power.

1. The solar panel generates electricity from sunlight.



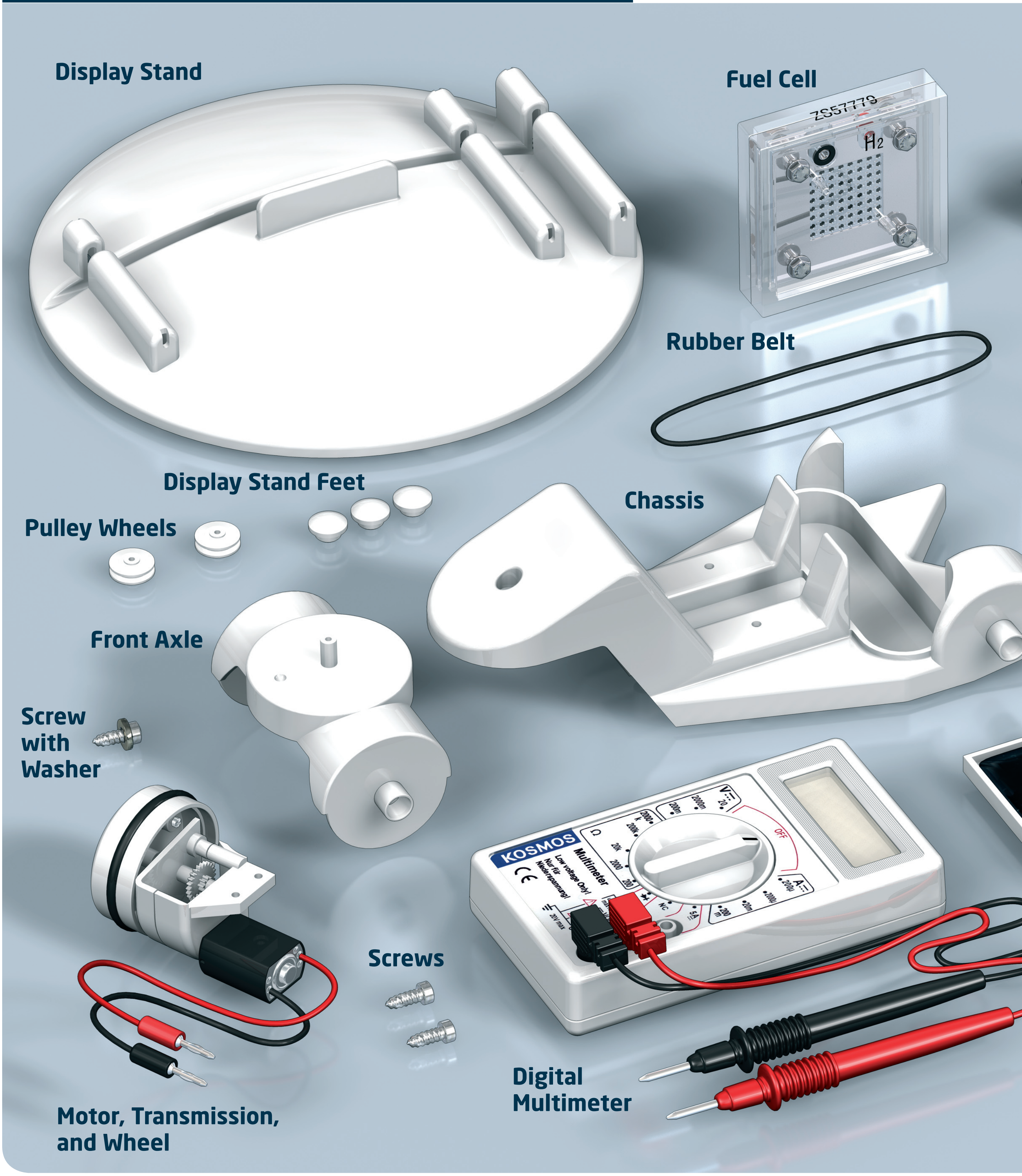
2. The electricity from the solar panel is used for electrolysis of water.

3. The hydrogen gas produced during electrolysis is the fuel for the fuel cell.

4. The fuel cell uses hydrogen and oxygen to generate electricity to power the car's electric motor.

Fuel Cell 10

Overview of Components

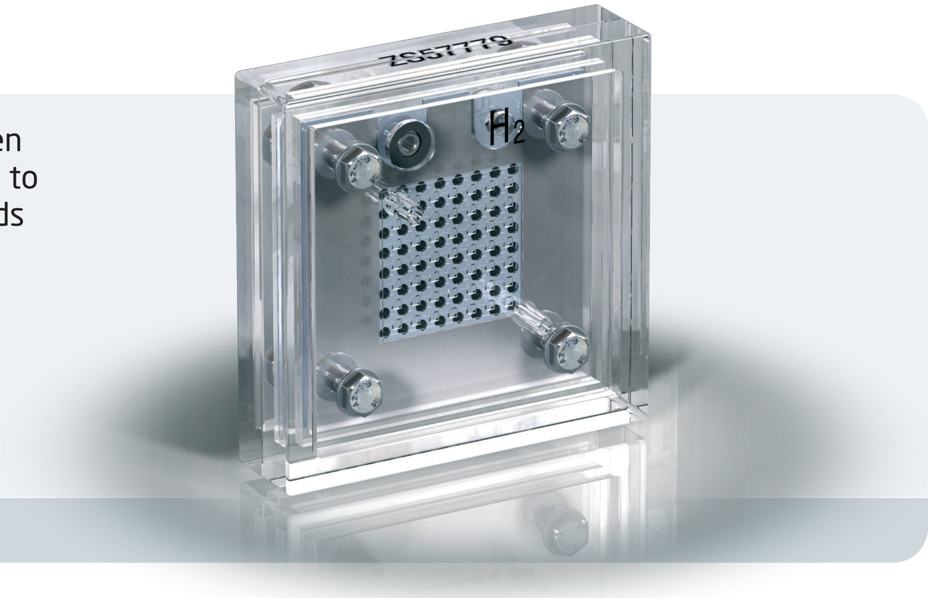


If you are missing a part, please contact Thames & Kosmos Technical Support.

Component Details

Fuel Cell

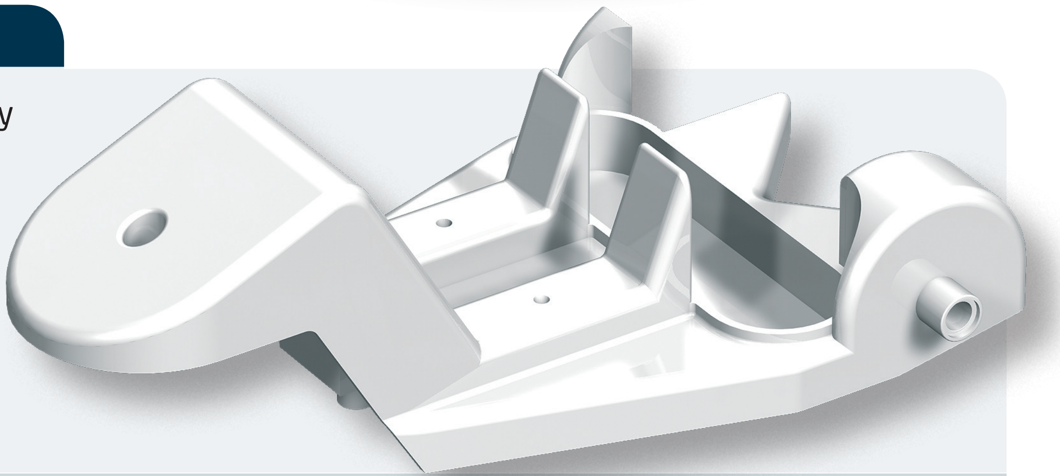
Compact, reversible hydrogen fuel cell, designed according to the latest technical standards



Part No. 708285

Vehicle Chassis

For model car assembly

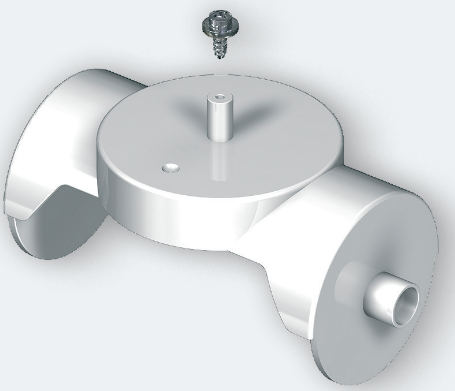


Part No. 708308

Front Axle

For model car assembly

Rigid front axle with sockets for wheels



Part No. 708293

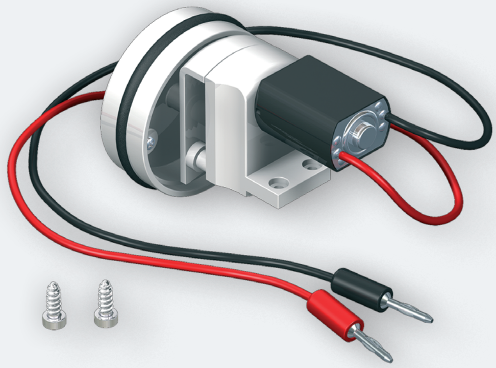
Screw with fixed washer for fastening

Part No. 708409

Motor, Transmission, and Wheel

For model car assembly

Pre-assembled unit with electric motor, gearbox, wheel, and connection wires



Part No. 708286

Two screws for fastening

Part No. 708289

Gas Tanks

For model car assembly

Two transparent containers for storage of hydrogen and oxygen gas with integrated cover and connection nozzles for gas hoses

Part No. 708412

Water Tank

For model car assembly

Transparent tank that holds water and the gas tank assembly. Allows for visual observation of the gases

Part No. 708416

Component Details

Solar Panel

Powerful, modern solar cells

Part No. 708287

Support for solar panel

Part No. 708288

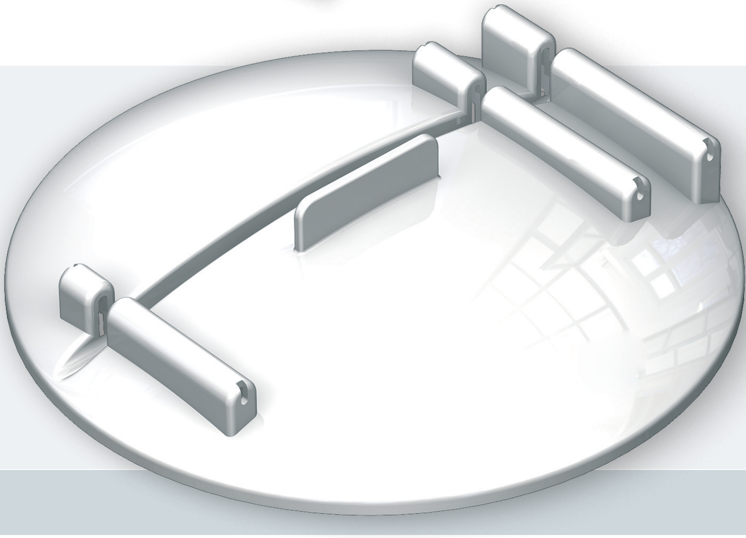
Display Stand

Experiment station with roller axle holders

Part No. 708301

Three rubber feet

Part No. 708300

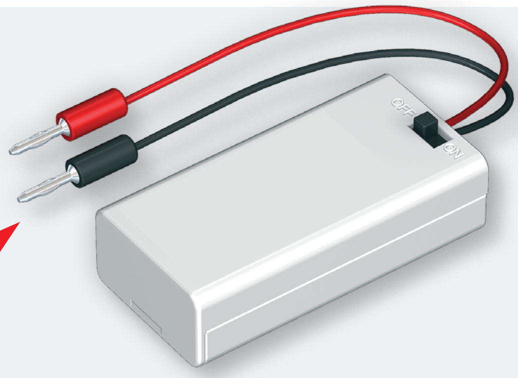


Battery Holder

Battery holder with ON / OFF switch and black and red connection wires.

Requires:
Two 1.5-Volt Batteries
Type LR6 / AA / Mignon
(not included)

Caution
Do not short circuit the battery holder. Use only with the correct type of batteries.



Part No. 708434

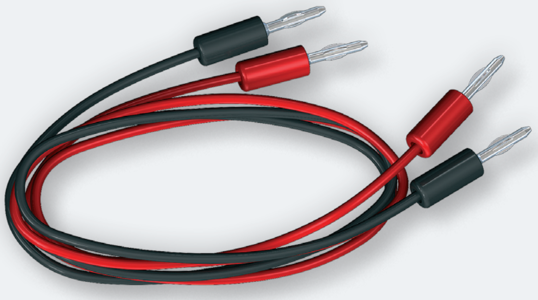
Connection Wires, 30 cm

Red wire

Part No. 708399

Black wire

Part No. 708400



Hose and Sealing Plugs

Transparent hose for connecting the gas tanks to the fuel cell

Part No. 708405

Plugs for sealing the ends of the hose

Part No. 287138

Wheels

Three wheels for model car assembly

Wheel with plug-axle for quick mounting to the fuel cell chassis

Equipped with rubber tires (O-rings) for smooth driving

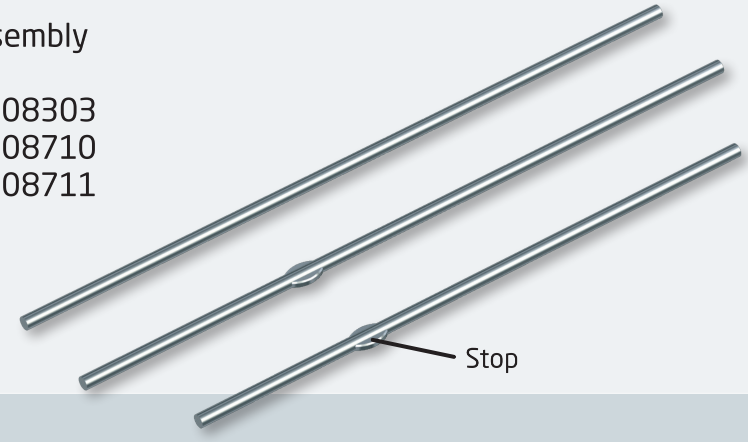
Part No. 708306

Component Details

Three Metal Axles

For the rollers on the display stand assembly

Long shaft without stop	Part No. 708303
Long shaft with stop	Part No. 708710
Short shaft with stop	Part No. 708711



Two Pulleys and Rubber Belt

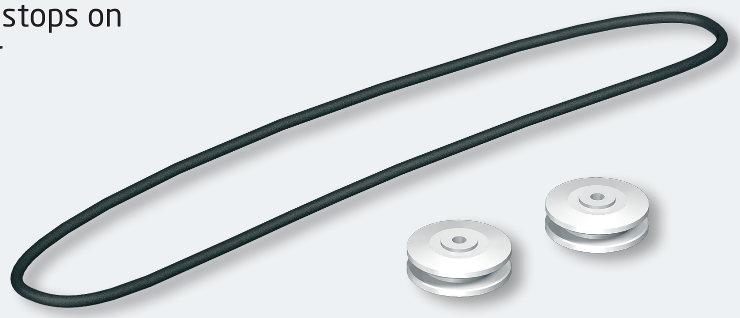
For attaching the two axles with stops on the display stand to each another

Pulley

Part No. 7083304

Rubber Belt

Part No. 708305



Six Roller Caps

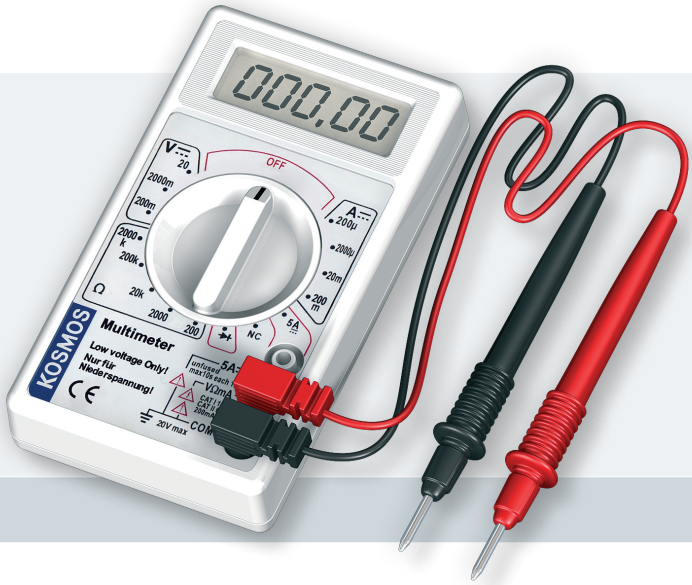
For the display stand assembly

Roller caps attach to the ends of the three axles

Part No. 708302

Digital Multimeter

Multimeter with cables
and probes



Part No. 708546

Connection Wires, 160 cm

Wires with connection plugs

Red wire

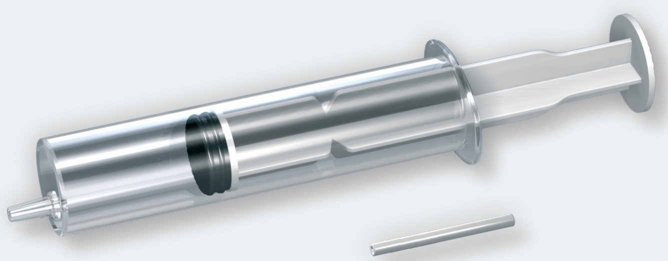
Part No. 708401

Black Wire

Part No. 708403

Syringe

Syringe for filling the fuel cell



Part No. 287140

Syringe tip

Part No. 708713

Experiment Vehicle and Display Stand

To begin your fuel cell experiments, you will first assemble the base of the experiment vehicle and the display stand with rollers.

As you have probably already noticed, the fuel cell car model does not look much like a real car. The model was designed first and foremost to function well and be easy to experiment with.

The ultimate design goal was to create a model car that clearly and simply demonstrates the mechanical, chemical, and electrical processes at work in a fuel cell car.

The main components of the kit are:

1. **Experiment Vehicle**
2. **Display Stand**
3. **Fuel Cell**
4. **Geared Electric Motor**
5. **Digital Multimeter**
6. **Solar Panel**

A

Experiment Vehicle

The vehicle consists of these individual components:

- **Chassis**
- **Front Axle**
- **Four Wheels**
- **Water Tank**
- **Two Gas Tanks**
- **Geared Electric Motor**
- **Fuel Cell**

The fuel cell sits in the middle of the chassis. Behind the fuel cell, there are transparent water and gas tanks.

The motor and transmission are located at the rear of the car on the right side. For technical reasons, only one wheel is powered. A rubber O-ring wraps around each wheel to make the car drive more smoothly.

B

Display Stand

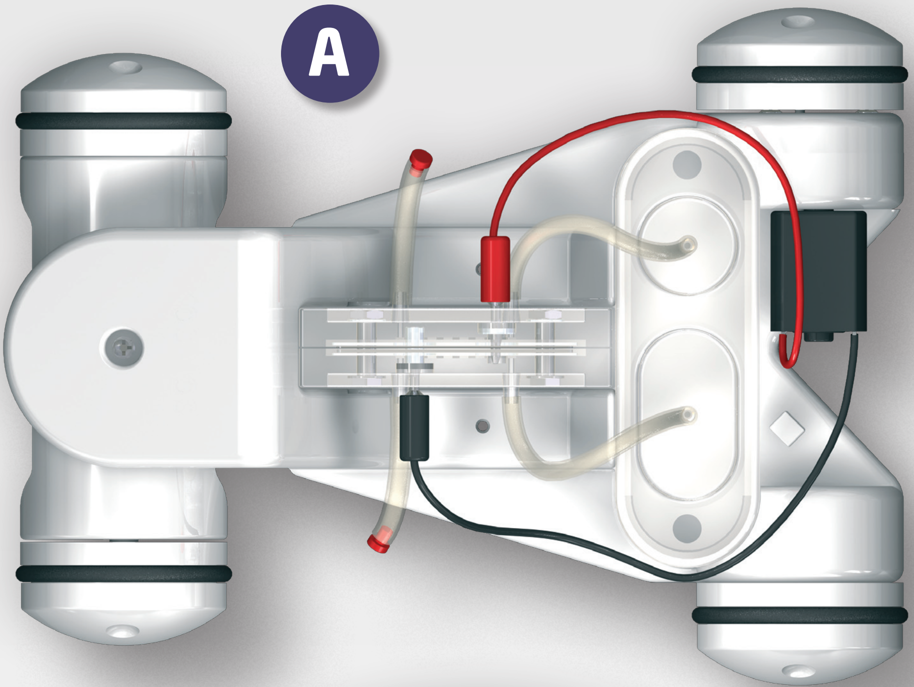
The display stand allows you to run the fuel cell car in one place while you do your experiments. The display stand consists of the following components:

- **Base Plate**
- **Rollers**
- **Axles**
- **Two Pulley Wheels**
- **Rubber Belt**

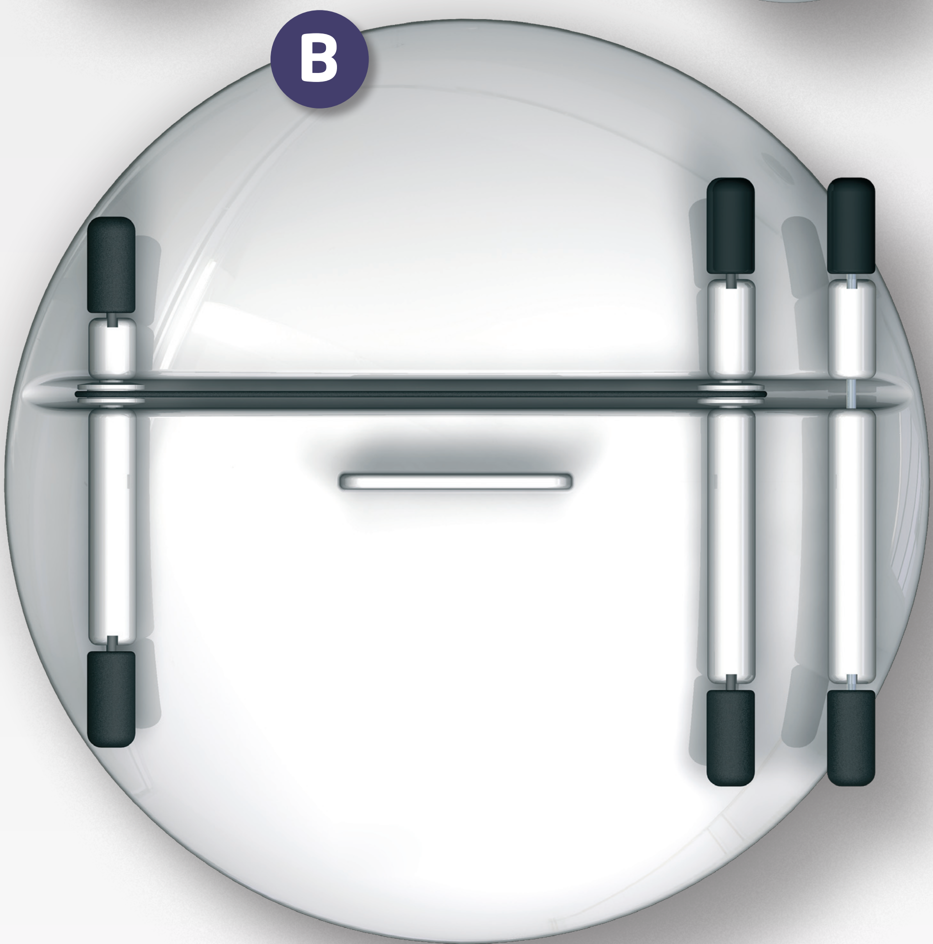
The first and second rollers are connected with a rubber belt so that they turn at the same rate. This allows the front wheels of the vehicle to turn even though only one of the rear wheels is powered.

There are three rubber feet on the bottom of the base plate to keep it stable, and a guide rail to help orient the vehicle straight ahead on the stand.

The display stand also serves as a place to store and show off your car when it is not in use.



