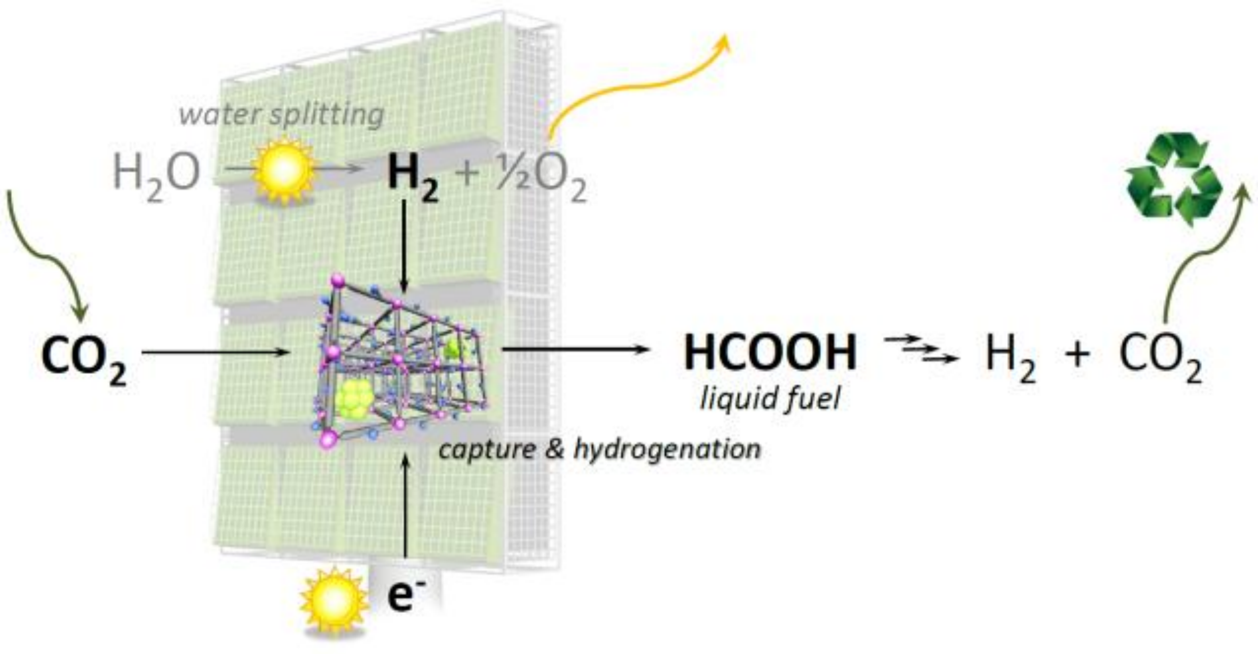
ARTIFICIAL SOLAR TREE

a physics-chemistry module

4th grade



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VEK/STT-2012/052217

Uw kenmerk
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Date 22 May 2012
Regarding Sustainable Transportation Transition

Dear Sir/Madam

In May 2012 we started a programme called 'Sustainable Transportation Transition'.
In short this project aims at a transition to a more sustainable way of transportation, by means of a solution that can be implemented in a relatively short time-frame and that is economically feasible.

Based on these aims and on the research project 'Wind & Hydrogen in transport: possibilities and challenges' a shortlist of wishes and demands has been created:

- For economic reasons no major changes in road structure are possible (one should be able to use the roads that are currently available)
- For practical reasons the energy carrier should be a liquid (or should be relatively easy to liquefy)
- For socio-political factors, the resources to produce the energy should be locally available as much as possible

Wind energy as a primary energy source is not an option. Large scale wind energy is not an option because of legal reasons (e.g. obtaining permits). Small scale wind energy is currently not feasible economically.

Ministerie van Vervoer en Klimaat

Ministerie van
Vervoer en Klimaat

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We hereby would like to inform you that you have been selected to take place in the feedback committee, in order to advise on the matter. You, as part of your research group in your engineering agency, or as a member of a scientifically well-educated group of representatives of your resident's association, can give your recommendations in a report in which you give your advice on which route we could follow, based on economic, environmental, social etc. reasons.

Our own scientific bureau has already prepared some background information on the different aspects of the project. The main information is collected in the module, accompanying this letter. More information might follow, which will then be send to you through your science teacher.

Sincerely,

THE MINISTER OF TRANSPORT AND CLIMATE

Ms. O.W.N.S. Mani–Cars MBA

What you will learn:

- *You can explain what the greenhouse effect is.*
- *You understand why the search for alternative energy sources is important.*
- *You have a global idea what an artificial solar tree is.*
- *You understand the goal of this course.*

Global warming

Our planet is warming up. The poles are melting and in a while they will, so to speak, only exist in the history books your grandchildren will be reading. The polar bear in the picture has already seen the ice melt under his feet. Probably, you have seen a lot more of these pictures of melting ice shelves on the news or the Internet. That's no coincidence: global warming is a hot topic all over the world. In particular, this can be attributed to Al Gore (if you don't know him your parents will). In 2000 he started giving speeches on his worries about the health of the Earth. The documentary 'An inconvenient truth', based on these speeches, received an Academy Award for Best Documentary in 2007. Although some scientist question the reliability of the facts that Al Gore uses, his movie certainly made the world realize that our planet is in danger.

Figure 2 Global warming brought this polar bear in trouble

Figure 1 Al Gore

Question 1

Find out what the most important message of 'An inconvenient truth' was. You may use the Internet.

The greenhouse effect

So what's this global warming all about? It all has to do with the greenhouse effect. The Earth's atmosphere contains carbon dioxide (CO_2). This gas acts as a blanket around the planet, capturing some of the suns energy. However, human influences like factories, cars and the cutting down of complete rainforests bring an extra amount of CO_2 in our atmosphere every day. So, the blanket around our planet gets thicker and thicker and the Earth gets hotter every day.

Figure 3 Factories are a cause of global warming

Fossil fuels

Besides the big issue of dealing with the greenhouse effect there is another problem: our reserves of fossil fuels is shrinking fast. In about 60 years all of the oil and gas will be vanished and 70 years after that there will not be any coal left either. This, in itself, does not have to be a disaster: since CO_2 is emitted when burning these fuels it would be better not to use them at all. However, there has not been found a sustainable way of producing energy that can substitute these fossil fuels. This is exactly the problem that many scientist are working on nowadays.

A method for generating energy should be:
- sustainable
- CO_2-neutral

Question 2

Can you think of other properties that a method for generating energy should have?

Light is the answer

In search of an energy generating technique it can be useful to learn from Mother Nature. For example, the growth of plants is a very intriguing process. Let's consider an arbitrary flower. Using the energy of the sunlight, it converts CO_2 and water into food and oxygen. This is called photosynthesis. So, in short, plants collect the energy to grow from sunlight. Now, if a simple plant can do that, why can't we? The idea seems tempting.

The light of the sun is always available and it will never run out. In this course you will be learning about a technique that converts sunlight into fuel. This technique is called the artificial solar tree.

Figure 4 A flower growing in the sun

Artificial solar tree

The artificial solar tree works like a real one. Just like the photosynthesis of a real tree, an artificial one uses sunlight for the generation of energy. The aim is to store the energy so we can use it wherever and whenever we need it. This can be done by making a liquid fuel that can be transport and used when needed. In the remainder of this course you will learn what challenges are involved when designing an artificial solar tree. These challenges are not solely scientific ones. You will also have to consider costs, environmental consequences and so on. When you have obtained enough knowledge about the artificial solar tree you are ready to make your own working fuel cell!

Question 3

Look at the schematic picture of the artificial solar tree. What challenges can you already find?

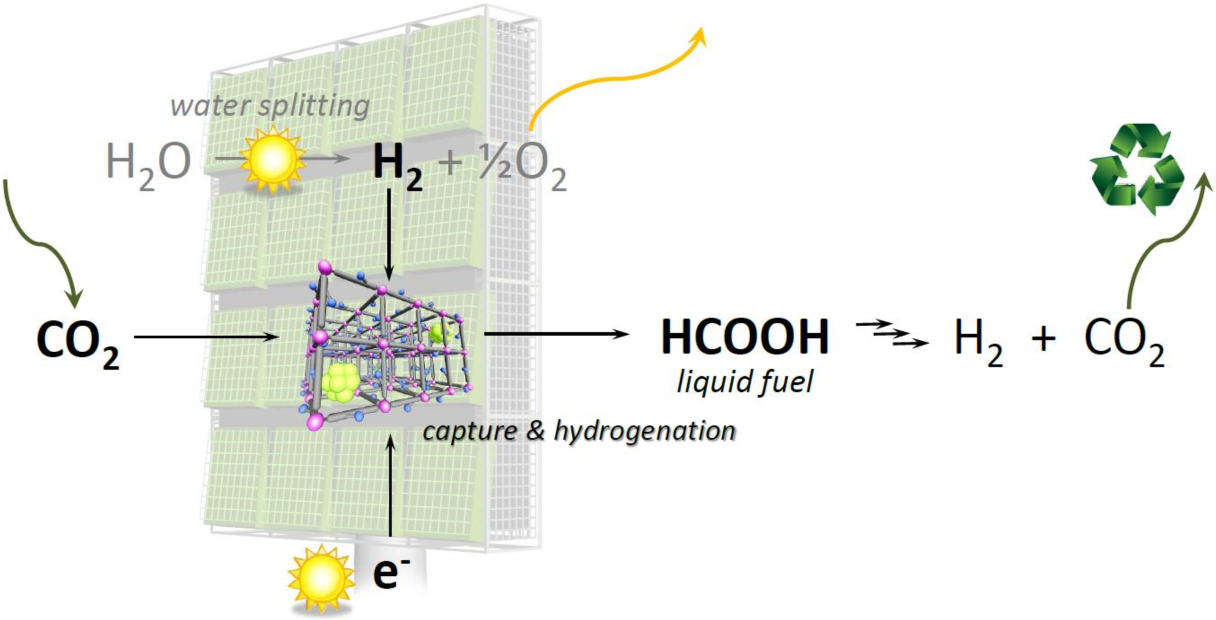


Figure 5 Schematic representation of an artificial solar tree

What you will learn:

- *You can give a schematic presentation of the carbon cycle*
- *You can explain the role of photosynthesis in the carbon cycle and can explain why CO_2 resulting from the combustion of biomass does not necessarily contribute to climate change*
- *You can identify carbon sinks and carbon sources.*
- *You can describe how human actions interfere with the natural carbon cycle.*

Introduction

Carbon is a very important element. You could not live without carbon. If something you eat has protein or fats, then it contains carbon. When your body breaks down that food to produce energy, you breathe out carbon dioxide. Carbon is also a very important element on Earth. Carbon is provided by the environment, moves through organisms and then returns to the environment again. When all this happens in balance, the ecosystem remains in balance too.