Experiment Vehicle



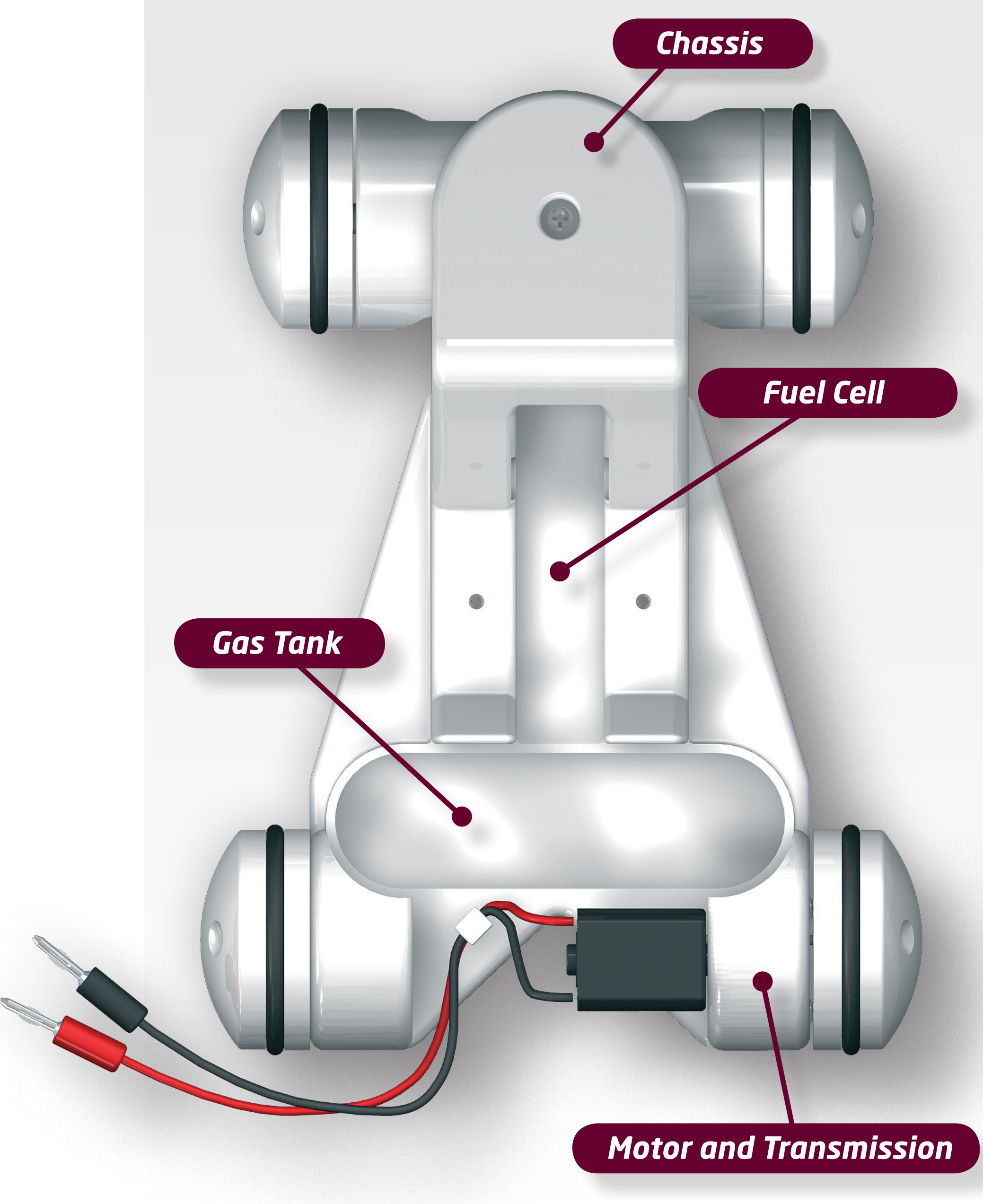
Display Stand

The Experiment Car Base

The chassis is the base of the fuel cell car. The other components will be attached to it. The fuel cell will sit in the rectangular area in the middle of the chassis. The water tank and the gas tanks will be placed behind the fuel cell, at the back of the car.

The motor and transmission are attached directly to the right rear wheel.

Concept **Component Layout**



Placement of the main components on the chassis

Front Axle

Insert the front axle's center pin into the hole in the front of the chassis from the bottom. The indentation (A) must be in the front. Secure using the screw (B) with the fixed washer.

Tighten the screw with a small Phillips head screwdriver to a point where the axle can still turn a little, but is securely attached. When the indentation (A) is oriented to the front, the axle will stay straight.

The mobility of the front axle can be adjusted by tightening or loosening the screw (B).

For the experiments in this manual and when running the car on the display stand, the front axle should always be oriented straight ahead.

Wheel Mounting

The wheels, axles, and tires come pre-assembled.

The black rubber tires, or O-rings (D), allow for better driving on smooth surfaces.

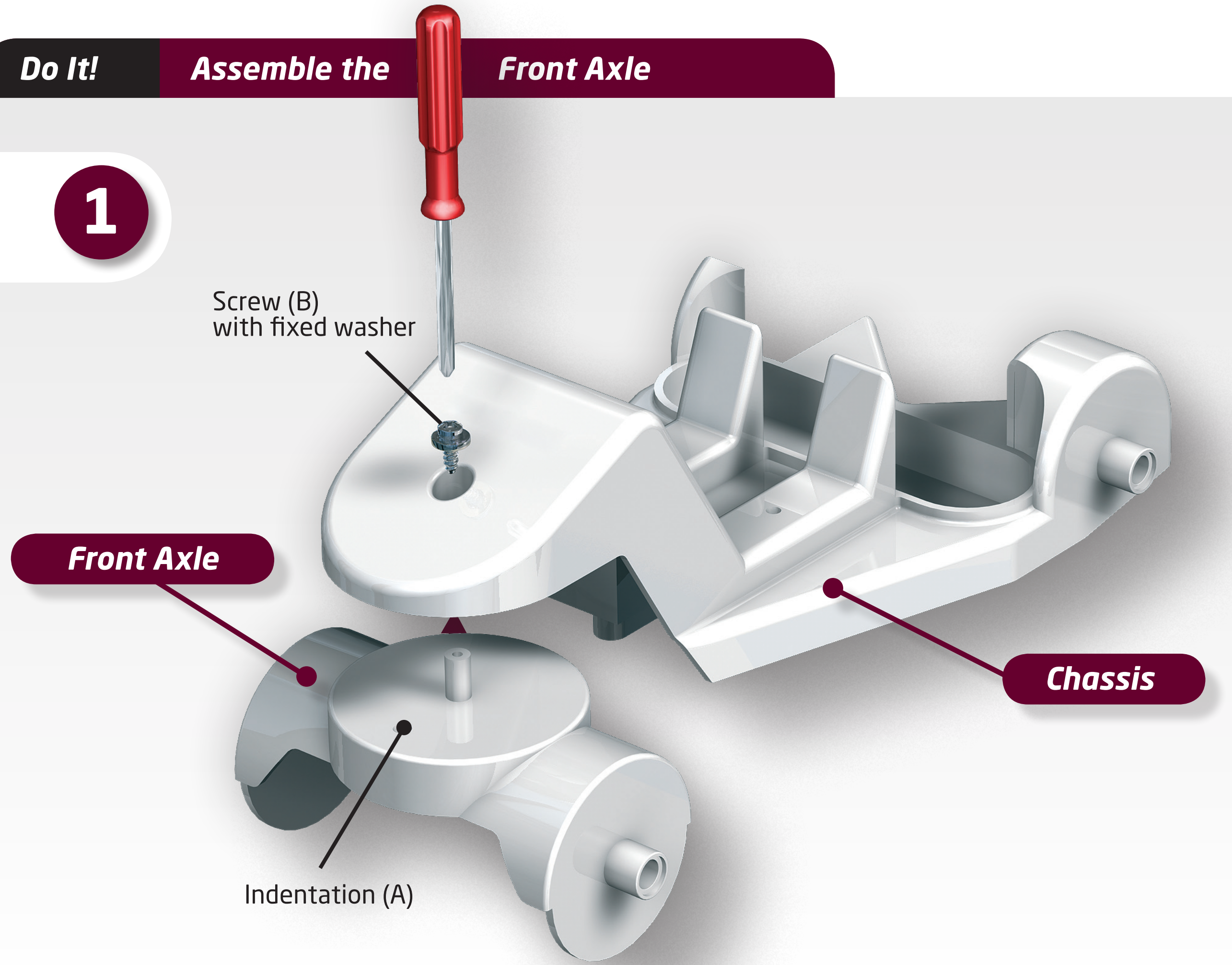
The wheels have short connector axles (E) inside them that easily snap into the holes in the front axle and at the rear of the chassis.

Snap the three wheels into the holes and roll the car on the table or floor to make sure all the wheels are properly seated and rolling smoothly.

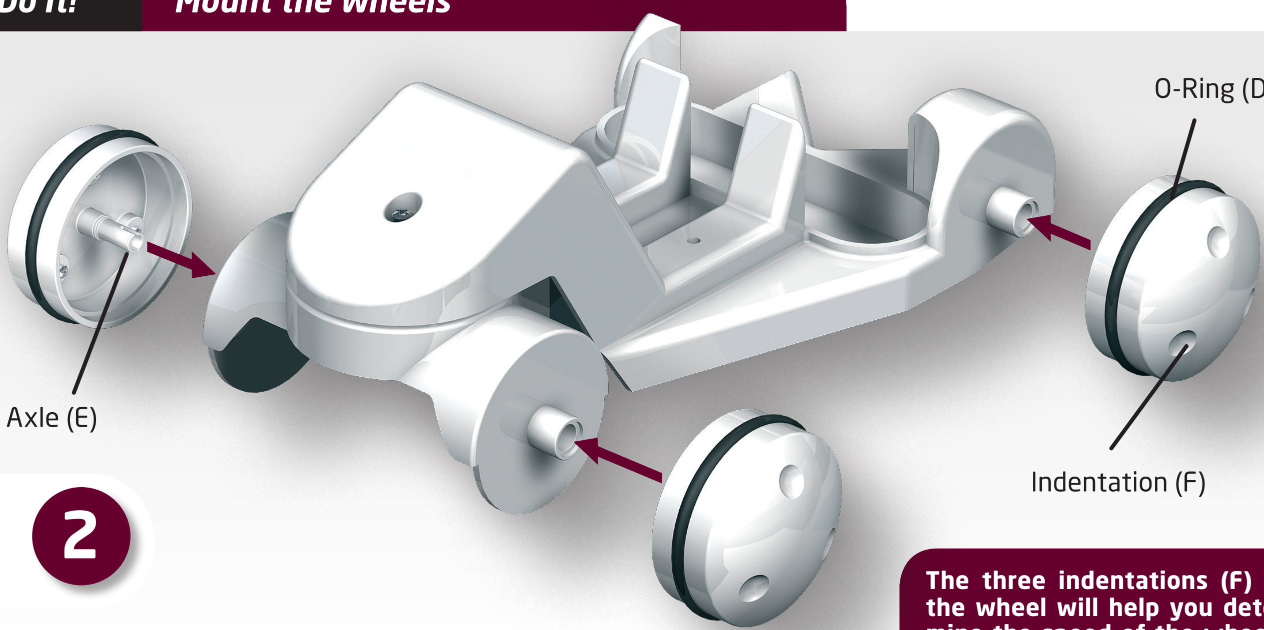
Vehicle Assembly

Do It! Assemble the Front Axle

1



Do It! Mount the Wheels



2

The three indentations (F) on the wheel will help you determine the speed of the wheel's rotation during the experiments.

Attaching the Motor and Transmission

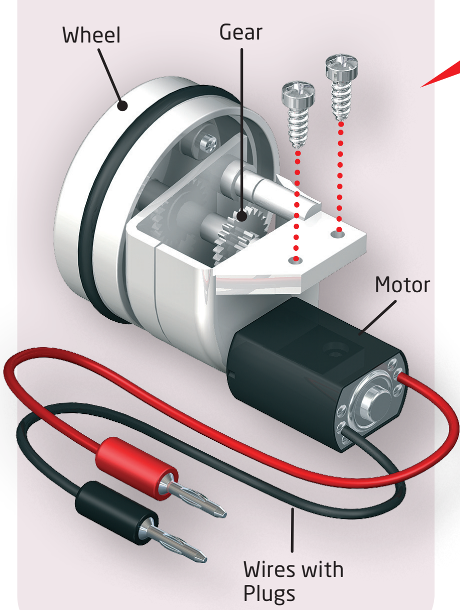
After you have attached the front axle and the three wheels to the chassis, you can install the motor and transmission unit onto the chassis.

This unit comes pre-assembled and needs only to be mounted to the left rear of the chassis.

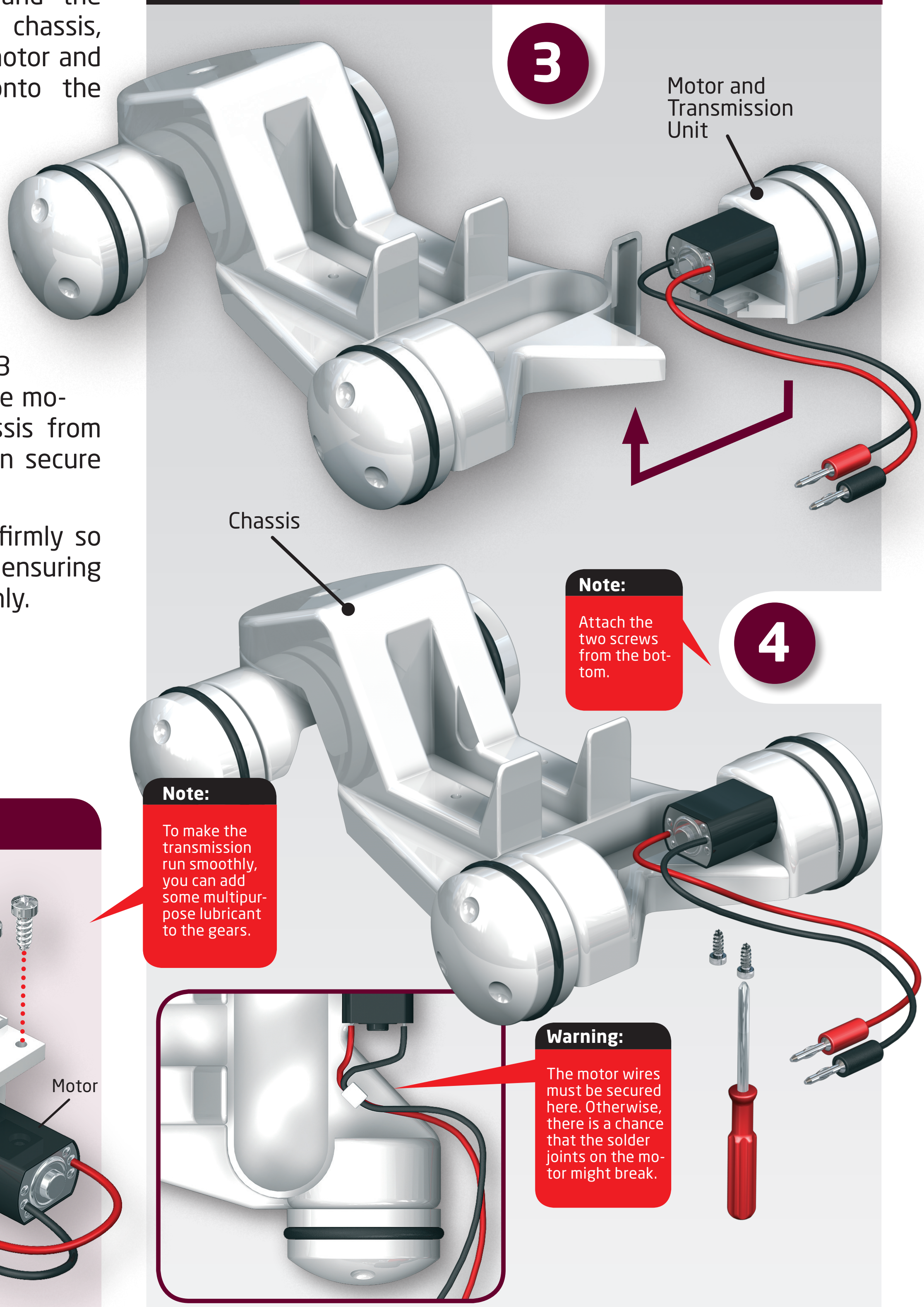
As shown in steps 3 and 4, first attach the motor unit to the chassis from underneath, and then secure it with two screws.

Tighten the screws firmly so the wheel is stable, ensuring the car drives smoothly.

Motor Unit



Do It! Attach the Motor and Transmission Unit



Note: Attach the two screws from the bottom.

Note: To make the transmission run smoothly, you can add some multipurpose lubricant to the gears.

Warning: The motor wires must be secured here. Otherwise, there is a chance that the solder joints on the motor might break.

Note: *Do not disassemble the motor and transmission unit!*

Mounting the Water Tank and Fuel Cell

Insert the water tank into the well at the rear of the chassis. The water tank holds the gas tank unit, and the gas tank unit also serves as a lid for the water tank.

The water tank is transparent so that you can easily observe the gas production and consumption during operation of the car.

Fuel Cell

The most innovative component in this kit is undoubtedly the reversible fuel cell. The fuel cell and its significance to the future of transportation and the environment is described in detail further on in this manual.

The fuel cell sits in the middle of the car chassis. It is important that you push the fuel cell all the way to the bottom of its rectangular compartment, so that it sits snuggly in the chassis.

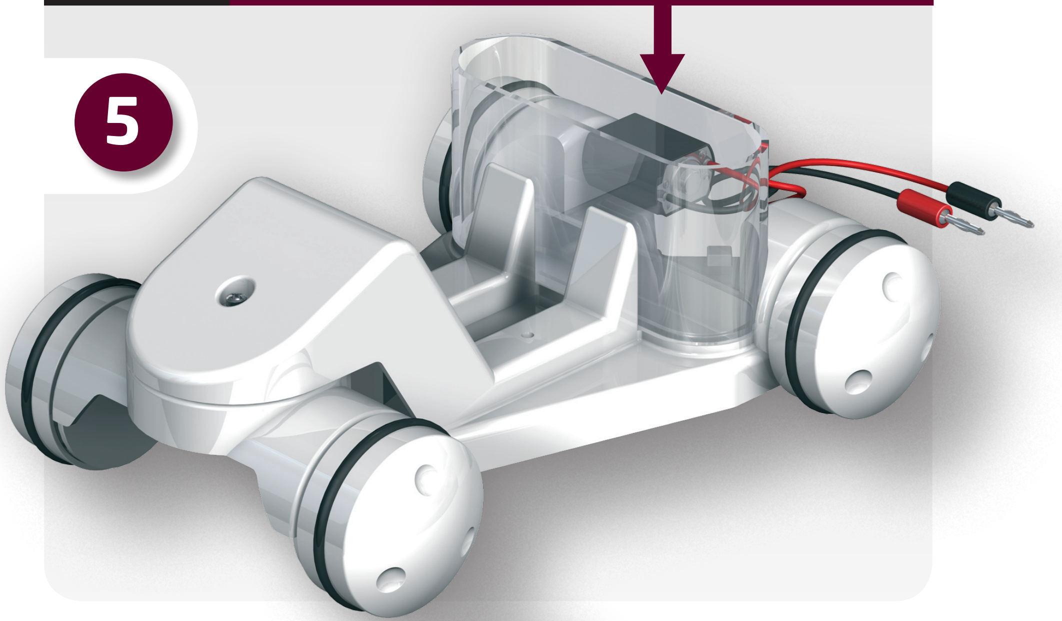
The fuel cell and water tank are not needed for the following two experiments, so they can be removed for now.

Warning:

Under no circumstances should the fuel cell be dismantled. If it is improperly opened or reassembled, it will not work.

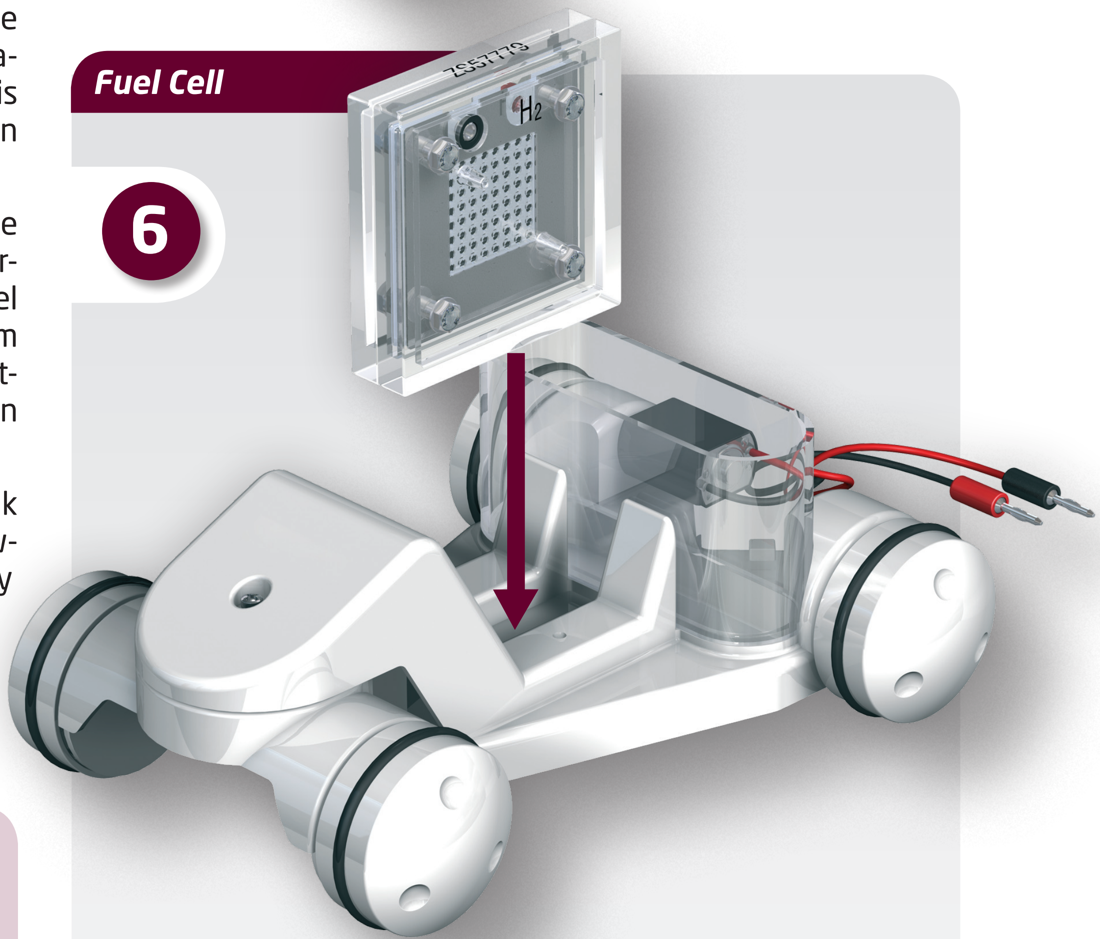
Do It! **Insert the Water Tank**

5



Fuel Cell

6



Note: *This initial set-up is temporary.*

Finishing the Initial Assembly of the Experiment Vehicle

Gas Tanks

Insert the transparent gas tank unit into the water tank. The gas tank unit has an integrated cover and connection nozzles for the gas hoses. The cover of the gas tank unit should seal the water tank.

The gas tank unit has two tanks: the larger tank is for hydrogen and the smaller tank is for oxygen. There are nozzles on the top of both tanks that are used to connect the hoses to the fuel cell.

Make sure the cover is seated tightly on the water tank.

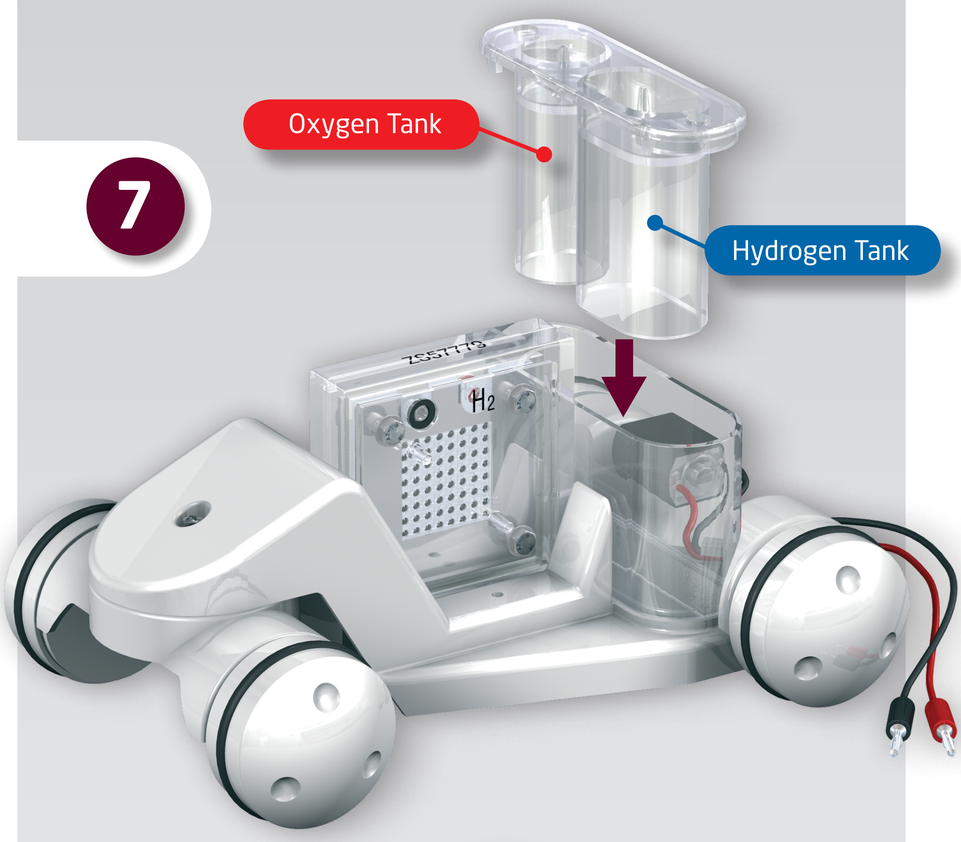
Now the test vehicle is set up. We will not need the wires and hoses shown in Figure 8 until later.

Important:

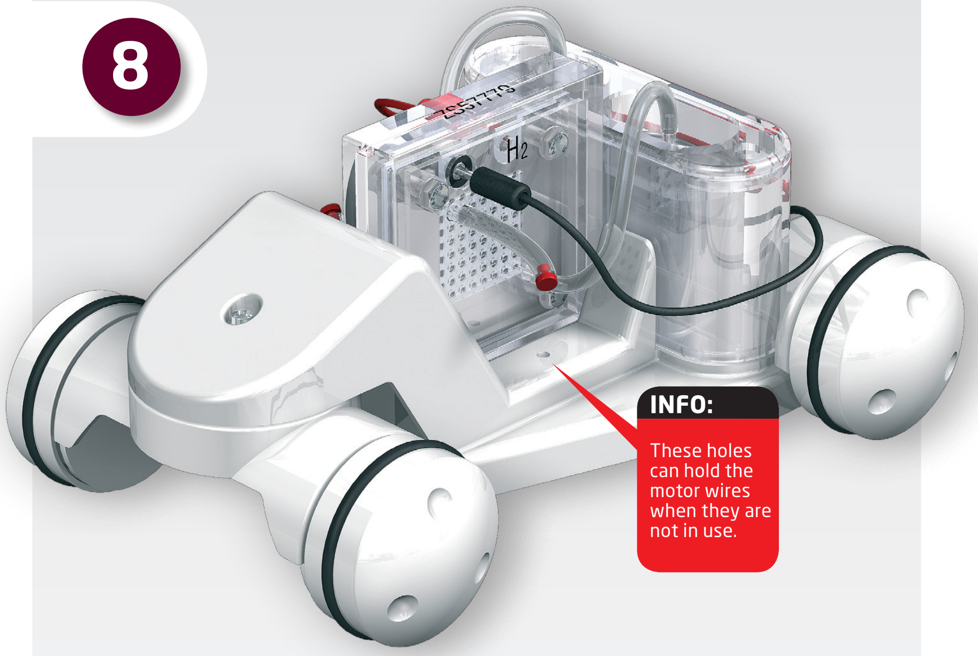
In this configuration, the model car is not yet operational. The individual steps for the operation of the model are described further on in this experiment manual.

Do It! Install the Gas Tanks

7



8



Hint: *This initial set-up is temporary.*

Assembling the Display Stand with Rollers

Rubber Feet

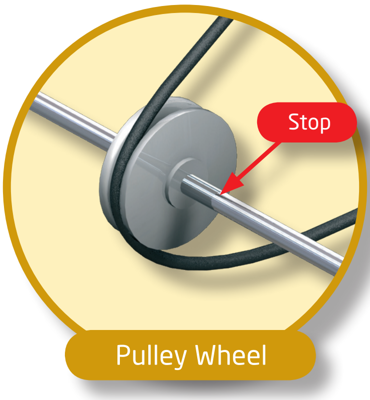
Check to make sure the three rubber feet are attached to the underside of the base plate. These provide a more stable footing for the display stand.

Axles and Pulley Transmission

Start sliding the short axle with shaft stop into axle holder 1. Carefully position the rubber belt and the first pulley wheel in the groove between the two sides of the axle holder so that the axle slides through both of them as it passes through the groove.

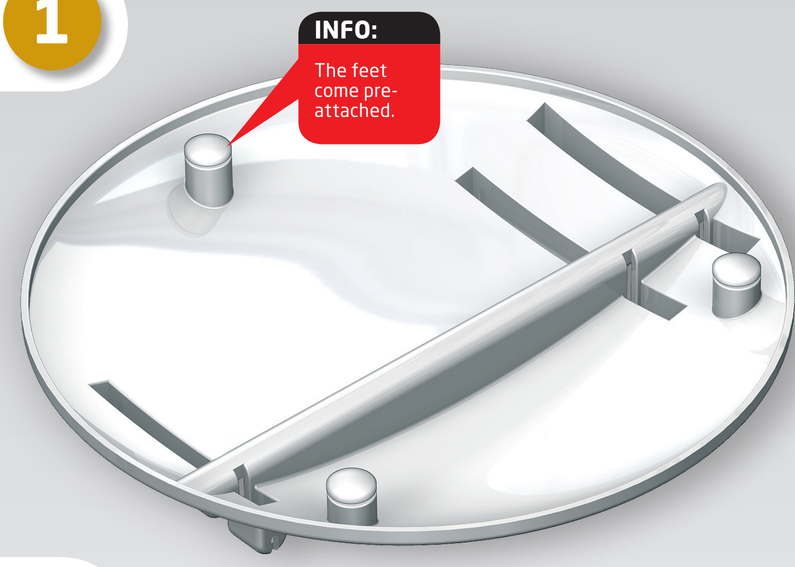
The pulley wheel should engage securely to the axle at the axle stop.

Put roller caps on both ends of the first axle.

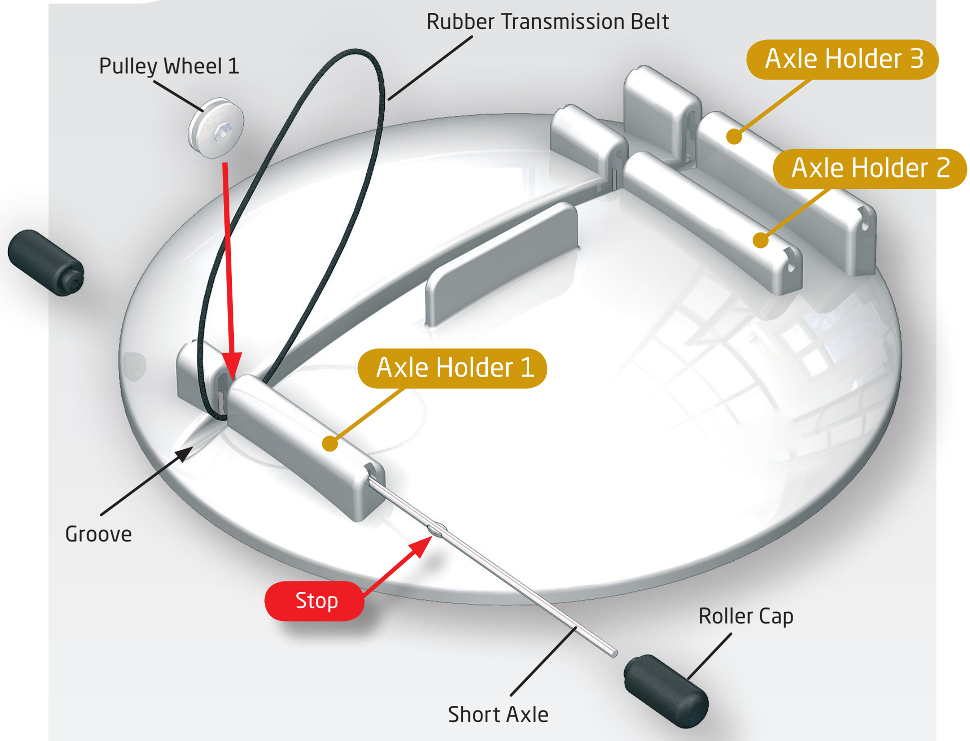


Do It! ***Assemble the Display Stand***

1



2



Note: *This assembly is intended to be permanent.*

Finishing the Assembly of the Display Stand

Second and Third Axles

Insert the long axle with the shaft stop into axle holder 2. As with the first axle, position the rubber belt and the pulley wheel in the groove between the two sides of axle holder 2. Slide the long axle through the pulley and the belt.

The shaft stop should engage with the pulley wheel to make a tight connection. Put roller caps on both ends of the second axle.

The third axle has no shaft stop. Simply insert it into axle holder 3 and then put roller caps on both ends.

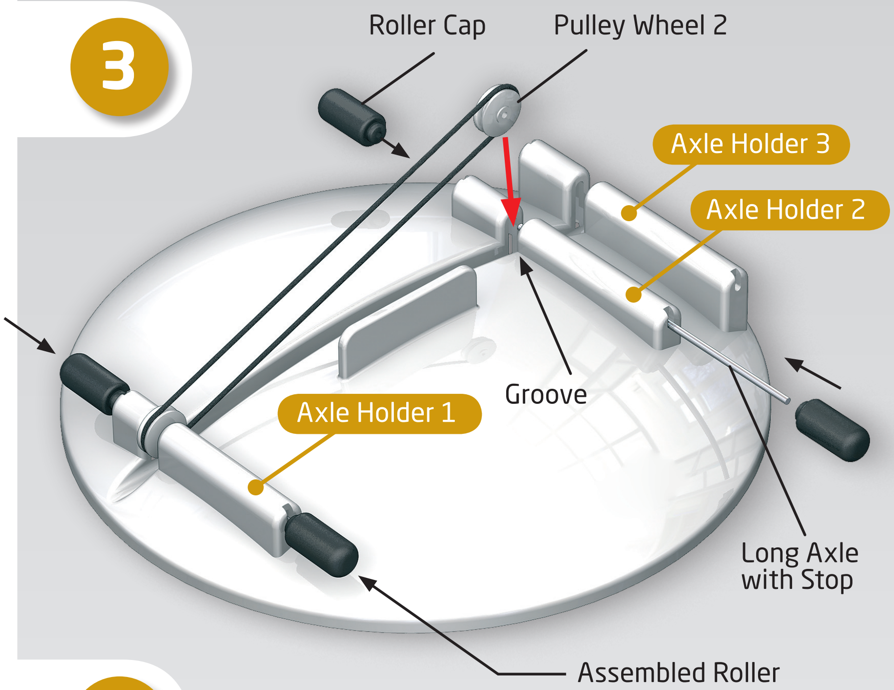
Figure 4 shows the completed display stand with rollers.

Testing the Rollers

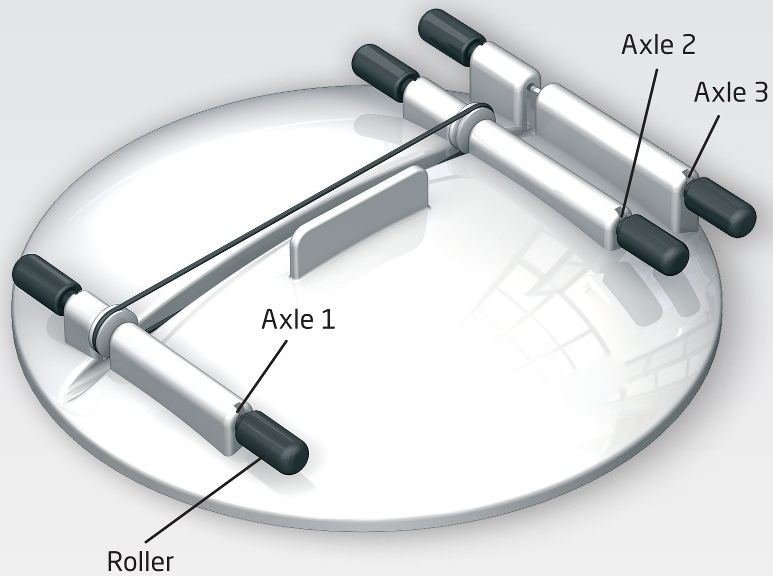
Now check to make sure all of the axles turn smoothly. The rubber belt around axles 1 and 2 ensures that their turning is synchronized. To make the axles spin more easily, you can put a drop of multipurpose lubricant on the points where the axle holders make contact with the axles. Keep the six roller caps absolutely free of lubricants.

Do It! ***Complete the Display Stand***

3



4



Important: ***All three axles must rotate smoothly and easily.***

Positioning the Vehicle on the Display Stand

When positioned as shown here, the fuel cell car can drive in place on the display stand rollers. It can also simply sit on the display stand when it is not running.

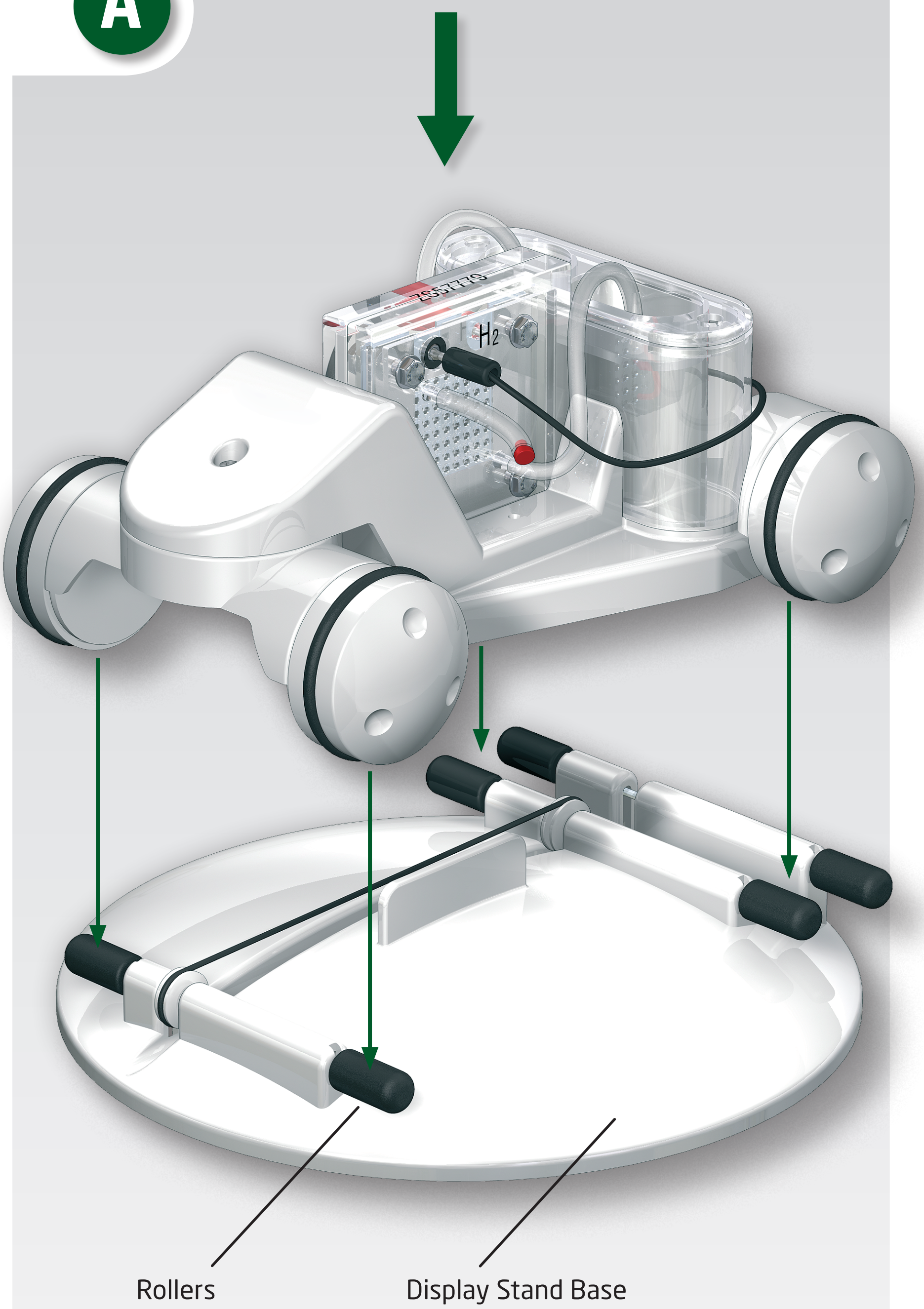
The two rear wheels sit evenly between axles 2 and 3. The two front wheels should be centered on the front axle.

All of the wheels should be sitting evenly over the supporting rollers. The front wheels should be oriented straight ahead.

Figure B shows the guide slot on the underside of the car chassis. The guide slot should slide onto the guide rail on the center of the display stand.

Do It! **Place the Vehicle on the Display Stand**

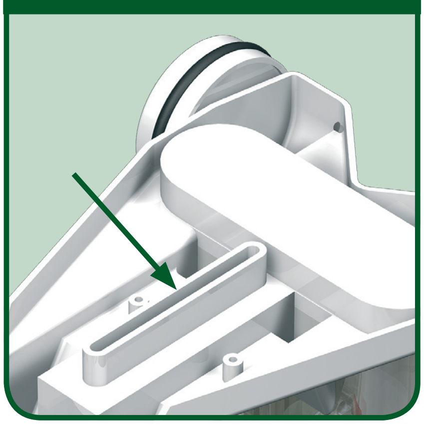
A



Note: ***The vehicle must be placed precisely on the stand.***

B

Guide Slot



Underside of the Vehicle

Experiment 1

Battery Powered Car

With this first model design, we will start to learn a little about the function of the car. In battery mode, we will study its chassis, steering, and power transmission, its forward and reverse drive, and the way the rolling display stand works.

This first experiment also serves to verify whether we have all components of the car and the display stand assembled correctly.

To prevent the car from zooming away from you, first place it on the display stand. Make sure you have assembled the display stand correctly.

Next, place the battery holder on the model's seats, after installing two 1.5-volt type AA (penlight) batteries inside it. Pay attention to the polarity of the batteries when inserting them.

Set the switch on the battery holder to OFF, and attach its plugs to the two motor connectors, as shown in the picture.

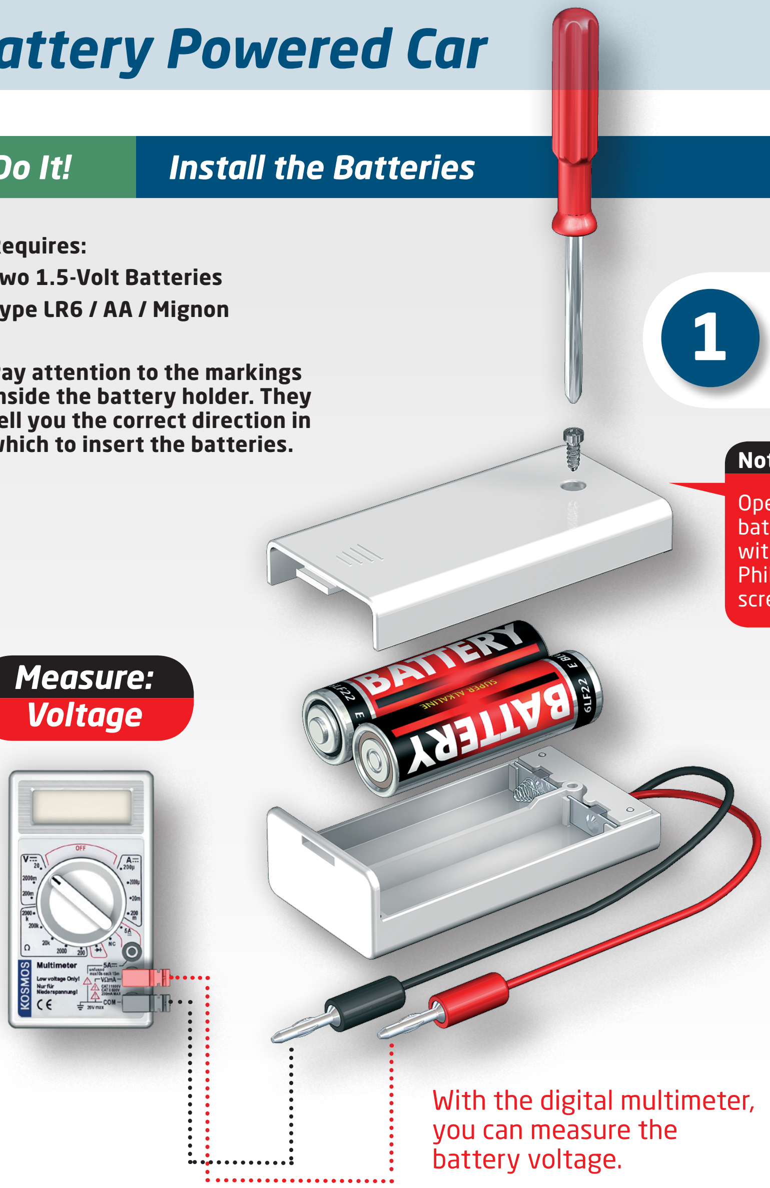
To make the model drive forward, the black cable coming from the battery's negative terminal has to be connected to the motor's black cable, while the red battery cable connects to the red motor cable. Connect the wires as shown in Figure 2.

Do It! Install the Batteries

Requires:
Two 1.5-Volt Batteries
Type LR6 / AA / Mignon

Pay attention to the markings inside the battery holder. They tell you the correct direction in which to insert the batteries.

1



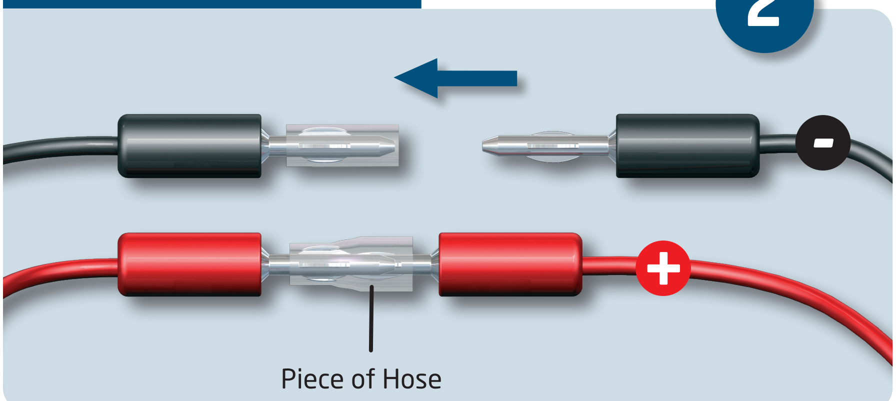
Note:
Open the battery case with a small Phillips head screwdriver.

Measure: Voltage

With the digital multimeter, you can measure the battery voltage.