Carbon atoms frequently move from place to place, change their chemical partners, and change their physical state. Most of this happens within a relatively short amount of time but some processes take millions of years. Scientists define two carbon cycles: the long term and short term carbon cycle. The short term carbon cycle is caused by biochemical processes. The long carbon cycle is less known and has to do with long-term geochemical processes. Both cycles will be discussed in the next paragraphs.

Short term carbon cycle

The short term carbon cycle begins with carbon dioxide (a gas composed of one carbon and two oxygen atoms) and the process of photosynthesis. Each day, plants absorb carbon dioxide from the air. Through photosynthesis, carbon dioxide plus water and energy from sunlight is transformed into food with oxygen given off as a waste product. Chemists write equations for different types of chemical reactions. The equation for photosynthesis looks like this (equation 1) :

$$6CO_2 + 6H_2O + \text{energy from sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$$

Equation 1 Carbon dioxide, water, and energy from sunlight are turned into glucose (a sugar) and oxygen through photosynthesis.

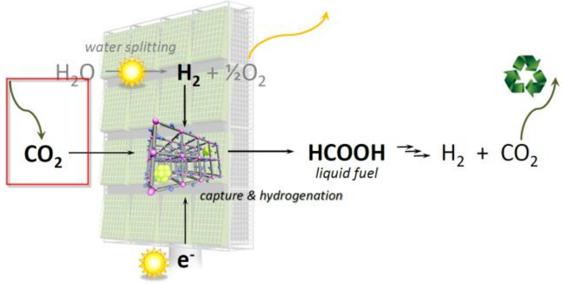


Figure 6 The role of carbon in the process

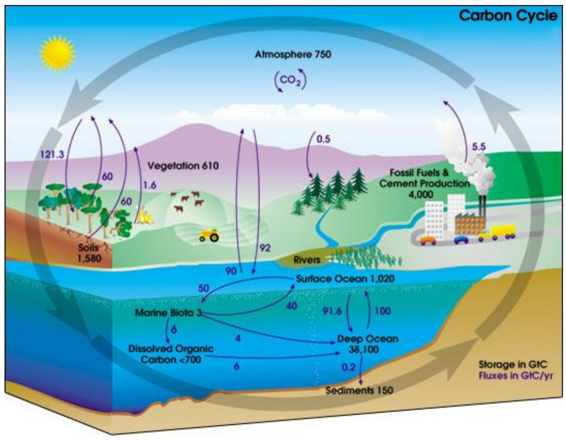


Figure 7 This diagram of the carbon cycle shows some of the places a carbon atom might be found.

The amazing transformation that has happened here is changing energy from sunlight into chemical energy that plants and animals can use as food (figure 7). Through the food chain, this carbon moves into all other living things.

Question 1

Describe the short term carbon cycle in a drawing and write the corresponding equation of photosynthesis.

Question 2

How can carbon return very quickly back into the atmosphere?

We can use the energy stored in plants in other ways too. Scientists are interested in biomass energy for things such as fuel for your car (figure 8). Biomass can be found all over the world and there is an endless supply since it can keep growing. Things such as corn stalks that are leftover from harvesting, and forest brush that may cause a fire hazard, can be converted into fuels. These biomass fuels burn cleaner than gas or oil does, so it is also better for the environment.

Long Term Carbon Cycle

As described above, an individual carbon atom could cycle very quickly if the plant takes in carbon dioxide to make food and then is eaten by an animal, which in turn breathes out carbon dioxide. Carbon might also be stored as chemical energy in the cells of the plant or the animal. If this happens, the carbon will stay stored as part of the organic material that makes up the plant or animal until it dies. Some of the time, when a plant or animal dies, it decomposes and the carbon is released back into the environment. Other times, the organic material of the organism is buried and transformed over millions of years into coal, oil, or natural gas. When this happens, it can take millions of years before the carbon becomes available again.

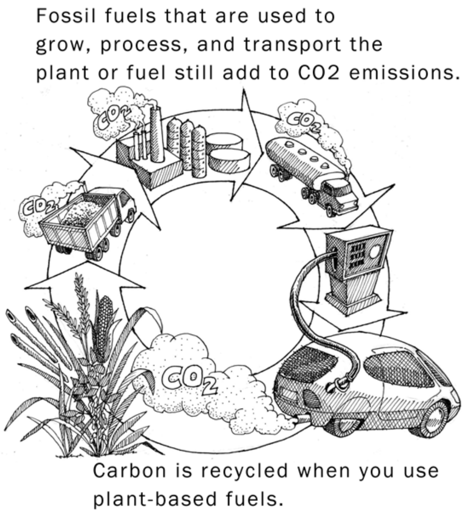


Figure 8 Carbon is recycled when you use plant-based fuels. Plants use carbon from the air to make oils, sugars, and cellulose that humans turn into fuels. When these fuels are burned, the carbon goes back into the air as carbon dioxide that other plants then absorb to make oils, sugar and cellulose.

> **Question 3**
> Name two ways that carbon is stored for a very long time in the natural cycle.

Carbon Sinks and Carbon Sources

We can think of different areas of the ecosystem that use and give back carbon as carbon sources and carbon sinks. Carbon sources are places where carbon enters into the environment and is available to be used by organisms. One source of available carbon in the environment happens when an animal breathes out carbon dioxide. So carbon dioxide added to our atmosphere through the process of respiration is a carbon source. Carbon sinks are places where carbon is stored because more carbon dioxide is absorbed than is emitted. Healthy living forests and our oceans act as carbon sinks.

> **Question 4**
> Describe what makes a carbon sink and what makes a carbon source and give an example of each

Human Actions Impact the Carbon Cycle

Humans have changed the natural balance of the carbon cycle because we use coal, oil, and natural gas to supply our energy demands. Remember that in the natural cycle, the carbon that makes up coal, oil, and natural gas would be stored for millions of years. When we burn coal, oil, or natural gas, we release the stored carbon in the process of combustion. That means that combustion of fossil fuels is also a carbon source.

The equation for combustion of propane, which is a simple hydrocarbon looks like this (equation 2):

$$C_3H_8 + 5\,O_2 \rightarrow 3\,CO_2 + 4\,H_2O$$

Equation 2 The Combustion of propane involves propane and oxygen reacting to become carbon dioxide and water.

The equation shows that when propane burns, it uses oxygen and the result is carbon dioxide and water. So each time we burn a fossil fuel, we increase the amount of carbon dioxide in the atmosphere. Another way that carbon dioxide is being added to our atmosphere is through the cutting down of trees. Trees are very large plants, which naturally use carbon dioxide while they are alive. When we cut down trees, we lose their ability to absorb carbon dioxide and we also add the carbon that was stored in the tree into the environment. Healthy living forests act as a carbon sink, but when we cut them down, they are a carbon source.

> **Question 5**
> Name two ways that humans interfere with the natural carbon cycle.
>
> **Question 6**
> What are the implications of taking carbon from the long term cycle and adding it to the short term cycle?

Importance of the Carbon Cycle

You may wonder why scientists study the carbon cycle or why we would be concerned about such small amounts of carbon dioxide in our atmosphere. Carbon dioxide is a gas that can act like a greenhouse (figure 9). In our atmosphere, it helps hold some of the sun's energy within the earth's biosphere and keeps our planet at a liveable temperature. Increasing the level of carbon dioxide in our atmosphere causes our planet to hold more of the sun's energy within the earth's biosphere. This appears to be increasing the average temperature of the earth. (People refer to this as Global Warming.) This may also be altering the earth's climates in unexpected ways. (People refer to that as Global Climate Change.)

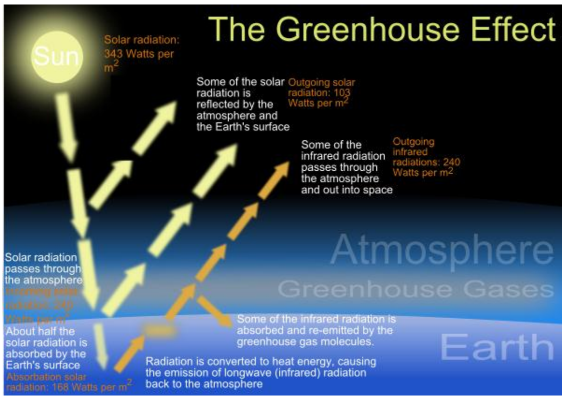


Figure 9 This diagram explains the role of greenhouse gases in our atmosphere.