Wire Connections

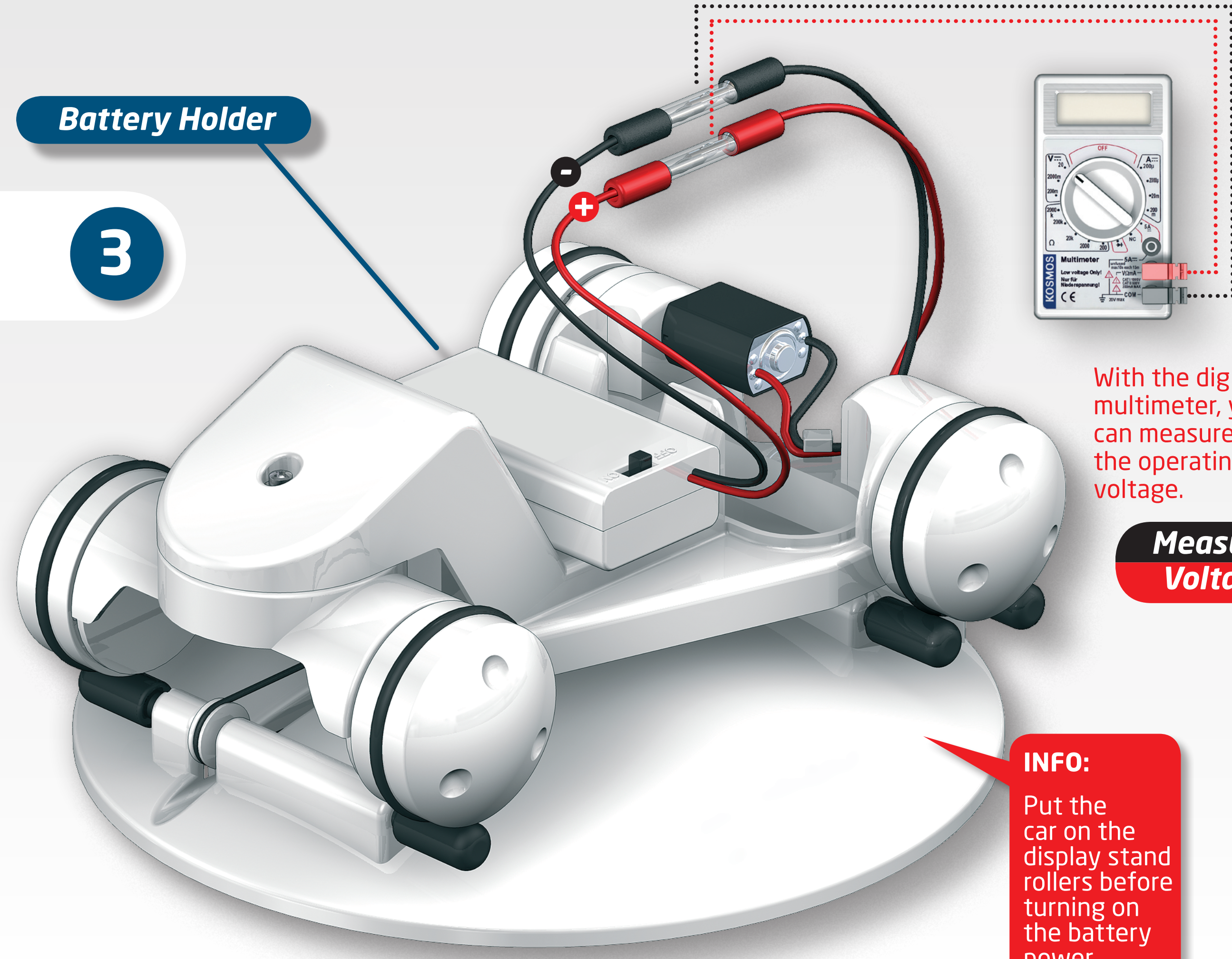
2



To attach the wires together, cut two sections that are about one centimeter in length from the gas hose. Push one of the hose sections onto each of the plugs, and then push the other plugs into the hose to make the connection.

Running the Battery Powered Car on the Display Stand

Do It! Run the Car on Battery Power



With the digital multimeter, you can measure the operating voltage.

Measure: Voltage

INFO: Put the car on the display stand rollers before turning on the battery power.

Note: *Only turn the battery holder on when connected.*

Now set the switch to ON. The motor will start humming away, with the wheels spinning on the display stand's imaginary roadway. To drive in reverse, we just have to reverse the polarity of the motor, i.e. connect red to black and black to red.

Once the car has successfully completed its test run, you can try driving it on the ground.

The front axle is mounted in such a way that it can be swiveled, to make it possible to drive around curves. On the display stand, the front axle has to be locked in the forward position to drive straight ahead.

Also, the two holes in the side sections of the car (left and right) can be used to hold the motor connector wires when the motor isn't in use.

The Solar Panel

In this experiment, we will run the car with electricity produced directly from solar energy, without any interim storage of the energy.

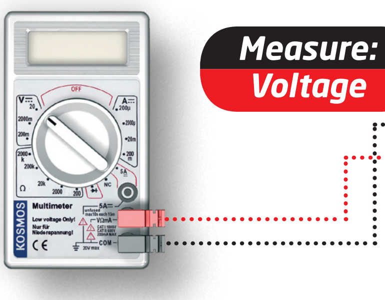
To do this, we will use the solar panel included in the kit. See Figure 1. The solar panel converts the energy in light into electrical energy that can then be used to power the electric motor. This works only when there is direct sunlight hitting the solar panel.

The solar panel has two sockets for connecting wires. The electricity flows in and out of these sockets.

- The red socket is for the positive red wire.
- The black socket is for the negative black wire.

Since the solar panel generates DC (direct current), it is very important that the polarity be correct. In other words, it is important that the wires are connected as the manual instructs.

With the digital multimeter, you can measure the no-load voltage in direct sunlight.



Measure: Voltage

The Solar Panel

Free electricity from the solar cell

Running the Solar Powered Car on the Display Stand

Do It! Run the Car on Solar Power

The illustration shows how the motor wires should be connected to the solar panel to run the motor directly with electricity generated by the solar panel. To be safe, you can secure the solar panel to the car with two small strips of tape. The model will drive as long as the solar panel has the sun's rays shining on it, and it will stop as soon as it hits a shadow. Unfortunately, our model lacks a way to store energy.

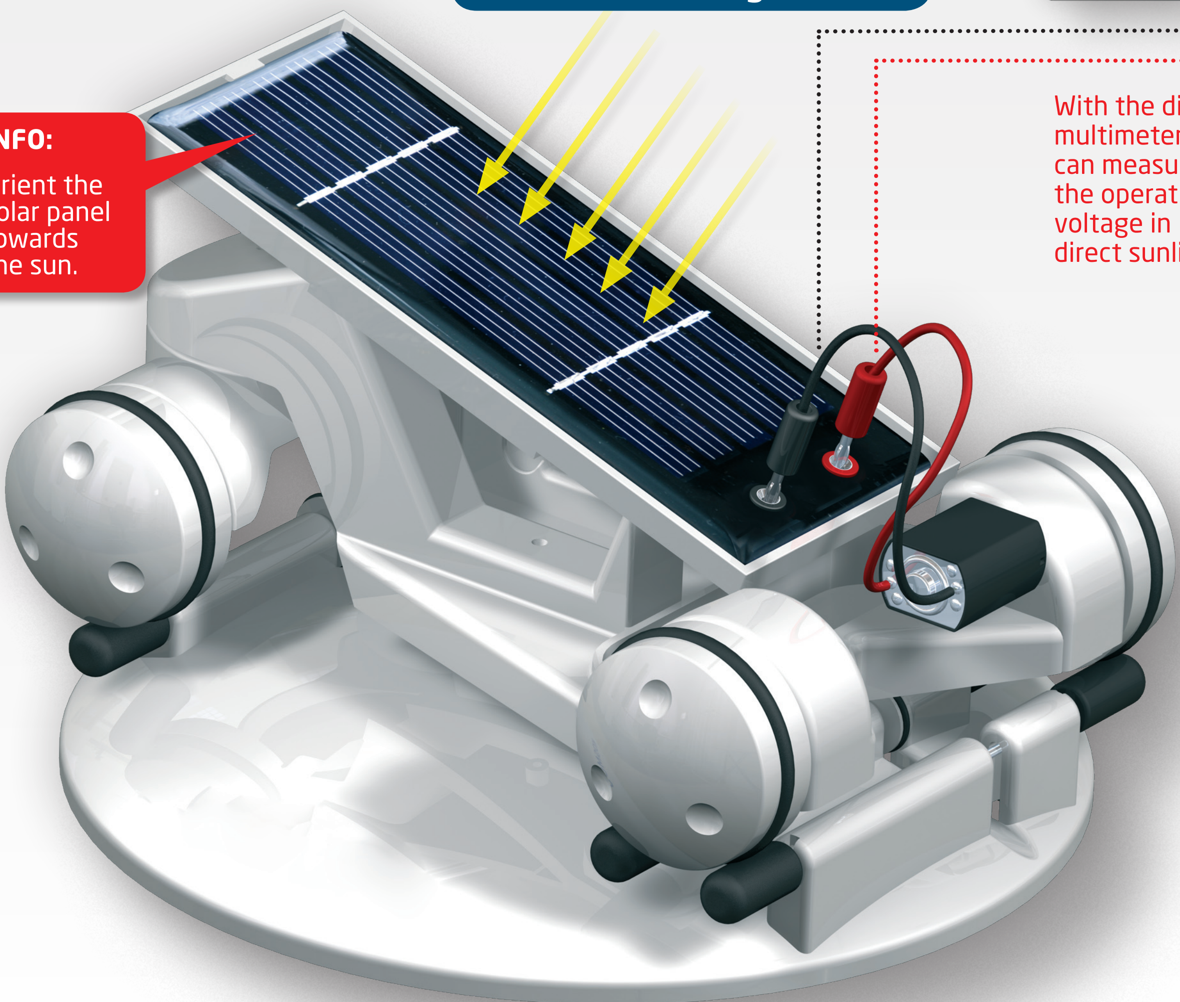
If you want the model to drive on the display stand without the stand being in direct sunlight, you can set the solar panel on a windowsill, where it can catch the rays of the sun, and use the long connection cables to connect it to the motor.

2

Measure: Voltage

With the digital multimeter, you can measure the operating voltage in direct sunlight.

Direct Sunlight



INFO:

Orient the solar panel towards the sun.

Note: *The solar cell will only produce enough electricity to run the motor in direct sunlight.*

Preparing the Fuel Cell Car

To drive our model car exclusively with the fuel cell, we will first have to get the following parts ready:

- **Fuel cell**
- **Water tank**
- **Gas tanks**
- **Hose**
- **Two small red sealing plugs**
- **Solar panel**
- **Red connection wire**
- **Black connection wire**
- **Distilled water**
- **Syringe**
- **Syringe tip**

Start with the partially assembled car with wheels and motor attached, as shown in Figure 2.

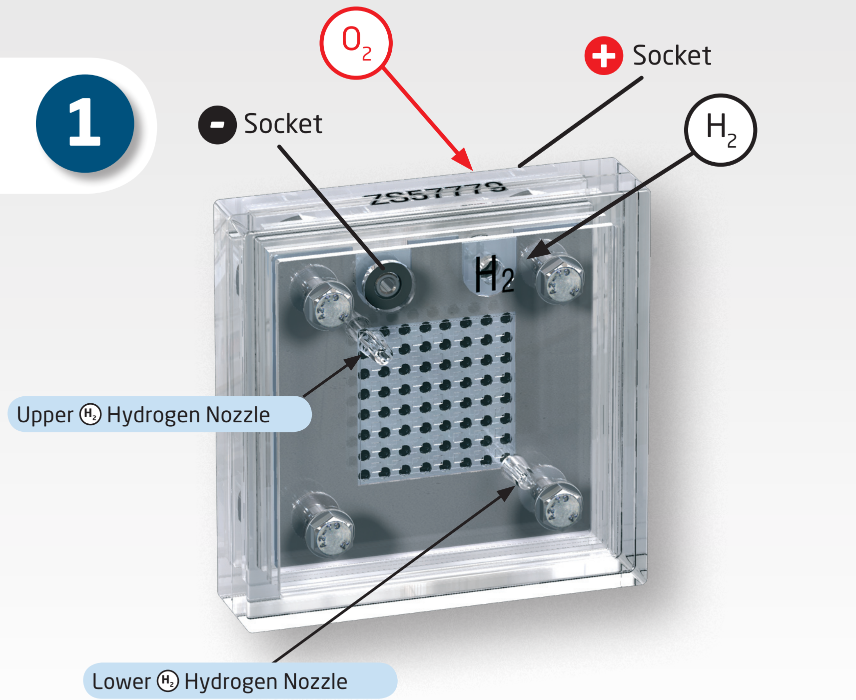
Assembly

Now we will add the fuel cell to the car. The cell has one side imprinted with "H_2" in black, and a black socket with two hose connectors. The cell's other side is imprinted with a red "O_2," and has a red socket with two hose connectors.

Place the fuel cell in the well between the two seats. It should be inserted so that the black socket H_2 is to the left and the red socket O_2 is to the right, when facing the direction in which the car is driving. The H_2 and O_2 marks should be visible at the top.

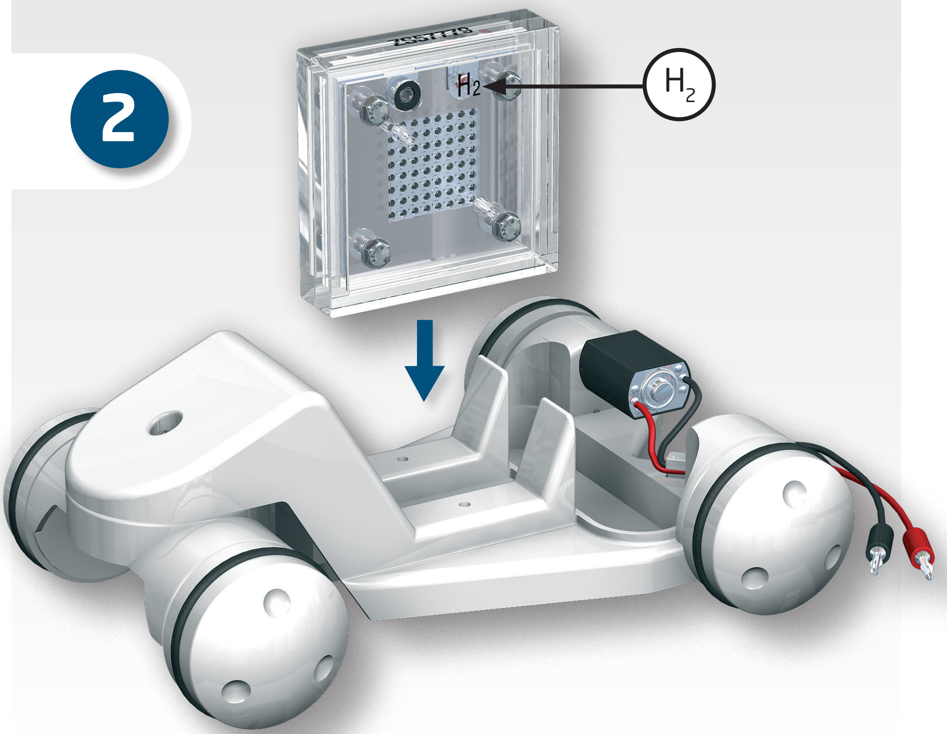
Fuel Cell

1



Do It! **Place the Fuel Cell on the Chassis**

2



Preparing the Water Tank and Gas Tanks

Now set the water container into the recess at the rear of the car, and insert the gas tank unit so that its larger container — which is the hydrogen tank — is to the left and the smaller oxygen container is to the right, as shown.

Gas Tank Setup

Now, the fuel cell has to be connected to the tanks with the help of the hose sections:

Cut the following lengths from the hose:

- two **4 cm** hoses
- two **10 cm** hoses

Insert the short 4 cm hose sections onto the upper nozzle connectors on the cell.

Insert the long 10 cm hose sections onto the lower nozzle connectors of the fuel cell and to the nozzles on the gas tanks, as shown.

The fuel cell and gas tanks are now connected to each other.

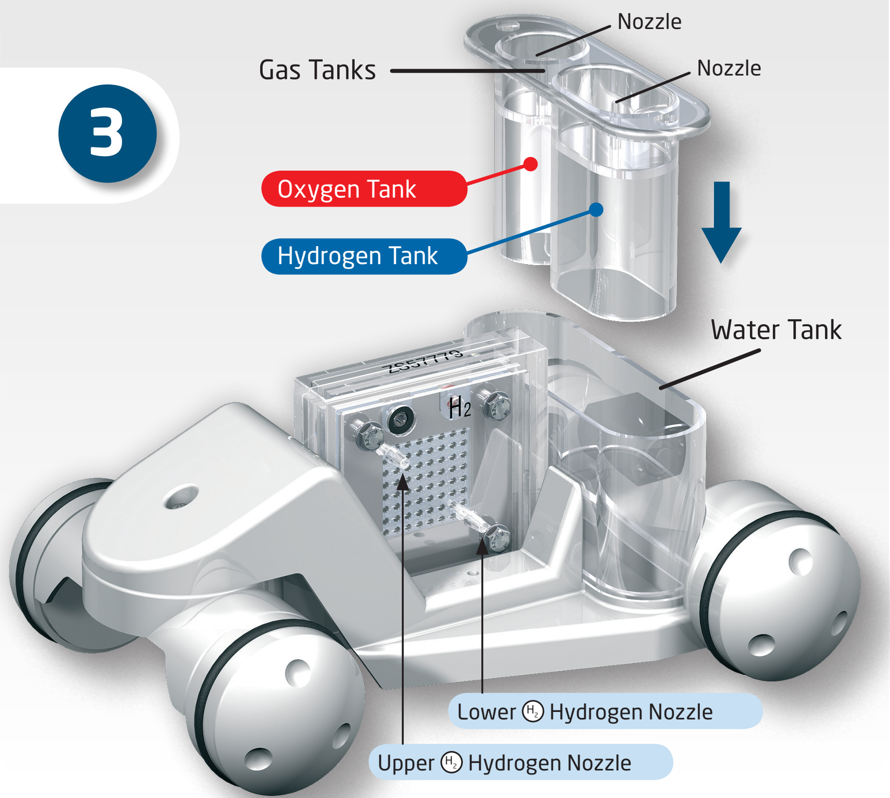
Check:

The hose from the H_2 side should lead to the larger tank and the one from the O_2 side should lead to the smaller tank.

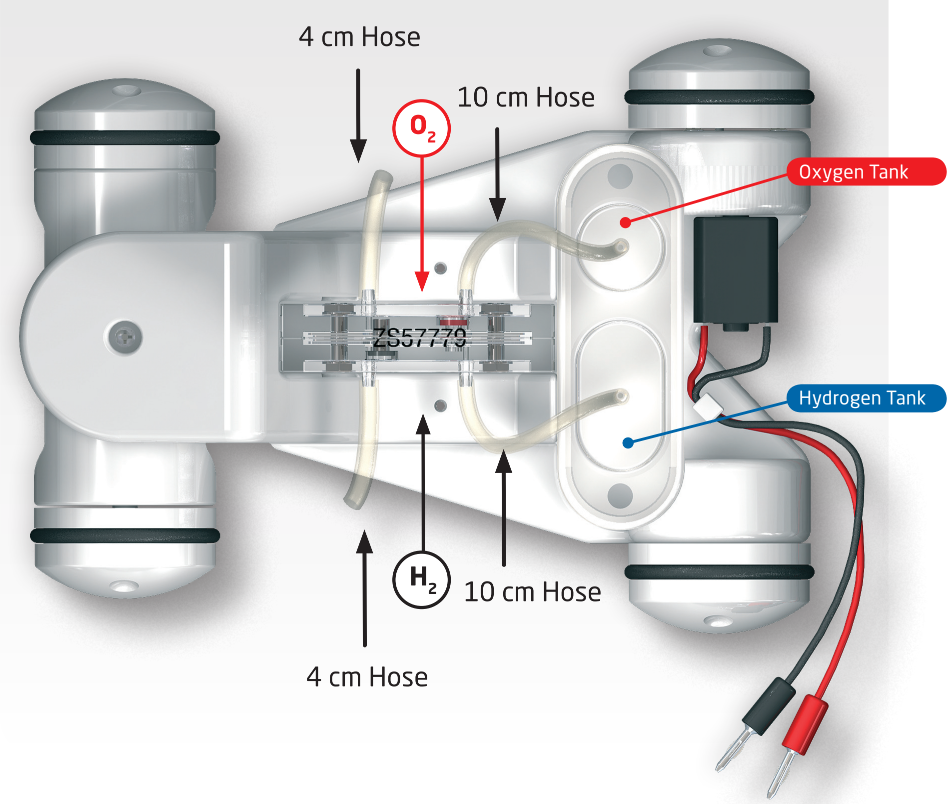
The short, still-open hose sections should be on the upper nozzle connectors of the cell.

Do It! **Insert the Gas Tank into the Water Tank**

3



Do It! **Attach the Hoses**



Preparing the System by Filling the Water Tank

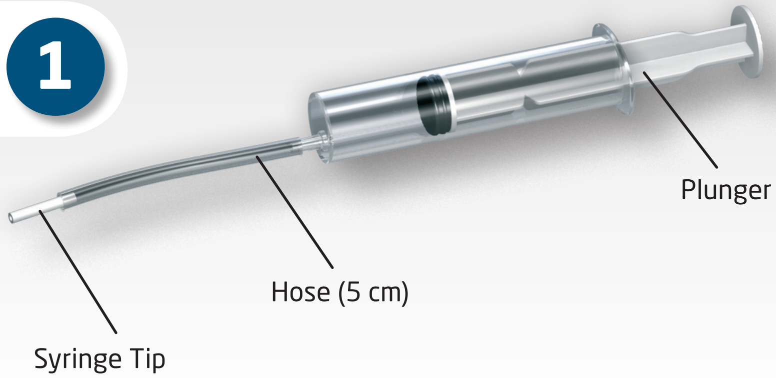
Syringe Preparation

Cut about 5 cm off of the supply hose. Insert this short hose section over the syringe opening, widening the hose section a little if necessary.

Insert the syringe tip into the open hose end. Push the syringe plunger all the way in.

The Syringe

1



Filling the Tank

The tanks and the fuel cell must only be filled with distilled water, which is available in supermarkets and pharmacies.

The system will now be filled with distilled water. Do this in the following steps:

1

Pour about ¼ liter of distilled water into a clean glass.

2

Draw water into the syringe by pulling up carefully on the plunger.

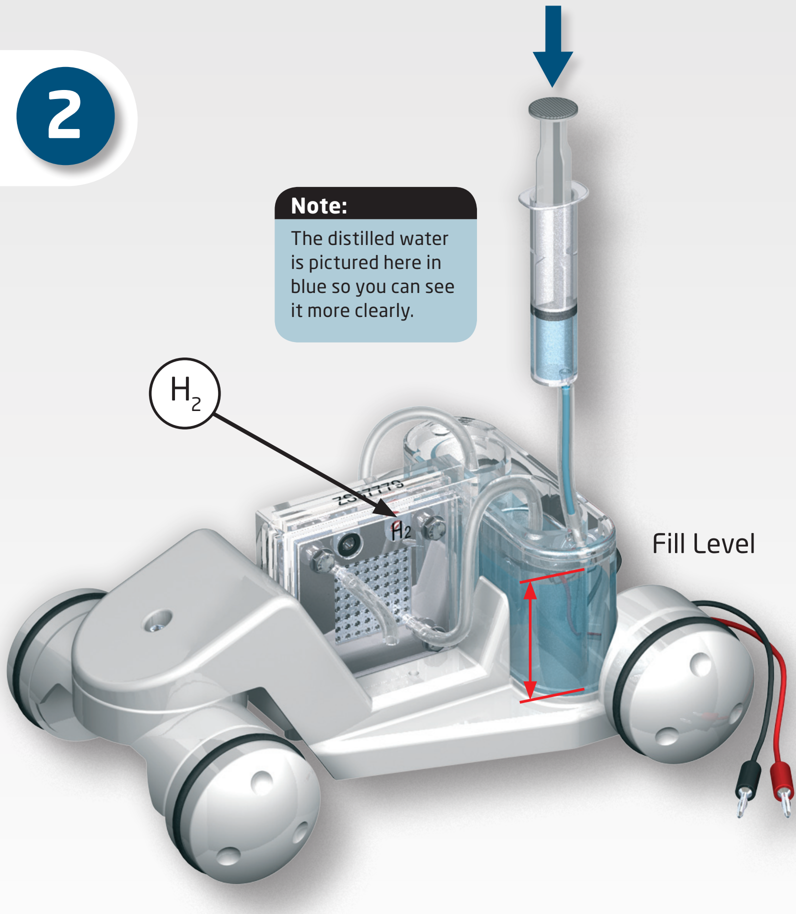
3

Inject the water into the water tank. Repeat until the water is up to the rim of the water tank. Wait for the water in the inner gas tanks to adjust to the water level in the outer tank.

Do It! Filling the Water Tank

2

Note:
The distilled water is pictured here in blue so you can see it more clearly.



Note: Use only distilled water.

Preparing the System by Priming the Fuel Cell

Priming the Cell

Now the distilled water has to be sucked out of the tanks, through the connector hoses, and into the fuel cell:

4

Push the syringe plunger all the way in.

5

Insert the free end of the syringe tip into the short hose section on the hydrogen H_2 side of the fuel cell. Slowly suck out water until there are no more air bubbles.

6

Pinch the short hose section between your thumbnail and index finger, pull out the syringe tip, and replace it with a sealing plug inserted into the end of the hose.

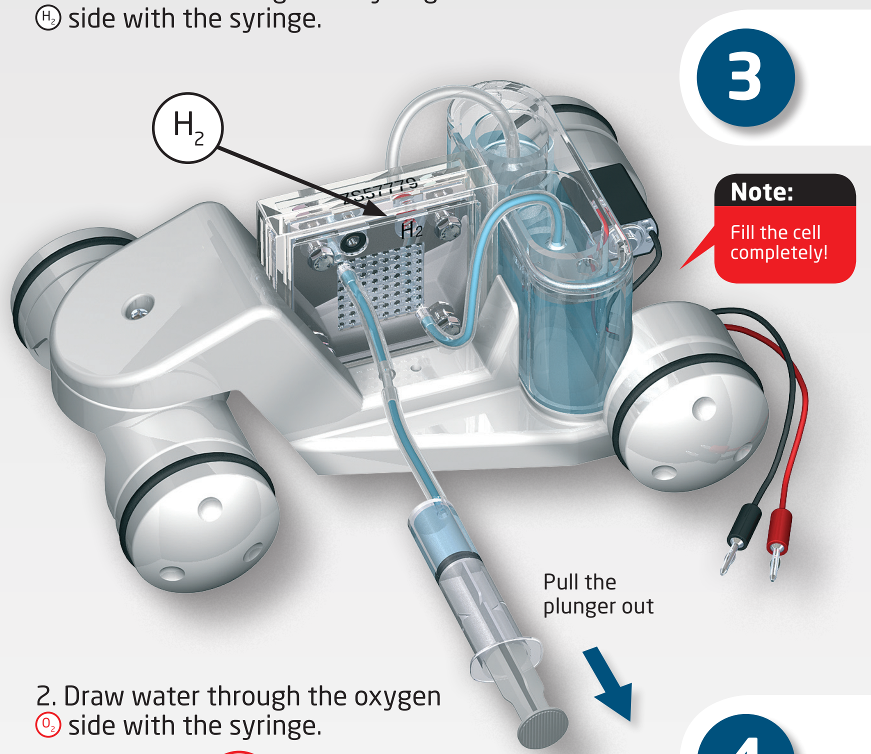
Inject the sucked-up water back into the water tank. Carry out the same procedure on the oxygen O_2 side of the cell.

The fuel cell is now sealed off from the outside air.

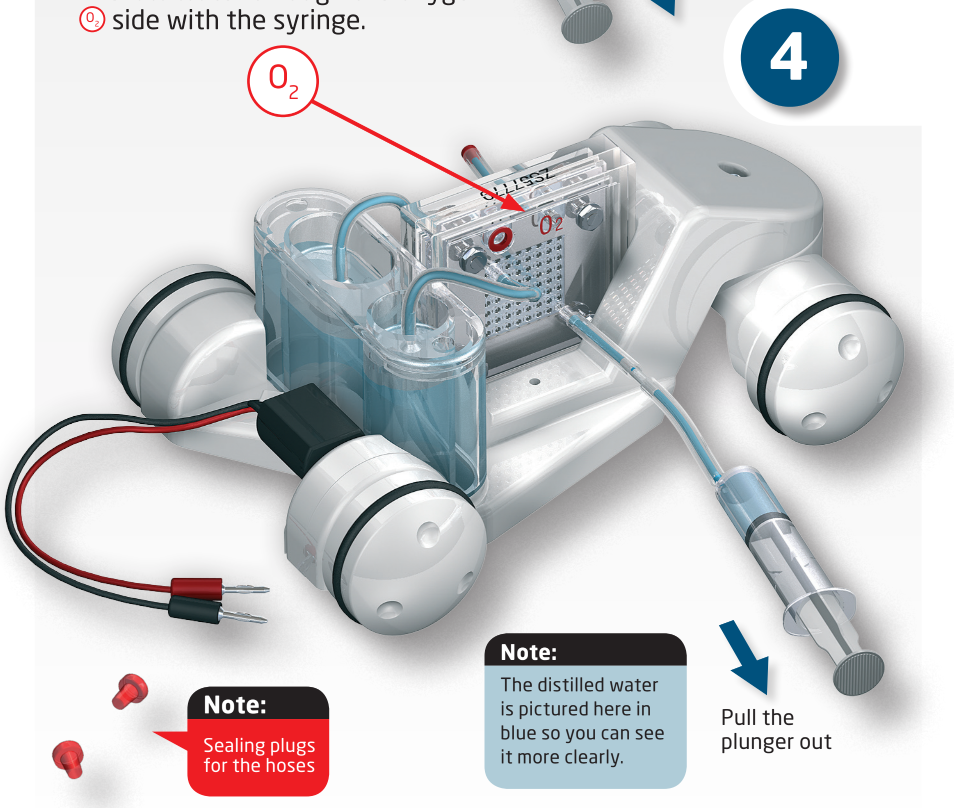
When you are done, the water tank should be filled up to about 1 cm below the rim.

Do It! Filling the Fuel Cell with Water

1. Draw water through the hydrogen H_2 side with the syringe.



2. Draw water through the oxygen O_2 side with the syringe.



Note: The fuel cell must be primed this way in order to work.

Experiment 4

Producing Gas with the Solar Panel

Now that the fuel cell is connected to the gas tanks, we can start to make the fuel for our fuel cell.

The fuel cell is powered by hydrogen and oxygen gas. The fuel cell can also make these gases by separating water into its component elements, hydrogen and oxygen.

To do this, it needs electricity. The solar panel can provide the necessary electricity when it is exposed to sunlight.

After the gases have been produced and stored, the system can work in reverse: The gases are led back to the cell where they combine, which releases electricity. (Chapter 7 explains the electrochemical processes that take place in the cell.)

In order to produce the fuel, we will first need to take the following steps:

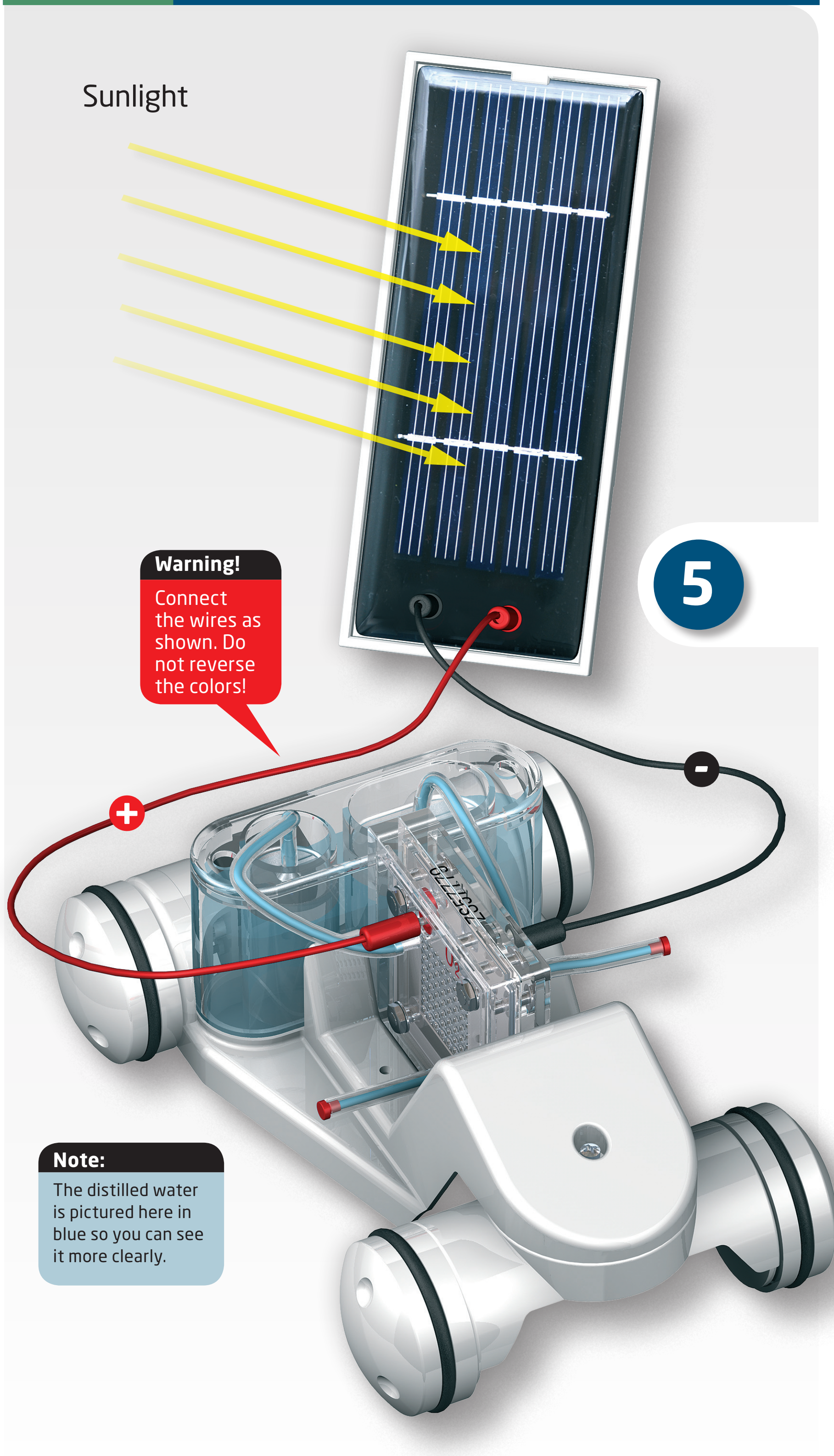
1

Orient the solar panel toward the sun.

2

Connect the (red) positive terminal of the solar panel to the red positive O_2 terminal of the fuel cell with the red cable.

Do It! **Make Fuel from Water and Sunlight**



The hydrogen and oxygen are stored in the gas tanks.

Producing Electricity from Light and Gas from Water

3

Connect the (black) negative terminal of the solar panel to the black negative (H_2) terminal of the fuel cell with the black cable.

4

Check the gas production: Now electrolysis begins in the fuel cell, which is the splitting of water into its elements (See Chapter 7).

The gas that is produced pushes the water that remains inside from the fuel cell through the long hoses into the gas tanks in the water container.

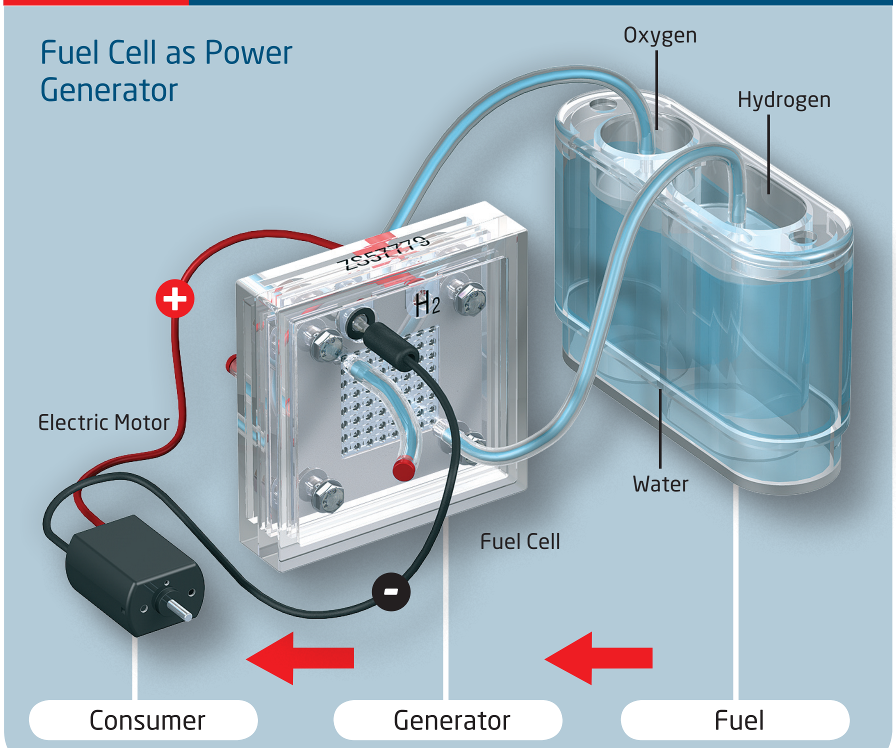
The larger tank fills with hydrogen gas, the smaller one with oxygen. After just a few minutes, you will be able to see how the gases push the water down in their storage tanks and the water level in the water tank will start to rise.

When the first bubbles rise out of the gas tanks to the water's surface, the gas tanks are full.

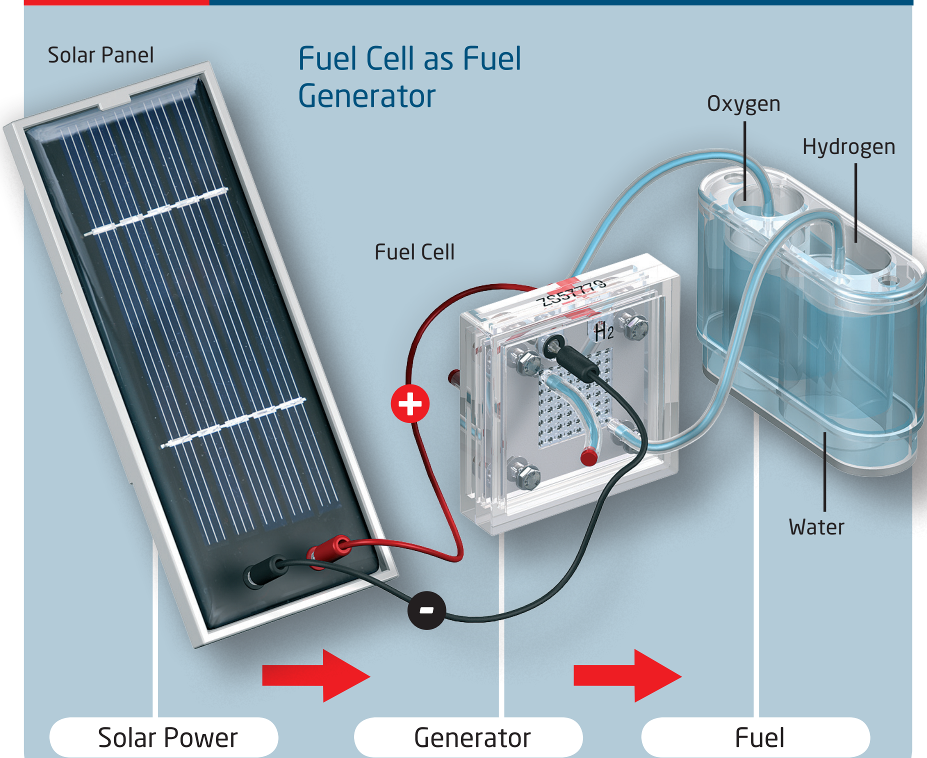
5

Remove the cables between the fuel cell and solar panel.

Concept — ***The Fuel Cell Generates Electricity***



Concept — ***The Fuel Cell Generates Fuel***



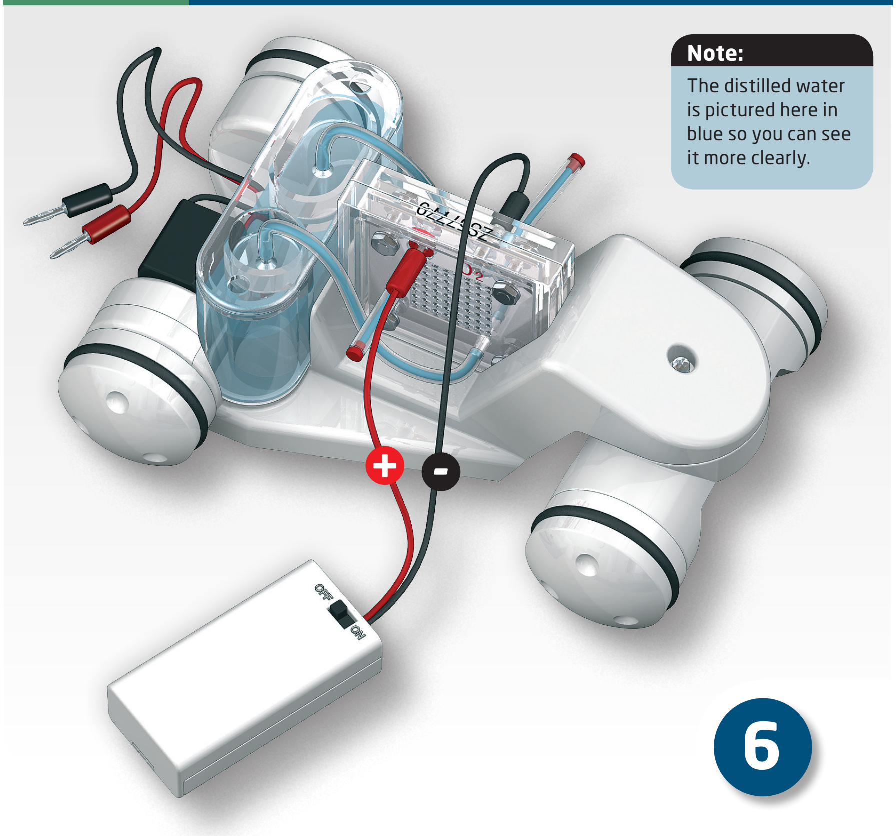
Experiment 5

Production of Fuel with Battery Current

When the sun is not shining, you can also produce fuel with battery power.

- Connect the red battery terminal to the red oxygen O_2 socket of the fuel cell.
- Connect the black battery terminal to the black hydrogen H_2 socket.

Do It! Produce Fuel with Battery Power



Note:
The distilled water is pictured here in blue so you can see it more clearly.

Checking the Gas Production

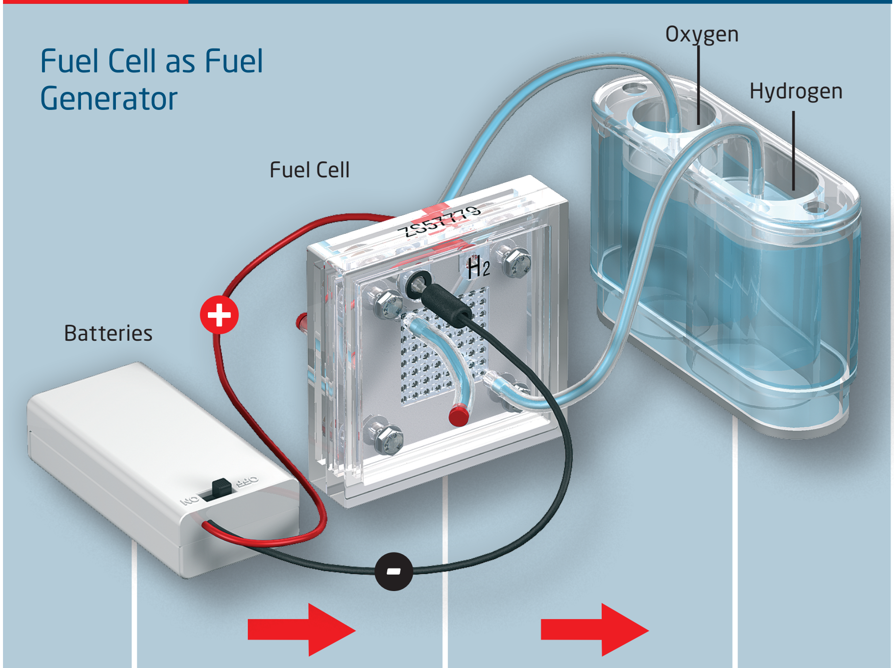
Now electrolysis begins in the fuel cell, which is the splitting of water into its elements, hydrogen and oxygen. The water that remains in the tubes is pushed from the cell through the long hoses to the gas tanks and the water tank by the gas that is produced. The larger tank fills with hydrogen gas, the smaller one with oxygen. After just a few minutes, you will be able to see how the gases push the water down in their storage tanks and the water level in the water tank starts to rise.

When the first bubbles rise out of the gas tanks to the water's surface, the tanks are full.

Remove the cables between the fuel cell and solar panel.

Concept The Fuel Cell Generates Fuel

Fuel Cell as Fuel Generator



Experiment
6

Running the Fuel Cell Car

The vehicle's gas tanks are now filled with fuel for the fuel cell.

To drive, the fuel cell car needs neither batteries nor the solar panel. Now, the electrolysis process will be reversed: The previously separated elements of oxygen and hydrogen will join together again and release electricity to the motor. We will get the car ready to roll by taking the following steps:

The gases will be pushed out of the tanks through the water tank's water pressure. As that happens, the water level will drop along with the pressure that pushes the gases into the cell. The electric motor will keep getting current until the two gases are almost used up. For the pressure of the water column to be enough to push the gases out, the initial water level in the container has to be correct. (See Step 1).

Of course, the car can also be driven on level ground.

The whole process can be repeated as often as you like. But it is important to be sure that the fuel cell is completely replenished with distilled water at the start of each cycle.

Tap water or spring water will destroy the fuel cell!

1

If necessary, refill the water tank with distilled water until the water level is just beneath the two openings in the lid.

2

Set the vehicle on the display stand. Be sure that the guide rail in the center of the stand fits into the slot in the bottom of the vehicle.

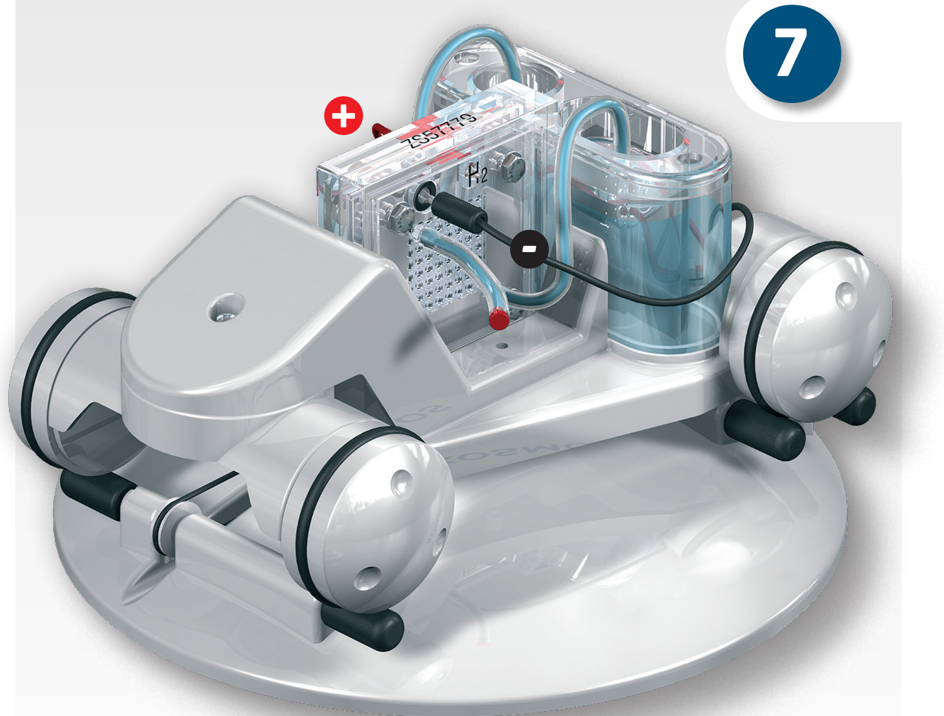
3

Connect the motor cables to the fuel cell: red to red and black to black. The engine starts right up, and the drive wheel starts to turn. The other three wheels will also start to rotate via the display stand's connected rollers.

Do It! ***Run the Car with the Fuel Cell***

Operation of the fuel cell car on the display stand

7

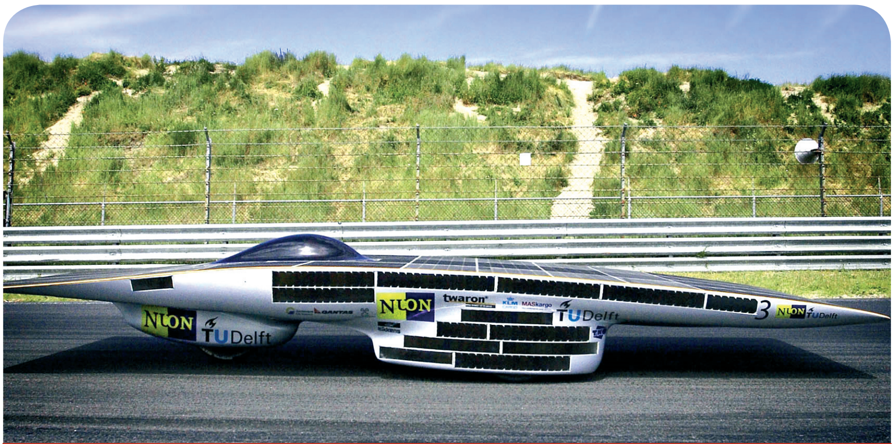


Note: Use only distilled water!

Solar Vehicles

There are road vehicles whose low, flat bodies are completely plastered with solar cells, allowing them to tank up on operating power from the sun as they drive. Their batteries are relatively small, and the cars themselves are ultra-light, unusual-looking one-man vehicles. These experimental cars are designed by students at technical universities and perfected on an ongoing basis through participation in regular competitions, all in order to explore the limits and possibilities of a solar powered car.

The Australian World Solar Challenge 2005 was won by the Dutch "Nuna 3," which was able to cross the entire continent on a 3,021-kilometer route in just 29 hours and 11 minutes – on nothing but solar energy. Its average speed was 103 kilometers per hour!