Question 7
Is global warming something that could impact you in your lifetime?

Question 8
Mention the 3 most important greenhouse gases

Question 9
Explain how understanding the carbon cycle helps atmospheric scientists understand and prepare for global climate changes.

Question 10
How could the understanding of the carbon cycle be helpful in designing climate policy to reduce concentrations of greenhouse gasses in the atmosphere?

Question 11
Explain why CO_2 that is the result of the combustion of biomass does not necessarily contribute to climate change.

Vocabulary

Carbon sink: an area of an ecosystem that has absorbed more carbon dioxide than it has produced.

Carbon source: an area of an ecosystem that emits more carbon dioxide than it absorbs.

Greenhouse gas: gases like carbon dioxide that absorb and hold heat from the earth's infrared radiation.

Global warming: warming of the Earth brought about by adding additional greenhouse gases to the atmosphere.

Photosynthesis: the process using carbon dioxide, water, and energy from sunlight by which plants and algae produce their own food. Although algae are plants as well, it's part in the carbon cycle is so big, it is worthwhile mentioning algae separately.

HOMEWORK ASSIGNMENT: THE CARBON CYCLE GAME

In this interactive game, you are going to play the role of carbon atoms. You will travel through the carbon cycle. For information to help you with this assignment, read:

1. The animation found on the website: http://www.windows.ucar.edu/earth/climate/carbon_cycle.html
2. Resources you find by entering the term "carbon cycle" into a search engine such as Google.

Write a creative story about your trip through the carbon cycle. Include information about:

- Where you went,
- How you got to each destination, and
- What happened to you while you were there?

Your story must meet the following criteria:

- Your carbon atom must complete a cycle. In other words, it must end in a location similar to where it started.
- Your carbon atom must spend time at least once in each of the following locations:
  - ✓ The atmosphere
  - ✓ A living thing
  - ✓ The ocean
- Each time your carbon atom moves, describe what caused it to move.
- For each location your carbon atom goes to, identify whether the compound your carbon atom is in, is in a gaseous, liquid, or solid state.

What you will learn:
In this lesson the basic concept of light is treated. After this lesson you will know more about light in general and you know that there is energy in light.

Light sources

You probably know that light isn't always around. If you wake up in the dark you have to search for a light switch or a flashlight so you can see what is going on around you. These things weren't always around and people made lighted candles to see during the night. During the day the light that we see is radiated from the sun. If something emits light we call it a light source.

Question 1
Name five sources of light.

Seeing things

In everyday life we see a lot of things around us. In order to see light must reach our eyes and then our brains can processes this light in order to make a picture from it. However not all of the things we see emit light and still we can see them. You might wonder how is this possible. The answer is very simple: light is reflected from surfaces of objects and after that it travels to your eye. We now know there are two ways for light to reach your eye:

Light source → eye
Light source → surface reflection → eye

It is due to these reflections that people are able to see different colours. Light from the sun contains every possible colour. When light is reflected not all colours are reflected and therefore some objects appear blue and others appear red. An example of an object that doesn't emit light but only reflects light is the moon.

Figure 10 The reflection of sunlight on the moon

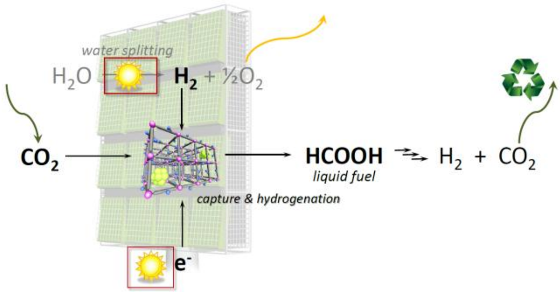


Figure 11 The role of light in the process

Question 2
Think of a reason why people know that the moon isn't a light source.

What is light?

What is light? This question kept a lot of physicist busy during the 17th century. One argued that light would be some sort of particle. The other argued that light would be some kind of wave. Now why would they say such a thing. The statement of the particle is supported by observations that show light being bended due to the effect of gravitation. This must mean that light has some kind of mass and therefore must be a particle.

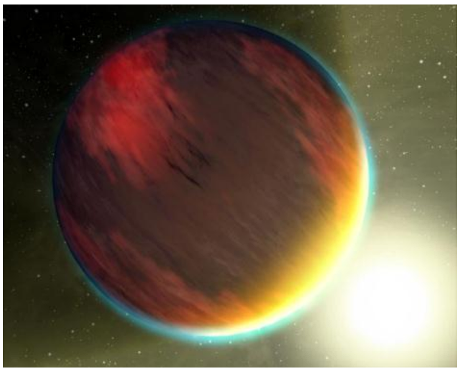


Figure 12 When light travels near a planet it does not travel in a straight line but is bended

However if we shine a beam of light through a double slit we see an interference pattern as shown in figure 13.

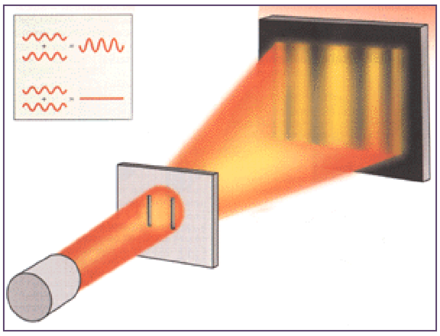


Figure 13 Interference pattern of a laser beam through a double slit

This interference pattern is the same as would arise when two bricks are thrown into the water. These bricks would create wave circles as can be seen in figure 14. In some points the waves amplify each other, while at other points they cancel each other. This phenomenon can't be explained by seeing light as particles.

Figure 14 Interference pattern in water

So what is light? Is it a particle or is it a wave or is it even something else? The answer is: we don't know exactly. Physicist have agreed to see light in the way that is easiest for their calculations. So if we for example want to do calculations with gravitation we see light as particles and if we want to know the interference pattern we do calculations as if it is a wave.

The name physicist have given to the light "particles" is: ***photons****.*

Properties of light:

It takes a certain time for light from to sun to reach the earth. Therefore light must have a finite velocity. This velocity is determined to be:

$$c = 3{,}00 \cdot 10^8 \text{ m/s} \qquad (= 300.000 \text{ km/s})$$

Light can be described as a wave and therefore light must have a wavelength λ and a frequency f. The relation between these properties is:

$$f = \frac{c}{\lambda}$$

You can heat things by shining light on them. For example when a sportsman wants to relax his muscles he uses an lamp that shines infrared light on them. This helps the muscles heat up and relax. Therefore light must poses a certain energy E. This energy E can be related to the frequency as:

$$E = h \cdot f$$

h is called '*Planck's constant*' and $h = 6{,}63 \cdot 10^{-34}\ \text{J} \cdot \text{s}$

Question 3
Calculate the frequency of light with a wavelength of 760 nm.

Question 4
Calculate the energy of light with a frequency of: $4{,}0 \cdot 10^{14}$ Hz.

Question 5
Calculate the energy of light with a wavelength of: 400 nm.

Question 6
Determine which light has the highest energy red or blue and explain why.

A way to see the energy of light is the photoelectric effect. The photoelectric effect occurs when light shines on a surface. In some materials (but not all material) electrons can escape from the material due to energy they get from the light. This effect is called the photoelectric effect. As mentioned before this doesn't happen with every material. Every material has its own ***binding energy*** which is the minimum energy an electron needs to absorb in order to escape from the material. If the electron absorbs more energy than the binding energy, this energy will give the electron a certain velocity, and thus kinetic energy. To understand the photoelectric effect the following questions need to be answered with the uses of the applet that can be found at: http://phet.colorado.edu/en/simulation/photoelectric . This applet looks like figure 4. In the applet photoelectric created electrons are used to close a current loop. The current can be viewed in the display. The lamp that is used to free electrons can be controlled by setting the intensity and wavelength of the light. You will see electrons leave the material as blue dots. In the control panel on the left a material can be selected, some graphs can be shown and you can choose to only view the electrons with the highest energy. Also a battery is present which creates a voltage difference between two parts of current circuit.

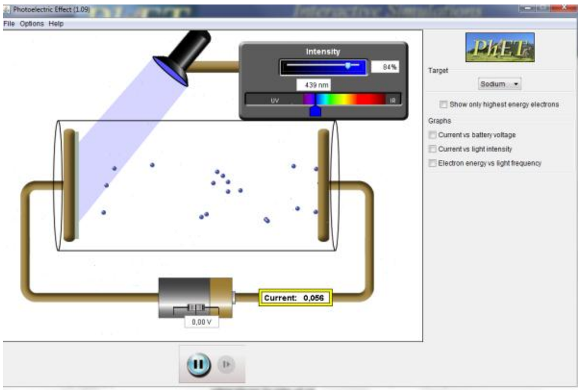


Figure 15 Photoelectric effect Java applet

Question 7

Answer the following questions using the before mentioned applet:

a. How can electrons be accelerated using the battery?
b. What happens to the emitted particles when the wavelength becomes larger?
c. How can you see for which wavelengths particles have higher energies?
d. Does the intensity influence the energy of the light? And if so, how?

What you will learn:
- ✓ What a solar cell (photovoltaic cell) does
- ✓ How much energy there is in the light directly available to us.

In this lesson a basic introduction to the workings of a photovoltaic cell is given. In order to do that, some new concepts must be introduced. It is not necessary to fully comprehend these concepts or to do complicated calculations. The exercises indicate the level of understanding that is required.

What is a photovoltaic/solar cell?

In everyday use the word 'photovoltaic' is often omitted and we speak of a 'solar cell'. Strictly speaking the two terms are not interchangeable as there are other kinds of solar cells than photovoltaic cells. It has become so common practice however to just say 'solar cell' that we will not be strict about it.

A photovoltaic cell is a device that converts light into electrical energy.

As we have seen in lesson 3, light is a form of energy and consists of particles called 'photons'. The concept that light can be converted into other forms of energy is not new. As, for example, we are all familiar with the fact that sunlight feels warm as light is begin converted into heat. The direct conversion from light into electrical energy is more complicated however.

One might wonder 'What is electrical energy anyway?'. In this context it is the ability to let charged particles flow through a device.

Power plants generate electrical energy, and when you hook up, for example, a vacuum cleaner the current that will flow through that vacuum cleaner enables it to work.

Question 1
What particles make up the current used in everyday devices?

How is a photovoltaic cell constructed?

A photovoltaic cell can be made of different kinds of materials, as long as these materials have certain properties. The material used most is crystalline silicon

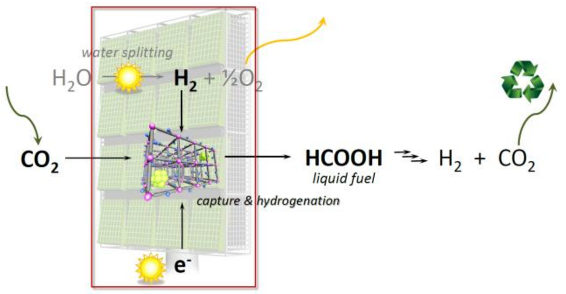


Figure 16 The role of solar cells in the process

(c-Si) with the addition of certain elements to obtain the wanted properties. In figure 17 an example of a silicon based cell is shown.

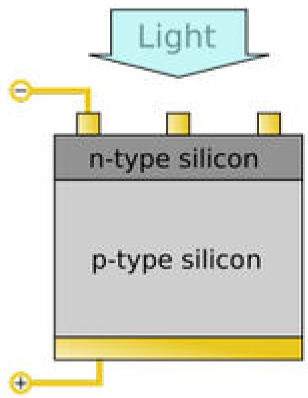


Figure 17 A silicon based photovoltaic cell

The most important property of a photovoltaic cell is that electrons <u>that can move freely</u> are drawn towards the N-type material. This is due to a <u>natural electric field</u> that is present on the border between the N-type and the P-type material.

Question 2
Give the description of an N-type and a P-type material in less than four lines

Question 3
What is an electron-pair hole?

How does a photovoltaic cell work?

To convert light into electrical energy there needs to be a link between light particles (photons) and charged particles that flow.

One might be tempted to think photons are transformed into charged particles. Such a thing is not possible!!!

Due to the materials used in a photovoltaic cell, there is always an electric field present inside the cell at the border between the N-type and the P-type material. If we connect the solar cell to a device, this electric field can cause a current to flow and thus provide electrical energy.

So why do we need light at all? Only charged particles that can move freely in the photovoltaic cell can be used for this process. However, most electrons are bound by atoms and can't move freely. Without light there are simply not enough of electrons (and holes) that can move freely to be of any use. The role of light is then to free electrons from there atoms.

The freeing of electrons costs energy and light provides that energy.

So what happens in a photovoltaic cell:

1. Light penetrates into the solar cell.
2. Bound electrons in the p-type material absorb that light and become free.
3. These free electrons get drawn to the n-type material due to the natural electric field in the cell.
4. The free electrons can be used by an electrical device hooked up to the solar cell.

Question 4
Find some pictures of solar cells. Explain what part of the visible spectrum is best absorbed.

Question 5
What is the formula for the energy of a photon?

Question 6
How much Joule is 1 electron volt (eV)?

Question 7
How much energy (in Joule) does a bound electron in silicon need to absorb to become free? *Note: - This energy is called the band-gap of silicon.*

Question 8
What is the maximum wavelength a photon needs to have in order to free an electron in silicon?

Question 9
Consider this statement: '*A blue photon is able to free more electrons than a red photon*'. Explain whether you agree or not.

Is there enough energy in sunlight?

Before we even consider the use of direct solar energy we first have to estimate whether it will be profitable to do so. An estimation doesn't need to be exact, as long as we get numbers that approximate reality.

The worlds electrical energy consumption is about $20 \cdot 10^{12}$ kWh per year (20.000.000.000.000 kWh).

Let's say the solar energy at the earth's surface is 1000 W/m^2 and the average number of hours of sunlight is 6 hours per day. In these assumptions we already accounted for all kinds of effect, for example clouds, seasonal changes etc.

Modern solar cells are capable of producing electrical power at about 30% efficiency. That means that 30% of the sunlight at the earth's surface is converted into electrical power.

At this moment 30% is only achieved under optimal conditions, in real world applications we have to consider effects that decrease this efficiency drastically. In the following exercises assume a photovoltaic cell has an efficiency of 15%.

Question 10
What is the definition of 1 kWh?

Question 11
What area of photovoltaic cells is needed to produce the total worlds electrical energy consumption?

Tip! Answer these questions first:
- How many hours of sunlight fit in a year?
- How much energy does a photovoltaic cell (15% efficiency) of 1 square meter produce in a year?

Question 12
Compare this to the area of Germany

Question 13
Does this quite rough estimate justify the research and development of photovoltaic cells?

Preparation:

- ✓ Before you start the next lesson about electrolysis, you have to find out some more information about the subjects below.

Space Shuttle

The Space Shuttle needs an enormous amount of energy to escape from the earth's gravity and go into an orbit around the world. This energy is provided by the rockets boosters which are located on either side of the rusty orange-coloured external propellant tank.

Figure 18 The Space Shuttle and the rocket boosters

In figure 18 you can see the white solid rocket boosters (SRB's) and the orange external tank (ET), on which the shuttle is mounted. The solid rocket fuel is used up within 2 minutes after launch and provides about 80% of lift-off thrust. The other 20% is provided by the fuel in the external tank. The external tank supplies this fuel to the three main engines of the Space Shuttle.

Figure 19 shows the dimensions of the external tank. The fuel in the SBR's and in the ET have to bring the Space Shuttle into orbit.

Figure 19 The External Tank (ET) of the Space Shuttle

Question 1

a. Find out which fuel is in the external tank (ET).

b. Which reactants are used and which products are produced during the combustion of the fuel? Write down the (simple) chemical reaction equation.

c. Find out what the combustion energy (enthalpy) is of the component that is being burned (oxidized) in $J \cdot m^{-3}$ or $J \cdot mol^{-1}$.

Question 2

During the next lesson you have to identify some gasses that will be produced. Therefore it is important for you to recollect what you still know about the determination of some gasses.

How can you determine the following gasses:

a. Carbon dioxide: $CO_2(g)$

b. Hydrogen: $H_2(g)$

c. Oxygen: $O_2(g)$

d. Sulphur dioxide: $SO_2(g)$

e. Chlorine: $Cl_2(g)$

Figuur 1 Artist's impression van de Space Shuttle

After this lesson:
- ✓ You can explain what electrolysis is and how it works;
- ✓ You know the role of electrolysis in the process;
- ✓ You know what happens during the electrolysis of water.

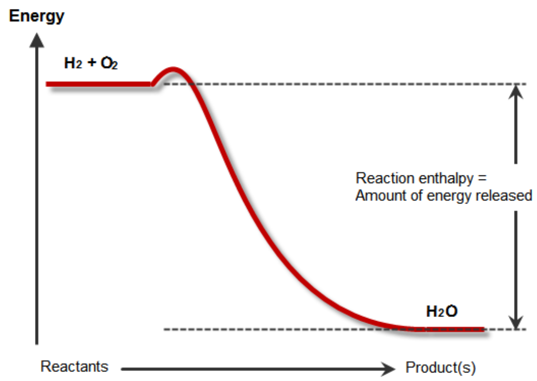
Water

Without water life on earth would be impossible. Water is therefore the most important substance on the planet. The human body consists of approximately 70% water. Unfortunately water does not contain a lot of energy so we cannot use it as a fuel. We even use water to extinguish fires.

The Space Shuttle and water

During the preparation for this lesson you saw that hydrogen (H_2) and oxygen (O_2) together are an excellent fuel. They contain so much energy that it is used to send the Space Shuttle into space. You also saw that the product of the reaction between H_2 and O_2 is water (H_2O) **and** lots of energy. Apparently H_2 and O_2 contain massive amounts of energy, which is released as the low energy product water is produced. This is shown in figure 21.

Figure 21 Energy diagram of the oxidation of hydrogen

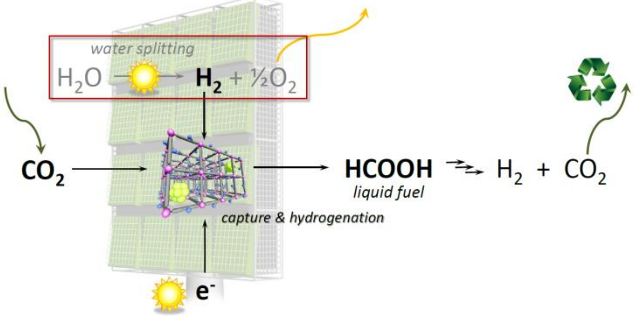


The reverse route

In figure 20 you can see that in the Solar Tree the reverse route is necessary because the key product to be produced is H_2. Instead of producing water from H_2 an O_2, water now has to be split into H_2 and O_2. Instead of freeing a lot of energy by producing water, the splitting of water needs a lot of energy.

The reaction is as follows: $2\ H_2O(l) \rightarrow 2\ H_2(g) + O_2(g)$

Figure 20 The role of electrolysis in the process



Question 1
What *type* of reaction is this?