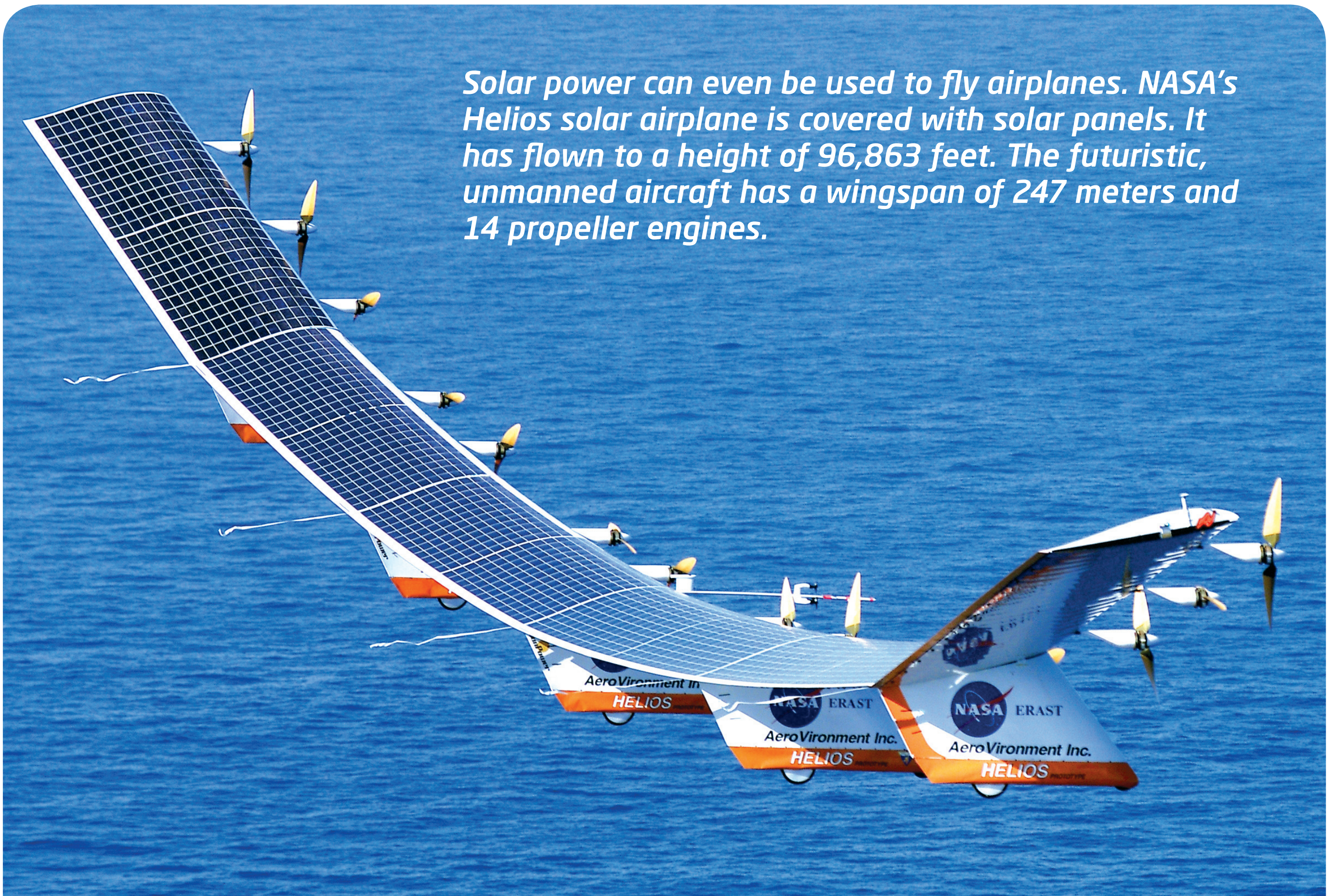


The Nuna 3 in the Australian World Solar Challenge 2005


Solar Boat


Aerodynamic Solar Car

Solar Aircraft



Solar power can even be used to fly airplanes. NASA's Helios solar airplane is covered with solar panels. It has flown to a height of 96,863 feet. The futuristic, unmanned aircraft has a wingspan of 247 meters and 14 propeller engines.

NASA's Helios holds the world record for time in flight.

Around the World with Solar Power

Bertrand Piccard's "Solar Impulse"

"Solar Impulse" is a solar powered airplane that is as big as an Airbus 340, as light as a medium-sized car, and runs without any fossil fuels.

On the surface of the wings there are 12,000 silicon solar cells that can produce enough energy to keep "Solar Impulse" in the air at a top speed of 49 miles per hour. The engines operate with only 40 horsepower.

Electric Cars

Road vehicles with battery-powered electric motors have been around for decades. These include forklifts and electric carts of all kinds, although they are usually just found at factories and airports, to be used over short distances. That is because their heavy lead batteries can only store a modest amount of energy, and, of course, part of that energy has to be used for transporting the battery itself. So the battery has to be recharged frequently.

If people succeed in developing long-lived, light batteries with large storage capacities, along with extremely efficient electric motors and generators, electric cars would become practical.

In sun-rich and oil-poor Israel, a network with 500,000 stations for operating electric cars is being constructed for completion by 2011. Electric cars for that network are being developed by the car companies Nissan and Renault, and the plan is for them to be able to drive 125 miles on a single battery charge.

Tesla Electric Roadster – An electric sports car uses lithium-ion batteries to go from zero to 60 miles per hour faster in four seconds.

Batteries instead of a gas tank – The Tesla Model S electric car goes from 0 to 60 miles per hour in 5.5 seconds and has a range of 300 miles.

Three-phase charging port on the Tesla

Gerneral Motors Volt – This electric car (with extra fuel generator) has an impressive 640 mile range.

A Practical Electric Car

Other car manufacturers have introduced entirely electric car prototypes as well.

The revolutionary Opel Ampera will be the first zero emission electric car that will meet all the demands of the everyday driver. The Opel Ampera will be electrically driven at all times regardless of the speed.

Distances of up to 40 miles are possible with the electric charge from its lithium-ion battery alone, which is recharged from a normal power outlet.

Longer journeys are made possible by a small internal combustion engine that functions as an electric generator to power the electric motor. In this way, a range of more than 500 miles is possible.

With its pioneering electric propulsion, Ampera helps solve the present and future challenges in the energy and environment sectors.

The five-door car with hatchback offers comfortable space for four passengers including enough trunk space for luggage. Production starts on the vehicle in 2011.

Filling Up

Charging up at a mini-electric power station.

These kinds of electric cars only make a contribution to a cleaner environment if the electricity itself is clean – that is, if it comes from solar, wind, biomass, or hydropower, or some other renewable energy source.

(See Chapter 6)

Fuel Cell Vehicles

A Viable Fuel Cell Car from Mercedes-Benz

Mercedes-Benz sees the great potential for emission-free fuel cell powered transportation, especially in urban centers. In 2010 Mercedes-Benz will release its first fuel cell vehicle into series production: the B-Class F-Cell.

To power the F-Cell, the driver simply has to supply the fuel cell with hydrogen, which undergoes a chemical reaction with atmospheric oxygen. This reaction produces electricity which is used to power the electric motor.

The only by-products are water vapor and heat. It does not release any pollutants or carbon dioxide, the greenhouse gas. Hydrogen can be produced in many ways, some of them renewable. That is to say, it can be produced with methods that are CO_2-neutral and thus environmentally safe.

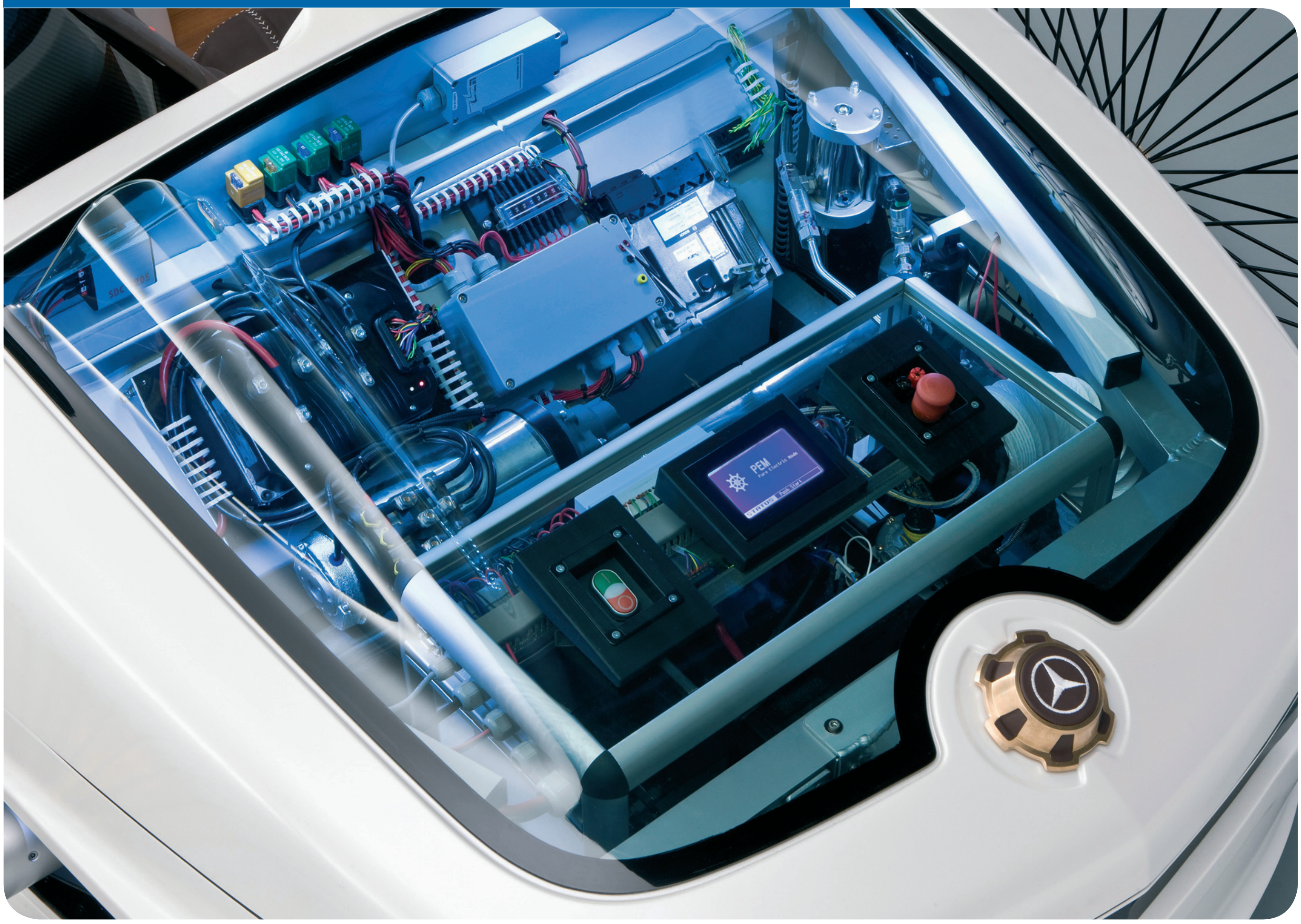
Experts say that hydrogen is the fuel that has the greatest potential for the future. Fuel cell technology and performance have steadily improved over the past decade.

Mercedes-Benz F-Cell, Fuel Cell Car

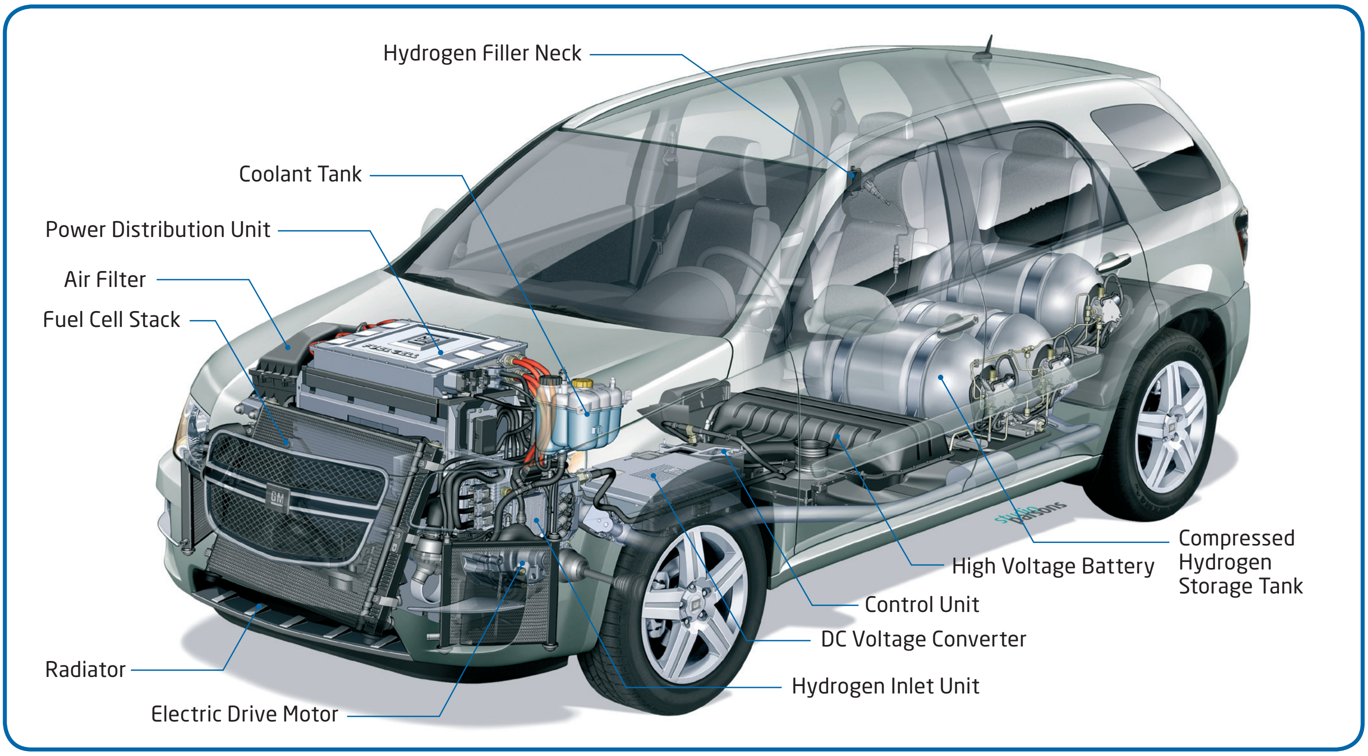
Concept Cars

Mercedes-Benz Roadster CELL, Concept Car

Mercedes-Benz Roadster CELL with Fuel Cell Propulsion



Fuel Cell Technology in Cars



Hydrogen: Fuel of the Future

Hydrogen offers the promise of a sustainable energy source for the future of transportation, and the potential to greatly reduce CO_2 emissions.

Hydrogen is the most commonly occurring element in the universe. It is a colorless, odorless, non-poisonous gas that is lighter than air. Hydrogen is one of the most important alternative fuels for the future, because it has the ability to replace all the fossil fuels used on the road today, and thus to reduce greenhouse gas emissions.

The governments of countries around the world see the promise of hydrogen and are investing billions of dollars in research and development for hydrogen energy technologies.

The U.S. Department of Energy has a Hydrogen Program that is working with industry, schools, laboratories, and other government agencies to overcome the obstacles standing in the way of widespread fuel cell adoption. They are addressing issues in hydrogen production, delivery, storage, safety, and fuel cell technology itself.

According to HyWays, a research project funded by the European Union, building a hydrogen infrastructure in Europe would allow for a reduction in CO_2 emissions from automobile transportation of over 50 percent by 2050, and it could be done in an economically acceptable manner.

A critical hurdle for the use of this innovative fuel that must be overcome is the distribution of hydrogen to individual automobiles. A large network of hydrogen fueling stations would need to be installed, just like our current network of gasoline fueling stations. This is only economically viable and feasible as a large-scale effort. Strong joint efforts from all of the stakeholders in both the public and private sectors is crucial to the successful adoption of hydrogen technology.

The Significance of the Fuel Cell

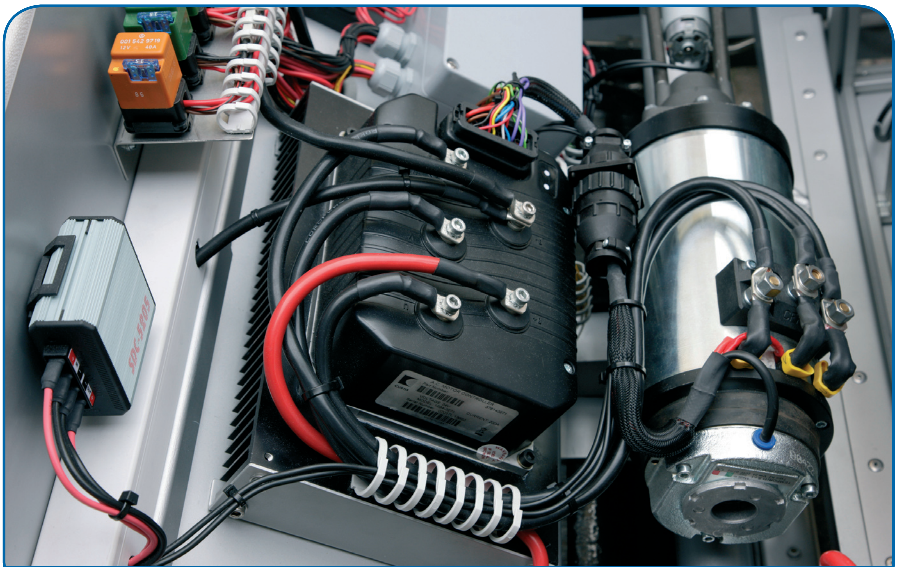
The fuel cell can play an important role as we change the way we meet our energy needs. It has a range of advantages:

1. It provides electricity in a more efficient manner than conventional power plants, which obtain electricity on a "detour" from chemically-produced heat energy through mechanical to electrical energy. The fuel cell, by contrast, creates electricity directly from chemical reaction energy (by "cold" combustion). So it has a significantly greater degree of efficiency than conventional types of energy conversion (with the exception of gas turbine power plants).

2. The fuel, which is hydrogen or other gases, can be obtained from renewable energy sources.

3. It is clean, since instead of climate-harmful CO_2, the only "waste" it releases is water vapor. Also, it is quiet.

4. Special fuel cells can be conveniently used in the cellar of a house as miniature off-grid residential heating and power units. In addition to electricity, they also give off plenty of heat from their gaseous fuel and the surrounding air.



Fuel Cell Engine in a Car

A Hydrogen Fueling Station in Europe

Time for a New Energy Era

Air pollution from industrial plants

Fossil fuels such as petroleum, natural gas, and coal are still our main sources of energy. But these resources are dwindling, and in a few decades they will be used up. The world's hunger for energy, by contrast, is growing.

There is an even more threatening side to the crisis: climate change. When coal, petroleum, and petroleum products are burned, it lets off carbon dioxide (CO_2), which makes a considerable contribution to the warming of the planet. And this leads to unusual extremes in the weather: Storms, hurricanes, catastrophic droughts and floods, forest fires and blizzards are occurring more and more frequently. Masses of continental and arctic ice are melting and flowing into the oceans. This isn't the only reason for the rise in the water levels of the world's oceans — the warming process is also causing the water to expand. Climate researchers are predicting a rise of at least 60 cm in sea levels by the end of this century, if we continue what we've been doing. Islands will disappear, entire areas of dry land will turn to swamp, dikes and levees will collapse, and seaports will have to give way to the power of the ocean.

The greatest CO_2 emitters are power plants, home and office heating systems, airplanes, ships, and road traffic. Can we rescue ourselves from this climate and fuel scarcity trap? Experts suggest a range of conservation measures when using fossil energy sources. Most important among them are:

We have to get more out of the raw energy materials stored in the Earth – in other words, our technology for utilizing fossil fuel energy has to be more efficient. In the next thirty to fifty years, after all, we will have to depend on it. The primary way to obtain a higher energy yield is by lowering heat losses that occur in the process of energy conversion. That happens in power plants and car engines. The degree of efficiency (the ratio of energy used to energy invested, expressed as a percent) has to be higher.

We have to reduce the amount of CO_2 that is released into the atmosphere. Of course, the most obvious way to do this is to stop burning fossil fuels. But there are other methods, such as planting more CO_2-consuming trees, or pumping the CO_2 into the ground where it can be stored out of the atmospheric system for very long periods of time.

We have to insulate our buildings better, and conserve heating fuel and electricity any way possible.

As a whole, we have to be more careful with energy in our day-to-day lives by, for example, installing energy-efficient lighting, reducing the energy consumption of electric appliances, and driving energy-conscious cars.

While the savings potential is indeed great, these kinds of efforts will not be able to prevent the consequences of fuel scarcity and climate change. The global growth in energy consumption, driven by large countries such as China, India, and Brazil, can no longer be compensated for by greater savings and efficiency. If we want to put a halt to our energy-guzzling standard of living and also let other countries have the chance to develop, we will have to implement energy systems over the entire globe that do not release climate-damaging gases and that are also in plentiful supply – in other words, renewable energy systems. Renewable forms of energy are practically inexhaustible. And they are also sustainable, offering a guaranteed supply of energy for coming generations. Without a quick change to "renewables," modern industrialized societies will not have much of a future. In order to reduce carbon dioxide emissions, the United States has recently increased fuel economy standards for cars and trucks, and put money towards developing more efficient energy grids, green jobs training, home weatherization, battery technology, and cracking down on industrial CO_2 polluters. The countries of the European Union have committed themselves to obtaining 20% of their primary energy from renewable sources by the year 2020.

Slowly but surely, we will say goodbye to fossil fuel-burning automobiles. The first hybrid and "plug-in" cars are already on the road. By 2030, the fuel cell car may have established itself. It will certainly make an important contribution to lowering CO_2 emissions if its fuel, hydrogen, is obtained from renewable energy sources such as photovoltaic modules.

Renewable Energy Sources

Almost all types of renewable energy come either directly or indirectly from the sun.

Solar Thermal

Solar thermal energy uses the heat radiation of the sun. Water is heated for plumbing or home heating in black absorption plates (thermal or solar collectors) – a technology that is already widespread in many countries. To yield higher water temperatures of up to several thousand degrees, parabolic mirrors are used. They concentrate the sun's rays onto a single point or, in the case of trough collectors, a single line. A solar thermal power plant's parabolic troughs capture the sun's radiation for the production of steam. The high-pressure steam drives turbines, which in turn drive electric generators.

Wind is caused by solar heat.

Photovoltaics

Photovoltaic modules also make direct use of solar energy: The solar cells connected to solar modules convert sunlight into electrical current.

Photovoltaic System

Wind Power

Wind power uses solar energy indirectly: Differences in temperature and air pressure over the globe – caused by differences in warming by the sun – produce air currents from which energy is derived through the rotors of wind generators. In the future, electricity will be supplied by updraft power plants as well.

Real World Examples

Hydropower

Energy from dams and rivers has been used to produce electricity for over a hundred years. Hydroelectric power plants need the sun, which drives the hydrologic cycle.

Biomass

Energy is also prepared from biomass — a product of photosynthesis — by burning renewable, "carbon-neutral" raw materials (wood, straw, switchgrass, bamboo), by fermentation (alcohol), and by decomposition (biogas).

Ocean Energy

Of the various kinds of ocean energy, only wave power plants and ocean current power plants use the sun's energy (indirectly). Waves are ultimately produced by wind. Currents owe their kinetic energy to the wind, among other things, and to the radiation-determined differences in the water's density.

Tidal power plants derive their energy from the gravitational forces between the moon and Earth.

Geothermal (from Earth's heat) and **atomic energy** are other forms of energy that are independent of the sun.

Biomass Power Plant

Hydroelectric Power Plant

Tidal Power Plant

Solar Hydrogen

For a fuel cell, hydrogen is the ideal clean food.

That could make its future very bright, given the threat posed by global warming. Electricity can be produced from solar cells located in sunny regions and used to split water.

Water is Abundant...

As you know, there's a lot of water in the world, with three quarters of Earth's surface covered by oceans.

...And so is the Sun

And on the world's continents, there are many desert regions lying fallow in the strongest sense of the word. In most of them, the sun shines over 350 days a year! All for free, of course. We would be short-sighted indeed if we were to reject this amazing gift from outer space.

In any case, even though a lot of energy is shining down in vain, it isn't exactly cheap to use. The desert landscape would have to be carpeted with many square kilometers of solar panels to make it worthwhile. Relative to the power they would generate, these panels are still very expensive. Mass production could bring down their price sharply, though. In addition, researchers and engineers are working diligently on making the manufacturing technology simpler and cheaper.