Electrolysis

During the previous lessons we paid attention to producing sustainable energy in general and electricity in particular. Furthermore you learned about decomposition reactions in previous years: thermo*lysis*, photo*lysis*, electro*lysis (lysis (Gr.) = to separate*).
If you combine all this knowledge things become clear:

1. H_2 is very rich in energy and can excellently be used as a fuel;
2. To produce high energy products (e.g. H_2) you need a lot of energy;
3. Hydrogen (H_2) can be obtained through the decomposition of water (H_2O);
4. Electrolysis is a widely used method to decompose water;
5. Through electrolysis you put a lot of (electrical) energy into a reactant to produce high energy products.
6. The electrical energy will be converted into chemical energy, that can be stored and transported easily.

The Hofmann Voltameter

The German chemist Hofmann (1818-1892) invented the voltameter, an apparatus for electrolysing water (see figure 22). This apparatus is still used to demonstrate the splitting of water by electrolysis. In the next experiment you will investigate how you can best electrolyse water. To determine exactly what happens during the three experiments, you have to know which gasses are produced. During the preparation for this lesson you have recollected your knowledge about the determination of several gasses.

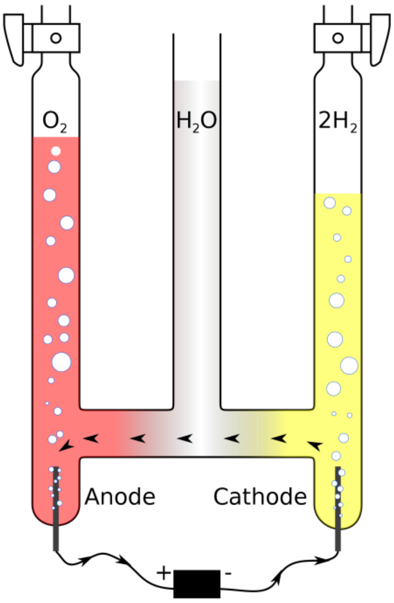


Figure 22 The Hofmann Voltameter: electrolysis of water. In the right tube there is twice as much gas above the liquid than in the left tube.

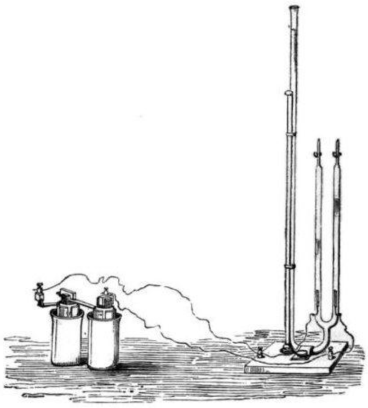


Figure 23 The apparatus from Hofmann's book in 1866

Experiment: electrolysis of water

Do the next three experiments with the Hofmann Voltameter. Every time a gas is produced you have to determine which gas it is. Always write down whether the gas is produced at the (anode(+) or the cathode (-).

1. Fill the voltameter with **distilled or demineralised water**. Turn the voltage of the power source slowly up until gas is produced or until a maximum of 12V. Determine which gasses are produced if any and write down what you have observed. Turn of the power source.

2. Add a small amount (about 10 mL) of a **sulphuric acid** solution 0,1M to the water. Slowly turn up the voltage until gas is produced or until a maximum of 12V. Determine which gasses are produced if any and write down what you have observed. Turn of the power source.

3. Empty the voltameter and clean it. Prepare a solution of sodium chloride of 10 g/L and fill the voltameter with this solution. Slowly turn up the voltage until gas is produced or until a maximum of 12V. Determine which gasses are produced if any and write down what you have observed. Turn of the power source.

Empty the voltameter and clean it.

Question 2
Describe every experiment and name the gasses that were produced.

Question 3
Explain de differences you have observed during the three experiments.

Half reactions

Probably you have concluded that experiment 2 and 3 produced different gasses. You probably also noticed that different gasses are produced at the two electrodes. Apparently another reaction occurs at the anode than at the cathode. That is, of course, not very strange because the cathode had a surplus of electrons and the anode has a shortage of electrons.

Preferably at the cathode (-) a reaction will take place that accepts electrons (there is a surplus).
At the anode (+) however a reaction will take place that wants to give away or donate electrons (there is a shortage).

At the right you see a part of table 48 from BINAS. In this table you can see some of the most common half reactions. These reactions are written in such a way that if you read the reaction from left to right it accepts electrons. If you read the reaction from right to left it donates electrons. This is just an easy way to categorise the reactions and it does not say anything about the direction or the reaction. It are all equilibrium reactions (⇆) so you can just as well read them from left to right as from right to left.

Example
Check the two orange coloured half reactions in the table (first and fifth from below). Suppose we have a beaker filled with a 0,1M sulphuric acid solution (H^+) and some solid lead(IV)oxide (PbO_2(s)) and solid chrome (Cr(s)). A reaction will take place and using the table we can determine with reaction. The complete reaction will always consists out of a half reaction that accepts electrons and a half reaction that donates electrons.

The two half reactions together lead to the following reactions:

$PbO_2(s) + 4 H^+ + 2 e^-$ ⇆ $Pb^{2+} + 2 H_2O(l)$ (3x)
Cr(s) ⇆ $Cr^{3+} + 3 e^-$ (2x) +
$3PbO_2(s) + 12H^+ + 2Cr(s)$ ⇆ $3Pb^{2+} + 6H_2O(l) + 2Cr^{2+}$

This is the standard method of notation of these kind of reactions.

Accept electrons		Donate electrons
$PbO_2(s) + 4H^+ + 2e^-$	⇆	$Pb^{2+} + 2 H_2O(l)$
$ClO3^- + + 6H^+ + 6e^-$	⇆	$Cl^- + 3 H_2O(l)$
$Cl_2(g) + 2 e^-$	⇆	$2 Cl^-$
$O_3(g) + H_2O(l) + 2 e^-$	⇆	$2 OH^- + O_2(g)$
$Cr_2O_7^{2-} + 14 H^+ + 6 e^-$	⇆	$2 Cr^{3+} + 7 H_2O(l)$
$O_2(g) + 4 H^+ + 4 e^-$	⇆	$2 H_2O(l)$
$Br_2 + 2 e^-$	⇆	$2 Br^-$
$Ag^+ + e^-$	⇆	$Ag(s)$
$S_4O_6^{2-} + 2 e^-$	⇆	$2 S_2O_3^{2-}$
$HCOOH + 2 H^+ + 2e^-$	⇆	$H_2CO + H_2O(l)$
$NO_3^- + H_2O + 2 e^-$	⇆	$NO_2^- + 2 OH^-$
$2 H^+ + 2e^-$	⇆	$H_2(g)$
$SO_4^{2-} + 2 H^+ + 2 e^-$	⇆	$SO_3^{2-} + H_2O(l)$
$Pb^{2+} + 2 e^-$	⇆	$Pb(s)$
$Sn^{2+} + 2 e^-$	⇆	$Sn(s)$
$Ni^{2+} + 2 e^-$	⇆	$Ni(s)$
$Co^{2+} + 2 e^-$	⇆	$Co(s)$
$Cd^{2+} + 2 e^-$	⇆	$Cd(s)$
$Fe^{2+} + 2 e^-$	⇆	$Fe(s)$
$2 CO_2(g) + 2 H^+ + 2 e^-$	⇆	$H_2C_2O_4$
$Cr^{3+} + 3 e^-$	⇆	$Cr(s)$
$Zn^{2+} + 2 e^-$	⇆	$Zn(s)$
$2 H_2O(l) + 2 e^-$	⇆	$H_2(g) + 2 OH^-$
$Zn(OH)_4^{2-} + 2 e^-$	⇆	$Zn(s) + 4 OH^-$
$Al^{3+} + 3 e^-$	⇆	$Al(s)$

You performed the reactions with the Hofmann voltameter and analysed which gasses were produced in which experiment. Using the table together with the example you should now be able to write down the complete reaction per experiment.

Question 4
Write down the reaction equation of every experiment in which gasses were produced. Use the example!

You know which gas is produced at which electrode - you wrote that down during the experiments – (+ or -), so you can find the half reactions in the table in the corresponding column. Add these half reaction according to the example to form the complete reaction.

Hydrogen production in practise

Commercial production of hydrogen out of water by electrolysis can be done using several methods. You have seen two methods:

1. Water + inert electrolyte, experiment 2:
   → hydrogen + oxygen
2. Water + electrolyte , experiment 3:
   → hydrogen + chlorine gas

Both methods have pros and cons. Oxygen can be collected and sold or you can let it escape into the air. Oxygen is however very dangerous in regard to fire. Especially in a production facility where a lot of current is used and sparks are likely to occur. Chlorine gas has to be collected. You cannot let it escape into the air. Chlorine is very aggressive and very toxic. You have to take a lot of precautions when working with chlorine gas. On the other hand you can get a good price for chlorine ($300 per ton) compared to oxygen ($30 per ton).

Economic and social aspects

Choosing for a specific production process, you have to take the economics into account like the buying price of the commodities. Method one uses sulphuric acid or another inert electrolyte. Method two uses the quite inexpensive sodium chloride which is a commodity. The selling price of chlorine gas is much higher than that of oxygen. It is important to have a profitable process and company.

But social aspect also play an important role. It all depends on where the gasses will be produced. Environmental organisations will be critical of chlorine production facilities and together with civilians protest against transport of chlorine gas through their neighbourhood. They will demand extra safety measurements which will make the production facility more expensive.
A cheap production process will produce cheap and clean car fuel which makes everybody happy. But what if this process produces potentially toxic waste or side products? What is more important?

Hazard symbols

If you use or transport chlorine gas you have to use the symbols: (oxidising, gasses under pressure, acute Toxicity, hazardous to the aquatic environment).

Figure 24 New Hazard Symbols (COSHH) for chlorine gas

If you use or transport oxygen you have to use the symbols: (oxidising, gasses under pressure).

Figure 25 New Hazard Symbols (COSHH) for oxygen

Figure 26 The yellow chlorine gas in a bottle

After this lesson:

- ✓ That CO_2 is not just a waste product but one of nature's most important building blocks;
- ✓ Why pure and high concentrated CO_2 is important for efficient use;
- ✓ How different techniques can be used to extract CO_2 from the air.

Carbon dioxide as building block

We must not forget that although the rise of CO_2 concentrations in the atmosphere is a threat to the environment, CO_2 is also one of the most important building blocks in nature. It is uses by plants and algae during photosynthesis to produce glucose. The glucose is then used by the plant to 'fuel' all the other processes taking place inside the plants. Not only plants use carbon dioxide we also use it to produce plastics.

Question 1
Lookup the general reaction for photosynthesis in with CO_2 is turned into glucose

Farmers that use greenhouses understand the photosynthesis process very well and the try to create excellent conditions for plants to grow. They found out that increasing the carbon dioxide concentration in the air helps the plants to grow even better. Nowadays exhaust gasses containing carbon dioxide from fossil fuelled power plants are transported to greenhouses were it is used to help plants grow.

Concentration and speed of reaction

The reason why plants grow better when CO_2 concentrations are higher is because the photosynthetic reaction is speeded up. This is not only the case for the photosynthetic reaction but is generally the case for all chemical reactions. If the concentration of reactants is

Figure 27 Greenhouses with a higher CO_2 concentration have a higher yield

increased the rate at which the reaction takes place is also increased. This is explained in figure 28 where two molecules of NO_2 react to form one molecule of NO and NO_3.

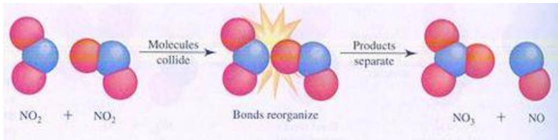


Figure 28 If more molecules are close together the bigger the change they will collide and react

To achieve this the two molecules of NO_2 have to be near to each other and collide. If the amount (or concentration) of NO_2 is increased the chance that molecules will collide will increase and thus the chance of NO and NO_3 being formed is increased as well. The same holds for plants; increasing the amount of CO_2 available increases the amount of glucose being produced. More glucose means more energy for the plant's growing process and thus better growth.

***In general**: increasing the concentration of reactants in a chemical reaction increases the speed (rate) of that chemical reaction.*

Capturing CO_2

If we want to use CO_2 in a chemical reaction effectively we will need it in large and concentrated amounts. One way of getting large amounts of getting if from the exhaust of fossil fuelled power plants. This carbon dioxide can then be converted into methanol. This can be used as a fuel for cars with a combustion engine. This will however not reduce the amount of CO_2 greenhouse gas produced.

Question 2
Why will using CO_2 from power plants not help to reduce the global greenhouse effect?

If we want to reduce the amount of CO_2 in the atmosphere effectively we will have to find ways to take away CO_2 that is already present in the atmosphere. Different techniques to do so are now being developed. We will discuss two of those techniques here:

1. *Artificial CO_2 capture tree*
   Plans already exist to use artificial CO_2 capture trees just like the artificial solar tree that has been discussed earlier. The idea behind this is to lead air with CO_2 through tubes ('branches') filled a solution of sodium hydroxide (NaOH). The carbon dioxide in the air will react with the solution to a sodium carbonate (Na_2CO_3 = soda) solution. This can then be transported and the CO_2 can be taken out and stored.

Question 3

- Give the reaction of CO_2 reacting with a sodium hydroxide solution.
- The artificial solar trees have to be placed at specific angels to the sun. For the artificial CO_2 capture trees this is not important. Explain the difference.
- Why will this method be more effective in reducing CO_2 concentrations in the atmosphere in comparison with CO_2 used from power plants?

Question 4

The biggest problem in extracting CO_2 from the air is that the CO_2 concentration in air is very low: 365 ppm. Calculate how many cubic meter of air is needed to extract one mole of CO_2.

2. *Conventional cooling towers used to capture CO_2 and create energy*
   In figure 29 a conventional cooling tower is sketched that could either provide electricity or CO_2 capture. Water pumped to the top cools the air which causes a downdraft inside the tower. The tower has a 10,000 m^2 opening. Cooling the air to the degree possible in a desert climate would cause - in the absence of obstructions - a downdraft in excess of 15 m/s generating a flow of nearly 15 km^3 of air per day through the tower. The air leaving at the bottom could drive wind turbines or flow over CO_2 absorbers. Based on the volumes of air flowing and the potential energy of the cold air generated at the top of the tower, the tower could generate 3 to 4 MW of electricity after pumping water to the top. The same airflow would carry 9,500 tons of CO_2 per day through the tower. This CO_2 flow equals the output of a 360 MW power plant.

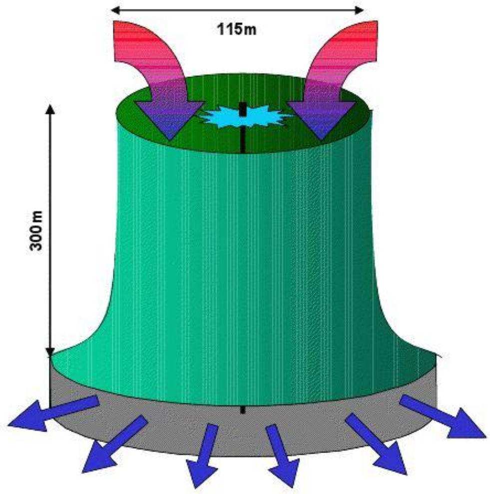


Figure 29 Cooling tower can be used to produce electricity of to capture carbon dioxide

After this lesson:
- ✓ You can explain the role of catalysis in a chemical process in terms of energy;
- ✓ you can explain the role of catalysis in a chemical process in terms of reaction products You know the role of electrolysis in the process;
- ✓ You can relate catalysis to a social context.

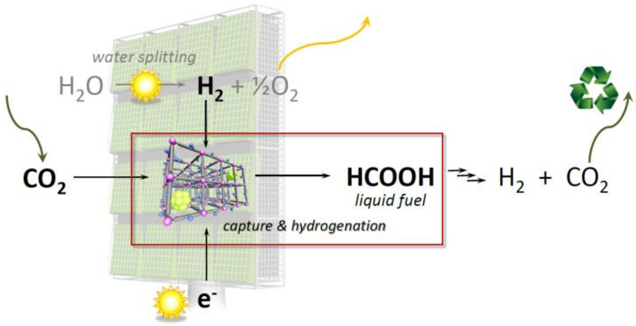


Figure 30 The role of catalysis in the process

What you have learned so far

In lessons 4, 5 and 6 you have discovered how the components, from which the liquid fuel can be made, can be collected and/or produced. You have seen how electrical energy can be generated from solar light energy. Furthermore you have seen how this electrical energy can be used to produce hydrogen from water. Finally you have seen that CO_2 can be collected and concentrated. In this lesson you will discover how the liquid fuel can be synthesized from these components (see figure 30), but first we will get you (re)acquainted with activation energy and catalysis.

Activation energy

In lesson 5 the energy-diagram of the reaction of H_2 with O_2 to form H_2O was shown. The chemical energy within the reactants H_2 and O_2 is higher than the chemical energy within the product H_2O. Energy is therefore released during the reaction. Can you remember the observations you did during the indication reaction of hydrogen gas? This reaction did not run spontaneously. You had to ignite the reaction mixture which means that the gas mixture had to be heated to reaction temperature first. In other words: the reaction had to be activated. This is indicated by the small bump, or barrier, in the energy-diagram, just to the right of the reactants (see figure 21). The height of this barrier is called *"the activation energy"*. This activation energy is caused by the higher energy content of the components, or intermediate products, in this so-called transition state of the reaction. Within this transition state the bonds within the reactants have partially been broken and new bonds have partially been formed.

In this example the bond between the two oxygen atoms of O_2 has to be broken before water can be formed. The energy that is needed to break this bond, attributes to the activation energy. During she second part of the reaction, wherein new bonds are formed, energy is released. The released energy from this exothermic reaction is enough to help other molecules to overcome the energy barrier and to make the reaction run by itself.

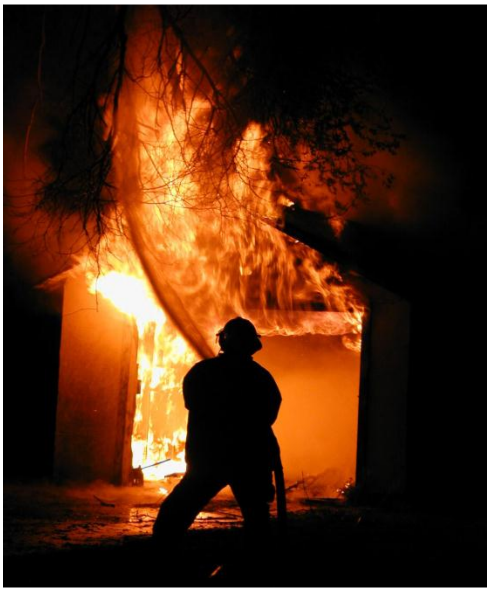


Figure 31 This exothermic reaction produces enough energy to keep itself going (source: korvelo.com)

In an endothermic reaction the energy that is released by going from the intermediate to the final products is not high enough to overcome the energy barrier of other molecules and the reaction will stop when no more energy is added from the outside.