But the electrolysis facilities needed to make hydrogen from water don't come for free, either. And, transporting the hydrogen to the stations where the cars can obtain it is an additional expense.

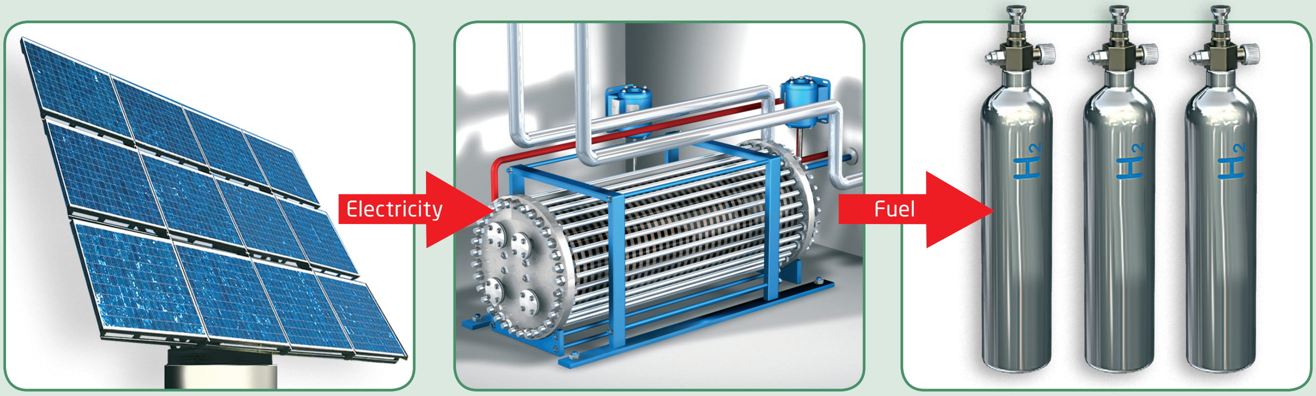
Moving Hydrogen

The transportation of hydrogen can be handled in two ways. One is to send it in gaseous form through pipes under high pressure from the deserts to the regions where it needs to be used. The second is to liquefy it under pressure

Solar panel system for the production of electricity for electrolysis

Hydrogen: The Fuel Cell's Fuel

Concept | ***Solar Hydrogen Production***



Solar Panel
Electricity is created when solar cells are exposed to sunlight.

Electrolysis Block
Water is split into hydrogen and oxygen with electricity from solar power.

Hydrogen (H_2)
Hydrogen serves as an environmentally friendly fuel.

Non-fossil fuel production of hydrogen

and refrigeration. Then it can be transported in special tanker trucks, by rail, or in tanker ships to its destination. In that case, the hydrogen would be available in concentrated form as liquid gas, which has a much greater energy density than the gaseous form.

It's Worth It

It may occur to you that it would also take a lot of money to build this kind of hydrogen transport and distribution network. But the investment would be worth it if the price of fossil fuels (petroleum, natural gas, and coal) rose above a certain critical threshold. That may well be the case in the near future. An energy economy with hydrogen obtained from photovoltaic power plants and other "renewables" (biogas, bio-ethanol) would be worth it even now if the necessary investments were weighed against the damage that ever more frequent climatic catastrophes will do to the planet.

About the Fuel of the Fuel Cell

At room temperature and normal atmospheric pressure, hydrogen is a colorless and odorless gas which, at 0.084 grams per liter, is about 14 times lighter than air. It is the lightest of all elements. That is why hydrogen easily penetrates porous partitions, in addition to metals such as platinum. It normally occurs in the form of a molecule with two atoms (H_2).

Under normal conditions, hydrogen is a diatomic (having "two atoms") and gaseous molecule. In its gas phase, it is colorless, odorless, and flavorless. It turns to liquid at -253 °C (20 K) and it freezes into a solid at -259 °C (14 K). At room temperature, it is very stable and slow to react. In mixtures with atmospheric oxygen and chlorine gas, hydrogen reacts explosively.

Hydrogen is a significant component of all organisms on Earth. The most important and best-known hydrogen compound is water (H_2O).

When ignited, it forms a bond with oxygen in the air, making a slight popping sound. With equal proportions of hydrogen, chlorine, and oxygen ("explosive gas"), you will get a loud explosion.

The Electrolysis of Water

Hydrogen can be produced in a variety of ways. One common way is to produce it with the help of electricity, which triggers certain chemical reactions that release H_2. This procedure is known as electrolysis.

What Do I Need?

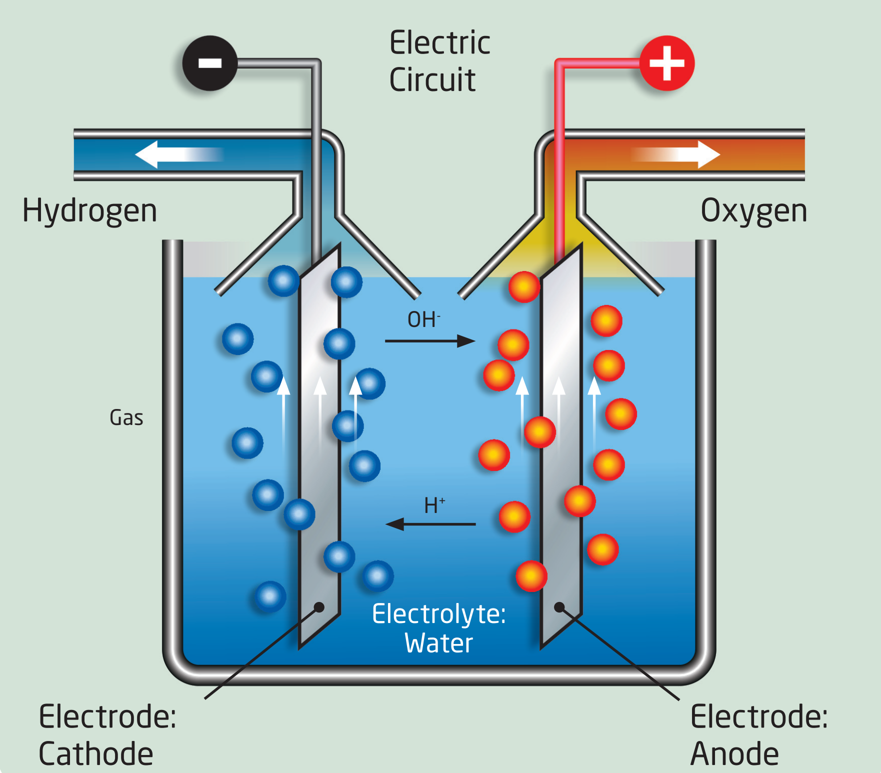
The first thing you need for electrolysis is an electrolyte – a liquid that can conduct electrical current. An example is water "contaminated" with a few salt crystals. (Gel-like electrolytes work well too.)

Why Liquids?

The molecules in liquids are flexible and always moving around – in contrast to solids, where the molecules are stuck in a crystal lattice. The hotter it gets, the more lively their movements, and the more likely they are to make brief occasional contact with other molecules.

They are, in a manner of speaking, "naked" and open to attacks by other electrons. They let themselves be won over to accepting extra electrons or giving some away. In chemical terms: They turn into electrically charged atoms, called ions, when current flows through the electrolyte.

Concept *Electrolysis of Water*



The Electrodes

The current reaches the electrolyte through two electrodes: the anode, which is connected to the positive terminal of an electricity generator, and the cathode, connected to its negative terminal.

The electrodes are made out of metals that themselves change as little as possible during the electrolysis process, or that move other processes along by acting as so-called catalysts. An example would be platinum. Their surfaces have to be large enough to permit as many molecules as possible to be "electrified."

The Voltage Source

A direct current is used for electrolysis. A battery, for example, can serve as a current source.

In order to be able to capture the gases, the electrodes have to be positioned far enough apart from each other, or separated by partitions. Also, there must be a way to capture the hydrogen and oxygen gases that are created, or else they will simply float away.

Production of Hydrogen by Electrolysis of Water

More Theory

In electrolysis, the voltage source causes a shortage of electrons in the anode and an excess of electrons in the cathode.

Electron **shortage**
in the **anode**
and
Electron surplus
in the **cathode**

If an electron is removed from an atom, then it loses a negative charge, and the positively charged protons in its nucleus get the upper hand. When that happens, the atom has a positive electrical charge and is called a cation.

If, on the other hand, it gains electrons, then the negatively charged electrons get the upper hand, and it becomes an anion. Ions strive to balance out their shortage or excess of electrons and neutralize one another electrically. To do that, they look for appropriate partners, giving rise to stable compounds.

In the electrolysis of water, the application of electrical voltage creates an electrical field. In that field, each pair of H_2O water molecules at the cathode takes up two electrons. In the process, two hydrogen molecules are created along with a "negative" remainder (2 OH), called an oxonium ion.

$$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$$

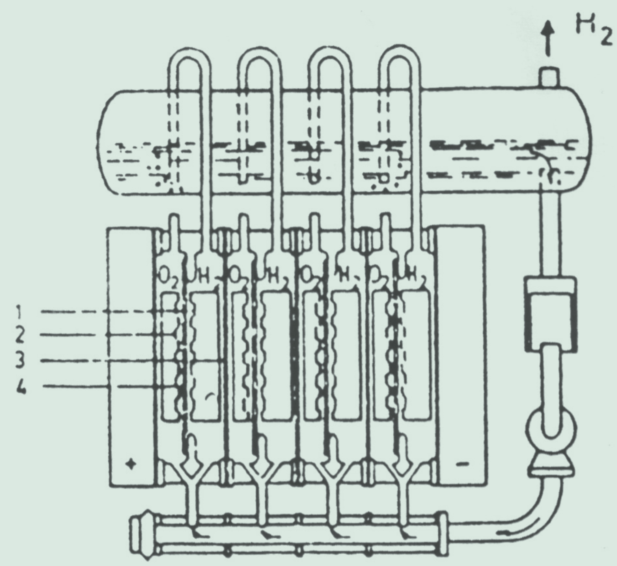
(The small "e" indicates an electron, a superscript plus sign indicates a positive charge, while a superscript minus sign indicates the negative charge of an ion. An electron is always negative.)

That's one side of electrolysis. It involves the production of hydrogen rising up from the cathode. Now, what happens with the negative remainder, the 2 OH^-? Four of these oxonium ions always have to work together for the formula to balance out, with the result being that one O_2 oxygen molecule and two molecules of water, H_2O, are produced. In addition, four electrons are given off at the positive terminal (anode), which move back to the current source. With that, the circuit is complete. In electrolysis – as in any closed circuit – the same number of electrons are given off at the anode as are taken up at the cathode. No electrons are lost.

$$4\ OH^- \rightarrow O_2 + 2\ H_2O + 4\ e^-$$

So gaseous oxygen rises from the anode, and water is also formed. That's the other side of the electrolysis of water.

History **Electrolysis**



This historical schematic diagram of an electrolysis system is over 100 years old.

How Do Fuel Cells Work?

The fuel cells being manufactured for cars just work in one direction: With the help of O_2 and H_2 gases supplied to them, they produce electricity for the electric motors.

That sounds simple, and it would be ideal if you could just hook up a cable to a bottle of hydrogen, another to a bottle of oxygen, and then get a glowing light bulb at the cables' other ends.

Unfortunately, no current would flow and nothing would happen at all. That's because the two bottles, which represent the energy source, are separated from each other, so their so-called electrochemical potential cannot be activated. What's missing is the shared current-conducting electrolyte.

Reversible Fuel Cell

The fuel cell in this kit works in both directions, and is capable of using electricity to produce its fuel, which it can then use to produce electricity again.

This kind of fuel cell is called a PEMFC, short for Proton Exchange Membrane Fuel Cell. Proton in this case is just another name for hydrogen ion.

The proton exchange is enabled by a special membrane, a partially permeable film made of Naphion®, a polymer membrane developed specifically for this purpose.

Polymers

A polymer is a very stable chemical compound consisting of many similar organic molecules that are very long. They can easily get tangled up together. In the Naphion, the polymers are so tightly attached to one another that only tiny spaces remain.

Only the protons – the hydrogen ions – can slip between them. The larger oxygen ions can't get through. So the Naphion membrane is a kind of very fine filter screen that lets hydrogen through but not oxygen.

The Membrane and Electrodes

The membrane is the heart of the cell. The current that it produces flows through two electrodes, the anode and the cathode. These are contact plates screwed onto both sides of the membrane and thus separated from one another by it.

The electrodes are made of carbon plates coated with platinum, connected to each other by an external electrical circuit. The anode is constantly supplied with hydrogen fuel, and the cathode is supplied with oxygen. To prevent anything from escaping in the process, there are gasket seals between the electrodes and the membrane, as well as to the outside.

History

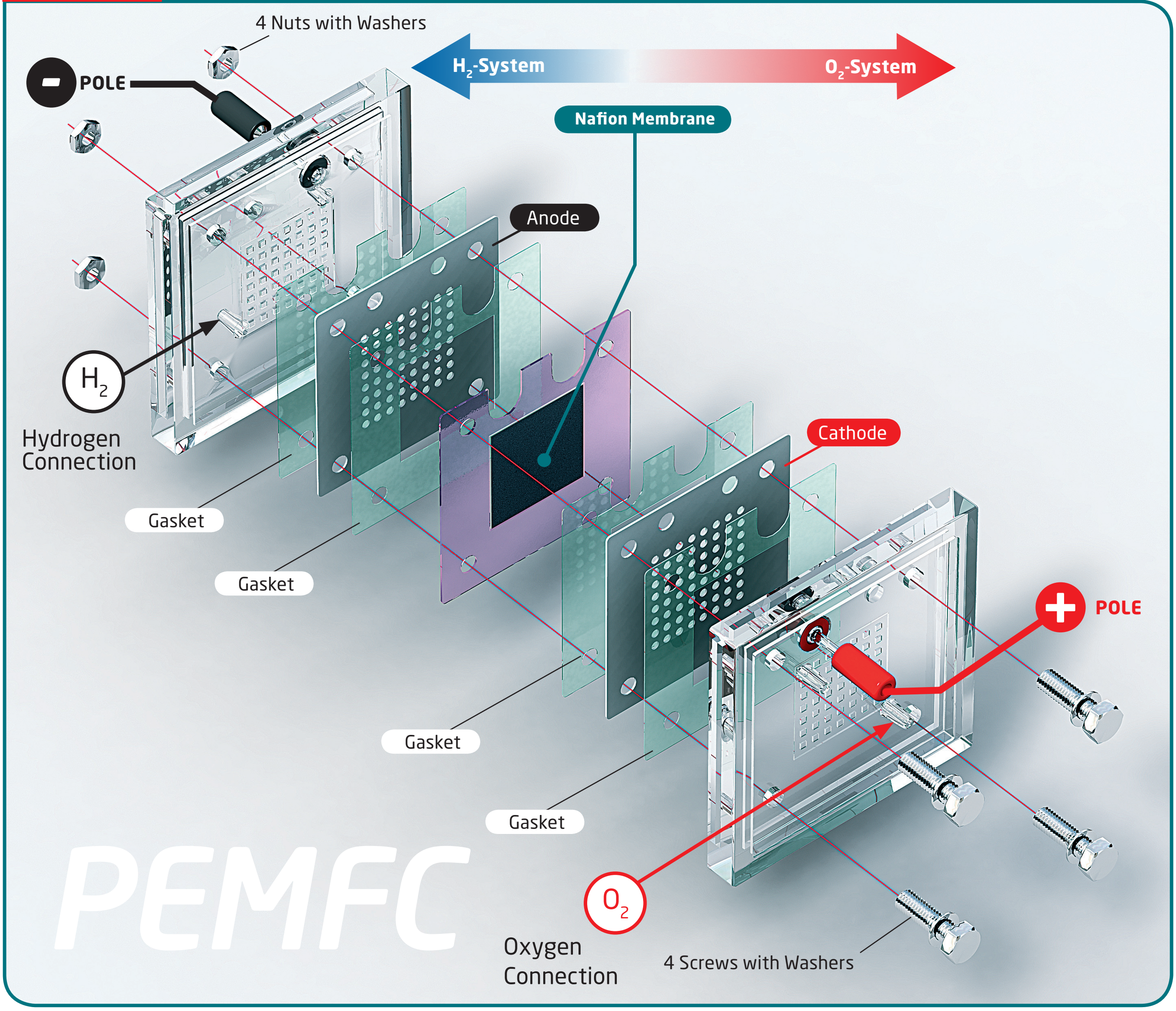
The PEM fuel cell was developed in the 1960s for space travel and military applications. At first, a General Motors fuel cell with a proton-conducting membrane was deployed in the Gemini space program. At that time, a sulfonated polystyrene membrane served as the electrolyte.

Since 1969, a Naphion® membrane developed by DuPont has been built into PEM fuel cells. The PEM fuel cell is particularly suitable for mobile applications, as well decentralized electricity production for individual single-family homes. Intensive research is being pursued around the world on applications for the PEM fuel cell in transportation.

There are still problems in the construction of appropriate hydrogen tanks. Nevertheless, the automobile industry expects a lot from PEM fuel cell technology, particularly as the permitted levels of CO_2 exhaust in traffic continue to drop.

What's Inside a Fuel Cell?

Concept **Construction of the Fuel Cell**



A Solid Electrolyte

In the fuel cell, unlike with electrolysis, the electrolyte is the membrane, not a liquid. After all, the task of the fuel cell is not to combine hydrogen and oxygen into water – nothing would be easier! – but, instead, to convert the electrochemical forces of attraction between them into electricity.

To do this, they have to play a trick on the molecules. In any case, as we will soon see, it does inevitably also produce water.

For this conversion from hydrogen and oxygen into water to take place, the proton-conducting membrane has to be moistened.

What Happens Inside a Fuel Cell?

So How Does the Fuel Cell Work?

At the anode, with the help of the platinum serving as catalyst (a mediator that does not itself undergo any change), the hydrogen molecules are split into two hydrogen atoms, which immediately release their electrons to the electrode. These electrons are then led to the cathode by way of the external circuit. The positively-charged hydrogen ions (protons) produced in this process diffuse through the proton-conductive membrane to the cathode. This is how it is expressed in a formula:

Anode: $H_2 \rightarrow 2\,H^+ + 2\,e^-$

That's one half of the job. The other happens at the cathode. Here, each liberated oxygen atom takes up two electrons and reacts with two positively-charged hydrogen ions (protons) that slipped through the membrane. The product: one water molecule.

Cathode:
$\tfrac{1}{2}O_2 + 2e^- \rightarrow O^{2-} + 2H^+ \rightarrow H_2O$

Overall Reaction:

$2\,H_2 + O_2 \rightarrow 2\,H_2O$

$\Delta_H = -241$ **kJ/mol**

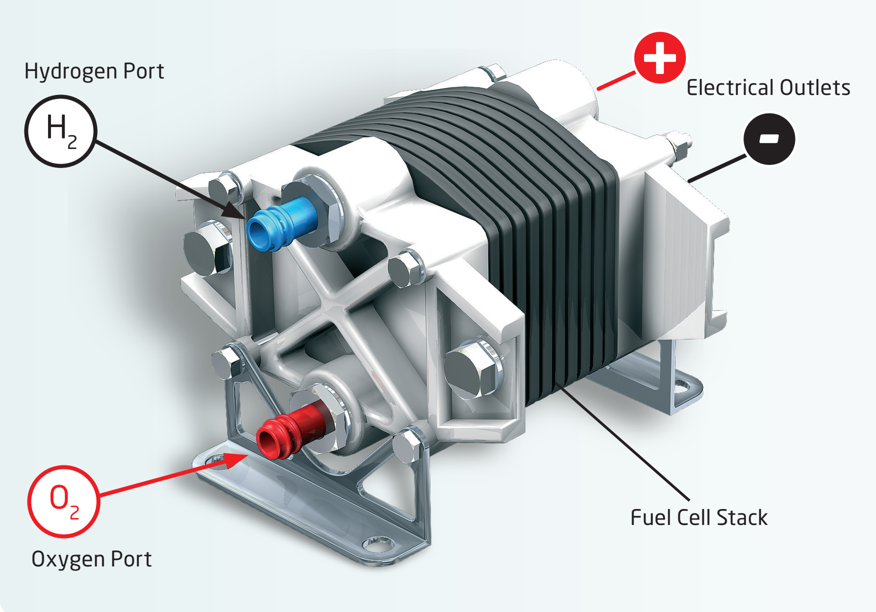
So at the anode of the fuel cell, the hydrogen atoms are robbed of their electrons (which move through the circuit to the cathode), and the remaining ions diffuse through the membrane to the oxygen ions at the cathode. Those ions, however, are missing precisely the two electrons that were pulled away at the anode side. The O^{2-} cannot slip through the membrane, and they therefore pick up the charge particles from the cathode. In the reverse process of electrolysis in the fuel cell, the electrolyte is the membrane, which brings about the synthesis of hydrogen and oxygen into water and electrical energy.

In theory, a PEM fuel cell can attain a voltage of 1.23 volts. In practice, it is a little less than this, since there are losses during operation.

The operating voltage lies somewhere between 0.6 V and 0.9 V.

For most applications, this voltage is too low. So individual fuel cells are connected in series and piled into so-called stacks, with the cells lying together like the parts of a sandwich. The strength of the electric current rises with the surface area of the electrodes.

Fuel Cell Stack



Construction and Function of a Solar Cell

The Solar Panel

The solar panel is the electrical energy source for the electrolysis mode of the fuel cell in this kit. The term solar panel is used to refer to several individual solar cells connected together.

A solar cell takes the light energy that falls on it and converts it into electrical current. This kind of conversion is known as a photovoltaic process.

The Solar Panel

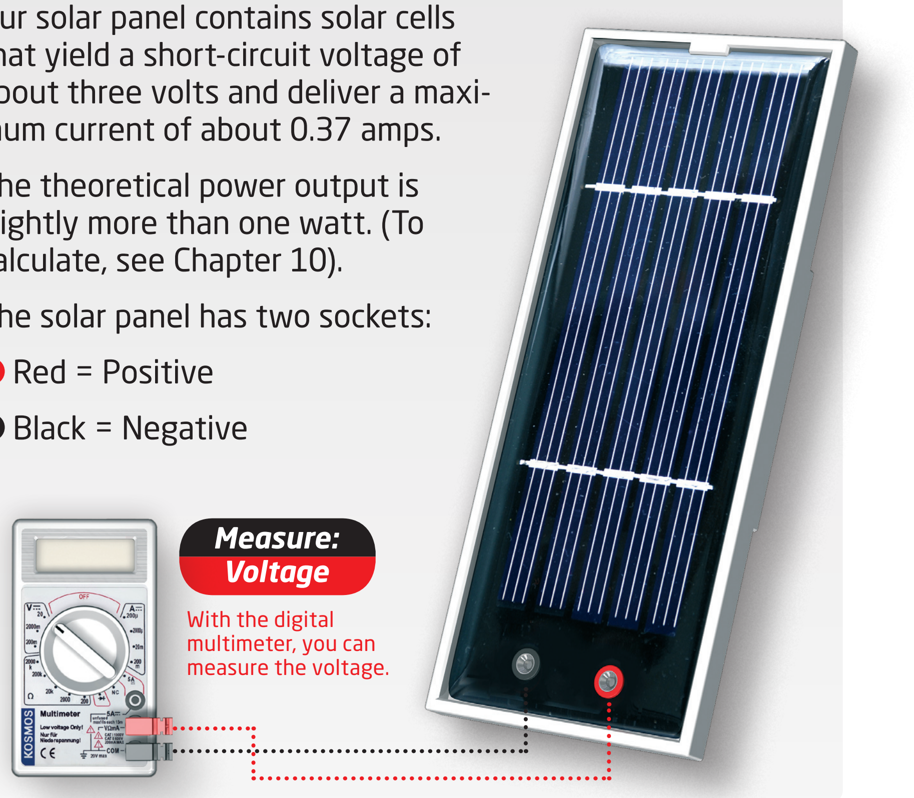
Our solar panel contains solar cells that yield a short-circuit voltage of about three volts and deliver a maximum current of about 0.37 amps.

The theoretical power output is slightly more than one watt. (To calculate, see Chapter 10).

The solar panel has two sockets:

+ Red = Positive

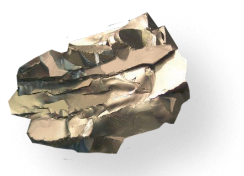
− Black = Negative



You can measure the solar panel's output with the multimeter.

The Core of the Solar Cell: Silicon

The cell is made of highly pure crystalline silicon (Si).



The metalloid silicon is a so-called semiconductor: It is only slightly electrically conductive, but its conductivity rises when it is warmed or – when it is appropriately manipulated – through the effect of light.

There are monocrystalline and polycrystalline solar cells, made from silicon with a chemical purity of up to 99.9999%.

The dark sections in our solar panel are monocrystalline. They are made by cooling molten silicon into a single giant crystal, which is then cut into razor-thin slices, or so-called wafers, which are in turn cut to fit the required cell dimensions.

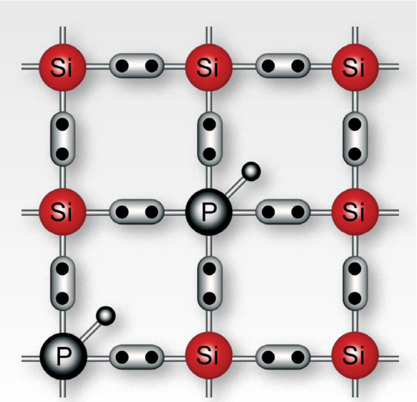
Polycrystalline solar cells come from silicon that hardens into multiple crystals when the molten silicon cools. Polycrystalline solar cells that are on the market have an efficiency of about 15%, while monocrystalline cells have an efficiency of about 18%. The degree of efficiency indicates the maximum percent of the incoming solar energy (about 1,000 watts per square meter) that is converted into electrical current.

Structure and Function of a Solar Cell

Doping the Silicon

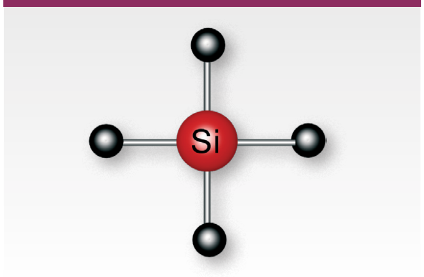
To create solar cells from the highly pure silicon wafers, they have to be somewhat "impurified" again. This process is known as doping. It involves vapor-deposition of tiny doses of pure elemental phosphorus on one surface of the wafer, and boron on the other surface. The proportion of these doping elements to the silicon is about equivalent to one drop of water in a swimming pool.

Silicon Crystal Lattice Doped with Phosphorus

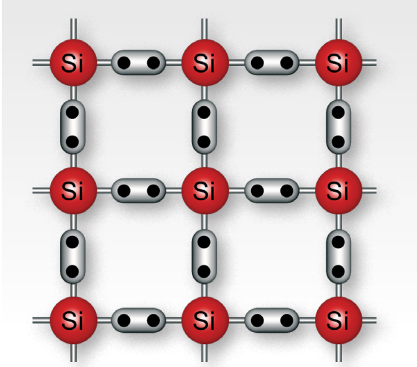


In the upper layer, a silicon atom will be replaced by a phosphorus atom in a few spots (above). In its outer shell, phosphorus has five electrons. There is one electron left over, since it can only

Silicon Atom



Silicon Crystal Lattice

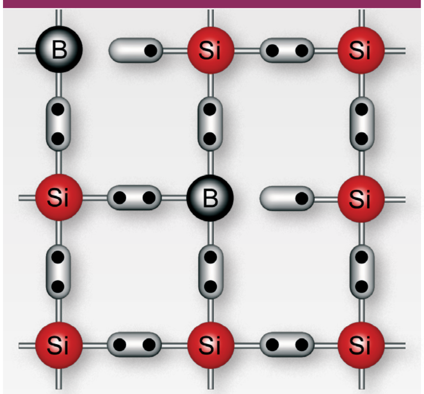


enter into a covalent bond with four silicon atoms in the crystal lattice. That is because silicon is usually tetravalent, meaning it has four "bonding arms."

So the phosphorus atom's fifth electron cannot find a bonding partner, and it is therefore very loosely attached to the phosphorus atom. Even at room temperature, the bond will be easily broken. So silicon doped in this manner has free electrons (negative charges) and is therefore called an n-doped layer.

The solar cell's lower layer is doped with boron in a similar

Silicon Crystal Lattice Doped with Boron



manner (below). Boron has three electrons in its outer shell, each of which enters into a bond with the neighboring silicon atom.

There is an electron missing for a fourth bond, however. This kind of defect or gap is known as an "electron hole."

Even at room temperature, an electron from a neighboring Si atom can "jump over" into this hole, making the hole seem to move. The conductivity of the silicon doped in this manner, in other words, depends on the mobility of the "holes" (positive charges). This zone is known as a p-doped layer.

Both the p-doped and the n-doped layers conduct well, and are neutral on their own. So there is no voltage.

This is how the silicon is manipulated to make it photoelectrically sensitive. A look into the solar cell's crystal lattice will show us how it works.

Creating the Voltage Potential

In the area where the p- and n-doped layers touch, a boundary layer known as a p-n junction forms, where a few electrons from the n-doped layer wander over into the p-doped layer. There, they replace electrons that are missing for covalent bonding. The movement of the electrons from the n-doped layer to the p-doped layer carries a certain amount of negative charge from the n-layer to the p-layer.

Due to the migration of the electrons, strongly bonded positive ions (electrically charged atoms) are left behind in certain locations. The electrons have moved into holes in the p-layer near the boundary, which leads to an excess negative charge.

In the boundary area, then, both layers are no longer electrically neutral: the n-doped layer is missing electrons, so it becomes positively charged, and the p-doped layer has a few electrons too many, becoming negatively charged (below). The voltage between the two layers comes to about 0.55 volts, creating an electric field.

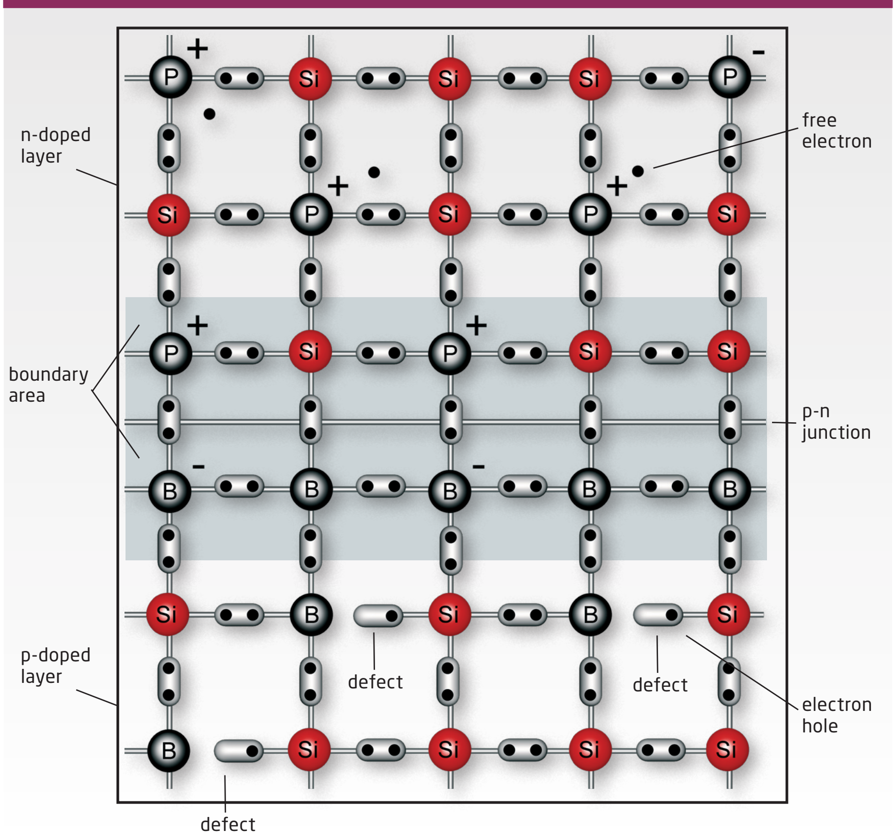
When Does the Current Flow?

With a solar cell, the n-doped layer is on the side toward the sun. Compared to the p-doped layer, it is kept very thin, so the energy-laden photons of light can penetrate to the p-n junction. The light rays constantly release electrons from existing covalent bonds between silicon atoms, creating free electrons and holes. This also happens in the p-n junction. The electrons that are released there are immediately shot into the n-doped layer by the electrical field forces along the field lines, and the holes shoot in the opposite direction. The resulting shortage of electrons in the p-layer gives it a positive charge.

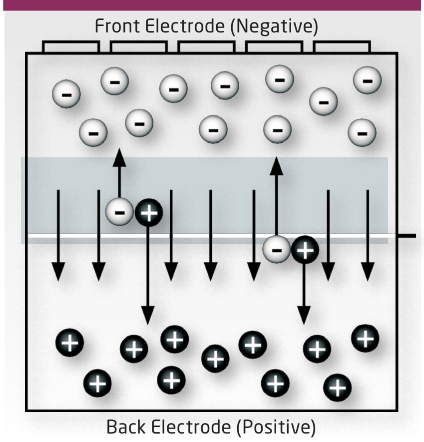
In the n-doped layer, an excess of electrons arises. If the circuit is closed by an externally connected conductor, it leads to a flow of electrons and, therefore, to an equalization of charges.

The current flows as long as the cell is hit by light. On the upper side of the solar cell, there is a contact strip made of metal, covered with lots of little contact fingers (negative terminal). The lower side has a continuous metal layer as its contact (positive terminal). The contact strip and the metal surface form the electrical poles of the solar cell (below).

p-n Junction



Solar Cell in the Light



Measuring Electricity

Electrical current is a form of energy. It refers to the movement of electrons through a conductor.

It arises through a difference in electrical charge between the two terminals in a circuit, which is created by a voltage difference in a power supply.

Direct Current

The current supplied by the battery and the solar panel is direct current, meaning that it flows only in one direction, from the positive to the negative terminal.

The symbol for **Direct Current** is
=

Alternating Current

This type of current is supplied, for example, by power plant generators and bicycle dynamos. In this case, the charge differences arise through electromagnetic forces.

The symbol for **Alternating Current** is
~

The voltage in the battery arises from an internal, chemically-produced difference between its two terminals.

If the terminals are connected to each other via a circuit and a load (e.g., a light bulb), the electrons move through the conductor in order to balance out this difference. So, in general, electricity can only flow when, in addition to the difference in potential, there is a way for the electrons to flow back to their source after they have done their work in the load.

Electricity can only flow in a circuit.

In a very good conductor, the electrons can move close to the speed of light. The rest mass of an electron comes to 9.11 x 10^{-31} kg – or a weight in kilograms of 9.11 divided by a 10 followed by 31 zeros.

Voltage

Voltage is the difference in electrical potential between two points on a circuit.

Potential Difference is measured in **volts**
V

Current

The quantity of electrons shooting through the conductor is called electric current.

Current is measured in **amperes**
A
or **milliamperes**
mA

If we consider the example of a waterfall, voltage corresponds to the height that the stream of water drops, while current strength corresponds to its thickness.

Power

To calculate power, multiply the voltage times the current strength.

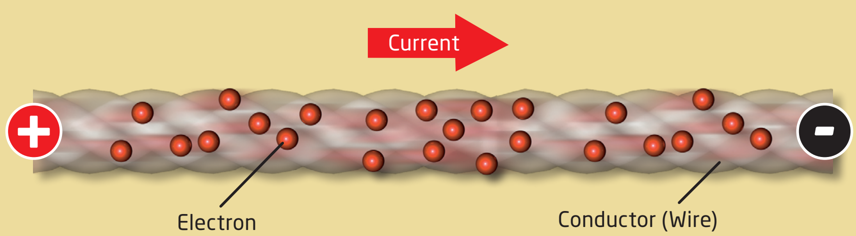
Power is measured in **watts**
W
or **milliwatts**
mW
1 Volt x 1 Ampere = 1 Watt

Resistance

Resistance is the opposition to the passage of current by a load or conductor.

Resistance is measured in **ohms**
Ω

Electron Flow (Direct Current)



What Is Energy, Really?

Nothing moves without energy. Blood won't move in our veins, water won't move in rivers and seas – to say nothing of cars on the street or rockets taking off into outer space.

But what is energy, actually? Plainly put, energy exists wherever a force moves a mass, or at least has the ability to do so. But where does the force come from? Forces come from differences that strive to balance each other out. There has to be a tension, or a gradient.

A dam or reservoir illustrates the point: It holds masses of energy, because its masses of water are positioned higher than the power plant turbines down below in the valley. As long as the water gates are closed, this energy merely slumbers. Because it could perform some work if it were released, we call it potential energy.

If the gates are opened, masses of water plummet through the sluice pipe to the valley as its potential energy is converted into kinetic energy, which turns the turbines and electric generators. So it performs work by making electricity.

In terms of physics, in other words, energy is the ability to perform work. That happens when a force moves an object (mass) along a certain distance. The force that brings the masses of water "down to Earth" is Earth's gravity. The greater the drop, and the thicker the stream of water, the more work can be performed.

Forces arise out of all sorts of differences: A car engine's piston is moved by the explosive force of the trapped fuel mixture pressing on the piston's surface. The greater internal pressure tries to balance itself out with the lower external pressure.

Even natural temperature differences produce forces and can perform work – for example, when warmer and therefore lighter masses of air move upwards into colder, heavier air and create an updraft.

This sort of thermal lift can carry a glider upwards or turn a turbine in a solar updraft tower. In galvanic elements (batteries), it is a difference in electrical charge that creates the tension, or voltage. When the electric current moves through an appliance from the battery's negative terminal to the positive terminal, this is a sort of attempt on the part of the carriers of the charge, the electrons, to balance things out.

In a closed system, energy can neither be created nor destroyed. It can merely be converted from one form into another – for example, from kinetic energy into electrical energy, or from chemical energy into thermal (heat) energy. However, no conversion can occur one hundred percent from one form into another. There is always the release of another form of energy as a "loss." A car's internal combustion engine only converts about 40 percent of the chemical energy present in the fuel into mechanical energy. The rest is released into the environment, primarily as heat.

Tests

The Digital Multimeter

This kit contains a digital multimeter. Unlike conventional analog meters, with a pointer and a scale for reading the values, this multimeter displays values on a digital LCD screen. The following pages will teach you how to take some measurements with the multimeter.

By turning the large rotary switch, you can measure different electrical properties in different ranges:

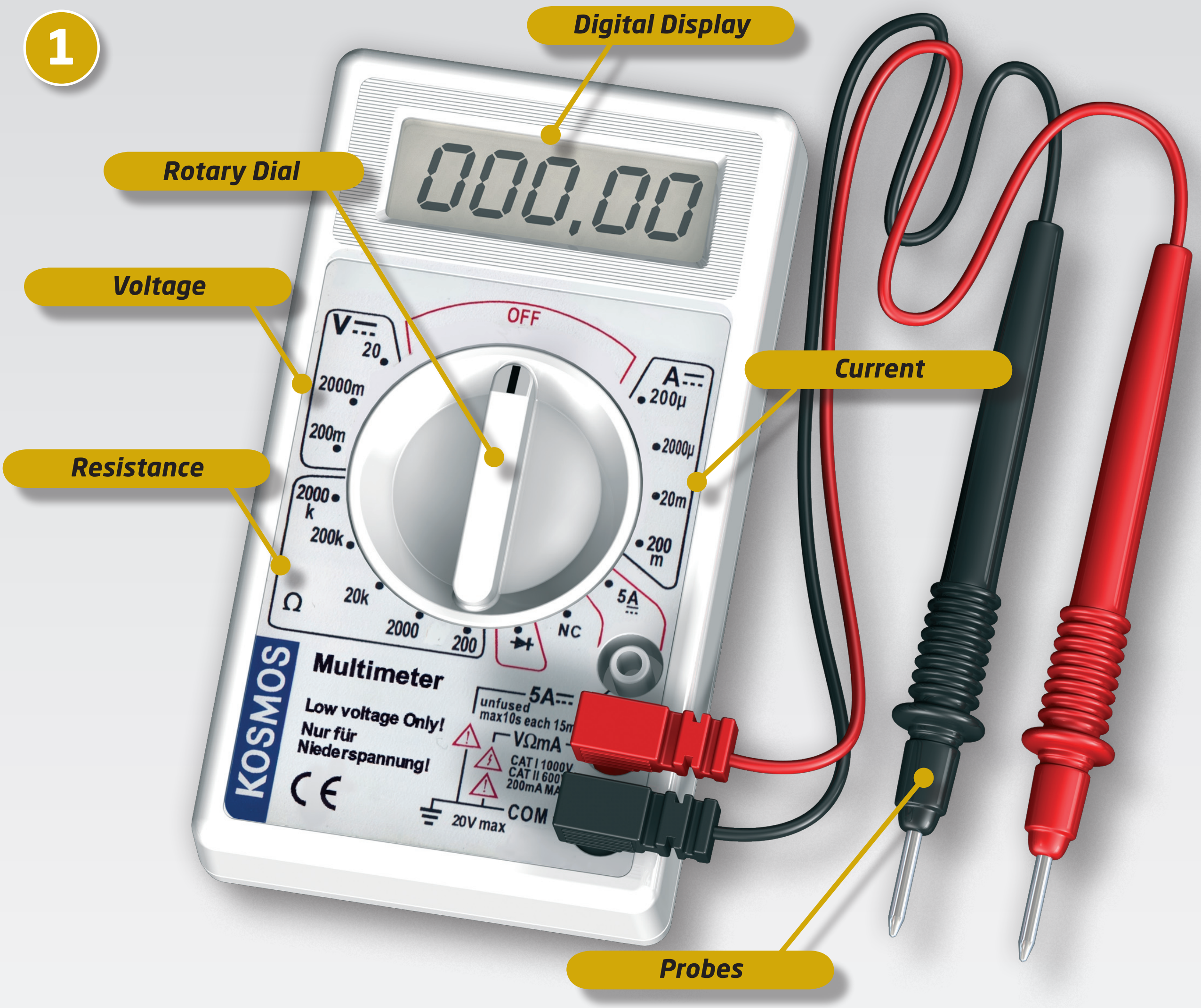
- **Voltage**
- **Current**
- **Resistance**

Connect the red and black cables with probes to the ports as shown below. Depending on the measurement you are attempting to take, set the rotary switch to one of the values.

When taking a reading, you can connect the probes to two points on a circuit and read the value of the voltage, current, or resistance between those two points.

Overview *The Main Functions of the Multimeter*

1



Note: The meter cannot be used for high voltages!

Tests

Measuring the Solar Panel and Fuel Cell Output

Solar Panel Voltage

To determine the power of the solar panel, we will measure the short circuit voltage on the V= side of the multimeter in measurement range 20 (Figure 2). The voltage will vary depending on the strength of the light hitting it, but it should be about 2.8 volts.

Solar Panel Current

We will measure its short circuit current on the A= side in the 200m range (Figure 3). The current will also vary depending on the amount of light, but an average current reading is about 250 mA.

Multiply 0.25 A x 2.8 V to calculate a power of 0.7 watts.

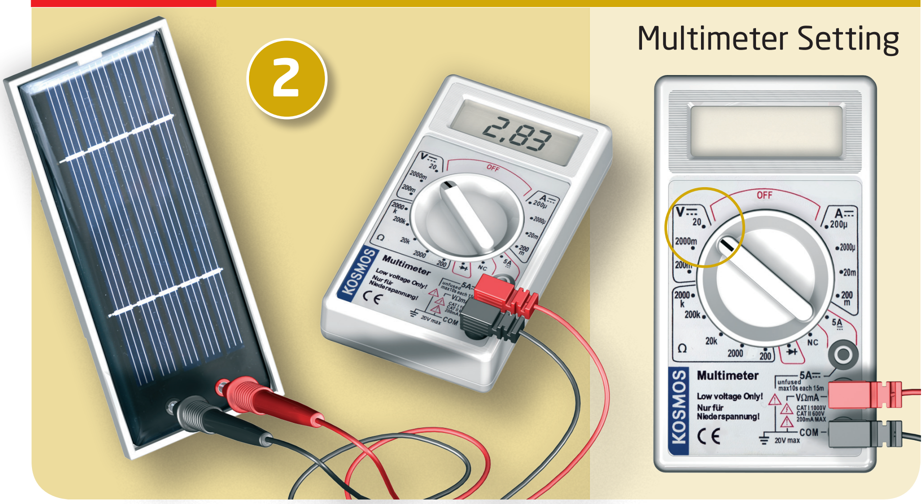
Fuel Cell Power

To measure the power of the fuel cell, first fill the tanks with hydrogen and oxygen. Instead of connecting the motor, insert the meter probes into the cell's ⊕ and ⊖ sockets and take a reading (Figure 4). Thus, we can calculate the fuel cell:

Power = Voltage x Current

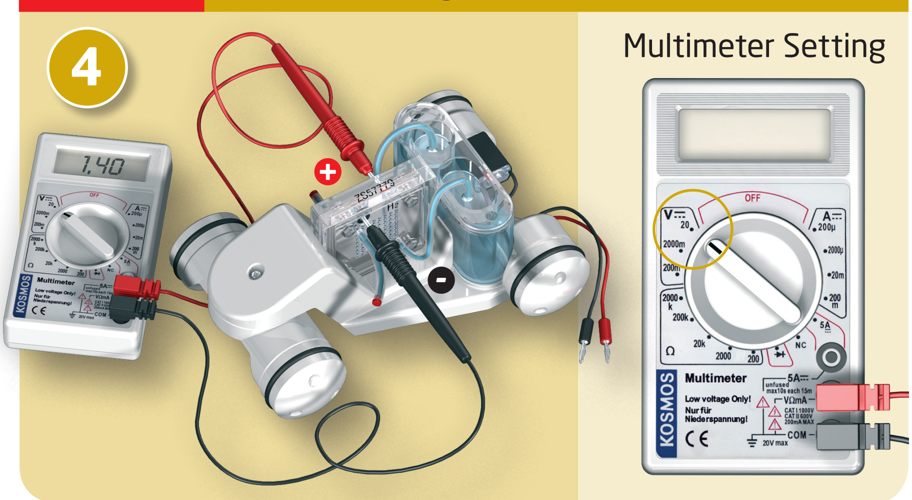
With 1.4 volts and 16 mA (0.16 A), the power output would be 0.22 watts. The values drop by half as soon as we hook up a load (the electric motor) to the circuit instead of just the multimeter. Then, the value readings are called operating voltage or operating current, instead of no-load values.

Measure *Solar Panel Voltage*



Measure *Solar Panel Current*

Measure *Fuel Cell Voltage*



Tests

Efficiency of the Fuel Cell

In these times of increasing shortages of the conventional fuels, i.e. coal, oil, gas, and uranium, and the increasing damage to the environment caused by their use, it is very important to convert and utilize energy as efficiently as possible. This experiment measures efficiency. In general, the efficiency indicates the ratio between useful energy and total consumed energy.

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}}$$

As an example, let us consider a common incandescent bulb. Its purpose is to deliver light. For this it needs energy which it receives in the form of electrical current. If the total energy were converted to light without losses, then 100% of the energy would be converted into the useful form (light) and the efficiency would be 100%. In reality the efficiency of an incandescent bulb is about 10%, so that only 10% of the energy supplied is converted into the desired form (light). The rest is converted into heat.

What Is Your Fuel Cell's Efficiency?

To find this we must again find the ratio between the energy we can use to the total energy input. In the fuel cell there are several steps of energy conversion, namely:

- Conversion of the electrical energy from the solar panel through electrolysis of water into hydrogen and oxygen
- Conversion of hydrogen and oxygen into electric energy in the fuel cell

The efficiencies of these two steps are combined to give an overall efficiency. This can be determined from the following formula. (η is the symbol for efficiency.) Strictly speaking, the formula is not completely correct. But it is fully satisfactory to give an impression of the order of magnitude of the efficiency.

$$\eta_{\text{Fuel Cell}} = \frac{\text{Operating Voltage}}{\text{Electrolysis Voltage}}$$

To measure the operating voltage of the fuel cell, set the multimeter to measurement range 20 on the voltage side of the meter. With the fuel cell running the motor, touch the black multimeter probe to black motor connection and touch the red probe to the red motor connection. Take a reading.

To measure the electrolysis voltage, keep the meter in the same range. While the solar cell is connected to the fuel cell and gas is being produced, touch the black multimeter probe to the black solar panel wire connection, and the red probe to the red wire connection. Take a reading.

If, for example, you measured a fuel cell operating voltage of 0.7 V and an electrolysis voltage of 1.6 V, then the efficiency of your fuel cell is calculated as follows:

$$\eta_{\text{Fuel Cell}} = \frac{0.7\ \text{V}}{1.6\ \text{V}} = 0.44$$

...or 44%. The difference from 100%, in this example 56%, is converted into heat.

Now insert your values:

η_{fc} = ... V / V

η_{fc} = ...

The efficiency of fuel cells is higher than that of an ordinary automobile. The figure below illustrates some efficiencies.