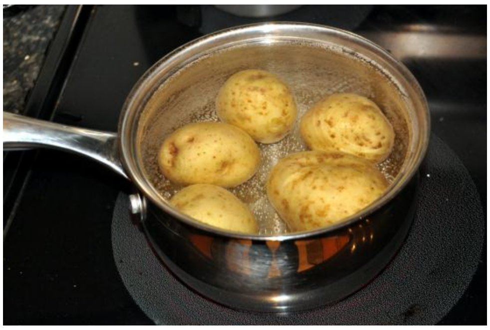


Figure 32 When you stop heating patatoes the endothermic reaction will come to a halt. The patatoes will not be done (source: slovakcooking.com)

Catalysis

As an introduction to this section you can watch the YouTube video on catalysis, made by Southampton University (http://www.youtube.com/watch?v=A_PhvIktMOw).

Figuur 2 Catalysis Introduction video

Besides increasing the temperature (adding thermal energy to the reaction mixture) to overcome the activation energy, a catalyst can be used to increase the reaction rate. The catalyst causes other intermediate products to be formed, causing the activation energy to be decreased. Therefore, at equal temperature, more particles will have enough energy to react.

Example: the respiration system
Think of the respiration system in living organisms in which oxygen is absorbed. The oxygen is used to dissimilate sugars into H_2O and CO_2 while releasing energy. This process is similar to the combustion of sugars, which occurs at much higher temperatures. Catalysts in your body, called enzymes, change the reaction path in such a manner that the reaction temperature is much lower and the 'combustion' reaction can occur within your cells.

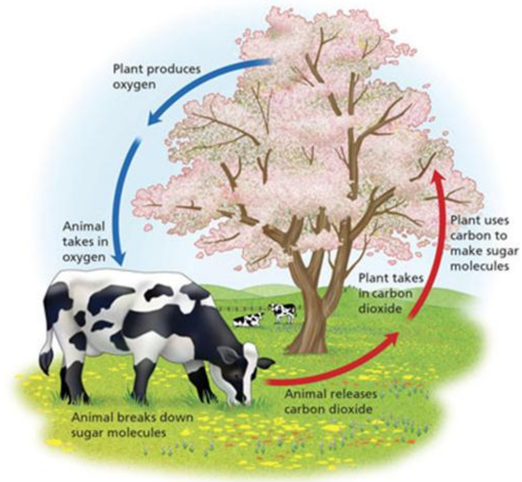


Figure 33 The respiration cycle (source: courtneystanifer.edublogs.org)

CO_2 and water as reactants

Different types of catalysts can result in different reaction paths with different intermediate products and, based on the activation energy of these paths, different products. The selection of the catalyst is therefore an important step in the design of the chemical process.

In this module we want to produce fuel from CO_2 en water.

Question 1
Why is a catalyst needed in this reaction?

Question 2
How do we know that in principle the conversion of CO_2 and H_2O at room temperature is possible?

Depending on the feedstock, reaction circumstances and type of catalysts, many different types of fuels can be made. Al of these fuels have different properties that influence, among others, the safety precautions that have to be taken when working with these fuels, or the possibilities of the fuels to be used in the different types of engines (which will be discussed in lesson 8. We will focus on the following products:

1. Methane
2. Methanol
3. Ethanol
4. DME (dimethyl ether)
5. Formic acid
6. Alkanes

The alkanes are not a single substance, but is a group of substances. Again, depending on the choice of circumstances and catalyst, there is a wide selection of alkanes that can be produced.

Question 3
What is an alkane?

Question 4
Write down the molecular formula and state of each of these fuels. Take propane, octane and cetane (hexadecane) as alkanes.

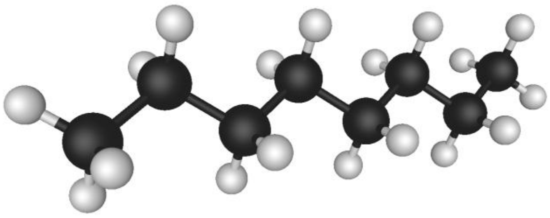


Figure 34 3D-model of an octane molecule

Question 5
write down the balanced reaction equations for the production of the 8 fuels that were mentioned (including the three alkanes of the previous question). Only CO_2 and H_2 are used as feedstock and only H_2O and the selected fuel are produced.

The production of H_2 is the most energy-consuming part of the overall solar-tree process. Therefore, the amount of H2 that is needed, in comparison to the amount carbon dioxide, can play in important role in the selection of the fuel.

Question 6
calculate the CO_2 : H_2 ratio for all products.

Other important influences on the fuel selection might be handling, storage and safety aspects.

Question 7
Explore different resources (like safety data sheets, the internet etc.) and make an overview of the (important) handling, storage and safety aspects of the eight discussed fuels.

After this lesson:

- ✓ You can describe the specific properties of a fuel cell;
- ✓ you can mention an advantage and a disadvantage of a fuel cell;
- ✓ You can relate fuel cells to a social context.

In the previous lesson you have examined several different types of fuel. In this lesson you will take a closer look at the process in which the chemical energy that is contained within the fuels, is converted into mechanical energy. This is the last part of the overall process, as shown in figure 35. In general two methods are available for this conversion process. These are the internal combustion engine and the fuel cell.

The internal combustion engine

The combustion engine can convert fuel into motion of the car. It does this by burning the fuel inside the engine, hence the internal combustion engine. Two types of engines can be distinguished: the diesel engine and the gasoline engine. The working principle of both types of engines is that a small amount of fuel is injected into a combustion chamber. After ignition of the fuel, combustion gasses that are formed, force the piston to move. The movement of this piston is converted into movement of the car.

Question 1
Explain why the produced gasses force the piston to move.

Question 2
What is the main difference between a diesel engine and a gasoline engine (besides the type of fuel that is being used)?

Question 3
What are the efficiencies of both types of internal combustion engines? In other words: how much of the chemical energy is converted into mechanical energy?

The fuel cell

In a galvanic cell, chemical energy is converted into electrical energy. Both batteries and fuel cells are types of galvanic cells. The fuel cell differs from the battery, however, in that the fuel is continuously supplied. This creates an advantage over a battery as it does not have to be recharged but refuelled.

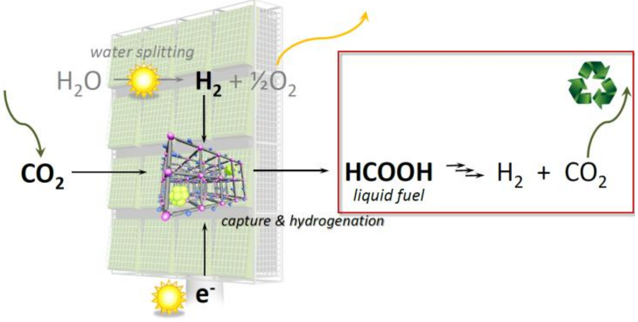


Figure 35 The role of the fuel cell in the process

Question 4
What is the advantage of refuelling over recharging?

In lesson 5 you have seen that some substances can be decomposed into other substances by means of electrolysis. In the case of water, hydrogen and oxygen were produced by sending an electrical current through the water. Two half reactions occurred, one at each electrode. In the same chapter you have seen the reverse reaction, the combustion of hydrogen gas. Although it might not be obvious from the combustion reaction, an electrical current can be produced by this reaction as well. Just as in electrolysis, two half reactions occur in the combustion reaction. By physically separating these two half reactions the electrons that are released in one half reaction can be send through an external wire, thus creating an electrical current, to the other half reaction in which the electrons are absorbed. In figure 36 this process is schematically shown. The (half) reactions that take place in this fuel cell are:

$H_2(g) \leftrightharpoons 2\,H^+ + 2\,e^-$ (x2)
$O_2(g) + 4\,H^+ + 4\,e^- \leftrightharpoons 2\,H_2O(l)$ (x1)
$2\,H_2(g) + O_2(g) \leftrightharpoons H_2O(l)$

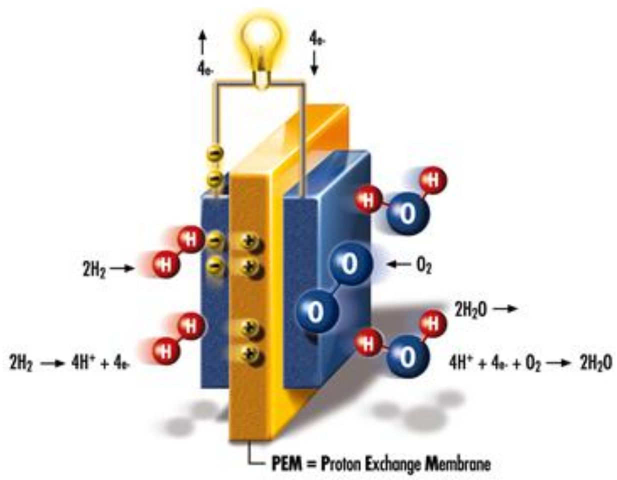


Figure 36 A schematic representation of a hydrogen fuel cell (PEM type). Source: www.h-tec.com/en/h-tec-education/technology/fuel-cells

The first half reaction will occur at the catalyst coated surface at the left side of the fuel cell, indicated by the left blue area. The created H^+ ions (protons), indicated by , migrate through the membrane to the other catalyst coated surface on the right side of the fuel cell. The electrons, however, indicated by , are transported through the electrical wire on the top, where they can deliver electrical energy before arriving at the catalyst on the right. There, the oxygen molecules, hydrogen ions and electrons meet and are combined to form water.

The fuel cell in figure 36 is only one out of many types of fuel cells being developed and produced. All these types of fuel cells differ in catalyst, operating temperature, type of fuel required etc.

Ethanol can be used in both a gasoline engine and a fuel cell. In the first it is combusted directly, while in the fuel cell the half reactions are physically separated.

Question 5
What is the reaction equation for the combustion of ethanol?

Question 6
What are the half reactions and overall reaction, when ethanol reacts with oxygen in a direct-ethanol fuel cell?

Question 7
Compare the combustion reaction of ethanol and the overall reaction in the fuel cell. How can you explain this?

Question 8
What is the efficiency of a typical fuel cell?

Question 9
Explain the difference in efficiency between a fuel cell and an internal combustion engine.

Question 10
Determine in what type of engine(s) the other types of fuel mentioned in lesson 7 (including the three alkanes) can be used. Is it a gasoline engine, a diesel engine or a fuel cell, or perhaps multiple types of engines?

An internal combustion engine costs about € 20 - € 30 per kW. The price of a fuel cell is much higher at the moment. For more information: www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_challenges.html.

Question 11
What part of the fuel cell makes it so expensive?

Question 12
What is the expected price of the fuel cell (in €/kW) for use in the automotive industry in the near future, presuming mass production?

Hint: *this can of course not be determined very precisely. Therefore, do an internet research and use information of reliable resources, e.g. the website on 'Energy Efficiency and Renewable Energy' of the U.S. Department of Energy: www.eere.energy.gov*

After this lesson:

- ✓ You have gained more insight in the use of electrolysis and electrochemical cells in practice;

Furthermore you will be able to answer the following research questions;

- ✓ Is your 'home-made' device suitable to produce a fuel from sunlight and photovoltaic panels?
- ✓ Is your 'home-made' device suitable to produce electrical energy by converting the fuel?

Introduction lab work

You have been given a home-made electrochemical cell (schematically shown in figure 37), that functions both as electrolyser and fuel cell. The protruding bolts serve as contact points for the energy supply and/or the multi meter. The electrolyte (the electrically conductive fluid) can be placed in between the separate transparent cover and the fixed transparent plate that is glued to the bottom plate.

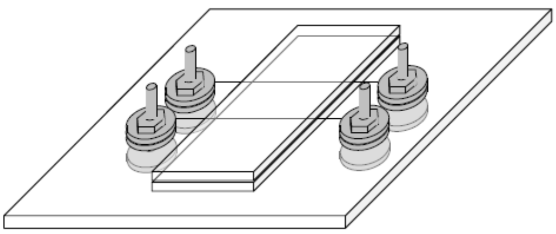


Figure 37 The 'electrolysis and fuel cell device'.

Because we want to do a number of quantitative measurements, you will not use a photovoltaic cell to power the electrolyser, but an adjustable power supply.

Materials

- Home-made electrochemical cell
- Adjustable power supply
- Multi-meter
- 4 measuring cables
- 2 alligator clips
- Stopwatch/timer
- 1,0 M NaCl-solution
- Dropper
- Wash bottle of demineralised water
- Universal pH-paper

Part A – Electrolysis 1,0M NaCl-solution

In this part of the lab work you will electrolyse water using a NaCl-solution as an electrolyte. The gasses that are produced can then be used to produce electrical energy using the same device. That will be done in part B of the lab work.

Experiment

Carry out the following assignment

1. Place three drops of the NaCl-solution on the fixed rectangular transparent plate, in between the two platinum wires, using a dropper.
2. Place a piece of pH-paper at a distance of about two millimetre from each of the two platinum wires, as indicated in figure 38
3. Place a drop of the NaCl-solution on each of the pH-papers.
4. Place the separate transparent plate on top of the fixed plate, as indicated in figure 38
5. Make sure the power supply is off and the voltage is zero...
6. Connect the power supply and the multi-meter to the device, as indicated in figure 38
7. Set the multi-meter at 20 V (the power supply is still at 0 V)
8. Connect the power supply to the power socket and turn it on.
9. Now slowly increase the voltage, until bubbles are formed at the electrodes (hint: do it slowly and watch carefully as small bubbles will be created. The reaction will start somewhere in the range of 2-3 V). Write down the voltage.

Minimum voltage electrolysis NaCl-solution

_______________ V

10. Increase the voltage to 2 V above the minimum voltage and let the reaction run for about 20 s.
11. Set the voltage back to zero, turn off the power supply and disconnect it by disconnecting the alligator clips from the electrolysis device.
12. Write down the observed change in pH at each electrode. Look carefully at the pH-paper. At one of the two papers, the effect will probably only be visible at the edge of the paper.

pH change	pH change
__________	__________

13. What do you smell close to the top plate?

Recognized smell ____

14. Do not take apart the device yet. You still need it in part B!

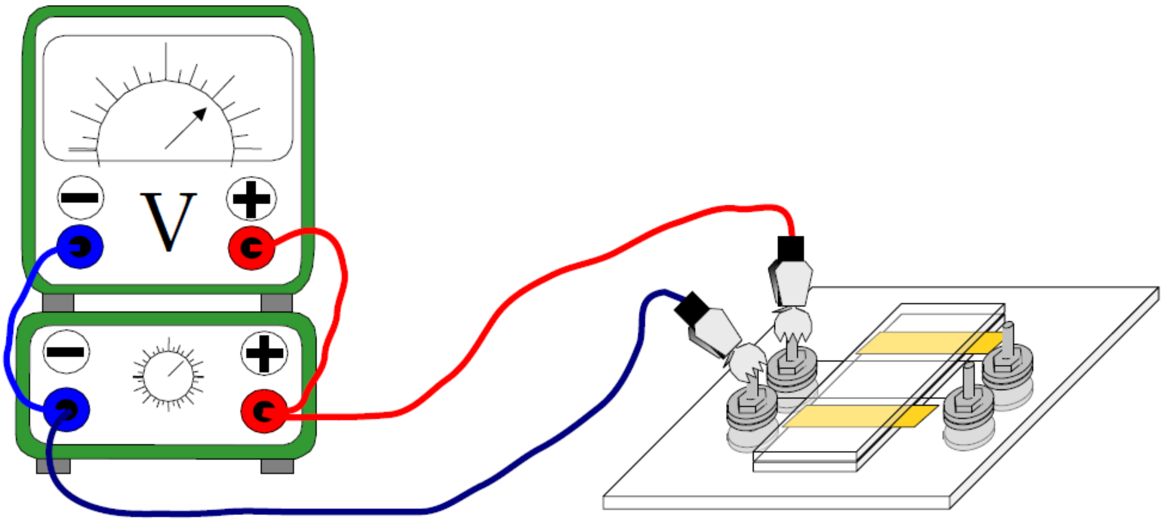


Figure 38 Set-up of the electrolysis device with power supply (bottom), multi meter (top) and pH-paper (yellow strips in between the transparent plates)

Part B – Determining the produced voltage

1. Connect the multi meter, as indicated in figure ....
2. Measure and write down the voltage every 30 seconds for 3 minutes in total.

Time [s]	Voltage [V]	Time [s]	Voltage [V]
0		120	
30		150	
60		180	
90			

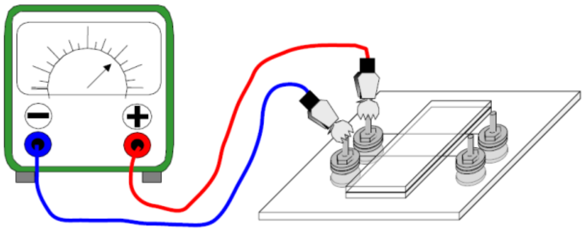


Figure 39 Set-up of the 'fuel cell' with multi-meter

Question 1
At one of the electrodes hydrogen gas was formed. What is according to your observations the other gas that was formed?

Question 2
What half-reactions occur at the electrodes during electrolysis of the NaCl-solution?

Question 3
You have probably noticed that at one of the electrodes the pH rose significantly. Explain which half reaction took place at that electrode.

Question 4
At the other electrode the pH slightly dropped. Explain this drop in pH (***hint**: when the product of the half reaction at this electrode reacts with water, what products are formed?*)

Before electrolysis the voltage over the device was 0 V. After electrolysis a non-zero voltage could be measured. We could thus say that the device was charged or fuelled during electrolysis. We could now use the device to supply a calculator with electrical energy for example.

Question 5
Why would the voltage over the device be zero *before* electrolysis?

Question 6
Why could this device be used to run a calculator but not to charge a phone? (***hint**: compare data from your measurements with data on your calculator and data on the charger or battery of your phone*.)

Question 7
Name two possible solutions you could implement to make the device suitable for charging a phone, while using the same materials for the device and electrolyte (***hint**: how could the voltage be increased?*)

In an electrochemical cell and with electrolysis graphite (carbon) electrodes are often used. The price of graphite is less than € 2 per kg. Platinum costs about € 40,000 per kg. However, we still use platinum wire to serve as electrodes in this device.

Question 8
Why is platinum used instead of graphite?

In part B you measured the open voltage which means that there was no current during the measurement. As there was no current there was no flow of electrons and there were no half reactions. Despite of that, the voltage dropped during the measurement.

Question 9
Explain why the voltage dropped (***hint**: the potential of the chlorine reaction did not change during the measurement, only the potential of the hydrogen reaction dropped over time. What substances are present in the fluid and what is the half reaction for hydrogen?*)

Question 10
If the device was to be developed further into a proper fuel cell to drive a car, what could we do to prevent the voltage to drop? (***hint**: compare the layout of our cell with the 'standard' layout of an electrochemical cell, or Daniell cell*.)

Question 11
Now answer the research questions that were stated at the beginning of this lesson. Clarify your answers.